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Geoscientific
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Discussions

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Interactive
comment

Interactive comment on "A new open-source visco-elastic Earth deformation module implemented in Elmer (v8.4)" *by* Thomas Zwinger et al.

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We thank PingPing Huang for this constructive review. Please, find our response inline to the suggestions:
The module proposed in this article is a good alternative in modeling Glacial Isostatic Adjustment (GIA) because it takes advantage of an open-source and free FEM pack- age Elmer. The article is well written with a clear structure. I can support publishing the article if the author can provide more details of the method and more benchmark tests:
We thank for the generally positive assessment of the reviewer and are grateful for the

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work invested to improve the manuscript.

In section 2, what are the boundary conditions on internal boundaries and external surface for a flat Earth model and how are they implemented in the model ?

The main new aspect introduced in this paper is, that we are solving the complete set of equation over the whole domain and hence do not need to prescribe Winkler foundations. Accounting for layer discontinuities in material parameters is being taken care by the fact that the term – in contrary to the modification of commercial codes, where this only occurs in the body force – is appearing in the system matrix and produces the restoring force as a natural condition. We will expand the current explanation in the text by another sentence: *This means that we are able to impose discontinuities in parameters over elements anywhere in the discretized computing domain without placing Winkler foundation boundaries at layer interfaces. In other words, no boundary conditions have to be set at internal layer boundaries. By including this term in the weak formulation of the problem, the method then automatically applies the needed restoring force on element boundaries with jumps in material properties or gravity, without the need to place boundaries in the mesh.*

For the external boundaries we will add the following paragraph at the end of section 3.3: *We apply zero deformation at the side and the bottom boundaries. At the upper surface, we impose the load as described in the paragraph above.*

In terms of solving Equation (9), what are the detailed form of the test and weighting functions and what is the integration method ?

Indeed, this information was missing. We will add the following paragraph after equation (9):

Equation (9) is solved using the standard Galerkin method with – in the case of the benchmark described in section 3 - first order basis functions. Apart from this particular choice, Elmer provides a variety of possible basis functions left to the choice of the user. The iteration for the viscous contribution is computed on the Gaussian integration points. In case of incompressibility, stabilization has to be applied by the residual free bubble method.

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In section 3. when doing benchmark tests, it is more convincing that if the numerical solution can be compared with the analytical or semi-analytical solution. Therefore, it is good to compare the result from Elmer/Earth with that from normal-mode method for a Heaviside single harmonic load and a flat Earth model.

We do not completely understand the request to test with spherical harmonics in combination with a flat-earth model and would need a detailed layout on a requested additional benchmark in terms of conditions imposed on Elmer/Earth, than currently given by the referee. It is our opinion that from the perspective of testing a flat-earth model, comparison to two other established models is sufficient for this manuscript.

Below are some small issues:

Figure 1 and Figure 2: font size on axises is too small.

We will provide figures with a larger font in a revised version of the manuscript.

Line 148: why does a high viscosity (e.g. 1×10^{44} Pas) in Lithosphere enables an approximately elastic behaviour?

At the centennial timescale of our benchmark, the extreme value of the viscosity ensures that all loads are accommodated by an elastic response of the Lithosphere. Theoretically, this can be explained by an extreme resulting high value of the Maxwell-time (viscous relaxation time) of 10^{33} seconds (10^{25} years). We will insert the following sentence:

This can be justified by the Maxwell-time $t_m = \nu/\mu$ being of the order of 10^{33} seconds (10^{25} years), which indicates that viscous effects in this layer only would be significant at timescales several order of magnitudes larger than the timing of the load signal in our experiment or even on timescales of glacial cycles on Earth.

Why the viscosity of upper and lower mantle are set to be 1×10^{18}Pa s and 1×10^{22} Pa s respectively ?

As the latter value is a commonly used value for the mantle, the relatively low value of 1×10^{18} Pa s for the upper mantle mainly is motivated to speed up the benchmark computation.

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