Icelandic rhythmics: Annual modulation of land elevation and plate spreading by snow load

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Received 5 September 2006; revised 31 October 2006; accepted 7 November 2006; published 20 December 2006.

[1] We find strong correlation between seasonal variation in 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 ± 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 ~37 mm. CGPS stations closest to the ice cap experience a peak-to-peak seasonal displacement of ~16 mm, consistent with our model. East and north of Vatnajökull we find the maximum of annual horizontal displacements of ~6 mm resulting in apparent modulation of plate spreading rates in this area. **Citation:** Grapenthin, R., F. Sigmundsson, H. Geirsson, T. Árnadóttir, and V. Pinel (2006), Icelandic rhythmics: Annual modulation of land elevation and plate spreading by snow load, *Geophys. Res. Lett.*, *33*, L24305, doi:10.1029/2006GL028081.

1. Introduction

[2] Time series of continuous GPS stations (CGPS) often reveal annual cycles in deformation of Earth's crust. Earlier studies relate this to seasonal phenomena like variations in the groundwater table [*Watson et al.*, 2002], water load [*Bevis et al.*, 2005; *vanDam et al.*, 2001], snow load [*Heki*, 2001], or soil moisture and atmosphere [*Blewitt et al.*, 2001]. The CGPS records on the subaerial part of the Mid-Atlantic Ridge that forms Iceland show pronounced seasonal signal variation [*Geirsson et al.*, 2006]. In a study focusing on Mýrdalsjökull, an ice cap in South-Iceland, *Pinel et al.* [2006] suggest annual variations in glacial load as the main cause of annual signals in time series of nearby GPS stations (Figure 1).

[3] The signals in the CGPS data from Iceland indicate influence of winter loading and summer unloading [*Geirsson et al.*, 2006]. The amplitudes of the time series correlate inversely with the stations distance away from the ice caps, suggesting their variable load may influence deformation. We expect contribution of water table processes to this observation to be less important as suggested by *Heki* [2001] for Japan. However, atmospheric effects might contribute significantly to the displacements, although the unstable oceanic Icelandic climate is unlikely to cause such clear seasonal deformation signals. Here we study the impact of annual changes in snow load at the four largest ice caps (Vatnajökull, Langjökull, Hofsjökull, and Mýrdalsjökull) on the deformation of Iceland and compare this to observations of the countrywide CGPS network that are relative to reference station REYK (Figure 1). To represent the deformation process we use a purely elastic model based on the Green's functions technique [e.g., *Pinel et al.*, 2006] which accounts for irregularly shaped loads. The crustal response to load changes in Iceland [e.g., *Sigmundsson*, 2006] suggests effective relaxation times of several hundred years for reaching a final relaxed state. Since annual load changes are orders of magnitude faster, it is reasonable to apply an elastic model when considering these.

2. GPS Observations and Data Processing

[4] We use continuous GPS time series from the ISGPS network, processed with the Bernese V4.2 software [*Hugentobler et al.*, 2001] in the way described by *Árnadóttir et al.* [2000]. 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. These trends in the time series are mostly due to plate motion or glacio-isostatic rebound due to glacial melting since the Little Ice Age (see negative net mass balance, b_n, in Table 1) [e.g., *Pinel et al.*, 2006].

[5] *Geirsson et al.* [2006] fit the detrended data to a harmonic function (cosine) using a least squares approach. The data show most prominent annual signals in east and vertical component at stations close to ice caps. Table 2 presents the amplitudes and phases for the best fit at four exemplary stations (HOFN, SAUD, SKRO, and SOHO; see Figure 1a)).

[6] The data presented by *Geirsson et al.* [2006] have been analyzed with three different software packages utilizing different analysis strategies, giving similar results regarding the annual signals in station displacement relative to the REYK reference station. This indicates they are true signals and not artifacts of data processing, allowing us to explore whether the annual cycles can be explained by Earth's response to surface loading.

3. Modeling

[7] In Iceland most precipitation occurs in the SE, and the central highlands; near and at the island's four largest ice

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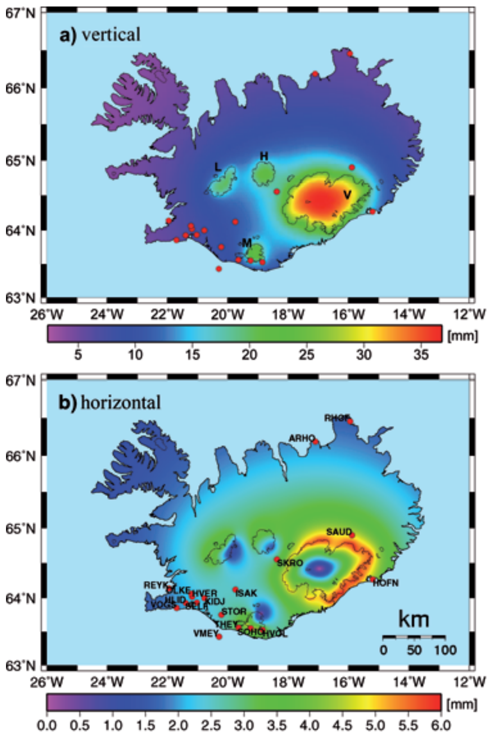

Figure 1. A map of Iceland and its largest ice caps (V: Vatnajökull, L: Langjökull, M: Mýrdalsjökull, and H: Hofsjökull). The red dots represent the CGPS stations in Iceland's ISGPS network as in 2005 and used in this study. The colors represent calculated absolute peak-to-peak seasonal displacement due to maximum winter load (see Table 1) using E = 40 GPa. (a) Vertical displacement with a peak of ∼37 mm under the center of Vatnajökull. (b) Vector lengths of horizontal displacements with a maximum of ∼6 mm east and north of Vatnajökull (displacement towards load during loading, opposite direction during unloading).

caps [*Rögnvaldsson et al.*, 2004]. The mass balances [*Paterson*, 2001] of these glaciers are relatively well constrained (see Table 1) whereas elsewhere measurements of solid precipitation are highly underestimated due to wind and snowdrift effects [*Haraldsdóttir et al.*, 2001]. Consequently, we focus on modeling the annual load cycles of the four largest ice caps (Figure 1). In general, the loads in our model are constrained by the ice caps outline and uniform load thickness, which is the evenly distributed winter mass balance, b_w (see Table 1).

3.1. Spatial Load Response

[8] Green's functions are a mathematical tool for solving linear differential equations which are derived for each specific problem. In order to get an estimate of the Earth's elastic response to a load, we consider an elastic halfspace and convolve Green's functions with the load as explained by *Pinel et al.* [2006]. Displacements are given as:

$$U_z\left(\vec{r}\right) = \int_R \frac{g}{\pi} \frac{(1-\nu^2)}{E} \frac{1}{\left|\vec{r} - \vec{r'}\right|} \rho\left(\vec{r'}\right) h\left(\vec{r'}\right) d\vec{r'} \quad (1)$$

$$U_r\left(\vec{r}\right) = \int_R -\frac{g}{2\pi} \frac{(1+\nu)(1-2\nu)}{E} \frac{1}{\left|\vec{r} - \vec{r'}\right|} \rho\left(\vec{r'}\right) h\left(\vec{r'}\right) d\vec{r'} \quad (2)$$

where U_z and U_r are, respectively, vertical and horizontal displacement at a point $\vec{r}$ (cylindrical coordinates). The elastic parameters characterizing the crust are the Poisson's ratio, ν, and effective Young's modulus, E; g is the acceleration due to gravity. The load's characteristics are the density, ρ, and the thickness, h, within the area R. An advantage of Equations 1 and 2 over traditional disk models comes with their allowance to apply arbitrarily shaped loads in a simple way. At each point $\vec{r'}$ in area R the load's height at this point, $h(\vec{r'})$, can be defined freely. Displacement at point $\vec{r}$ depends on the $|\vec{r} - \vec{r'}|$ distance.

[9] We used glacier outlines rastered in 50 m × 50 m cells. The displacements due to glacial load variations are modeled using an interpolated 1 km × 1 km grid. Using Earth's gravity constant as $g = 9.81$ m s^{-2} and a common value for the Poisson's ratio $\nu = 0.25$, the effective Young's modulus, E, is the only free parameter. 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 in increments of 5 GPa.

3.2. Temporal Load Model

[10] We model the effects of winter loading and summer unloading at the CGPS stations by introducing a simple approximation of the load history. We extend the spatial load model to:

$$h\left(\vec{r'}, t\right) = a + A\cos\left(\omega t + \varphi\right) \quad (3)$$

assuming the load, $h(\vec{r'}, t)$, varies as a harmonic function of time (t) in each location ($\vec{r'}$). We set the constant a and the amplitude A to $a = A = \frac{h_m}{2}$, with h_m being the maximum load height ($h \geq 0$). The angular frequency is $\omega = \frac{2\pi}{365}$ to span the period of one year. Phase shifting enables a control of the day when the load is maximum (t_{h_m}). Thus, the phase is set to $\varphi = -t_{h_m}\,\omega$ with t_{h_m} = 140 days corresponding to an

Table 1. Ice cap data[a]

Glacier	Observation Period	Area, km^2	Radius, km	b_w, m	b_s, m	b_n, m
Vatnajökull[b]	1991/92–2004/05	8100	50.77	1.5	−1.8	−0.3
Langjökull[b]	1996/97–2004/05	925	17.16	1.65	−2.95	−1.3
Mýrdalsjökull[b]	estimation	600	13.82	≈2.5	≈−3.0	−0.5
Hofsjökull[c]	1996/97–2001/02	890	16.83	1.25	−2.25	−1.0

[a]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, expressing mass accumulation of the glacier in these seasons. Mass balances are referred to as meters of water equivalent load thickness [*Paterson*, 2001]. b_w is the winter load height used as maximum load in the model. The net mass balance, $b_n = b_w + b_s$, is negative which indicates shrinking of the ice caps.

[b]H. Björnsson and F. Pálsson (University of Iceland, personal communication, 2006).

[c]Data from *Sigurdsson* [2003], extrapolated using weighted average means.

Table 2. Comparison of the best fits to the time series of four CGPS stations calculated by *Geirsson et al.* [2006] (Best Fit) to the model results of this study (Best Model) (all relative to REYK)[a]

	Best Fit[b]						Best Model (E = 40 GPa)						E at $RMSE_{min}$
Station	A_e	A_n	A_u	φ_e	φ_n	φ_u	A_e	A_n	A_u	$\Delta\varphi_e$	$\Delta\varphi_n$	$\Delta\varphi_u$	E [GPa]
HOFN	3.02	0.97	3.97	5.17	2.86	5.56	3.06	0.42	4.18	17	−10	1	40
SAUD	2.73	0.59	7.80	5.15	4.06	5.56	2.19	2.18	5.24	18	80	1	30
SKRO	1.33	0.30	7.91	5.52	5.01	5.83	0.55	0.49	6.09	−161	27	−1	35
SOHO	1.34	1.66	5.64	4.55	2.00	5.86	0.38	1.74	5.46	−113	19	−2	40

[a]The best fits to the time series at the CGPS stations are given by amplitude, A (in mm), and phase, φ, for the components east (e), north (n) and up (u). Model results, derived using an effective Young's modulus of E = 40 GPa, give the amplitudes for each direction (A_e, A_n, A_u) and the offset in the phase, $\Delta\varphi$, for each component in days using cross correlation r of best fit f and model results m: $r = f \star m$. The values in the last column are values for the effective Young's modulus derived from the minimum RMSE of the respective station. Using this value in the model, the time series of each individual station would be described best.

[b]*Geirsson et al.* [2006].

average beginning of the melting season in Iceland in mid-May (H. Björnsson and F. Pálsson, University of Iceland, personal communication, 2006).

[11] We get:

$$h\left(\vec{r'}, t\right) = \frac{h_m}{2}\left[1 + cos\left(\frac{2\pi}{365}\left(t - t_{h_m}\right)\right)\right] \qquad (4)$$

Replacing the height $h(\vec{r'})$ in Equations 1 and 2 by Equation 4 and introducing a time parameter results in vertical and radial displacement, $U_z(\vec{r},t)$ and $U_r(\vec{r},t)$, at a point $\vec{r}$ as a function of time t.

[12] The values of the winter mass balance b_w in Table 1 serve as h_m, because the linear trend, b_n, is removed. Since b_w is a water equivalent the density is ρ = 1000 kg/m^3. We use the CGPS sites as observation points and calculate the deformation histories due to application of annual loading.

[13] The implementation of both, spatial and temporal load model, is verified by *Grapenthin and Sigmundsson* [2006] using a disk load case. (available at http://www.raunvis.hi.is/~fs/green/)

4. Comparison of Observations and Load Models

[14] The ISGPS network is operated by the Icelandic Meteorological Office (see http://www.vedur.is). Time series of displacements and model displacements are calculated relative to station REYK, which was the first CGPS station installed in Iceland. We derive a best value for the effective Young's modulus (E) using the average of the standard root mean squared error (RMSE) for stations with a time series of at least one year. This value for E is used to model absolute displacements (Figure 1) and to fit the time series. Assuming harmonic load variations (which is a simplification – see discussion), the RMSE is calculated between model predictions and best fits to the time series (see chapter 2) on a daily basis:

$$RMSE_{mean}(E) = \frac{1}{3\,N}\sum_{i=1}^{N} RMSE_{i,e} + RMSE_{i,n} + RMSE_{i,u} \qquad (5)$$

with e, n, u being the east, north, and up directions, respectively. N is the number of CGPS stations. Figure 2 shows the difference in the $RMSE_{mean}$ as a function of E in the model for all CGPS stations, and a separate estimate for CGPS stations close to glaciers. For both cases, we derive a best model value of E = 40 GPa. A comparison with the respective null models (RMSE of best fits to the time series) shows more reduction of variance when considering only glacier stations. Using an E = 40 GPa we explain ~55% of the RMSE close to the ice caps and ~40% for all stations (Figure 2). The difference in amplitudes in the vertical component contributes the most to this discrepancy, which is due to the use of a single value for E in all Iceland.

[15] Figures 1a and 1b show absolute vertical and horizontal displacements at the onset of the melting season (t_{h_m}) for all of Iceland using E = 40 GPa and maximum snow load. Stations in western and northern Iceland have minor induced deformation, explaining the proportionally better fit of the model to CGPS stations close to ice caps. By fitting each CGPS station individually to the model and considering the scatter in best fit E, we infer a confidence interval of E = 40 ± 15 GPa.

[16] For E = 40 GPa, the largest horizontal displacement of ~6 mm occurs north and east of Vatnajökull (peak-to-peak seasonal displacement). The huge load of the Vatna-

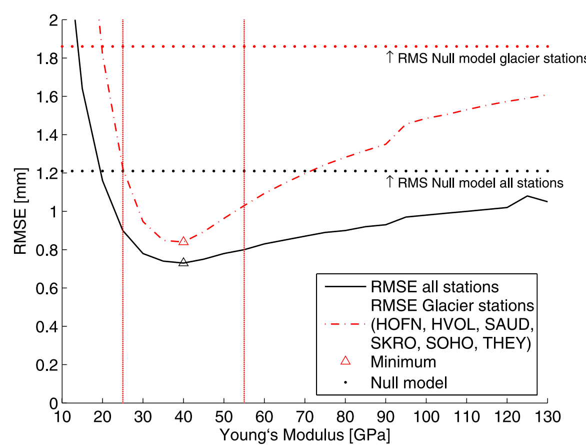

Figure 2. The root mean squared error (RMSE) between model results and best fit to data, as a function of the effective Young's modulus E. RMSE are calculated for all CGPS stations (solid line) and stations in the vicinity of the ice caps (dash-dotted line). Triangles mark the minima which is the best fit to the time series for E. The upper dotted line is the RMSE of the null model (RMSE of best fit to time series as given by *Geirsson et al.* [2006]) for stations nearby glaciers, whereas the lower dotted line is the RMSE of the null model for all stations; neither depends on E. The vertical lines mark the range of the optimal value for the effective Young's modulus suggested by our results.

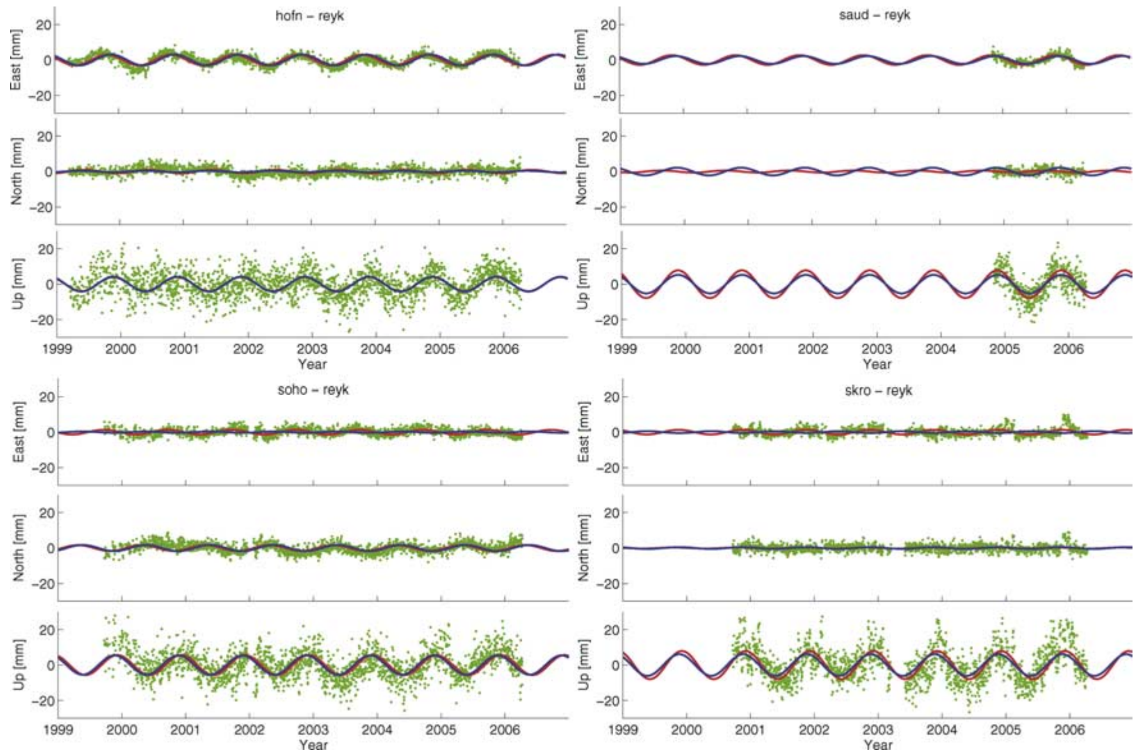

Figure 3. Comparison of predicted and observed results of temporal modeling using a harmonic load (as explained in the text) at four CGPS stations: HOFN, SAUD, SKRO, and SOHO, in east, north and up component over the years 1999–2006. The detrended CGPS time series are shown by green dots. The red line is the best fit to the time series [see *Geirsson et al.*, 2006]. The blue line is the modeled displacement using E = 40 GPa. Time series, best fit, and modeled displacement are relative to station REYK.

jökull ice cap affects the horizontal displacement field even at the other ice caps, pulling them significantly towards its center. For the vertical, maximum displacement is ~37 mm under the center of the Vatnajökull ice cap.

[17] Temporal variation at exemplary station locations using E = 40 GPa and varying loading over time are shown in Figure 3. Predictions for the vertical component are at all stations in close proximity to glaciers almost in phase (temporal comparisons with respect to best fit; cross-correlation: ±2 days, THEY: 15 days). Phase offsets between time series and model results can be explained by slight variation in the beginning of the melting season at different ice caps (assumed the same in the model). The amplitudes at stations west and north of Vatnjaökull are underestimated (see Table 2) which can be due to the less stiff, younger crust in the Eastern Volcanic Zone (see Discussion). At HOFN, however, the opposite seems to be the case, since the amplitude of the vertical component is slightly overestimated, whereas SOHO's vertical amplitude gets also underestimated. Only SOHO, south of the Mýrdalsjökull ice cap, shows a significant cycle in the north component which is fit quite well by the model. The best fit to the time series in the east component at station HVOL, also south of the Mýrdalsjökull ice cap, results in an amplitude of 1.12 mm. The model predicts an amplitude of 0.84 mm. Figure 1b), however, suggests only little or no east motion at this station. An absolute model run gives an east displacement of 0.11 mm. As concluded by *Geirsson et al.* [2006] this difference in absolute and relative values in the east component is mostly due to annual movement at REYK.

5. Discussion and Conclusions

[18] Results from our simple load model correspond to observations of earlier studies on the impact of annual loading cycles on crustal deformation [e.g., *Heki*, 2001; *Bevis et al.*, 2005] and match the data of CGPS stations in Iceland. Our modeled load, however, remains a simplification of the real seasonal load in Iceland. In particular, snow loading is not uniform over the extent of the ice caps, and the snow melting and accumulation seasons are not equally long. Using a harmonic approximation for load cycles with potential contributions of non-sinusoidal terms may underestimate the amplitudes and complicates determination of their uncertainties. An improved model should consider this and include other sources of seasonal load, i.e., ocean load, soil moisture, and atmospherical load [*Heki*, 2004]. Possible effects of ocean-loading tide on the annual signals should be considered [e.g., *Penna and Stewart*, 2003] although in our case the amplitudes of the annual signals are largest at stations close to the ice caps, suggesting their variable load is a primary source of the signals. The flat-Earth approximation would also need a consideration in an improved analysis. Numerical modelling shows that for distances less than 150 km from the Vatnajökull ice cap for a flat Earth and a spherical Earth the vertical response agrees to within 1%, and the horizontal to within 10% in amplitudes. Our

simple approach using flat Earth approximation is therefore valid for first order analysis of loading effects.

[19] Evaluation of modeled amplitudes suggests a sensitivity to the effective Young's modulus, apparently depending on locations of CGPS stations (see Table 2 and Figure 2). Phase offsets in the vertical component (i.e. STOR, THEY) might be due to recharge of the groundwater table. This might result in a less sharp displacement gradient in spring [e.g., *Heki*, 2001; *Watson et al.*, 2002] that is not yet considered in our model formulation. The observation that not all stations in the vicinity of a single ice cap behave in the same way (i.e. SOHO, THEY) might be caused by irregular melting of the ice caps, not including the small Eyjafjallajökull glacier west of Mýrdalsjökull, groundwater effects or other loads outside the ice caps not included in the model and needs future studies. Despite all these limitations, our simple approach explains a large part of the observed annual variations (with relatively large inferred uncertainty on the value for the Young's modulus), suggesting glacier load variation provides a major contribution to the annual ground displacements.

[20] We verify that seasonal changes of ice caps have an impact on crustal deformation far beyond the glacier outlines and we find mutual impact of the ice caps as suggested by *Pinel et al.* [2006] (Figure 1b) shows influence of Vatnajökull on other sites). They model deformation in a small area at Mýrdalsjökull not including other ice caps and infer a value of E = 29 GPa as a minimum value for the effective Young's modulus. This is lower than we find, but within our confidence interval. As stated by *Pinel et al.* [2006], parts of the annual signals in the CGPS data have to be considered to be artifacts of atmospheric effects, ocean load, or snow loads in the highlands and northern Iceland which are yet too poorly constrained for modeling. Thus, we infer the values of 40 ± 15 GPa (Table 2 and Figure 2) to be minimum values for E depending on the location. This range overlaps with the range of 60 ± 10 GPa inferred by *Sigmundsson et al.* [2006], considering deformation induced by glacial surges at Icelandic outlet glaciers. When individual CGPS stations are considered, the values of E appear to increase with distance from the active Eastern Volcanic Zone which roughly strikes NE under Vatnajökull. At station HOFN we infer a high value for E and find bedrock older than 3.1 m.y., whereas E is small at station SAUD which lies in an area younger than 0.7 m.y. (Table 2) [*Jóhannesson and Saemundsson*, 1989]. Future research is necessary to validate this apparent correlation of E with age of the bedrock in Iceland.

[21] The expansion of the ISGPS network combined with results of this paper might reveal information about snow load outside the ice caps, thus constrain Icelandic climate models better, which in turn might serve as a more sophisticated load model. Furthermore, future additional CGPS data can be used to infer the onset of the melting season for the individual ice caps. For complete understanding of the annual cycles in CGPS stations, other load sources like ocean and atmosphere, as well as feedback effects caused by interaction between those, also need to be taken into account. The expanded network, however, can help mapping the spatial variation of E in Iceland, improving our understanding of crustal deflection.

[22] **Acknowledgments.** 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. Furthermore we would like to express our gratitude to Paul Wessel, Walter H.F. Smith, and all participating volunteers for implementing The Generic Mapping Tools (GMT) which were used to create the maps presented in this paper. Constructive reviews by Paul Tregoning and Kosuke Heki improved the paper and are gratefully acknowledged. This research was partly supported by EU projects FORESIGHT (SSPI-CT-2003-511139) and VOLUME (contract 18471).

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