Water drainage beneath Skeiðarárjökull and its effects on ice-surface velocity

Matthew J. Roberts*

Physics Department, Icelandic Meteorological Office, 150 Reykjavík, Iceland

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* Collaborators: Eyjólfur Magnússon[1,2], Rick Bennett[3], Halldór Geirsson[4], Erik Sturkell[2], Helgi Björnsson[2], Finnur Pálsson[2], Helmut Rott[1], and Alexander H. Jarosch[2]

1: Institute of Meteorology and Geophysics, University of Innsbruck, A–6020, Austria

2: Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

3: Department of Geosciences, University of Arizona, Tucson, AZ 85721–0077, U.S.A.

4: Physics Department, Icelandic Meteorological Office, 150 Reykjavík, Iceland

1. Background and project goal

Wherever pressurised water exists beneath glaciers or ice sheets, increased rates of ice movement occur due to a reduction in effective stress at the ice-bed interface (Clarke, 2005 and references therein). Previous studies have shown how basal sliding – the most effective form of glacier motion – is governed by the supply of meltwater to the glacier bed (e.g., Iken and Bindschadler, 1986; Röthlisberger and Lang, 1987; Zwally *et al.*, 2002). Sudden reductions in effective stress, caused by enhanced ice-surface melting, rainfall or jökulhlaup, can result in heightened displacement rates at the glacier surface (Anderson *et al.*, 2003; Macgregor *et al.*, 2005; Roberts *et al.*, 2005). However the timing and subglacial extent of such velocity changes are often unknown because continuous measurements of surface movement are seldom made (Willis, 1995). In glaciated Maritime regions such as southeast Iceland, rainfall is common throughout the year, but the responsiveness of glacier motion to varying rainfall is unclear. Consequently, the goal of our research was: (i) to make continuous, long-term measurements of surface movement in the lower ablation zone of Skeiðarárjökull, southeast Iceland (Figure 1); and (ii) to determine the influence of variations in meltwater input to the glacier bed on rates of basal sliding.

2. Methods

Surface measurements of ice displacement were made using three, dual-frequency *Trimble*™ global positioning system (GPS) receivers equipped with Zephyr Geodetic™ antennae set to an elevation mask of 13°. From 18 April 2006, two 5700-type receivers were active on Skeiðarárjökull (SKE1† and SKE3); these instruments were replaced on 01 June 2006 with two NetRS™ receivers, plus an additional station: SKE2 (Figure 2). The three GPS stations collected data until 18 November 2006. The platforms on which each GPS was mounted were deployed to form a triangular network on the eastern side of Skeiðarárjökull (~1,380 km^2); the farthest station (~455 m a.s.l.) was located 8 km from the glacier terminus, where ice thickness exceeds 400 m (Björnsson *et al.*, 1999); the initial gap between stations was ~3 km (Figure 2).

The eastern side of Skeiðarárjökull was chosen for measurement because this region conveys the largest flux of ice and meltwater (Björnsson *et al.*, 1999) and jökulhlaup are common, either from Grímsvötn or from several ice-marginal lakes (Björnsson, 1992). Additionally, InSAR data from the ERS 1/2 tandem mission showed high, temporal variations in the surface velocity of Skeiðarárjökull, particularly above the inferred subglacial path of Skeiðará: the glacier's largest meltwater river (Magnússon *et al.*, in press).

Low-lying glaciers on the southern flank of Vatnajökull are subject to year-round melting. Over a four-month period from August to November 2001, ablation measurements at 349 m a.s.l. on the centreline of Skeiðarárjökull revealed 8.2 m of surface melting (Ó. Knudsen and M. J. Roberts, unpublished information, 2001). Such high melt-rates made antennae mounts drilled into the surface an unfeasible option (*cf.* Þorsteinsson *et al.*, 2005); therefore, we devised an alternative means for mounting the GPS equipment securely on the glacier. Inspired by the design of a *Landvirkjun* meteorological station on Brúarjökull (northeast Vatnajökull), we designed a broad, low platform that comprised four, diagonally opposed aluminium supports bolted to a central mounting plate for the GPS antenna (Figure 3). To provide foundation on the ice, a 20-cm steel pin was fixed to the lower end of each

† On 27 June, SKE1 was re-positioned by ~8 m due to crevassing, hence the station was renamed SKE4.

aluminium support; this pin was intended to anchor each corner of the platform partly within the ice. Heat conducted to the ice from the supports ensured that each platform remained embedded in the surface during the observation period. Additionally, nighttime freezing of meltwater pooled around each support improved the stability of the platforms to the extent that we were unable to lever them from the ice during maintenance visits.

Each GPS station was powered by two 12 V, gel-based *Tudor Exile*™ batteries, producing in combination 80 A h^{-1} of current. The batteries were connected in parallel to the receiver, and charge was maintained by a 50 W photovoltaic panel at SKE1 and SKE3, and a 20 W panel at SKE2 (Figure 4). Power consumption at each GPS station was ~4 W.

Throughout the observation period, each GPS receiver logged satellite data continuously at 15-second intervals, yielding daily files of about 0.7 MB. However from 16 September 2006, an additional one-second-sampling program ran at SKE1 and SKE3; during this period, total memory usage was ~9.5 MB per day at each receiver. Positional data were transferred from the receivers during maintenance visits to the network, which took place approximately every six weeks (Appendix 1). North (N(t)), east (E(t)), and vertical (Z(t)) time-dependent positions were processed into 24-hour and 3-hour solutions using version 4.2 of the *Bernese* software program. For each station, reference data were sourced from HOFN: a continuous GPS station sited 98 km east of the Skeiðarárjökull network (Geirsson *et al.*, 2006) (Figure 1). Surface motion with respect to ice-flow scaled linearly with time (t), and it was calculated from the derivatives $\partial N/\partial E = \partial N/\partial t \,/\, \partial E/\partial t$.

Alongside geodetic observations, we collated meteorological data from Laufbali, sited 44 km west of the GPS array at 490 m a.s.l., and Skaftafell, located 10 km east of the array at 90 m a.s.l. (Figure 1). Ten-minute measurements of rainfall from Laufbali were integrated with the displacement data, whereas, hourly air-temperate data and daily records of rainfall were selected from Skaftafell. Lastly, observations of seismicity from Skeiðarárjökull, registered by the SIL national seismic network (Figure 1), were incorporated with geodetic and meteorological data to ascertain the approximate extent and timing of significant changes in stress within the glacier. For details about the SIL network and its application to glacier seismicity see Bödvarsson *et al.* (1996) and Roberts (2005), respectively.

3. Results

Throughout the 180-day observation period, large variations in rates of horizontal and vertical movement were detected. The strongest increases took place during rainstorms in spring and autumn (Figure 5); these episodes of enhanced motion were accompanied by short-lived seismicity from Skeiðarárjökull, with some emissions comprising over 70 locatable 'icequakes' ranging in size from M_{LW} 0.4 to M_{LW} 1.6[‡] (Figure 2). From June to September 2006, the association between rainstorms and increased displacement rates was less pronounced (Figure 5). At SKE1 – the station with the highest drift-rate – horizontal velocities fluctuated from an equivalent of 0.14 m d^{-1} in November to 1.92 m d^{-1} in October; the latter value reflecting glacier-flow during persistent, heavy rain. Over monthly intervals, the mean, 24-hour solution for horizontal displacement at each station was remarkably constant, signifying the predominance of steady ice-flow. At SKE1, the monthly mean was 0.49 m d^{-1} (± 0.09), whereas at SKE2[§] and SKE3 the equivalent rate was 0.27 m d^{-1} (± 0.02) and

[‡] M_{LW} denotes local earthquake magnitude, 'weighted' to tectonic conditions in Iceland.

[§] Note that the record spans only four months at SKE2 but over seven months at the other stations.

0.20 m d^{-1} (± 0.07), respectively. Additionally, the mean direction of horizontal movement at SKE1 and SKE3 was 159°, while at SKE2 the mean was 136°, implying a divergence of flow toward the eastern edge of the glacier terminus (Figure 2).

From April to July 2006, whenever rain in excess of ~20 mm d^{-1} fell over southern Vatnajökull, icequakes were detected in Skeiðarárjökull (Figure 5); similarly, in September and October the same positive association was apparent. However, in August – the month with the highest mean air temperature in 2006 – no icequakes were registered in Skeiðarárjökull, despite at least 319 mm of rainfall at Skaftafell. Importantly, over the same period, no significant increases in glacier flow were observed.

Sudden increases in horizontal velocity at SKE1 were accompanied by significant, albeit temporary, uplift of the ice surface. Between 29 April and 05 May 2006, 143 mm of rain was observed at Laufbali. About five hours after the onset of rain, icequakes began to occur in Skeiðarárjökull (Figure 6); time lags of similar duration had been noted previously in relation to Skeiðarárjökull icequakes and nearby rainstorms (*Icelandic Meteorological Office*, unpublished information). Assuming the same intensity of rainfall at Laufbali and Skeiðarárjökull – a justified assumption given that 46 mm of rain was recorded at Skaftafell on 29 April – then for a 400-m-thick section of ice, a five-hour lag implies a mean penetration rate of ~0.02 m s^{-1} from the glacier surface to the glacier bed. From three-hour velocity solutions, seismicity was followed directly by accelerating ice flow, which, initially, led to a reduction in surface elevation; however this trend reversed several hours later to gradually increased rates of uplift (Figure 6). After the seven-day rainstorm (06 May), 0.65 m of progressive uplift had taken place at SKE1 relative to the station's position on 29 April. Under dry weather, this accrued uplift was dissipated over six days from 06 May at a negative exponential rate (Figure 6).

4. Insights

Despite large, transient increases in basal sliding in response to rainfall at the beginning and end of the melt season, the summertime flow of Skeiðarárjökull was remarkably steady. Nonetheless, order-of-magnitude flow variations within a 4.5 km^2 region of Skeiðarárjökull are an unexpected finding. The timing of rainfall-triggered speed-up events in April and October 2006 signifies that subglacial water pressure – and hence the effectiveness of basal sliding – is regulated by the hydraulic capacitance of subglacial drainage.

The 0.65 m of upward movement at SKE1 observed over a seven-day period could be indicative of changes in subglacial hydraulic pressure, forced by the temporary accumulation of water at the glacier bed (*cf*. Macgregor *et al.*, 2005). Alternatively, the uplift could have resulted from recoverable, vertical straining of the ice column beneath SKE1 due to accelerating flow (*cf*. Balise and Raymond, 1985). Curiously, the highest horizontal velocities are out-of-phase with the highest upward velocities (*cf*. Iken *et al.*, 1983), suggesting that although the ice was de-coupled partly from the bed due to water pressure, strain-induced thickening of the glacier occurred as well.

Besides the association between bed de-coupling and basal sliding, the velocity record from SKE1 also emphasises substantial variations in ice discharge. Supposing a 4-km-wide, 0.4-km-deep cross-section perpendicular to glacier flow beneath SKE1, then a mean sliding rate of 0.49 m d^{-1} yields a daily ice-flux of 705,600 tonnes. It follows, therefore, that meltwater-induced 'mini-surges' can cause short-term variations in glacier mass-balance (Joughin *et al.*, 1996).

5. Summary

Seasonal, sub-seasonal, and sub-daily variations in sliding at the base of Skeiðarárjökull were exhibited in the 180-day record of GPS-derived surface motion. A thirteen-fold increase in sliding rate at SKE1 between November and October 2006 demonstrated velocity excursions akin to 'mini-surging'. Clearly, a strong inter-dependence existed between rainfall and the documented velocity pulses. Upward displacement of the ice surface occurred during the onset of accelerating ice flow; however gradual uplift persisted during periods of decelerating flow, implying that gradients in horizontal velocity caused the glacier to thicken locally, hence increasing the elevation of the ice surface.

This study demonstrated conclusively the feasibility of GPS techniques for long-term, high-resolution monitoring of glacier flow. Furthermore, the proven design of our GPS platform gives promise to the establishment of permanent GPS stations on Icelandic glaciers. Year-round geodetic monitoring would allow inter-annual variations in glacier flow to be assessed, thereby providing unprecedented data for mass-balance computations and models of ice dynamics. Moreover, at Skeiðarárjökull, the subglacial propagation of jökulhlaup could be followed using a GPS station linked via telemetry to the SIL seismic network. Rapid processing of receiver data using predicted orbital information (Geirsson *et al.*, 2006) would facilitate accurate warnings about jökulhlaup routing and timing.

6. Plan for further work during 2007

- Correct geodetic data for the combined effects of ice-surface melting and down-glacier movement of the GPS platforms.
- Kinematic processing of geodetic data to constrain further the timing of velocity changes due to rainfall and to assess whether rapid motion initiates simultaneously at all three GPS stations.
- Determine strain-rates between GPS stations.
- Integrate present dataset with available river-stage measurements on Skeiðará.
- Re-deploy GPS receivers to the platforms on Skeiðarárjökull that remain as benchmarks.

Acknowledgements

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Appendix 1: Skeiðarárjökull GPS project: installation and maintenance trips

18/04/2006 – *Installed SKE1*

Participants: C. Pagli, E. Sturkell, E. Magnússon, M. J. Roberts, and T. Granvuinet

17/05/2006 – *Deployed platforms for SKE2 and SKE3 (5700 receiver installed at SKE3)*

Participants: A. H. Jarosch, E. Magnússon, M. J. Roberts, and R. Grapenthin

01/06/2006 – *Retrieved 5700 receivers and installed NetRS receivers at SKE2 and SKE3*

Participants: E. Sturkell, H. Hannesdóttir, and M. J. Roberts

27/06/2006 – *Installed NetRS receiver at SKE1 and repositioned the station*

Participants: H. Keys and M. J. Roberts

16/07/2006 – *Downloaded NetRS data from all stations*

Participants: H. Evans and M. J. Roberts

20/07/2006 – *Returned NetRS receiver to SKE2*

Participants: M. Ómarsdóttir, S. D. Eddudóttir, and M. J. Roberts

16/09/2006 – *Downloaded NetRS data from all stations*

Participants: E. Magnússon and M. J. Roberts

17/11/2006 – *Retrieved NetRS receivers from Skeiðarárjökull*

Participants: E. Sturkell, R. F. Kristjánsson, and M. J. Roberts

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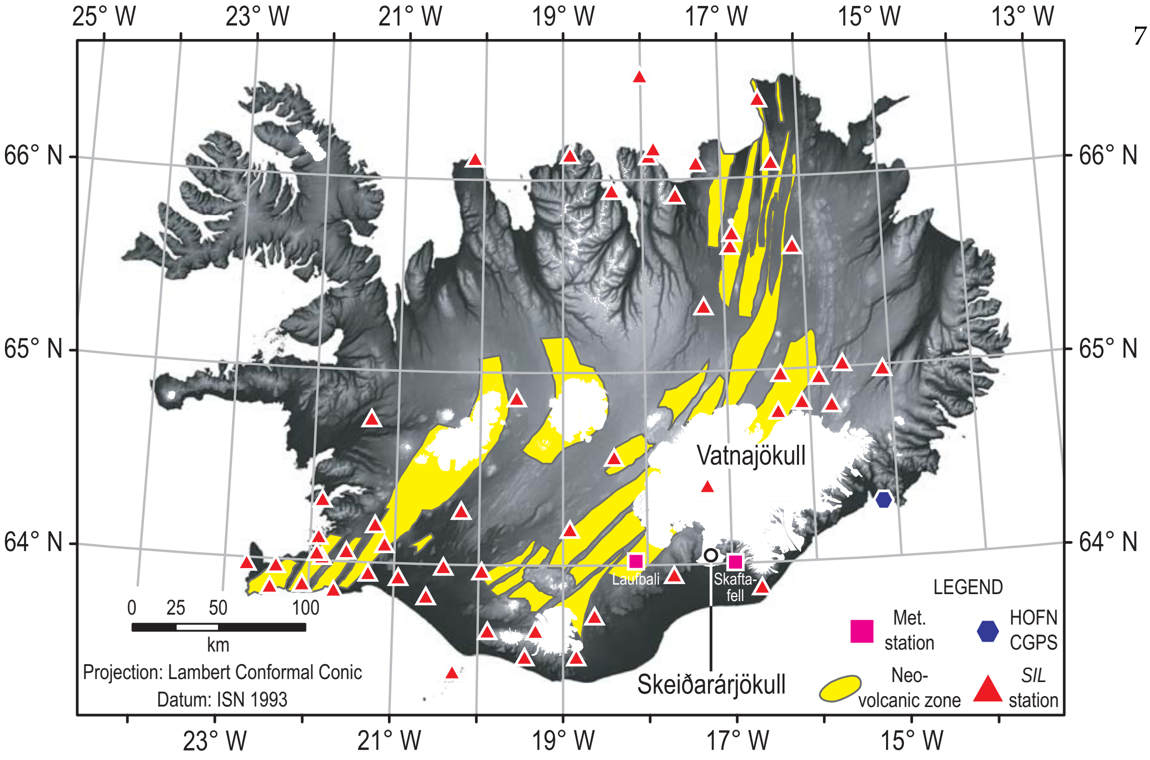

Figure 1: Skeiðarárjökull and the SIL seismic network, utilised here to monitor seismicity from the glacier. For more information about the SIL network, visit: http://hraun.vedur.is/ja Note also the location of the CGPS reference station used in this study and the position of meteorological stations near to Skeiðarárjökull.

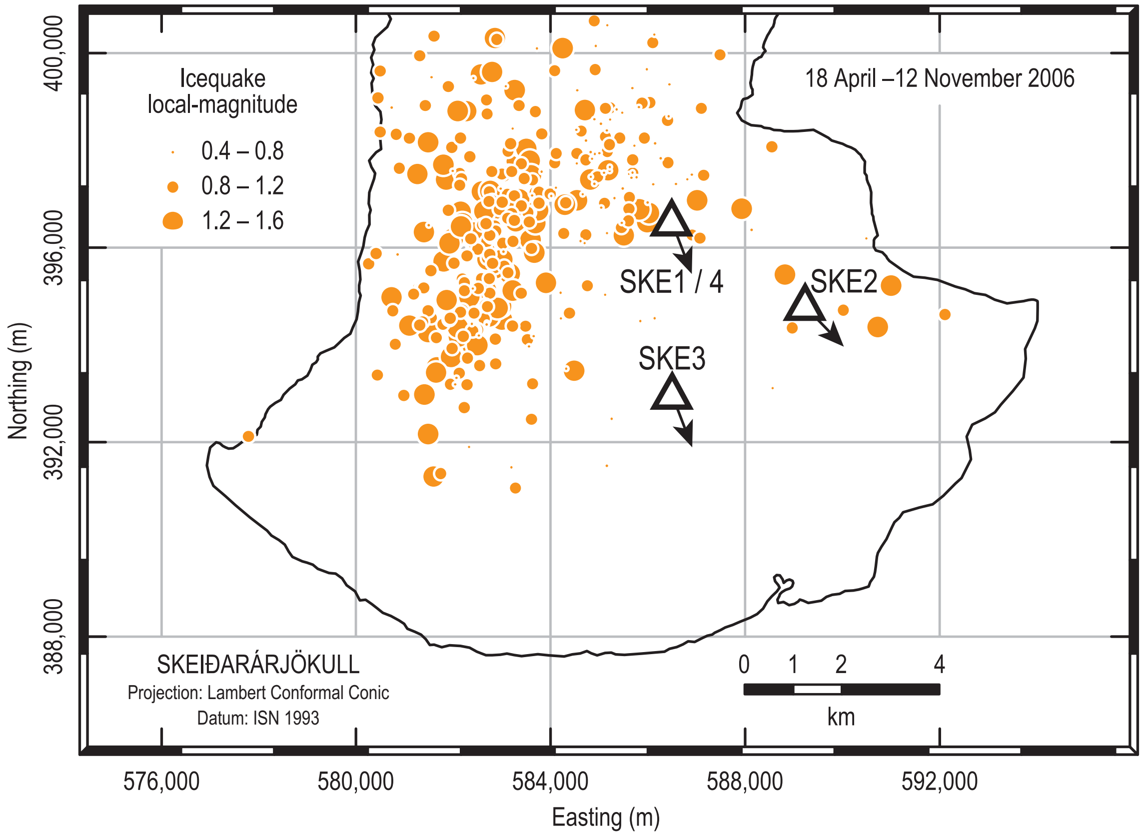

Figure 2: Location of GPS stations on Skeiðarárjökull and icequake epicentres registered during the study period by the SIL seismic network. Note that the arrows illustrate the direction of station movement but not the magnitude.

Figure 3: Each GPS platform was intended to be light, portable, and simple to construct. The pictured station is SKE1 during trials in Reykjavík on 16 April 2006; the station, designed and built by the author, was constructed mainly from bolted sections of aluminium. Upper photograph: bolted fittings enabled each platform to be dismantled for transport over Skeiðarárjökull. Middle photograph: a central plate united each aluminium strut, on which a threaded attachment for the GPS antenna was fixed (note tape measure for scale). Lower photograph: field-ready version of SKE1 ready for deployment on Skeiðarárjökull. Photographer: Matthew J. Roberts.

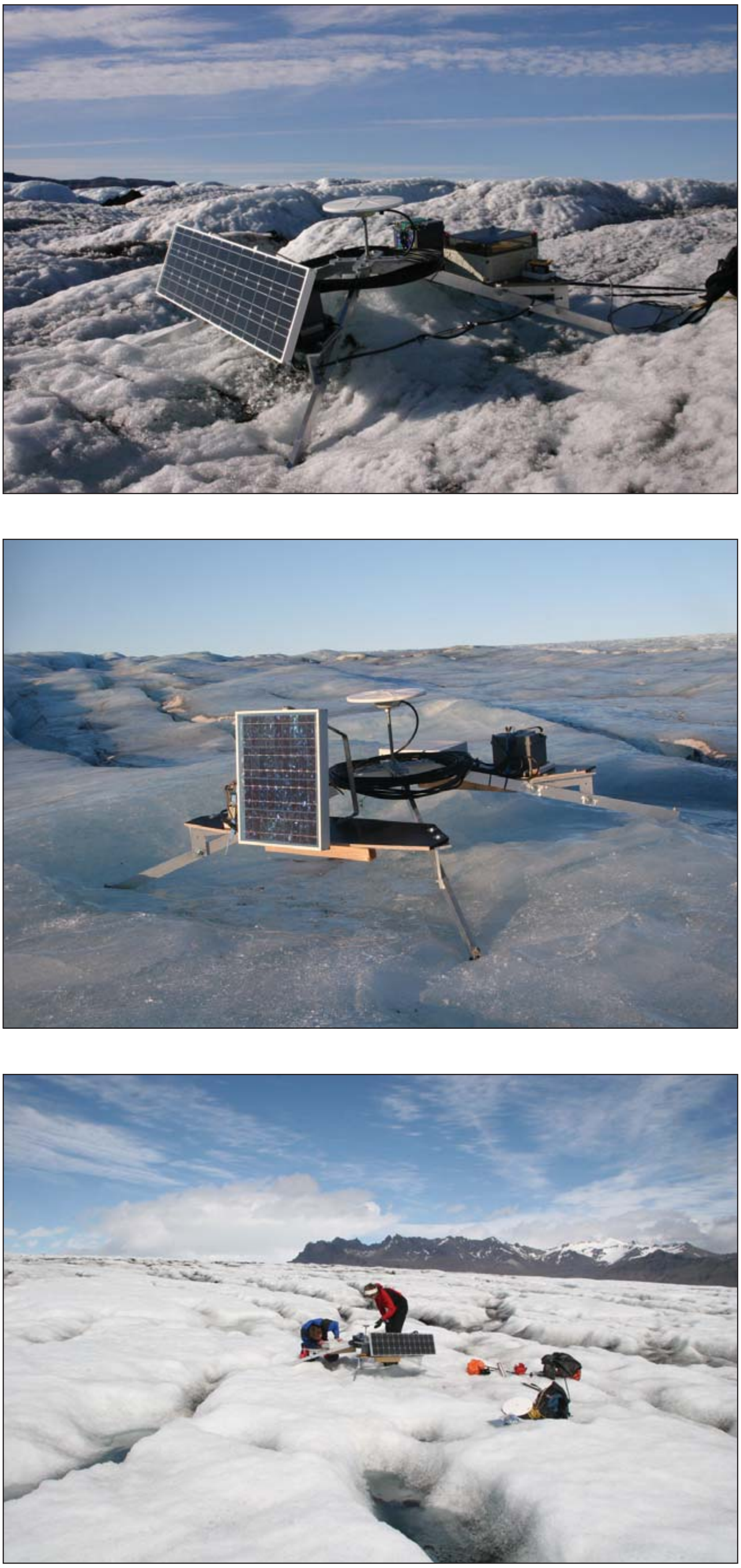

Figure 4: Photographs of the GPS stations on Skeiðarárjökull – see Figure 2 for station locations. Upper photograph: SKE1 on 16 September 2006. Middle photograph: SKE2 on 18 November 2006. Lower photograph: installation of a *Trimble*™ *NetRS*™ receiver at SKE3 on 01 June 2006. Photographers: Matthew J. Roberts (SKE1 and SKE2) and Erik Sturkell (SKE3).

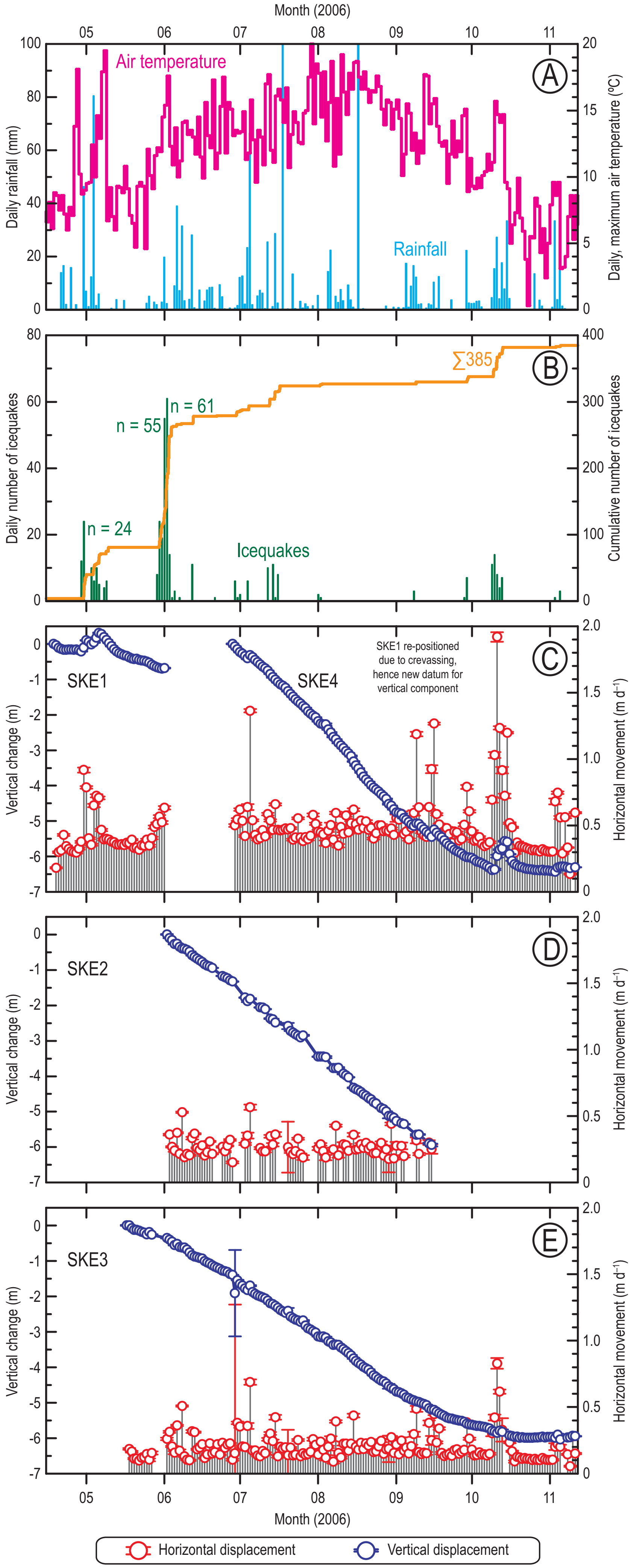

Figure 5: Stacked, time-series plots of rainfall and air temperature data from Skaftafell (A); icequake activity in Skeiðarárjökull (B); and movement of the three GPS stations (C–E).

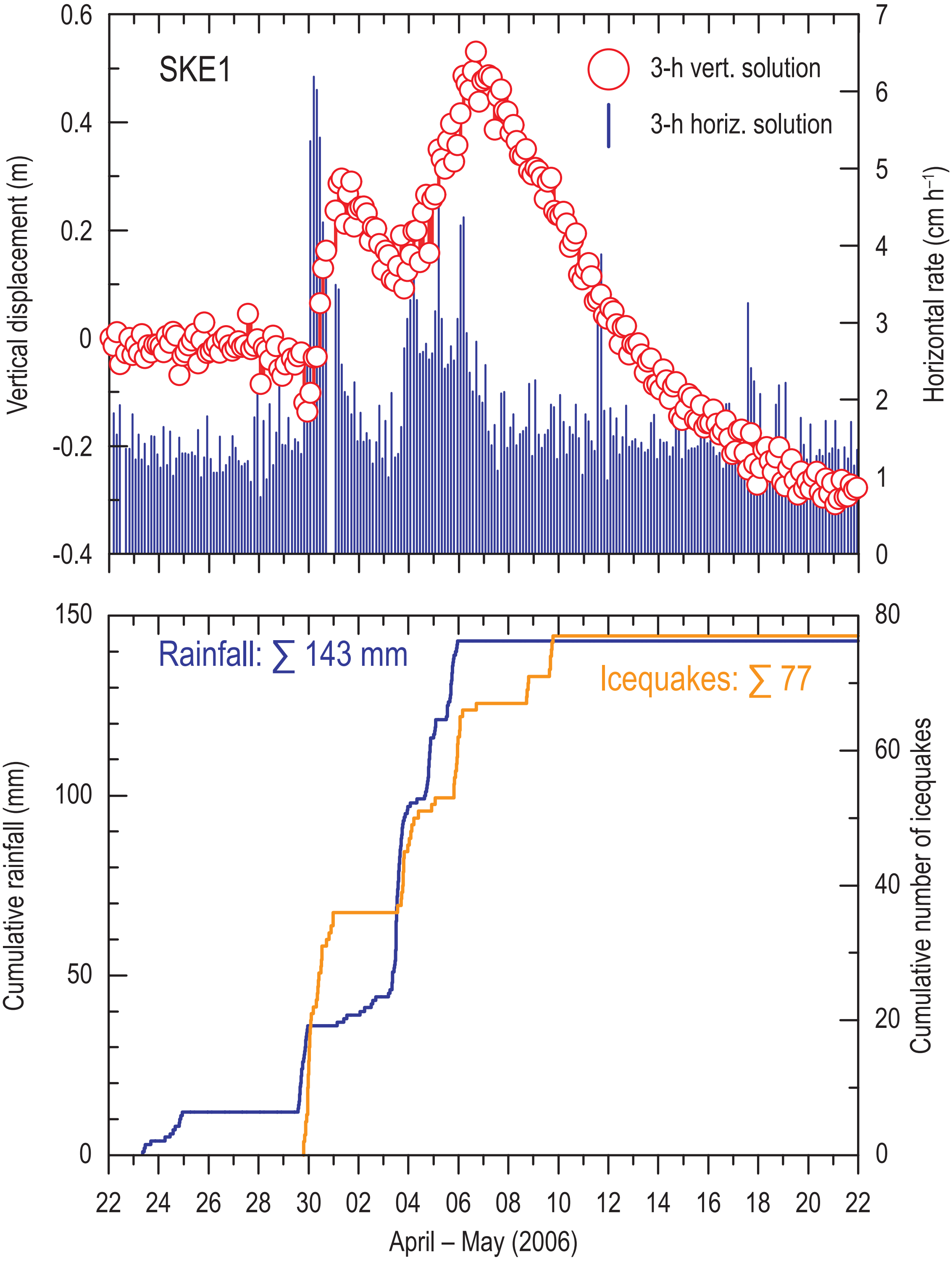

Figure 6: Increased horizontal movement at SKE1 and subsequent uplift of the ice surface. Note the period of sustained uplift in association with rainfall at Laufbali.

Meltwater Dynamics Beneath Skeiðarárjökull From Continuous GPS Measurements and Seismic Observations*

Matthew J. Roberts[(1)], Eyjólfur Magnússon[(2,3)], Rick Bennett[(4)], Halldór Geirsson[(1)], Erik Sturkell[(2)], Helgi Björnsson[(2)], Finnur Pálsson[(2)], and Helmut Rott[(3)]

(1) Icelandic Meteorological Office, Bústaðavegur 9, 150 Reykjavík, Iceland

(2) Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

(3) Institute of Meteorology and Geophysics, University of Innsbruck, A-6020, Austria

(4) Department of Geosciences, University of Arizona, Tucson, AZ 85721-0077, USA

Abstract: Glacier and ice-sheet motion is influenced strongly by the amount of meltwater within subglacial drainage. Velocity estimates from remotely-sensed data illustrate the variability of glacier flow in response to factors ranging from intense rainfall to glacial surges. Such time-dependent data illuminate the subglacial extent of pressurised water, but the exact timing, duration, and strength of the forcing is often unknown. Here we present results from ongoing measurements of surface movement in the lower ablation zone of Skeiðarárjökull (1,380 km^2): the largest piedmont glacier of the Vatnajökull ice-cap, Iceland. In April 2006, motivated by frequent floods and regional-scale seismicity from the glacier, we deployed three continuous, high-precision global positioning system (GPS) receivers on Skeiðarárjökull. The array had an initial station-to-station distance of 3 km, with the uppermost GPS station located 8 km from the glacier terminus - in a region where ice thickness exceeds 400 m and icequakes are common. Data, sampled at 15-s intervals, were processed alongside permanent stations in Iceland's national GPS network. To enable long-term observations, we devised a broad, low antenna platform, which comprised four aluminium supports designed to be embedded partly into the glacier surface. Each GPS receiver was powered by a 12 V battery connected to a 50 W solar panel. Within the study period, horizontal velocities varied from 0.3 to 1 m d^{-1}, with periods of temporary ice-surface uplift and glacier seismicity accompanying the highest displacement rates. In addition, a GPS record of ice-surface velocities exists for a glacial flood that took place in August 2006. In combination with meteorological data from nearby sites, our observations show that Skeiðarárjökull is remarkably sensitive to variations in meltwater input to the glacier bed. Seemingly, transient changes in sliding rate – forced by hydraulic jacking of the glacier base – can take place over large areas of the glacier bed during intense rainfall and glacial flooding.

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Unsteady Glacier Flow Revealed by Multi-Source Satellite Data*

Eyjólfur Magnússon(1,2), Helmut Rott(1), Helgi Björnsson(2), Matthew J. Roberts(3), Etienne Berthier(4), Finnur Pálsson(2), Halldór Geirsson(3), Sverrir Guðmundsson(2), Rick Bennett(5), and Erik Sturkell(2)

(1) Institute of Meteorology and Geophysics, University of Innsbruck, A-6020, Austria

(2) Institute of Earth Sciences, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland

(3) Icelandic Meteorological Office, Bústaðavegur 9, 105 Reykjavík, Iceland

(4) University of British Columbia, 6339 Stores Road, Vancouver, B.C., V6T1Z4, Canada

(5) Department of Geosciences, University of Arizona, Tucson, AZ 85721-0077, USA

Abstract: We use three types of data to study the flow dynamics of Skeiðarárjökull, an outlet glacier of the Vatnajökull ice cap, Iceland. Firstly, by combining InSAR measurements from ascending and descending orbits and mass continuity, a three-dimensional flow field is derived for the glacier from late December 1995. By using the derived horizontal flow direction, and assuming mass continuity, we then derive the three-dimensional flow field over 24 hours, for single interferograms, for 23 periods between 1995 and 2000. These data are from the ERS1/2 tandem mission, obtained within the ERS AO projects VECTRA and AO3.239. Secondly, we derive the annual, horizontal flow field by cross-correlating optical satellite images acquired at the end of the ablation season (August or September) for the years 1999-2005. Images from SPOT5, ASTER and LANDSAT sensors were combined for that purpose. Thirdly, we present continuous GPS data-sets from three stations that were deployed on Skeiðarárjökull in spring 2006 and will remain on the glacier until late 2006. The combined data-sets reveal consistent and stable ice-surface velocities; however, episodes of short-lived high velocity are apparent. Changes in basal water-pressure, caused by either water input from the surface (rainfall or intense melting), or drainage of subglacial or ice-marginal lakes seem to trigger these events. Comparison with the annual velocities derived from the optical imagery indicates that a significant part of the ice flux occurs during such speed-up events.

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