Icelandic rhythmics: Annual modulation of land elevation and plate spreading by snow load (AGU – G33B-0055)

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Abstract

We find strong correlation between seasonal variation in continuous GPS (CGPS) time series and predicted response to annual snow load in Iceland. The load is modeled using Green's functions for an elastic halfspace and a simple sinusoidal load history on Iceland's four largest ice caps. We derive $E = 40 \pm 15\,GPa$ as a minimum value for the effective Young's modulus in Iceland, increasing with distance from the Eastern Volcanic Zone. We calculate the elastic response over all of Iceland to maximum snow load at the ice caps using $E = 40\,GPa$. Predicted annual vertical displacements are largest under the Vatnajökull ice cap with a peak-to-peak seasonal displacement of $\sim 37\,mm$. CGPS stations closest to the ice cap experience a peak-to-peak seasonal displacement of $\sim 16\,mm$, consistent with our model. East and north of Vatnajökull we find the maximum of annual horizontal displacements of $\sim 6\,mm$ resulting in apparent modulation of plate spreading rates in this area.

1. Introduction

Time series of CGPS stations often reveal annual cycles in deformation of Earth's crust. Earlier studies relate this to seasonal phenomena, i.e. snow load [Heki, 2001]. The amplitudes of Iceland's CGPS time series correlate inversely with the stations distance from the ice caps, suggesting their variable load may influence deformation (Fig. 1), which is supported by a pattern of winter loading and summer unloading in the data [Geirsson et. al., 2006].

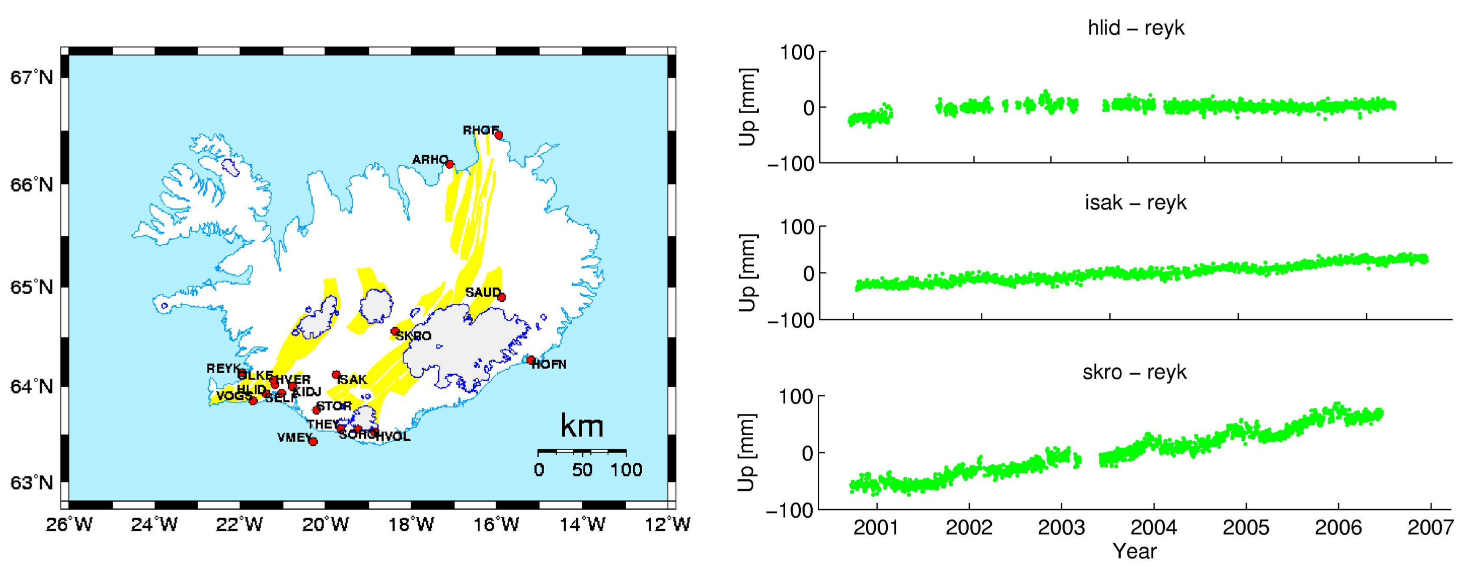

Fig. 1: Iceland's large ice-caps and CGPS stations of the ISGPS network as in 2005. On the right, time series of three stations show the amplitudes of the UP-component correlating inversely with distance from the ice caps (see linear and annual trend).

2. GPS observations and data processing

We use CGPS time series from the ISGPS network. All displacements are calculated relative to the REYK reference station. The data are corrected for outliers and offsets in the same manner as described by *Geirsson et. al.* (2006). Linear trends are removed using a least squares approach. They are mostly due to plate motion (horizontal) or glacio–isostatic rebound due to glacial melting since the Little Ice Age (vertical). *Geirsson et. al.* (2006) use a least squares approach to fit the detrended data to a harmonic function. The data show most prominent annual signals in east and vertical component at stations close to ice caps.

Glacier	Observation Period	Area [km^2]	b_w [m]	b_s [m]	b_n [m]
Vatnajökull[a]	1991/92-2004/05	8100	1.5	-1.8	-0.3
Langjökull[a]	1996/97-2004/05	925	1.65	-2.95	-1.3
Mýrdalsjökull[a]	estimation	600	≈2.5	≈-3.0	-0.5
Hofsjökull[b]	1996/97-2001/02	890	1.25	-2.25	-1.0

[a] Pers. comm., H. Björnsson and F. Pálsson, Univ. Iceland, 2006.
[b] Sigurdsson, O. (2003), Jöklabreytingar 1930-1960, 1960-1960 og 2001-2002, Jökull, 53, 55–60.

Tab. 1: Ice cap data. The net mass balance b_n expresses the mass accumulation of a glacier in the course of a year and can be devided into values for winter and summer mass balances, b_w and b_s, respectively. Mass balances are referred to as meters of water equivalent load thickness.

3. Modeling

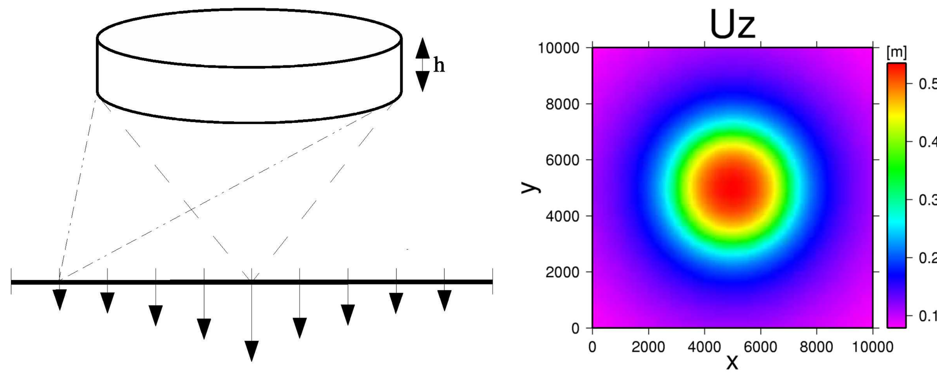

Fig. 2: A Green's function gives a system's response to a specifi c problem. Convolving a Green's function for subsidence with a disk load will, i. e. result in values for vertical displacement at each grid point (different line styles refer to subsequent steps). The color image shows vertical displacement due to a disk load: $r = 2\,km$, $h = 150\,m$, $\rho = 1000\,kg/m^{-3}$, $E = 10\,GPa$, $\nu = 0.25$.

We focus on modeling the annual load cycles of the four largest ice caps (Fig. 1), which are constrained by their outlines and a uniform load thickness. The latter is the winter mass balance, b_w (see Tab. 1). To estimate the Earth's elastic response to these loads, we consider an elastic halfspace and convolve Green's functions with the load as explained by *Pinel et. al.* (2006) (Fig. 2).

The displacements due to glacial load variations are modeled using an interpolated $1\,\text{km} \times 1\,\text{km}$ grid. Searching for an effective Young's modulus, E, that best fits the detrended time series, we model the elastic response in the interval 10–130 GPa. Effects of winter loading and summer unloading at the ice caps are modeled by a simple harmonic load history approximation at the stations with melt season starting in mid-May (Fig. 3).

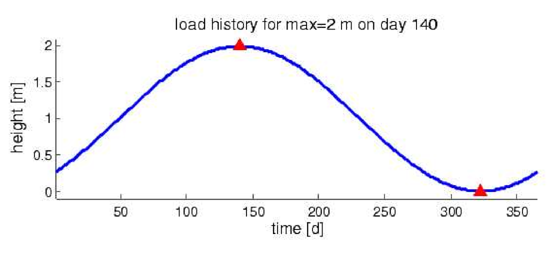

Fig. 3: A harmonic function returns the uniform load height of an ice cap on a specifi c day.

4. Comparison of observations and load models

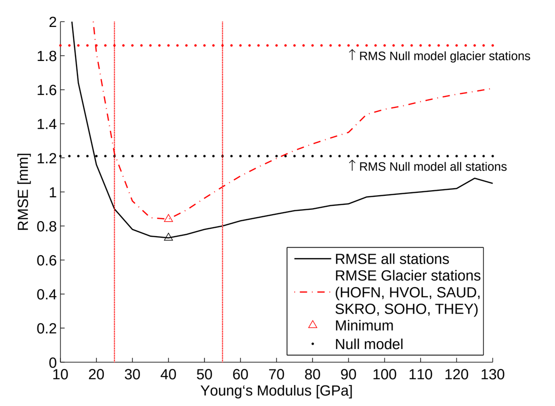

Fig. 4: RMSE for all CGPS stations (solid line) and stations close to ice caps (dash-dotted line). Triangles mark best fi t to the time series for E. Vertical lines are the suggested confi dence interval for E.

The averaged standard root mean squared error (RMSE) between model predictions and best fits to the time series allows us to derive a best value for E. Fig. 4 shows the difference in the *RMSE* as a function of E for all CGPS stations, and using only CGPS stations close to glaciers. We derive a best model value of $E = 40\,GPa$. Comparing the RMSE to the null models (of best fits to time series), variance is lower when considering only glacier stations.

Fig. 5 shows absolute vertical and horizontal displacements at the onset of the melting season for Iceland using $E = 40\,GPa$ and maximum snow load.

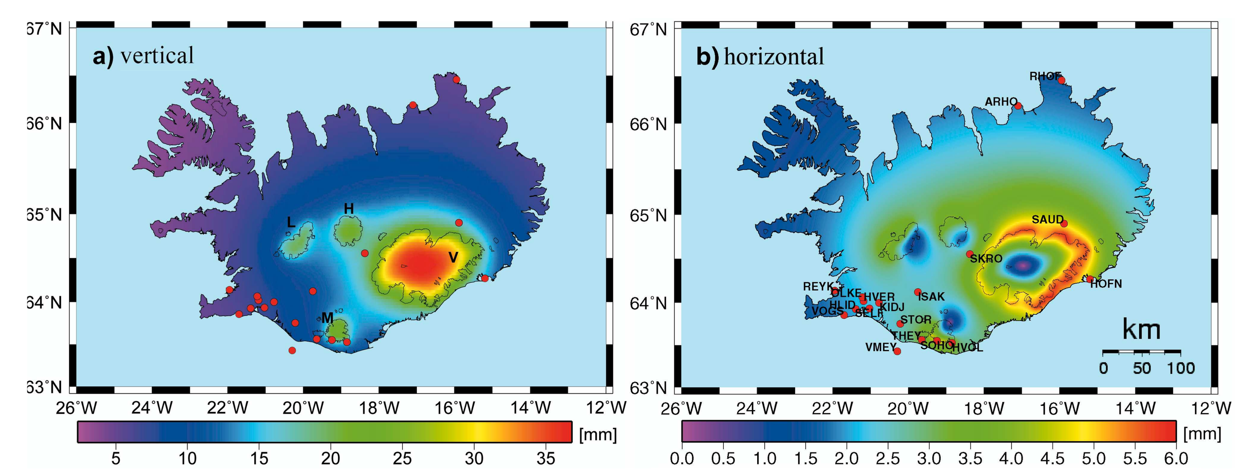

Fig. 5: Calculated absolute peak-to-peak seasonal displacement due to maximum winter load using E=40 GPa. (V: Vatnajökull, L: Langjökull, M: Mýrdalsjökull, and H: Hofsjökull) **a)** Vertical displacement. **b)** Vector lengths of horizontal displacements.

Western and northern stations in Fig. 5 have minor induced deformation. This explains the proportionally better fit of the model to CGPS stations close to ice caps. By deriving a best fit in E for each individual station, we infer a confidence interval of $E = 40 \pm 15\,GPa$. For $E = 40\,GPa$ the largest horizontal displacement of $\sim 6\,mm$ occurs north and east of Vatnajökull. The huge load of Vatnajökull pulls the horizontal displacement field of the other ice caps significantly towards its center. For the vertical, maximum displacement is $\sim 37\,mm$ under the center of Vatnajökull (Fig. 5).

Temporal variation for dynamic loading using $E = 40\,GPa$ is shown in Fig. 6. Predicted vertical deformation caused by our load model is at all stations in close proximity to glaciers almost in phase with the best fits. Phase offsets between time series and model predictions could be due to variations in the beginning of the melting season at the ice caps.

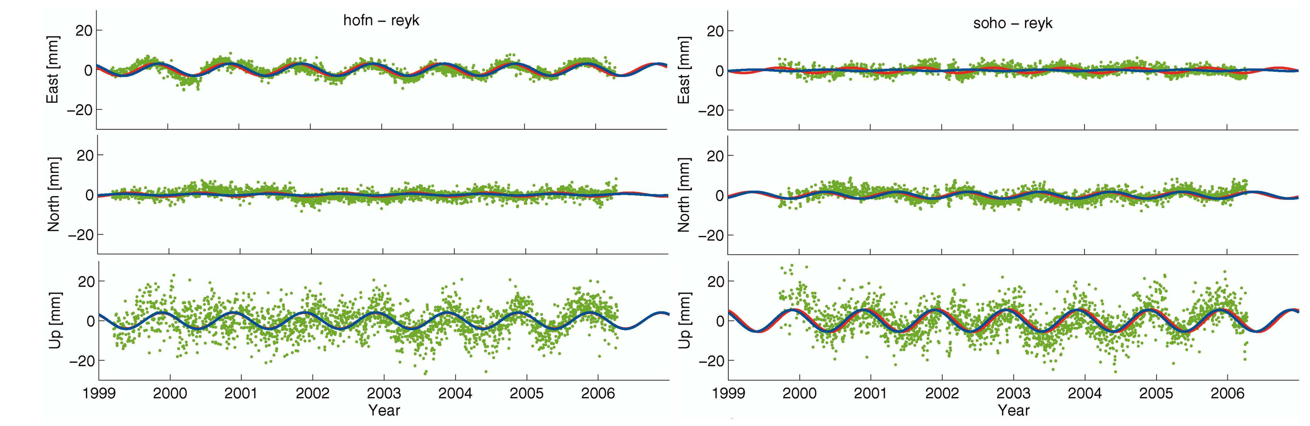

Fig. 6: Comparison of predicted and observed results of temporal modeling at CGPS stations HOFN and SOHO. Green dots: detrended CGPS time series showing station displacements relative to REYK, red line: best fi t from *Geirsson et. al.* (2006), blue line: modeled displacement using $E = 40\,GPa$.

5. Discussion and conclusions

Results from our simple load model correspond to observations of earlier studies and match the data of CGPS stations in Iceland. Future models should consider the different lengths of loading and unloading cycles. An inhomogeneous load distribution needs to be included as well as other sources of seasonal load, i.e. ocean load. Evaluation of modeled amplitudes suggests a sensitivity to E depending on location. Phase offsets in the vertical component (Fig. 5) might be due to recharge of the groundwater table, or caused by irregular melting of the ice caps. The impact of other load sources needs future studies. Despite the limitations, our simple approach explains a large part of the observed annual variations, suggesting glacier load variation provides a major contribution to the annual ground displacements. The value of $40 \pm 15\,GPa$ is inferred to be a minimum value for E depending on the location.

6. Future studies

An expanded ISGPS network combined with this work might reveal information about yet too poorly constrained snow loads outside of the ice caps. Furthermore, future additional CGPS data could be used to infer the onset of the melting season for the individual ice caps. The simulator this work was carried out with will be expanded to allow for application of more complex loading behavior to a more realistical Earth model.

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Acknowledgements: We would like to thank Finnur Pálsson and Helgi Björnsson at the Institute of Earth Sciences, Univ. Iceland, for providing us with the glacier mass balance data and helpful comments, and Rósa Ólafsdóttir at the Nordic Volcanologial Center who provided the glacier outlines. We thank Paul Wessel, Walter H.F. Smith, and all participating volunteers for implementing The Generic Mapping Tools (GMT). This research was partly supported by EU projects FORESIGHT (SSPI-CT-2003-511139) and VOLUME (Contract 18471).