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Sea levels and uplift rate from composite rheology in glacial isostatic adjustment modeling

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ABSTRACT

Since laboratory experiments point to the existence of both diffusion creep and power-law creep at realistic mantle conditions, a composite rheology in which both mechanisms operate at the same time so that their strains are combined might be more realistic and has in the past been shown to provide a better fit to observations of glacial isostatic adjustment (GIA) than purely linear rheology (Gasperini et al., 2004; Dal Forno et al., 2005). To further investigate the effect of such rheology on sea level curves and uplift rate resulting from GIA, composite rheology is implemented in the coupled Laplace-finite element method for a 3D spherical self-gravitating Earth. We vary the pre-stress exponent (assumed to be derived from a uni-axial stress experiment) and the Newtonian viscosity for a homogeneous mantle.

Composite rheology is found to have a statistically significant better fit with observed relative sea level data than linear rheology (diffusion creep only) and non-linear rheology (dislocation creep only). For the best-fitting composite rheology model it is shown that in the mantle below the former ice sheet margin, stress is high enough for power-law creep to become dominant during melting and shortly thereafter, causing the model to behave mostly in a non-linear way. It is found that composite rheology, with the parameters investigated in this paper, not only provides a better fit to sea level data than non-linear rheology but also slightly increases present-day uplift rate compared to non-linear rheology. This encourages application of composite rheology in GIA models that aim to improve knowledge of mantle rheology.

Low uplift rates for composite rheology can be further increased by a large increase in ice thickness in North America at the expense of violating total melt-water constraints. A 1 or 2 ka delay in Laurentide glaciation and deglaciation increases uplift rates for all values of the pre-stress exponent investigated, while fit to a number of relative sea level observations in the Laurentide ice sheet is improved. Large increase in ice thickness disagrees with other observations (total melt constraints), therefore a delay in glaciation is a promising direction if global ice models are to be adjusted for a composite rheology.

1. Introduction

Most glacial isostatic adjustment (GIA) models are based on a linear relation between stress and strain rate, i.e., linear or Newtonian rheology, which has been successful in explaining a large number of GIA observations simultaneously, including relative sea level (RSL) data, crustal velocities, gravity rates of changes, polar wander and non-tidal acceleration of the Earth (e.g., Peltier, 1998, 2004). However, this success alone does not justify the use of linear rheology. Laboratory measurements show that dislocation creep, which gives rise to non-linear or power-law creep, also operates in the mantle. Formally, power-law creep can be written in tensor form as (Ranalli, 1995):

$$\bar{\varepsilon}_{ij} = A\sigma'^{\,n-1}_E \sigma'_{ij} \tag{1}$$

where $\bar{\varepsilon}_{ij}$ is the deviatoric strain rate, σ'_{ij} is the deviatoric stress, $\sigma'^{\,n-1}_E = \sqrt{(1/2)\sigma'_{ij}\sigma'_{ij}}$ is the effective shear stress, n is the stress exponent, A is a parameter determined from shear experiments and is a function of pressure, temperature and material properties. It is also useful to define the effective viscosity η_{eff} as (Wu, 1998):

$$\eta_{eff} = \frac{1}{2A\sigma'^{\,n-1}_E} = \frac{1}{3A^* q^{n-1}} \tag{2}$$

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where $q = \sqrt{3}\sigma'_E$ is the von Mises equivalent stress, and A^*, the parameter determined from uni-axial experiments, is related to A by $A^* = (2/3^{(n+1)/2})A$ (Ranalli, 1995). The parameter A^* and the von Mises equivalent stress are introduced because the ABAQUS finite element model uses them as inputs for Earth deformation calculations, and previous works (Wu, 1995, 2001, 2002; Wu and Wang, 2008) have used A^* instead of A.

Laboratory experiments found that power-law creep ($n > 1$) operates when the stress level is high or the grain size is large (e.g. Goetze and Kohlstedt, 1973; Ranalli, 1991; Karato and Wu, 1993; Li et al., 2003; Cordier et al., 2004; Mainprice et al., 2005). In contrast, if the stress level is low or the grain size small, deformation occurs mainly through diffusion creep and the flow law is linear ($n = 1$). However, due to the large uncertainty of the conditions for the linear–non-linear transition (e.g. Ranalli, 2001), the presence of water in the mantle and post-perovskite in the lower mantle, microphysics alone cannot say definitively which part of the mantle behaves linearly or non-linearly.

GIA observations have been used to address this question, see a recent review by Wu and Wang (2008) which we will summarize below. For a power-law mantle, Schmeling (1987) argued that GIA should see a linear creep law while mantle convection should see a non-linear creep flow. While this is true for RSL data near the center of rebound, Wu (1995) showed that RSL curves near the ice margin are diagnostic of non-linear rheology. This was confirmed in a 3D flat Earth model with a realistic ice history and ocean loading (Wu, 2001). The best fit to RSL data was obtained for an Earth model with power-law rheology restricted to the lower mantle (Wu, 2002; Wu and Wang, 2008).

These studies limit non-linear rheology to certain layers in the mantle, while linear rheology is assumed in the other layers. However, there is no reason why linear and non-linear rheology cannot co-exist, and a so-called composite rheology seems a better approximation to real Earth deformation (Ranalli, 2001; Korenaga and Karato, 2008). A composite rheology can be constructed by the Ellis model (e.g., Bird et al., 1960), which sums the creep rate from linear and non-linear flow laws. It is used in mantle convection by, e.g., Parmentier et al. (1976) and a similar model is used by van den Berg et al. (1993) and Gasperini et al. (1992). The latter is the first application of composite rheology in GIA modeling and is followed by investigations in a series of recent papers. Gasperini et al. (2004) used a flat axisymmetric model and found that composite rheology was able to fit RSL data better than linear rheology. This is confirmed by Dal Forno et al. (2005) and Dal Forno and Gasperini (2007).

Previous studies with composite rheology use a flat Earth geometry (Gasperini et al., 2004; Dal Forno et al., 2005; Dal Forno and Gasperini, 2007) while sphericity can become important for the Laurentide ice sheet especially for RSL data far from its center. Finally, self-gravitation and the self-consistent sea-level equation are neglected in previous studies (Giunchi and Spada, 2000; Gasperini et al., 2004; Dal Forno et al., 2005; Dal Forno and Gasperini, 2007). The sea-level can be important at the edge of the former ice sheet, where the ice attracted large amounts of sea water and where also linear and non-linear rheologies behave differently (Wu, 1995). Thus, it might be important to model self-gravitation when comparing different rheologies. In this paper, the effects of Earth's sphericity, the self-consistent sea-level equation and self-gravitation are included in our study of composite rheology.

A comprehensive comparison of linear, non-linear and composite rheology has not been shown in the previous studies. Dal Forno et al. (2005) and Dal Forno and Gasperini (2007) showed that composite rheology fits the RSL data significantly better than linear and non-linear rheology. However, a global misfit number does not illuminate the temporal and geographic spread of differences in sea level curves, while the RSL behavior at a specific location is sometimes useful to distinguish between linear and non-linear rheology (e.g. Wu, 1995). Currently, it is not clear how composite rheology behaves for different values of A^*, whether the predictions are closer to linear or non-linear rheology, and how predictions using a composite rheology depend on location and time. The answers to these questions can help us relate previous studies of non-linear rheology by Wu (2002) and Wu and Wang (2008) to studies of composite rheology (Gasperini et al., 2004; Giunchi and Spada, 2000; Dal Forno et al., 2005; Dal Forno and Gasperini, 2007). Moreover, present-day uplift rates from composite rheology have not been studied, while a known problem with non-linear rheology is the low uplift rates it provides (e.g. Wu, 1999).

Because Peltier's global ice models ICE-4G and ICE-5G are based on linear rheology they might require modification when using them in combination with a non-linear rheology which generally leads to faster relaxation during early deglacial time but lower present-day uplift rates. Wu (1998, 1999) showed that an increase in ice height improves fit with relative sea level data within the ice sheet margin. Wu and Wang (2008) found that a 2 ka delay deglaciation applied to ICE-4G makes for a better fit of sea level curves in the center of the former Laurentide ice sheet. However, it is not clear how modifications in the ice model affect the predictions of composite rheology. The answer to this question can contribute to an assessment of the performance of composite rheology and can also benefit future work aimed at making an ice model compatible with non-linear or composite rheology. In summary, this paper aims to address the following questions:

(1) In a composite rheology, which regions of the mantle are dominated by non-linear flow and how does the dominance of non-linear rheology in these regions change in time as deglaciation proceeds?
(2) How do sea level curves predicted by composite rheology differ from those predicted by non-linear and linear rheology?
(3) Can a good fit to sea level data as well as present-day uplift rate data be obtained with composite rheology?
(4) How can ice models be modified to improve fit of composite rheology with sea level data and present-day uplift rate in North America?

In order to investigate these questions, we use the definition of composite rheology in which strain rates from diffusion and dislocation creep are summed, assuming that both processes can occur simultaneously:

$$\bar{\varepsilon}_{ij} = \frac{\sigma'_{ij}}{2\eta} + A{\sigma'}_E^{n-1}\sigma'_{ij} = \frac{\sigma'_{ij}}{2\eta} + \tfrac{3}{2}A^* q^{n-1}\sigma'_{ij} \quad (3)$$

where η is the Newtonian viscosity, and other quantities are defined as in Eq. (1). This formulation is identical to Gasperini et al. (1992) and Giunchi and Spada (2000) except that we keep the creep parameter A (or rather A^*) as input parameter instead of the transition stress as in these studies (see Dal Forno et al. (2005) for the relation between transition stress and the linear viscosity and the creep parameter A). We have also implemented a composite rheology in which the strain rates from diffusion and dislocation creep are not summed, but the strain rate of the medium is the larger strain rate of the two. However, we found that the differences between predictions from these two formulations are small, so we just use the formulation of Eq. (3) in this paper.

For this study we make the assumption that the value of A (or A^*) is the same throughout the mantle although in reality A (or A^*) is dependent on activation energy, activation volume, temperature, water content, grain size and shear modulus (e.g., Turcotte and Schubert, 2002; Karato and Wu, 1993). Thus, our study should