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Recent advances in the modelling of glacial isostatic adjustment: A report from the IAG Joint Study Group on "Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment"

INTRODUCTION

- Glacial isostatic adjustment (GIA, Fig. 1) is a process that drives a dynamic present-day displacement, gravitational changes, rotational parameters, stress state, and sea-level, both in the open ocean and at coastal environments
- Several areas around the world see the ongoing land-uplift in the vertical GNSS velocities (see Figs. 2 to 4)
- Computation of forward and inverse GIA models is critical to proper simulate past, recent, and future changes in Earth's topography, gravity, rotation, stress state, sea-level, and the stability of the reference frames
- Establishment of an IAG joint study group in 2019 to create a dialogue between various disciplines to better inform the implementation of state-of-the-art Earth models and quantify their influences on geodetic observations
- GIA models are needed to correct the GNSS velocities in several areas around the world to allow the usage of the affected stations, for example, in plate motion models (Vardić et al., 2022) and reference frame calculations (Kierulf et al., 2014)

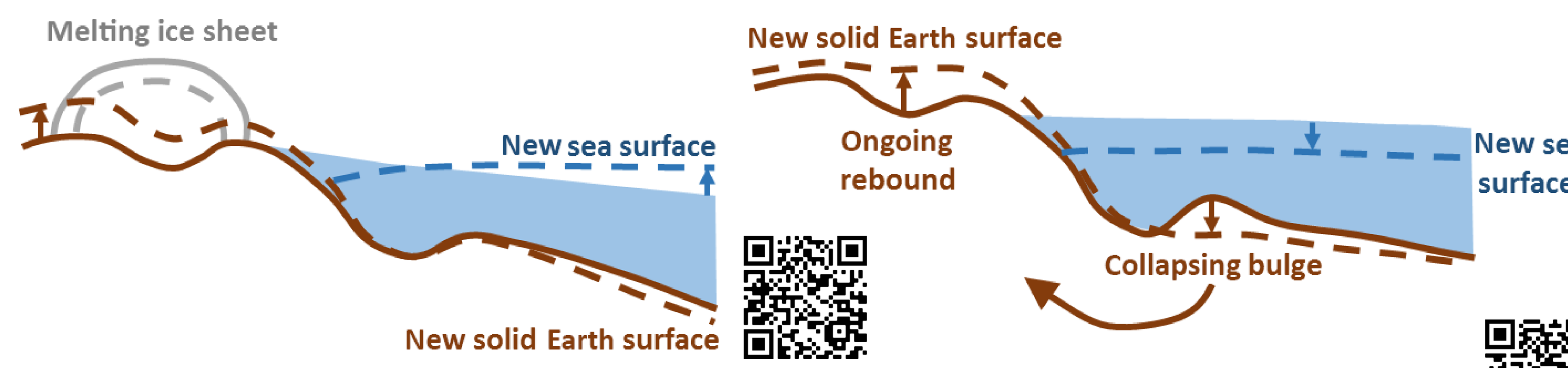


Figure 1. Schematic overview of the GIA process (Whitehouse, 2018).

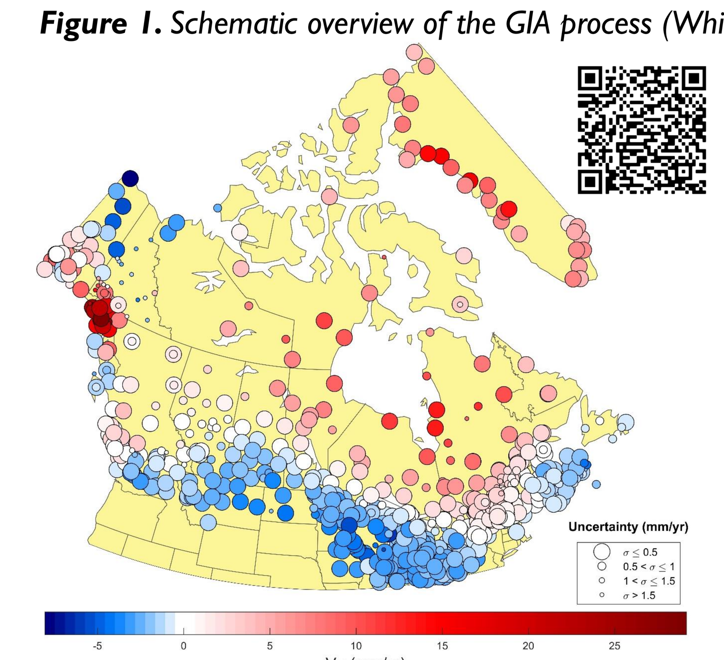


Figure 2. Vertical velocity field in North America (Robin et al., 2020).

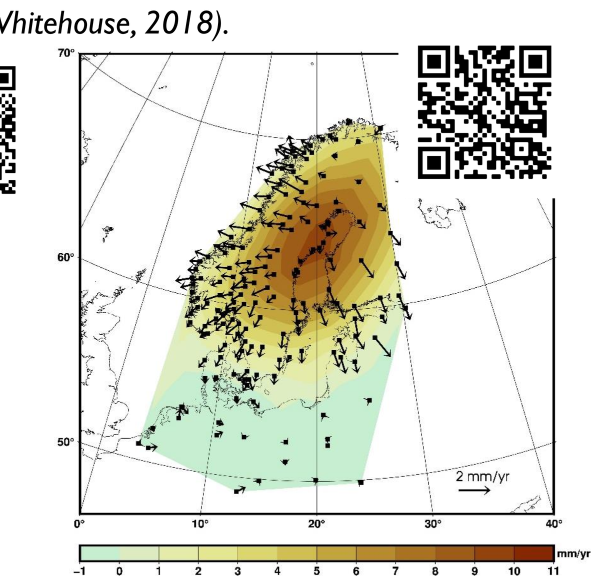


Figure 3. Vertical (contours) and horizontal (arrows) velocity field in northern Europe from BIFROST 2014 (Kierulf et al., 2021).

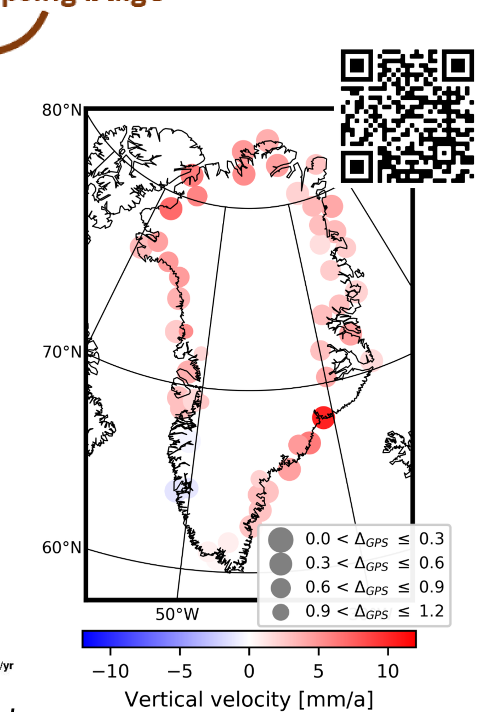


Figure 4. Vertical velocity field in Greenland (based on Khan et al., 2016).

One-dimensional vs. three-dimensional GIA models

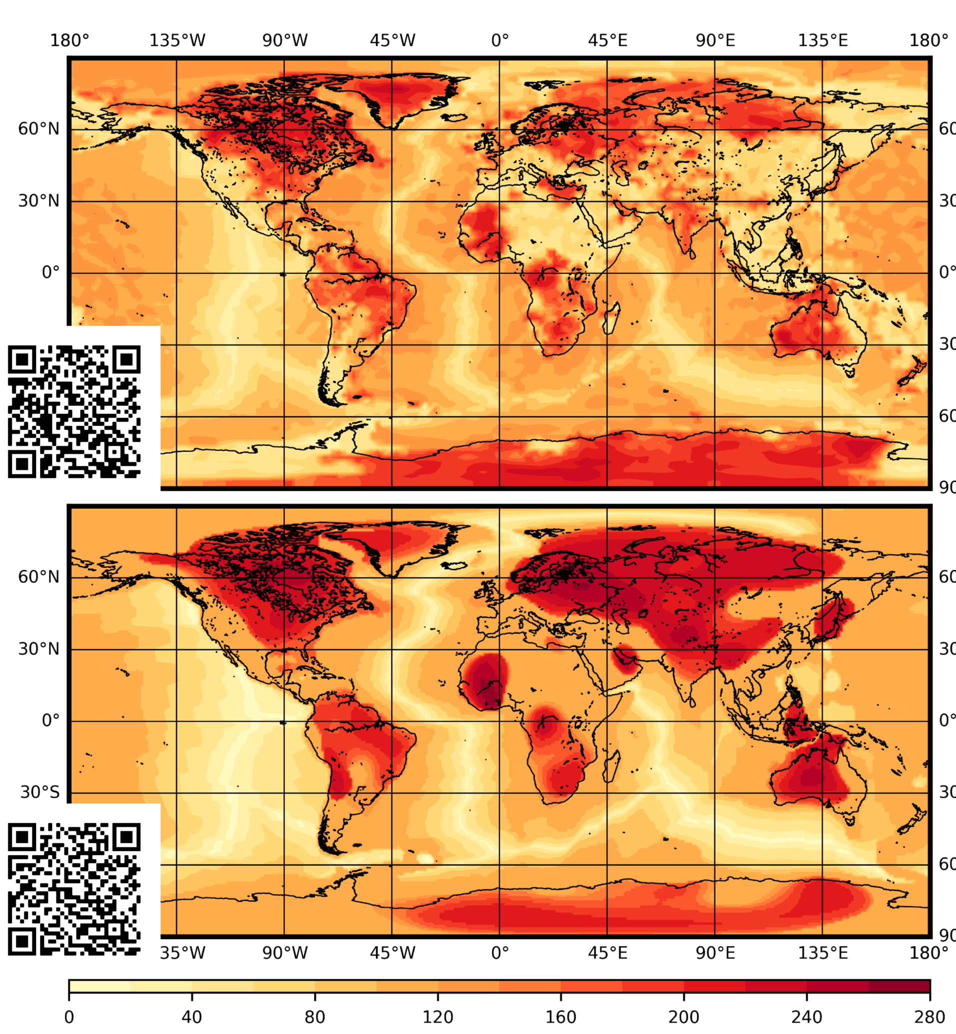


Figure 5. Various lithosphere models exist, which can be implemented into 3D GIA models. Upper subfigure: Lithosphere model based on various geophysical data (Afonso et al., 2019). Lower subfigure: Lithosphere model from Conrad & Lithgow-Bertelloni (2006) based on seismological data. The latter is commonly used in GIA models.

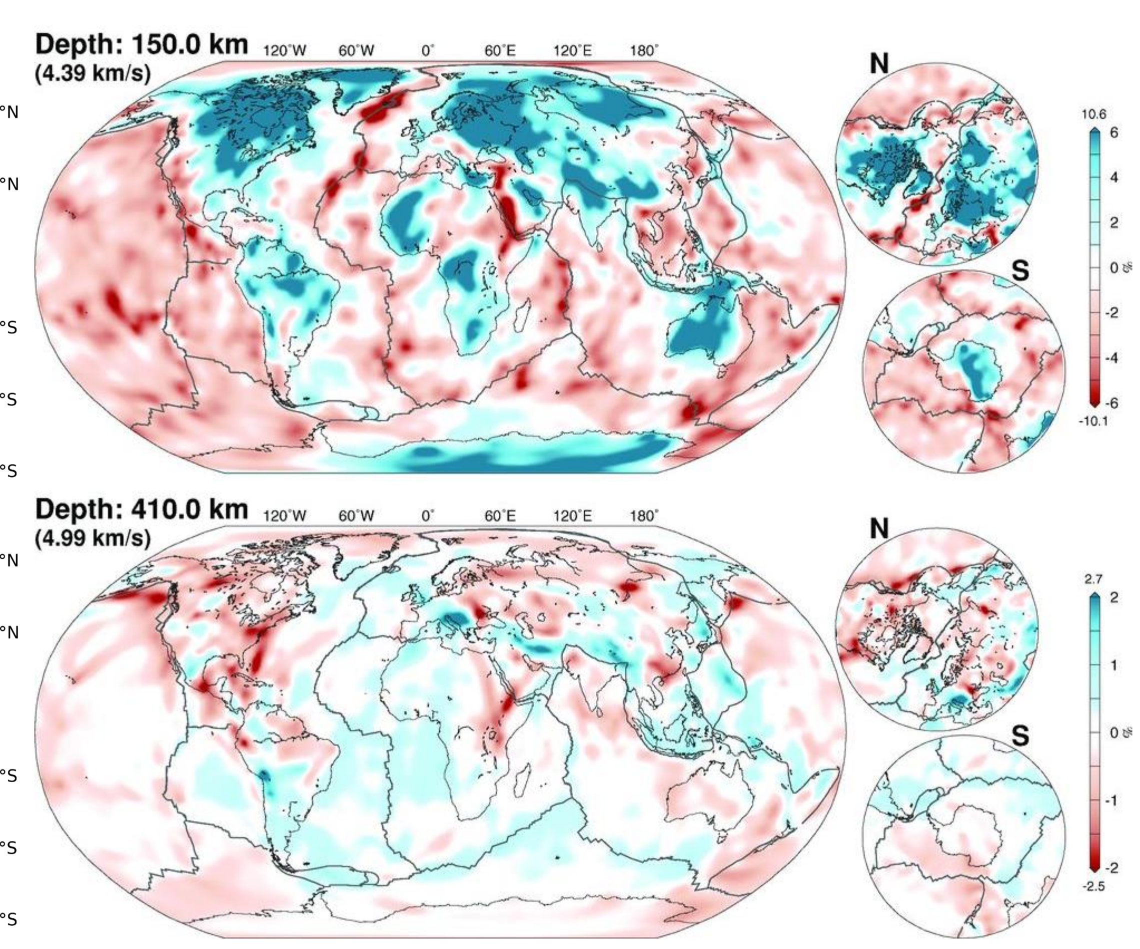


Figure 6. The mantle is not homogenous as shown by seismic tomography studies. Shear wave velocities vary largely between the oceanic areas and beneath the continents, also depending on the depth. The shear wave velocities can be converted into viscosity values, used as input in 3D GIA models. Seismic tomography model shown is SL2013sv by Schaeffer et al. (2013) at selected depths (150 km and 410 km). Variation with respect to the mean shear wave velocity is shown:

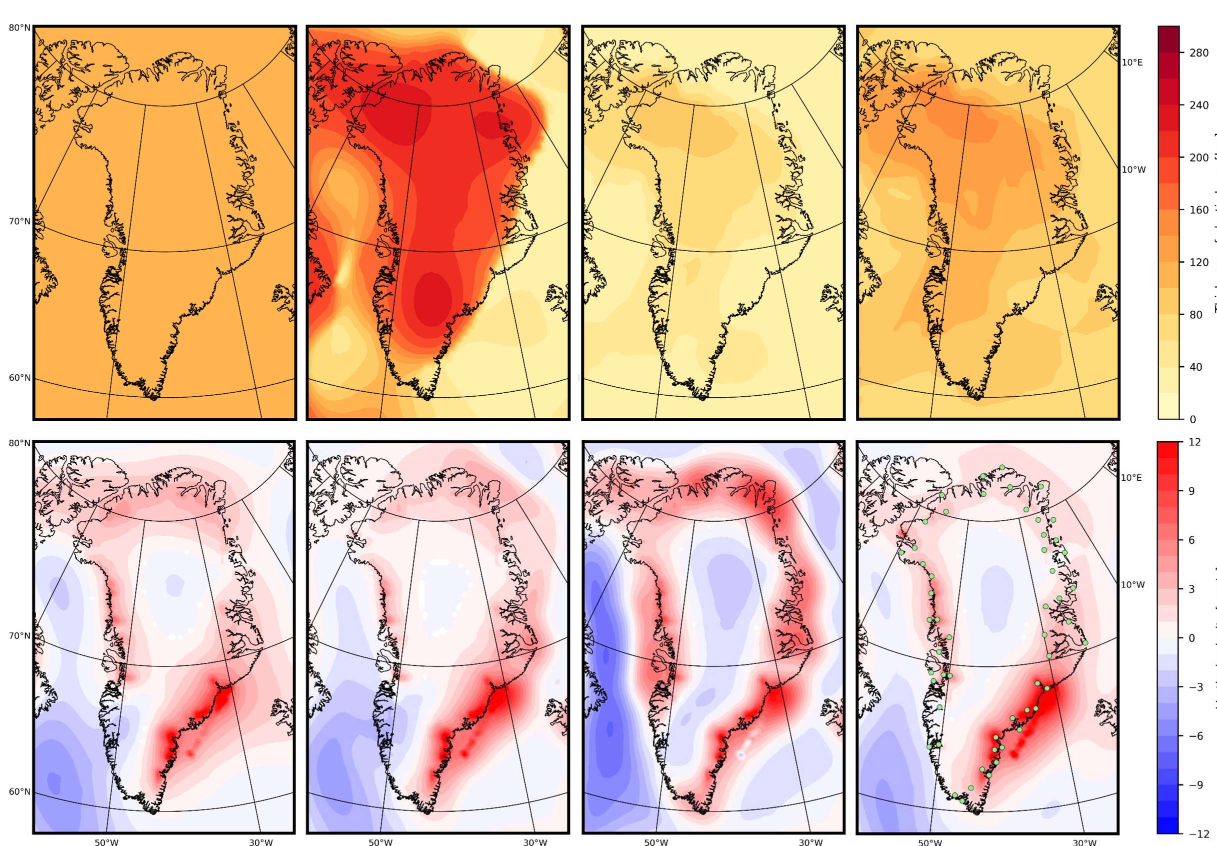
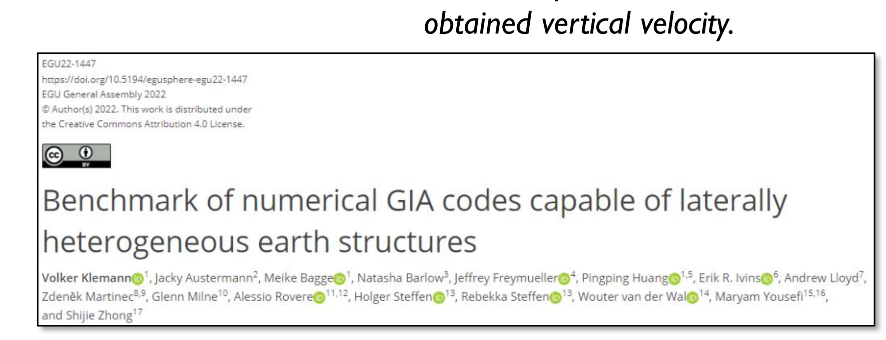


Figure 7. The effect of heterogenous lithosphere and mantle models on the vertical velocity, as shown for Greenland. From left to right: 1) homogenous lithosphere model with 120 km thickness combined with a radial varying viscosity in the mantle; 2) laterally varying lithosphere model based on SL2013sv (Schaeffer et al., 2013) combined with a radially varying viscosity in the mantle; 3) laterally varying lithosphere model based on the effective elastic thickness from Steffen et al. (2018) combined with a radially varying viscosity in the mantle; 4) laterally varying lithosphere model based on the effective elastic thickness from Steffen et al. (2018) combined with laterally varying viscosity model in the mantle based on SL2013sv. Upper row: lithosphere model, bottom row: obtained vertical velocity.

Next step: Benchmark is planned to verify GIA codes capable of including laterally heterogenous Earth structures



Maxwell rheology vs. transient rheologies

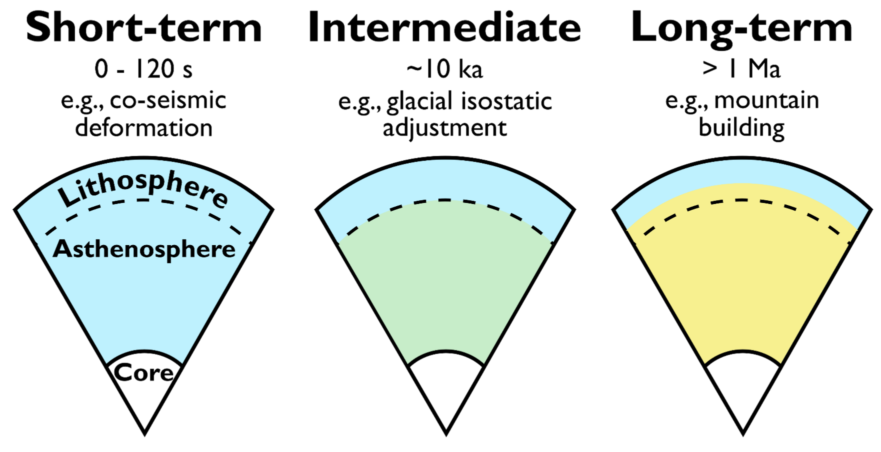


Figure 8. Schematic diagram showing the different definitions of a lithosphere (after Watts, 2015). The short-term loading uses an elastic half-space as model assumption, the intermediate loading an elastic plate on a viscoelastic half-space, and the long-term loading an elastic plate on an inviscid fluid.

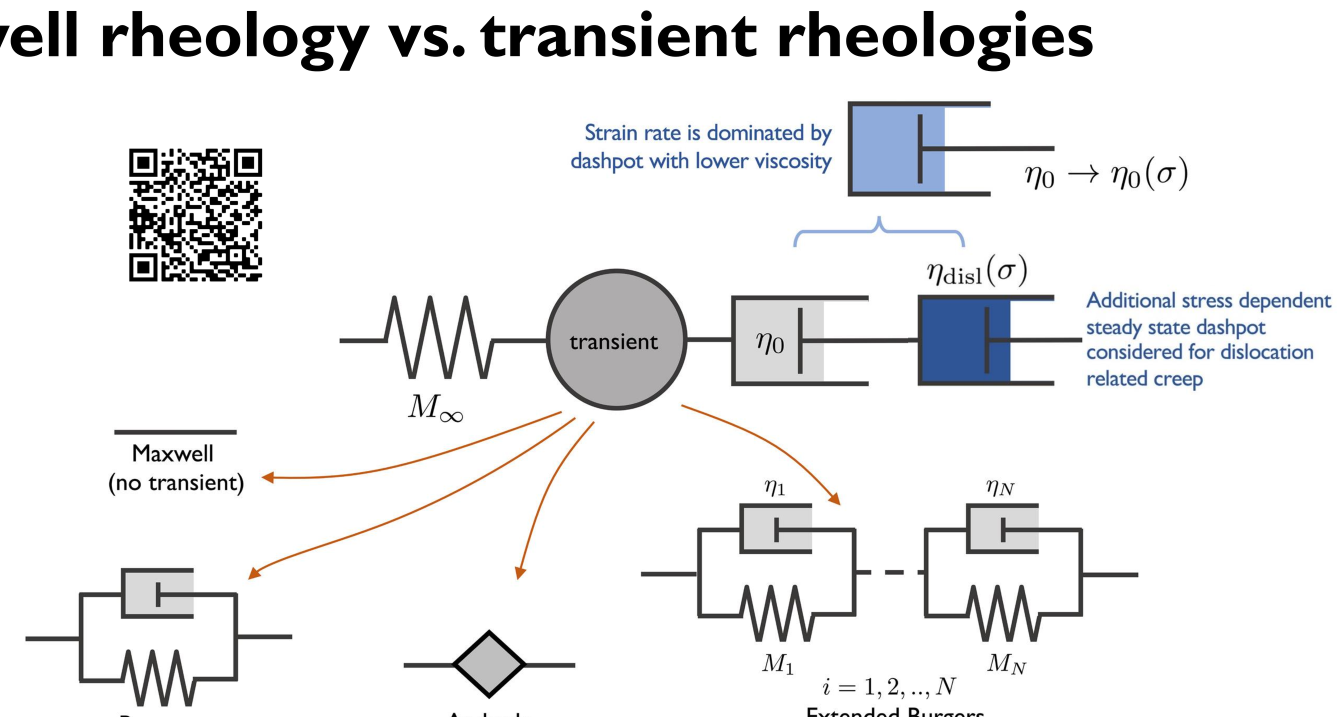


Figure 9. Depiction of 1-D phenomenological viscoelastic models. The dark gray circle symbolically represents any combination of springs and dashpots that mimic (transient) deformation. Replacing the circle with any of the components linked by an arrow will form the commonly adopted models labeled. With the addition of steady state dislocation creep, the viscosity of the steady state dashpot (η_0) becomes stress (σ) dependent. From Lau et al. (2021).

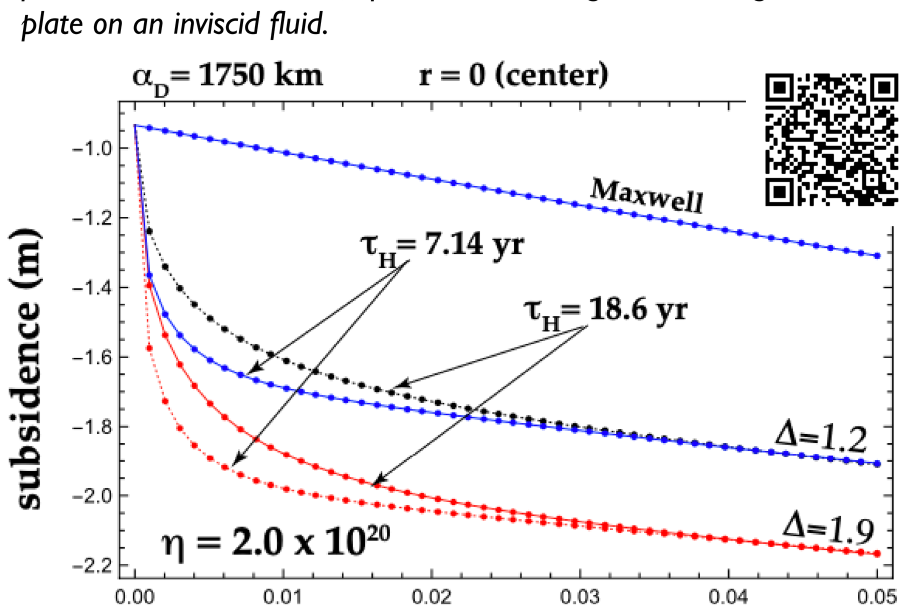


Figure 10. Subsidence history following the instantaneous placement of a 25 m water disc load, evaluated beneath the disk-centre, for a Maxwell rheology and Extended Burger Models (EBM). Δ is the EBM relaxation strength and τ_H being the long period cut-off value for EBM. From Ivins et al. (2022).

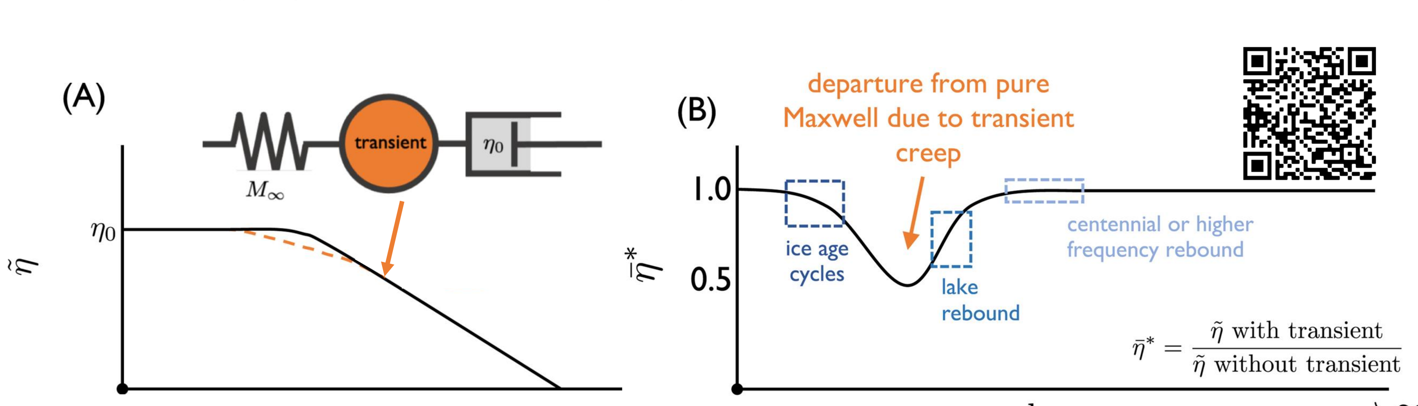


Figure 11. Schematic diagram of the variation of viscosity η over time: (A) Two trends of the viscosity of a viscoelastic model with a transient element and equivalent Maxwell model (i.e., no transient element). The location in which the two trends depart is shown by the dashed orange line. (B) The ratio of these two trends in (a), where the dip in this value indicates additional dissipation due to transient components in the viscoelastic model. At the purely viscous and purely elastic extremes, these two curves are unity. From Lau et al. (2021).

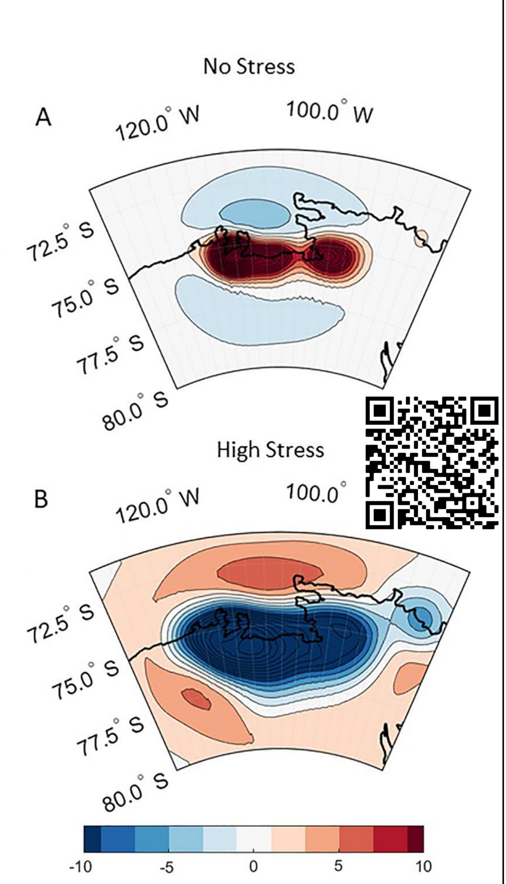


Figure 12. The effect of using a non-linear rheological material in a GIA model (see Fig. 9, the additional blue dashpot) on the vertical velocity for West Antarctica (Amundsen Sea Embayment). The modelling results in the upper row (A) includes no depenncy of the viscosity on stress, while a stress-dependent viscosity is used to obtain the uplift signal in the lower row (B). From Blank et al. (2021).

Compressible vs. incompressible

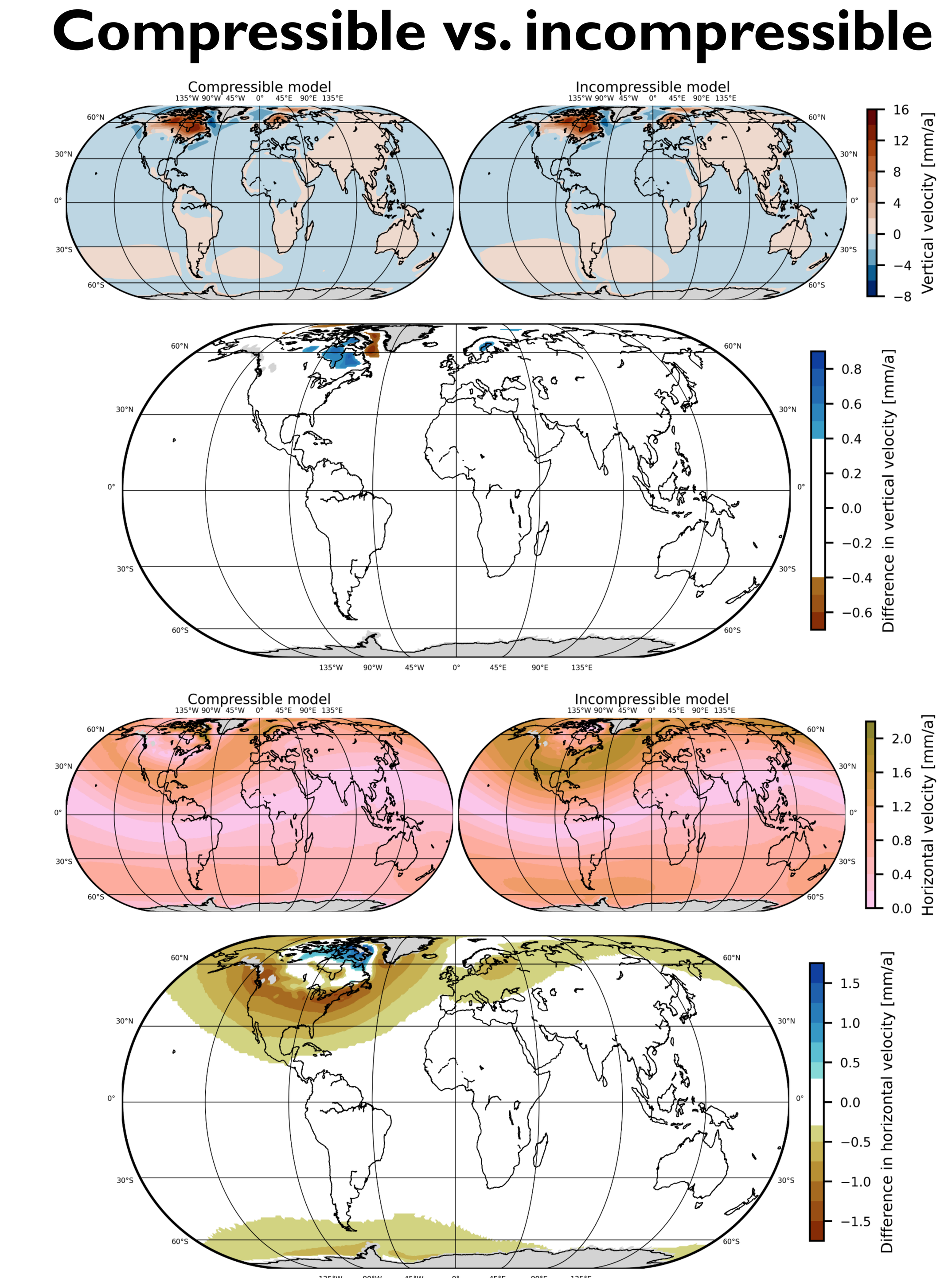


Figure 13. The effect of compressibility vs. incompressibility on the vertical (upper row) and horizontal (lower row) velocities based on the ICE-6G ice model and the accompanying VM5a Earth model (see Argus et al., 2014, and Peltier et al., 2015). White area is within the respective velocity uncertainty.

Next step: Benchmark initiative to verify the effect of compressibility in GIA modelling codes ⇨ comparison to geodetic quantities

More information about this IAG Joint Study Group:

Overview article in GIM International:

Geodesists' Handbook 2020 (page 134):