Society report

Survey of flow, topography and ablation on NW-Mýrdalsjökull, S-Iceland

Þröstur Þorsteinsson[1,2], E. D. Waddington[1], Kenichi Matsuoka[1], Ian Howat[3] and Slawek Tulaczyk[3]

[1]*University of Washington, Seattle, WA 98195-1310, USA*

[2]*Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, 101 Reykjavík*

[3]*University of California, Santa Cruz, USA* throsturt@raunvis.hi.is

Abstract — *Ground Penetrating Radar, velocity (stake displacements measured by GPS), and ablation measurements were carried out on an approximately 4 km by 4 km area on NW-Mýrdalsjökull in 2003. The ice thickness ranges from 112–304 m within the study area, revealing significant bed topography, with a total relief of 185 m. The surface conditions vary considerably during the ablation season, with surface lowering of 4–10 m from April 22 to September 18, 2003. The dependence (relevant length scale) of velocity on surface slope and ice thickness was difficult to estimate due to sparse velocity data and large spatial variations.*

INTRODUCTION

To investigate the relationship between bed topography, basal lubrication, and surface velocity, an area on NW-Mýrdalsjökull was chosen. The field site location (Figure 1) had sparse radar coverage (Björnsson, Pálsson and Guðmundsson, 2000) and no velocity measurements were known to the authors prior to this survey. Furthermore, accumulation and ablation had not been measured at the site; however, it is known that accumulation, especially on the south side, is as high, or higher, than on other glaciers in Iceland.

The initial phase of the measurements took place in April 2003, during a 5-day field campaign from a base-station at the nearby Sólheimahjáleiga farm guesthouse. Bad weather during the summer disturbed fieldwork schedules, but subsequent trips were made in June and September.

Surface conditions at the field site during the ablation season were difficult, with many crevasses and dirt cones (Figures 2 and 10). Traveling to and from the field site meant traversing several cauldrons associated with the Katla volcanic system.

In April we traversed the glacier using jeeps and for the initial setup had help from the local rescue squad in Vík with hauling gear across the glacier. In June and September we used snow scooters and had guides from Arcanum adventure tours to navigate the heavily crevassed glacier. Below is a short description of the equipment setup, the survey measurements and preliminary results.

THE SURVEY

GPS measurements

In April, 2003, we established a grid of 13 poles/wires (Figure 2) which were steam-drilled to a depth of 8–10 m with the aim of allowing determination of all components of the surface strain-rate tensor and the longitudinal component over 3 length scales ($\sim$3–10 ice thickness' assuming 300 m ice thickness). Surveys were done using four Trimble GPS receivers, two 5700's and two 4000's. Surveys between the 4 receivers were performed for approximately 25 minutes; then all four receivers were moved to new locations, which gave up to 5 closed loops to solve per survey. Antenna heights were recorded; however, most antennae were placed on the snow surface with a pole inserted into the steam-drilled hole. The repeat survey

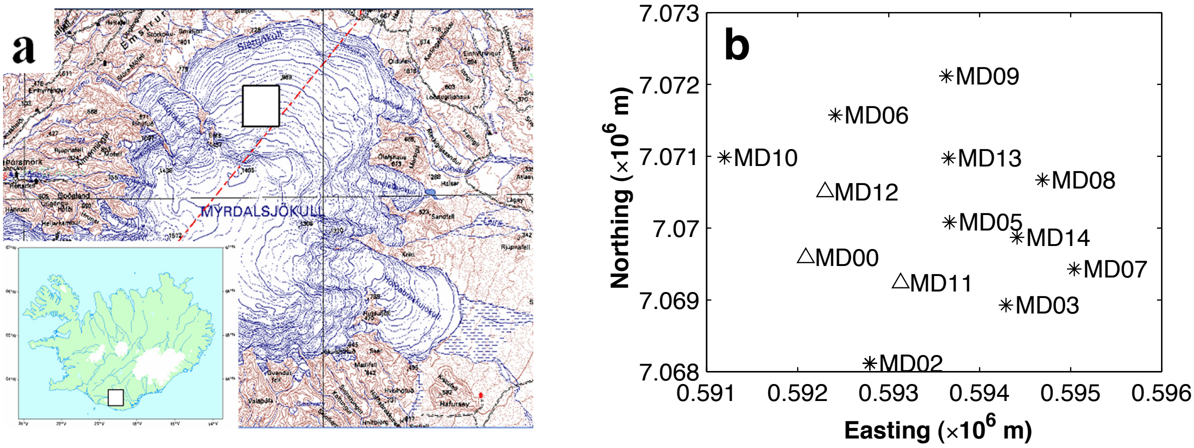

Figure 1. a) Location of the study area on the northern part of Mýrdalsjökull, S-Iceland. The area is about 4 km x 4 km (black box). b) Locations of the stakes in UTM coordinate system, in the 28N zone. – *a) Staðsetning mælisvæðisins á norðanverðum Mýrdalsjökli. b) Mælipunktarnir í UTM hnitakerfi, svæði 28N.*

in June was supposed to follow exactly the same procedure as the survey in April, in order to allow an analysis of baseline length change, yielding high accuracy strain rates. Unfortunately, bad weather, crevasses, and equipment failure made that impossible.

Figure 2. Visiting the permanent stations in September was tricky due to dirt cones and crevasses. The large amount of melting can be seen from the triangular platform that was 20 cm off the snow surface in June. – *Dríli og sprungur gerðu leiðangursmönnum erfitt fyrir að komast að mælistöðvum í september. Á þríhyrningslagaða loftnetspallinum má glöggt sjá hversu mikill bráðnun hefur átt sér stað frá júní, en þá var hann 20 cm yfir yfirborði.*

The Icelandic Meteorological Office operates a permanent GPS station (SOHO) near the south terminus of Mýrdalsjökull, about 20 km south of the survey area. Absolute base coordinates of the station are listed as 63.55247°N, 19.24665°W, at 791.6 m elevation. Daily RINEX files are available on the Internet, eliminating the need for setting up a base station for this survey.

Three of the marks, MD00, MD11, and MD12, were set up for semi-permanent recording (Figures 1–4). In each case 3 poles were drilled to a depth of approximately 8 m and fitted with a wood plug at the bottom to prevent self-drilling. A triangular plywood platform served as the antenna-mounting surface atop the three poles (Figure 3). Rough solar panels mounts were constructed of wood. A 20 amp hr battery was used to power the three receivers. Solar panel mounts were hose clamped to a ∼30 cm long PVC tube that fit over one of the survey poles, allowing the panels to subside with the surface melting (Figure 4). The battery and receiver were tied to a similar tube or the mount itself, in hope that they too would subside with glacier surface ablation. A 10 m antenna cable was coiled under the platform; allowing the receiver box to subside relative to the fixed antenna as the surface melted. Melt rate during the April fieldwork was between a few and up to 20 cm d^{-1}.

The permanent stations were set to record data at 30 sec intervals with a 13° elevation mask. The Trimble 5700 receivers were set to log continuously, while the Trimble 4000 receiver was set to log six 1 hr files spaced at 4 hr intervals each day (start times of 00, 04, 08, 12, 16, 20 h).

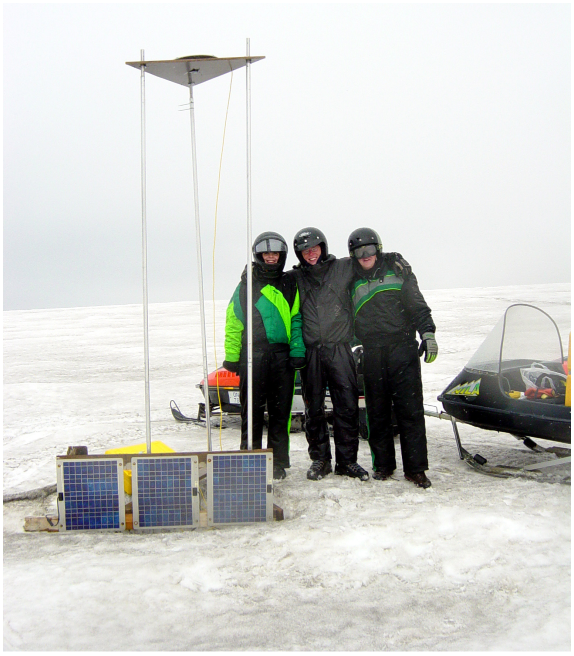

Figure 3. Semi-permanent GPS-station visit. The ablation (lowering of surface) from April 22 to June 28 at this site was about 3 m. Pictured are Elín, Björn, and Gísli Árni. – *Ein af langtímamælistöðvunum. Bráðnun (lækkun yfirborðs) frá 22. apríl til 28. júní var um 3 m. Á myndinni eru Elín Helga Þórarinsdóttir, Björn Oddsson og Gísli Árni Gíslason, sem eiga miklar þakkir skyldar fyrir hjálpina.*

The new Trimble 5700 receivers stopped recording couple of days after being installed due to hardware problems. The Trimble 4000 receiver also only ran for a short time, perhaps due to power disruptions from which they did not recover. On Thursday September 18, 2003, we finally managed to retrieve the instruments. The trip had been cancelled several times, due to frequent low pressure fronts across the south coast.

Radar measurements

A University of Washington radar system operating at 5 MHz was used. The distance between the transmitting (T) and receiving (R) antennas was 15 m and data was collected every 8 m along each survey line.

The data was band-passed between 3 and 7 MHz (Figure 5). Ice thickness in the area ranges between about 112 m to 304 m. The intensity of radar echoes changed by a factor of 10 within the study area due to changes in bed conditions, internal reflectors and/or surface conditions (Matsouka *et. al.*, submitted).

The strong reflector in the S-part of Figure 5 is most likely from an ash layer from the Katla eruption in 1918.

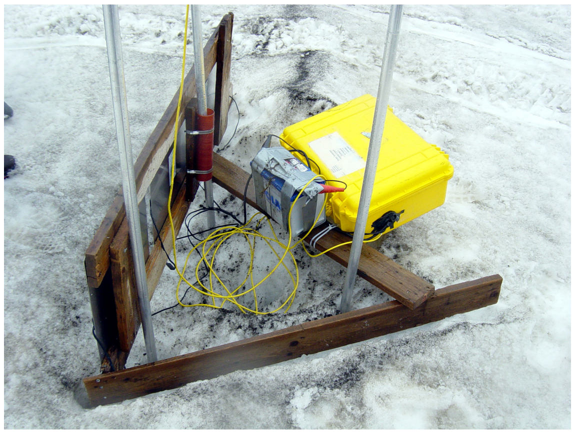

Figure 4. The semi-permanent GPS-station setup. The solar-panels were used to charge the battery, and the wooden framework was designed to slide up-and down. – *Uppsetning langtíma GPS-stöðva. Sólarsellurnar voru notaðar til að hlaða rafgeyminn og grindin var hönnuð þannig að hún fylgdi yfirborðinu.*

Ablation measurements

The poles at the semi-permanent stations and wires at other sites also served as ablation measurement points. The wires had a weight attached to the end that went into the drill hole and then froze. The difference in the length of the wire between measurements thus provides a measure of surface subsidence. Following installation in April, measurements were made at accessible points in June and September.

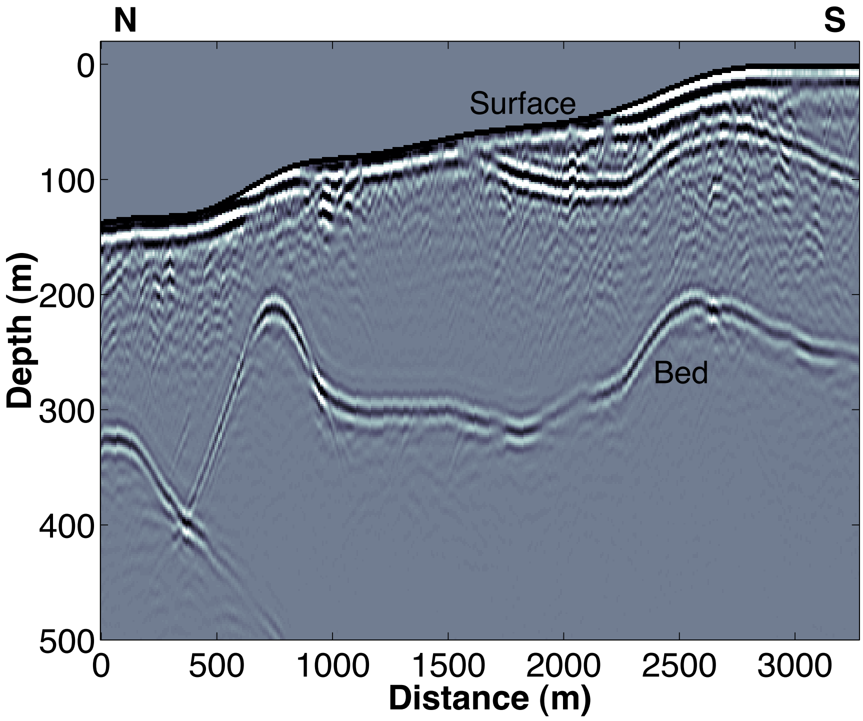

Figure 5. Radar-profile along MD10 to MD02 at the western margin of the study area. The depth ranges from about 100 m to 250 m. A strong echo, most likely from an ash layer, is visible near the surface in the southern part of the profile. – *Ísjár-snið milli MD10 til MD12, á vesturhlið mælisvæðisins. Dýpið er breytilegt, frá um 100 m til 250 m. Sterkt endurkast, líklegast frá öskulagi, sést nálægt yfirborði í syðrihluta þversniðsins.*

RESULTS

Radar

Figure 6 shows the surface topography calculated from the pressure record attained during the radar measurements and the elevation of the GPS-points. The origin of the local coordinate is at the UTM coordinate of 5.91x10^5 m easting and 7.068x10^6 m northing, in the 28N zone (Figure 1b).

The ice thickness (Figure 7) was calculated from the two-way travel time, assuming a radio-wave speed of 169 m μs^{-1}. The ice thickness decreases from SE to NW, from some 300 m in the SE part of the survey region to about 112 m in the NW part.

Figure 8 shows the bed topography inferred from surface elevation and radar data (GPR-data). The bed relief within the study area is about 185 m.

Location of measurement marks in April

Data processing revealed extremely small errors in the data, < 2 cm in the horizontal direction and 2.5–3.5 cm in the vertical direction (given 1 cm horizontal set-up error and 2 cm vertical set-up error). Redundant occupations of 50% of the network and extremely high quality data (even with the Trimble 4000's) contribute to the excellent data quality. Little or no data editing was necessary to attain statistically valid solutions. Most of the short baselines solved well with single frequency solutions. Survey conditions pn April 20 were extraordinarily quiet (the best GPS data S. O'Neel the UNAVCO GPS specialist had ever seen).

Continuous GPS survey April 22–May 7, 2003

Continuous GPS measurements were carried out at MD00, MD11, and MD12 (Figure 2). The MD00 sta-

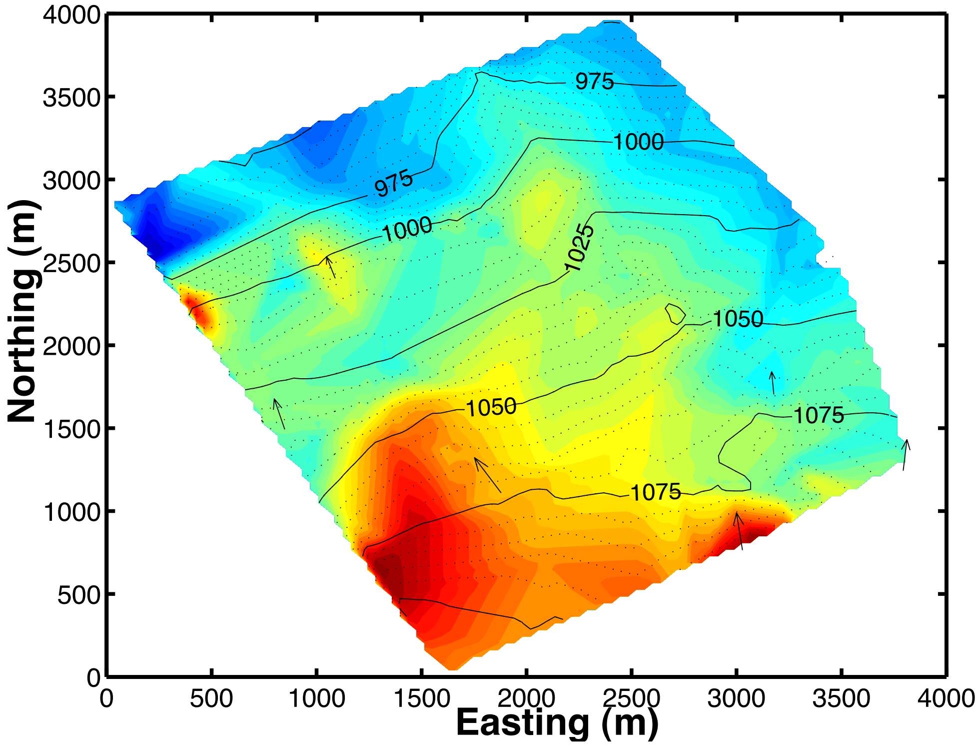

Figure 6. Surface topography (contour lines in m a.s.l.) from air-pressure records and GPS points, shaded bed relief (blue-to-red, see Fig. 8), and measured displacements. The displacements are calculated from point positions in April and September. – *Yfirborð (hæðarlínur) fengið frá þrýstingsmælingum og GPS-punktum, botn (litaskali, blár til rauður) og mældar færslur á stikum. Færslan er reiknuð útfrá staðsetningu í apríl og september.*

tion (Trimble 5700) failed after 2 days, the others ran for 14 and 16 days, respectively.

MD00 moved at 33 m a^{-1} during the 2 days it was recording, at an angle of 20°W of N. MD11 (Figure 9) moved at 24 m a^{-1}, at an angle of 16°W of N, and MD12 moved at 22 m a^{-1} and 19°W of N (Table 1).

Horizontal and vertical displacements

The horizontal displacements from April to September were between ∼12 m to 21 m, yielding velocities from 29.5 m a^{-1} to 54 m a^{-1}. Displacement errors (Table 2) refer to the error given for the solution ellipse (major and minor axes always being equal) in GPS Pathfinder for the September measurements.

Table 1. Continuous GPS measurements April 22^{nd} – May 7^{th}, 2003. – *Samfelldar GPS-mælingar, 22. apríl – 7. maí.*

Station	Time (d)	Velocity (m a^{-1})	Direction °
MD00	2	33	20
MD11	14	24	16
MD12	16	22	19

All points moved faster during the peak summer, May–September, than for the period April to May, although the data series is quite short for the spring period. The biggest difference in velocity was observed at MD11, from 24 m a^{-1} in April to 54 m

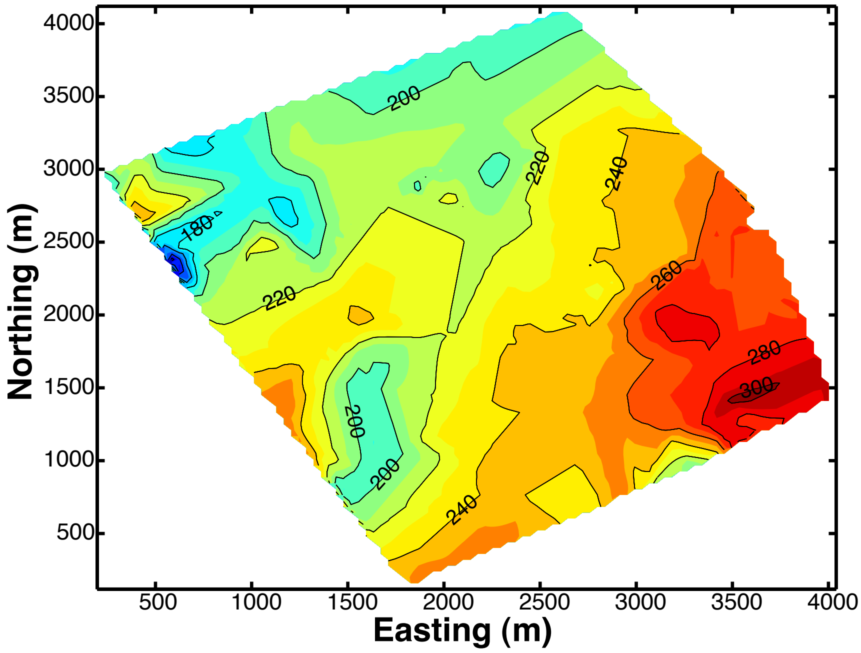

Figure 7. Ice thickness, from radar measurements, ranges from ∼112 m to ∼304 m within the study area. – *Ísþykkt, fengin frá ísjármælingum er 112–304 m á mælisvæðinu.*

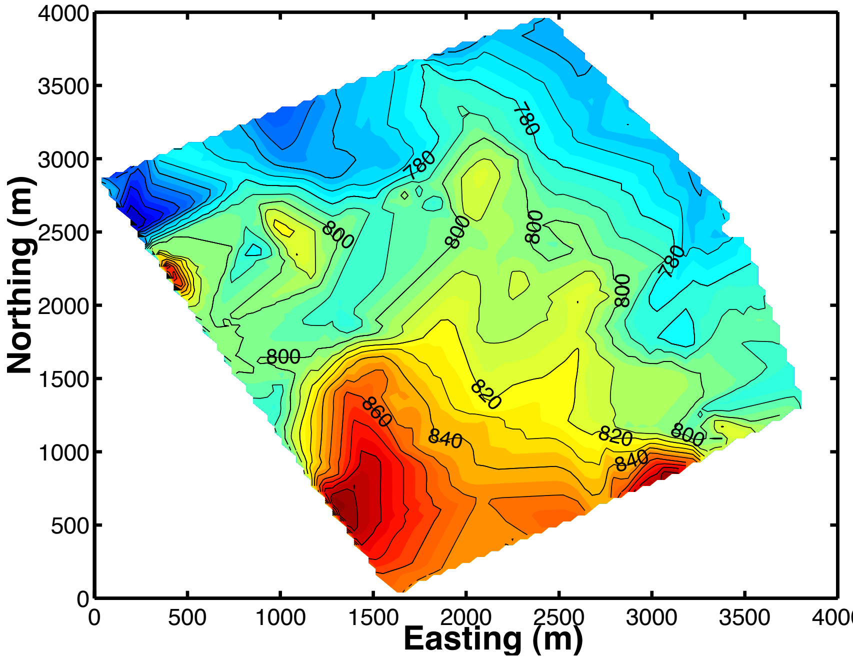

Figure 8. Bed topography from radar-data. Bed relief is about 185 m, from 713 m to 898 m a.s.l. – *Botnkort af mælisvæðinu. Hæðarbreytingar upp á 185 m eru á svæðinu, frá 713–898 m y.s.*

Table 2. Stations measured in both April and September. – *Mælipunktar mældir bæði í apríl og september.*

Station	Displacement	Velocity	Direction	GPS	Wire
	(m)	(m a^{-1})	°	Δh(m)	Δh(m)
MD00	16.4 ± 0.8	41.6	15.1	5.3 ± 1.3	5.5 (fallen)
MD11	21.2 ± 1.2	53.8	30.8	8.4 ± 2.5	4.9 (fallen)
MD12	11.7 ± 0.9	29.5	17.5	4.0 ± 1.6	4.4
MD03	19.4 ± 1.8	49.2	7.1	4.5 ± 2.5	7.7
MD14	11.7 ± 0.8	29.8	4.5	9.3 ± 1.3	Missing data
MD07	16.2 ± 1.0	41.5	-5.4	8.9 ± 1.4	7.5

a^{-1}, from April to September. MD11 also shifted direction, from 16° to 31°. Other stations had much smaller direction change, and their velocities changed by ∼7–8 m a^{-1}.

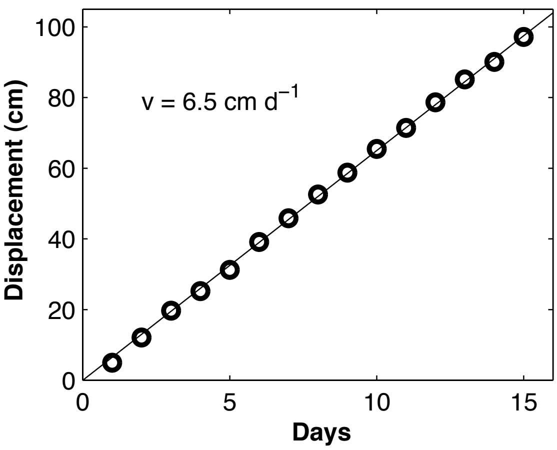

Figure 9. Displacement at MD11 over 16 days, from April 22^{nd} to May 7^{th}, 2003. The velocity from linear fit to the data is v = 6.5 cm d^{-1} (R^2 = 0.9993). – *Færslur mælipunkts MD11, frá 22. apríl til 7. maí, 2003. Hraðinn út frá jöfnu bestu línu er v = 6.5 cm d^{-1} (R^2 = 0.9993).*

Two types of surface measurements were obtained, one determined by GPS and the other by measuring the poles directly. The error in GPS elevation in Table 2 is from GPS Pathfinder, from the data collected in September. In most cases the two methods yield similar results, but the error in vertical measurements using GPS is large, and the software probably underestimates them.

Figure 10. There were some significant crevasses on the northern part of Mýrdalsjökull in September. – *Það var umtalsvert af sprungum á norðurhluta Mýrdalsjökuls í september.*

DISCUSSION

Besides obtaining detailed data for the bed topography, one of the purposes of this study was to compare measured velocities to theoretical values. Significant bedrock topography, large melting rates, heavy crevassing (Figure 10), and thin ice made exact calculations of surface velocities very difficult. Conventional methods that treat bedrock as a perturbation (Thorsteinsson *et al.*, 2003), or use averaging over several ice thicknesses (Paterson, 1994) cannot be applied. In this type of landscape, full-blown numerical modeling is probably needed to get realistic velocity fields.

However, it is clear that the velocity increase observed at MD11 has to be related to sliding. The same explanation is valid for the other locations as well. Whether sliding was a contributing factor already in April is impossible to verify, from the data we obtained.

Acknowledgements

The success of a field campaign like ours depends on assistance from skilled people familiar with the survey region. We especially wish to thank Benni, Hansína and their staff at Arcanum (http://snow.is) and the rescue squad at Vík in Mýrdal, Grétar and Þórður, for snowmobiles, navigation and assistance. We thank Eyrún and family at Sólheimahjáleiga for providing wonderful food and good accommodations. Helgi Björnsson and Finnur Pálsson at the Institute for Earth Sciences, University of Iceland, were extremely helpful in providing us with their data and sharing their experience. Finally, but most importantly, we thank Björn Oddsson, S. O'Neel (UNAVCO GPS specialist), Gísli Árni Gíslason, Pétur Már Sveinsson, and Elín Helga Þórarinsdóttir, for assistance in the field.

ÁGRIP

Ísjármælingar, mælingar á hreyfingu yfirborðs með GPS og mælingar á bráðnun voru gerðar á um 16 km^2 svæði á NV-Mýrdalsjökli árið 2003. Úfið landslag er undir jöklinum á þessu svæði, þar sem hæðarmunur reyndist 185 m og ísþykktin 112–304 m. Mikil bráðnun mældist yfir sumarið en yfirborð jökulsins lækkaði um 4–10 m frá 22. apríl til 18. september. Erfitt reyndist að finna rétta lengdarskala fyrir tengsl ísþykktar og yfirborðshalla við hraða á yfirborði vegna fárra mælinga á hraða og hve botn var ósléttur.

HEIMILDIR

Björnsson, H., F. Pálsson and M. T. Guðmundsson 2000. Surface and bedrock topography of the Mýrdalsjökull ice cap, Iceland. *Jökull* 49, 29–46.

Matsouka, K., Th. Thorsteinsson, H. Björnsson, E. D. Waddington. Radio-wave scattering from within temperate glacier ice, Myrdalsjökull, Iceland. *J. Glaciology* (submitted).

Paterson, W. S. B. 1994. *The Physics of Glaciers*. Pergamon, 3rd edition, 480 pp.

Thorsteinsson, Th., C. F. Raymond, G. H. Gudmundsson, R. A. Bindschadler, P. Vornberger and I. Joughin 2003. Bed topography and lubrication inferred from surface measurements on fast-flowing ice streams. *J. Glaciology* 49, 481–490.