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Sea level curves, geoid rate and uplift rate from composite rheology in glacial isostatic adjustment modeling

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Laboratory experiments show that both diffusion creep and power-law creep can exist for realistic mantle conditions. Therefore a composite rheology which includes both creep laws might be a better approximation of the deformation process in the mantle. Here we study the effect of such a rheology on glacial isostatic adjustment (GIA) observables. Composite rheology has in the past been shown to provide a better fit to sea level data for a wide range of parameters investigated with 2D finite element models. Here, we use the Coupled Laplace Finite Element Method for an incompressible 3D spherical self-gravitating Earth to study the effect of composite rheology on relative sea level (RSL) curves, maximum present-day uplift rate and maximum present-day geoid rate with the ICE-5G model. The long computation time of this model limits the number of cases that can be investigated to a handful. The stress exponent is taken to be 3, the pre-stress exponent (A) derived from a uni-axial stress experiment is varied between 3.3 x 10^{-33}/10^{-34}/10^{-35}/10^{-36} $Pa^{-3}s^{-1}$, and the Newtonian viscosity η is varied between 1/3/9 x 10^{21} Pas. Because the ice models are developed under the assumption of linear rheology any rheology with a non-linear component usually under predicts the uplift rate and geoid rate. Therefore, to see if the ice model can provide a better fit, we investigate simple modifications to the ICE-4G model, such as i) scaling of the ice height by 1.5 and 2.0; and ii) delay in glaciation by 1 and 2 kyears.

The non-linear component in the composite rheology becomes important for high effective stress, which is shown to occur at the edge of the ice sheet at the end of deglaciation. As in previous studies, composite rheology is found to have a smaller misfit value with observed RSL data than linear rheology. However, a purely non-linear rheology with A = 3.3 x 10^{-35} $Pa^{-3}s^{-1}$ still has a slightly better fit than composite rheology, although this is sensitive to outliers in the misfit computation and might also not hold true when other values of the A and η are investigated. The best fitting composite rheology has A = 3.3 x 10^{-35} $Pa^{-3}s^{-1}$ and η = 9 x 10^{21} Pas. For this model, transition stress is 1 MPa, which is low enough so that most of the sea level curves follow those of non-linear rheology. Exceptions are sites in the center of the ice sheet (Laurentide) and the center and margin of the ice sheet (Fennoscandia), where there is a significant contribution of linear rheology at the start of melting, and Antarctica, where apparently stresses are not high enough for non-linear deformation to become important. The maximum geoid rate of the best fitting composite rheology model is 1.0 mm/year (compared to 0.85 for the best fitting purely non-linear model and the observed 1.4 mm/year) and the uplift rate is 7.5 mm/year (compared to 6.0 mm/year for the non-linear model and the observed 11 mm/year). Thus, the best fitting composite rheology model increases the uplift and geoid rate compared to a model with only power-law creep, at the expense of a small decrease in sea level misfit.

The following conclusions are obtained from the simulations with a modified ICE-4G ice history:

i) Increasing the ice thickness increases the present-day uplift rate, but only when the non-linear deformation component in the model is small. The misfit value with sea level data in Laurentide increases, and the fit with individual sea level curves becomes worse except for two sites.

ii) A delay in glaciation increases the uplift rate for all values of A, and a 1 kyear delay improves the misfit with Laurentide RSL sites, and even a 2 kyear delay improves sea level fit for a number of stations. Therefore, delay in glaciation is a more promising direction to adjust ice models for composite rheology than increasing the ice thickness.