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Rheology beneath Iceland: new insights from InSAR measurements and finite element modeling of uplift due to ice load changes around Vatnajökull ice cap

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Iceland, a subaerial part of the Mid-Atlantic ridge, is 11% covered by ice caps. The largest ice cap is Vatnajökull, with an area of $\sim$8100 km^2 and average thickness of 400 m. Due to recent climate changes, Icelandic ice caps have been experiencing significant ice loss since 1890, estimated at $\sim$458 km^3 up until 2010 for Vatnajökull. This induces extensive uplift in most of Iceland due to the elastic and viscoelastic responses, which we have measured and modeled.

Uplift is measured using the Interferometric Synthetic Aperture Radar (InSAR) technique. It is a phase differencing technique that provides good spatial coverage with mm to cm scale accuracy. We performed a time series analysis of the acquisitions to retrieve the deformation in time and extract line-of-sight (LOS) velocity maps giving the rate of deformation. We used data from the ERS satellite spanning 1992–2002 to measure the deformation to the south and west of the ice cap. For the eastern half of Vatnajökull, we processed data from the Envisat satellite spanning 2004–2009. Velocities from several GPS stations located within our scenes were used to convert LOS velocities to a known reference frame. Our InSAR results give a highly detailed map of surface displacements from $\sim$50–60 km away from Vatnajökull ice cap all the way up to its edge, enabling us to retrieve the broad picture of the uplift as well as displacements at the ice cap edge. The superior spatial sampling of InSAR reveals new patterns of deformation: high-rate uplift close to the ice edge at fast melting outlet glaciers (up to 25–28 mm/yr) and spatially-varying behavior of neighboring outlet glaciers (significant difference in the uplift is attributed to a difference in melting rates). Other processes are also recorded by InSAR (surging glaciers, plate spreading, caldera subsidence and magmatic intrusion) but can be distinguished from the GIA signal thanks to their spatial extent and associated deformation pattern.

We performed three-dimensional finite element modeling, taking into account two Earth layers (an elastic layer on top and a viscoelastic layer below), considering melting at all Icelandic ice caps. We used the ice cap geometry and detailed melting rates, assumed constant since 1890 (isostatic equilibrium is inferred prior to that). We solved for the thickness of the elastic layer and the viscosity of the second layer to find the best fitting model to each of our InSAR scenes. Modeling results were compared to the InSAR and, for each model, we estimated the fit between the two datasets using the normalized χ^2 and variance reduction. Our results show good agreement between the model prediction and the InSAR data, as proven by the variance reductions for our best models ranging from 94.8 to 98.5%. Results demonstrate that the deformation for both the western and eastern parts of the ice cap can be fit with similar parameters, with an elastic crustal thickness of 20–30 km and a viscosity of underlying layer of 6–10 x 10^{18} Pa s.