3D glacial-isostatic adjustment models using geodynamically constrained Earth structures

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Motivation

The interaction between ice sheets and the solid Earth plays an important role for ice-sheet stability, sea-level changes, and global climate dynamics. Glacial-isostatic adjustment (GIA) models can simulate the solid-Earth response due to variations in ice-sheet and ocean loading, which translates into sea-level changes and surface deformation. Because on glacial time scales the solid-Earth response depends on the rheology of the solid Earth, the use of independently determined 3D Earth structures (e.g., from seismic velocities) in GIA models is crucial.

- **Using an ensemble of mantle viscosity distributions, we investigate the influence of 3D Earth structures on sea-level reconstructions.**

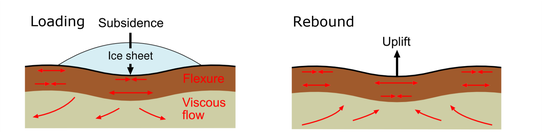

Fig. 1: Principle of glacial-isostatic adjustment (© V. Klemann)

Numerical GIA Models

The **VIscoelastic Lithosphere and MAntle Model VILMA** (Martinec 2001, Hagedoorn et al. 2007, Klemann et al. 2008) calculates the deformation of a viscoelastic and gravitating continuum in spherical domain, where lateral viscosity variations can be considered. Loading is prescribed as ice and ocean mass changes, which are determined consistently with respect to mass conservation, geoid changes and shoreline displacements by the sea-level equation.

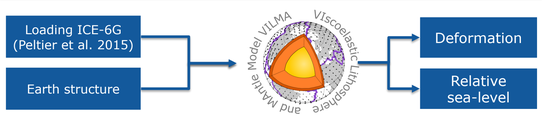

Fig. 2: Input and output of the GIA model VILMA

Validation

To validate our models, we use geological **sea-level data**: 1) Oregon (Central Oregon Coast): 130 data points (Engelhart et al. 2015) and 2) Patagonia (San Jorge Gulf): 32 data points (Rostami et al. 2000, Schellmann & Radtke 2003).

Oregon, Central Oregon Coast

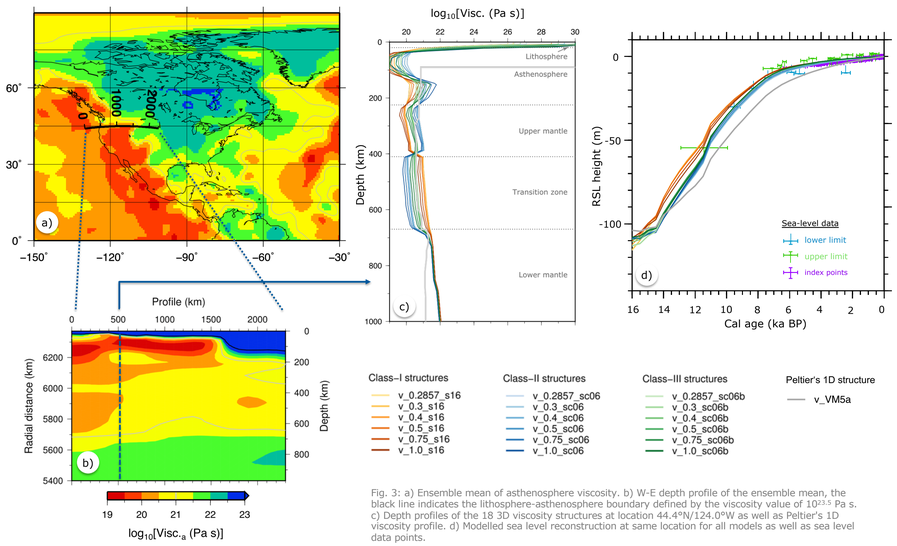

Fig. 3: a) Ensemble mean of asthenosphere viscosity. b) W-E depth profile of the ensemble mean, the black line indicates the lithosphere-asthenosphere boundary defined by the viscosity value of $10^{21.5}$ Pa s. c) Depth profiles of the 18 3D viscosity structures at location 44.4°N/124.0°W as well as Peltier's 1D viscosity profile. d) Modelled sea level reconstruction at same location for all models as well as sea level data points.

Patagonia, San Jorge Gulf

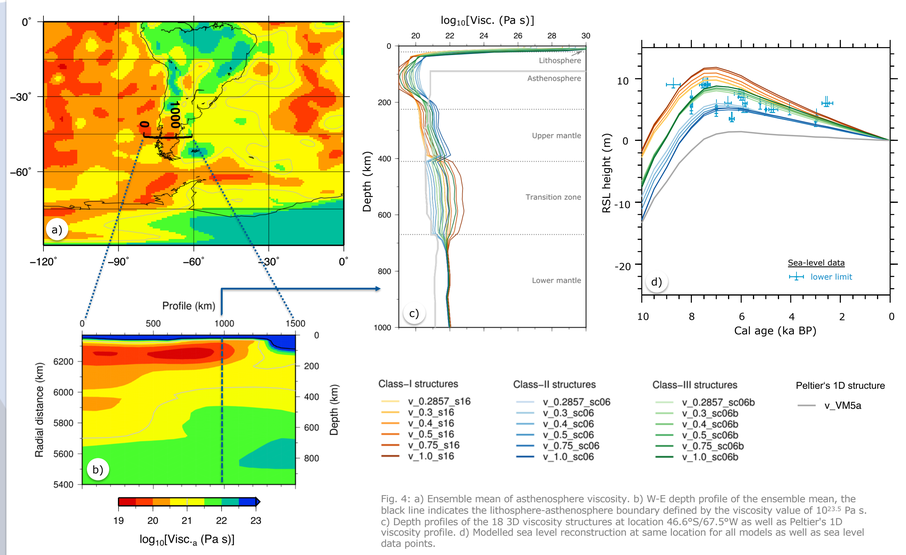

Fig. 4: a) Ensemble mean of asthenosphere viscosity. b) W-E depth profile of the ensemble mean, the black line indicates the lithosphere-asthenosphere boundary defined by the viscosity value of $10^{21.5}$ Pa s. c) Depth profiles of the 18 3D viscosity structures at location 46.6°S/67.5°W as well as Peltier's 1D viscosity profile. d) Modelled sea level reconstruction at same location for all models as well as sea level data points.

Earth Structures and Variations

We present **18 3D Earth structures** (Figs. 3+4) derived from seismic tomography models (Schaeffer & Lebedev 2013, Grand 2002, Steinberger 2016, Steinberger & Calderwood 2006). The conversion of seismic velocity variations into viscosity variations depends on transfer functions and is affected by uncertainties. The ensemble of 18 3D Earth structures differs in this respect

- in the radial viscosity profile (variation between classes)
- in the reduction factor *r* of the Arrhenius law (variation within classes).

For comparison, we also apply the 1D Earth structure VM5a (Peltier et al. 2015).

Oregon and Patagonia

The choice of a 3D Earth structure instead of a radially symmetric 1D Earth structure is particularly important in regions with strong lateral variation, which is why we examine the regions of the Cascadia subduction zone (Oregon, Fig. 3) and the San Jorge Gulf (Patagonia, Fig. 4). Both regions show strong viscosity contrasts and are located in close distance to formerly and partly recent glaciated areas.

Results and Conclusion

- The comparison of the predicted sea-level curves with observational data (sea-level indicators) shows that 1D models underestimate sea-level rise during the Late Pleistocene in Oregon and Patagonia.
- In general, the 3D models better fit the observational data, although the uncertainties considered in the derived viscosity structure can lead to RSL deviations of several meters within the last 10,000 years.
- In both regions, the radial viscosity profile s16, which is associated with low viscosities in the asthenosphere and upper mantle and with high viscosities in the transition zone, predicts highest RSL. The effect of the reduction factor shows a more complex behaviour. In Patagonia, highest RSL is predicted for *r*=1.0 in Class-I and lowest RSL for *r*=1.0 in Class-II, while in Oregon, the behaviour is vice versa.

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This study is submitted as:
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