Developing an open-source 3D glacial isostatic adjustment modeling code using ASPECT

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Models of Glacial Isostatic Adjustment (GIA) processes are useful because they help us understand landscape evolution in past and current glaciated regions. Such models are sensitive to ice and ocean loading as well as to Earth material properties, such as viscosity. Many current GIA models assume radially-symmetric (layered) viscosity structures, but viscosity may vary laterally and these variations can have large effects on GIA modeling outputs. Here we present the potential of using ASPECT, an open-source finite element mantle-convection code that can handle lateral viscosity variations, for GIA modeling applications. ASPECT has the advantage of adaptive mesh refinement, making it computationally efficient, especially for problems such as GIA with large variations in strain rates. Furthermore, ASPECT is open-source, as will be the GIA extension, making it a valuable future tool for the GIA community.

We are building onto the free surface traction cookbook from the ASPECT repository, whose development was lead by Fiona Clerc. A surface traction is applied to the free surface of a viscoelastic 3D box model. In order to compare the numerical deformation results with an analytical solution of a loaded infinite viscoelastic half-space from Nakiboglu & Lambeck (1982), the boundaries on the far side of the load need to be 'open' boundaries. Closed boundaries result in the numerical free surface vertically riding up or down the far boundaries for mass conservation. Daniel Douglas provides an open boundary solution by applying an initial lithostatic pressure along the far boundaries (Fiona Clerc and Daniel Douglas, personal communication, 2020).

We use a 500x500x500 km viscoelastic box model. A quarter cylindrical ice load is applied to the top surface of the box. The free surface allows for tracking topography changes, the open boundaries allow for material to escape such that material doesn't ride up or down the boundary, and free slip means that there is no normal velocity along these boundaries. The ice loading increases linearly to 1.000 years, and remains constant until 10.000 years. The box model and ice loading properties can be found in Figure 1. The deformation results are shown in Figure 2, on the left a cross-section shown for 1.000 year intervals as function of the distance from the load center, and on the right the maximum deformation as function of time.

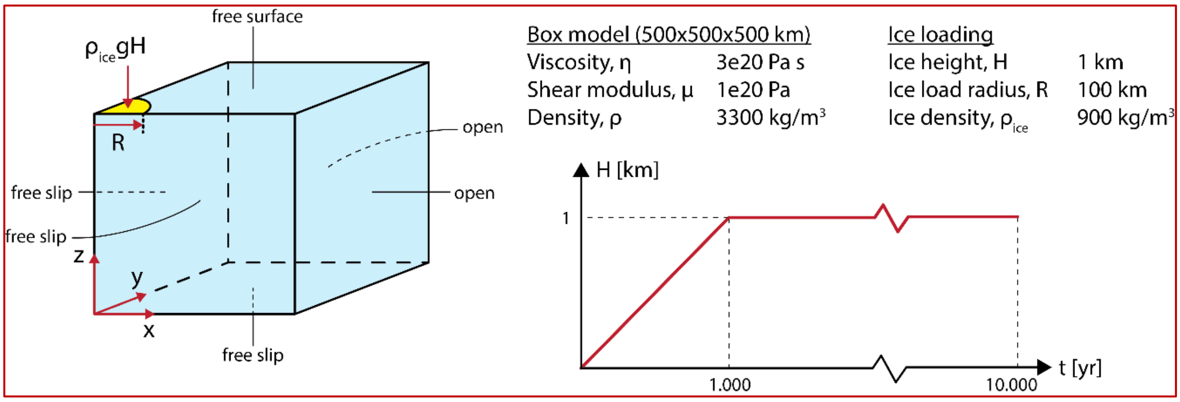

Figure 1: Box model and ice loading simulation set-up.

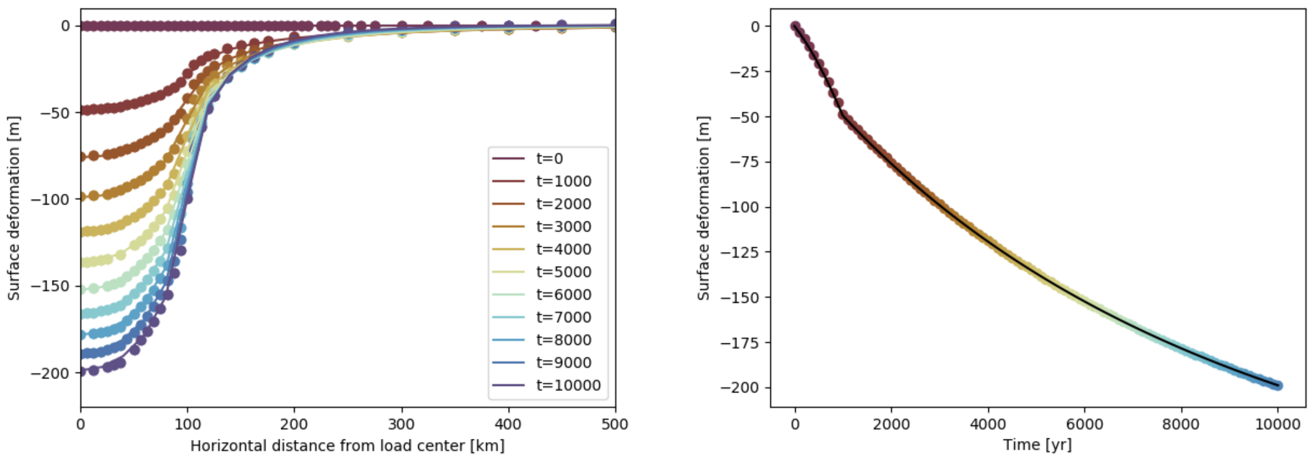

Figure 2: Deformation profiles as function of the distance from the load center shown for 1000 year intervals (left) and maximum deformation as function of time (right). Lines represent the analytical solution and dots the numerical solution.

From figure 2 it can be seen that the numerical and analytical solution agree very well, especially for the maximum deformation through time. The deformation profile at 10.000 years is a little off from the analytical solution. We can get a better agreement by choosing a deeper depth of the model, as the analytical solution assumes an infinite half-space. Furthermore, we can reduce the time step size, which is now maximum 5 years, and we can increase the number of initial adaptive mesh refinements.

In this simulation, there is no peripheral bulge present. For the analytical solution, that is because of the infinite half-space assumption. For the numerical solution, that is because of a combination of parameter values: the depth of the box model, the ice load height and width, and the material properties of the box model. These can be tuned for a peripheral bulge to appear in the deformation solution.

For GIA applications, we need to be able to impose ice loading scenarios above potentially complex earth structures. Here, we show a simulation with a lateral viscosity zone in the viscoelastic material model by adding compositional fields. Compositional fields are useful as they can track the travel path of material. We assign a viscosity of three orders of magnitude larger at x=100 km (the loading edge) to x=500 km. Apart from that, the box model, boundary conditions, and ice loading properties remain the same.

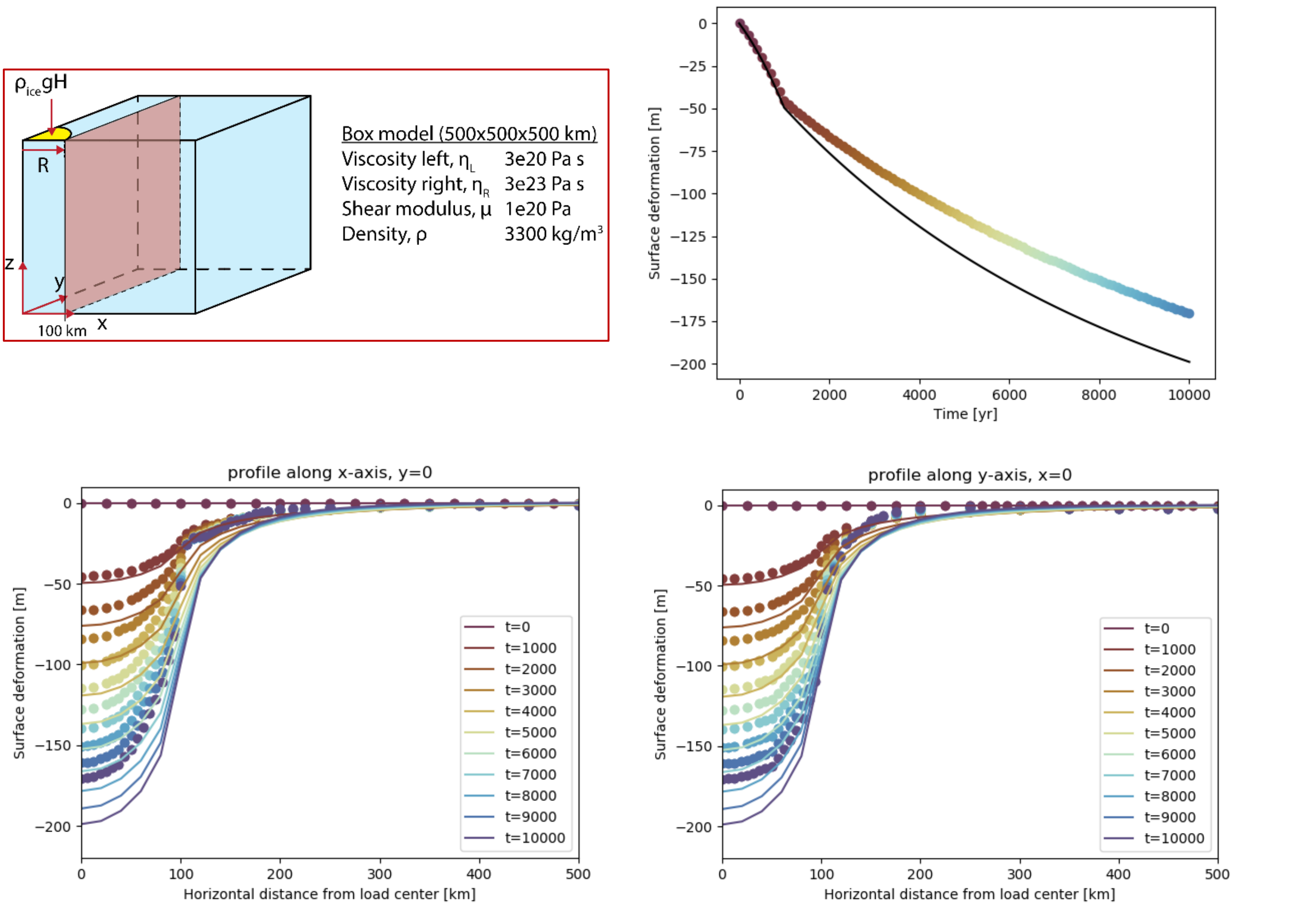

Figure 3: Lateral viscosity zone in box model (upper left), maximum deformation as function of time (upper right), deformation profiles along the x-axis (lower left), and deformation profiles along the y-axis as function of the distance from the load center shown for 1000 year intervals (lower right). Lines represent the analytical solution for the reference case and dots the numerical solution.

Figure 3 shows the deformation profiles for 1000 year intervals along the x- and y-axes of the box model. The analytical solution functions as reference to the previous simulation results. Both cross-sections show a smaller deformation than the reference simulation that does not include a lateral viscosity zone, in Figure 2. The much larger viscosity next to where the load is applied, causes resistance to material flow. This causes the smaller deformations at the load center, as well as the sharp edge at the viscosity boundary at 100 km, where material is pushed upward instead of flowing sideward. These effects are more pronounced along the x-axis, which crosses the viscosity boundary, whereas the y-axis doesn't cross this boundary at all. The deformation results for the cross-sections in between x=0 and y=0 lie in between these two solutions. The smaller deformation is also clearly visible in the maximum deformation as function of time (upper right), for the same reasons. The effects on the deformation are less pronounced when the viscosity boundary lies further away from the load, and when the viscosity difference between the two zones is smaller.

These results demonstrate the possibilities, capabilities, and potential of ASPECT for GIA modeling. In the near future, similar simulations will be performed but with a layered viscosity structure to show that ASPECT can be used for layered Earth models. We will benchmark the GIA extension using a similar case as in Martinec et al. (GJI, 2018), such that the performance of our GIA code can be compared to other GIA codes. In this case, a spherically symmetric, five-layer, incompressible, self-gravitating viscoelastic Earth model is used (Spada et al, GJI 2011). The surface load consists of a spherical ice cap centered at the North pole, and is applied as a Heaviside loading. The ice load remains constant with time. Beyond this benchmark, we will incorporate lateral viscosity variations underneath the ice cap, to demonstrate the ability of efficiently implementing laterally-varying material properties in ASPECT. Furthermore, we will further develop the code with the sea level equation (SLE) and an ocean basin, and will explore ASPECT's current capability of using time-varying distributed surface loads. These functions will allow for modeling of GIA for realistic ice load scenarios imposed above potentially complex earth structures.

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