VEÐURSTOFA ÍSLANDS

Report
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Matthew J. Roberts

Aerial and seismic observations of the August 2005 jökulhlaup from Grænalón

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Matthew J. Roberts

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BACKGROUND

Since September 2001, ten jökulhlaup have occurred in Núpsvötn due to water draining from Grænalón. On each occasion, the elevation of the lake decreased by 3–5 m and icequakes occurred in Skeiðarárjökull: commonly several hours before the beginning of flooding at the glacier edge.

Between 1951 and 2003 a buttress of ice protruded from the western flank of Skeiðarárjökull at the southeast corner of Grænalón (Thórarinsson, 1974; Roberts *et al.*, 2005). The size and configuration of this feature governed the level of Grænalón. After the disintegration of the ice buttress, Roberts *et al.* (2005) proposed that jökulhlaup of successively decreasing intensity would drain from Grænalón. This forecast held true for a jökulhlaup in May 2004. But in August 2005 a large jökulhlaup – similar in size to the September 2001 jökulhlaup – occurred, invalidating the forecast and revealing a greater complexity to ice-water interactions at Grænalón.

This report and the accompanying CD summarise aerial and seismic observations of the August 2005 jökulhlaup, with the goal of answering the following questions:

1. What was the elevation of Grænalón at the onset of drainage?
2. What factors enabled Grænalón to reach the elevation depicted in pre-flood photographs?
3. What is the present elevation of Grænalón and what is the likelihood of a jökulhlaup of similar intensity occurring?

OBSERVATIONS

The forty-seventh recorded jökulhlaup from Grænalón began on 07 August and it lasted for a week. Oblique aerial photographs, taken on 24 July 2005, showed that the lake had risen several metres above the ~520 m a.s.l. datum: the level that had prevailed following the September 2001 jökulhlaup. In an e-mail message to the "Mýrdalur" group on 25 July (Appendix 1), it was stated that the elevation of Grænalón was at least 542 m a.s.l. and, consequently, a jökulhlaup was likely. Thirteen days later – on 07 August – a Vegagerðin employee noticed that the level of Núpsvötn had risen markedly (Ragnar Frank Kristjánsson, personal communication, 2005). By 08 August, it was apparent that the river was in flood.

Fifteen icequakes were located in Skeiðarárjökull during the four-day rise of Núpsvötn to maximum discharge (Figure 1). Additionally, constant measurements of seismic tremor at SIL station Kálfafell – located ~30 km from Grænalón – showed an intensification of 1–4 Hz tremor, in tandem with the initial rise of the jökulhlaup. The tremor increase was clearest in the east component of the 2–4 Hz frequency band (Figure 2). Alongside locatable icequakes, many un-locatable events were registered at SIL stations Kálfafell and Grímsfjall. These micro-icequakes contributed significantly to the amplitude of high-frequency tremor recorded between 07 and 09 August (Figure 2).

Between August and September, 56 icequakes, ranging in size from M_W ~0.3 to M_W ~2.3, were detected in Skeiðarárjökull (Figure 1). Icequake activity was confined to 10 swarms that persisted from hours to days (Figure 1). Aerial photographs of Grænalón were taken during icequakes swarms in Skeiðarárjökull. The timing of these photographs demonstrated that icequakes occurred in sequence with the lowering of the lake surface. This implies that the interlude between swarms represents the recharge time for the lake during the period of ice-dam 'recovery' after the initial jökulhlaup.

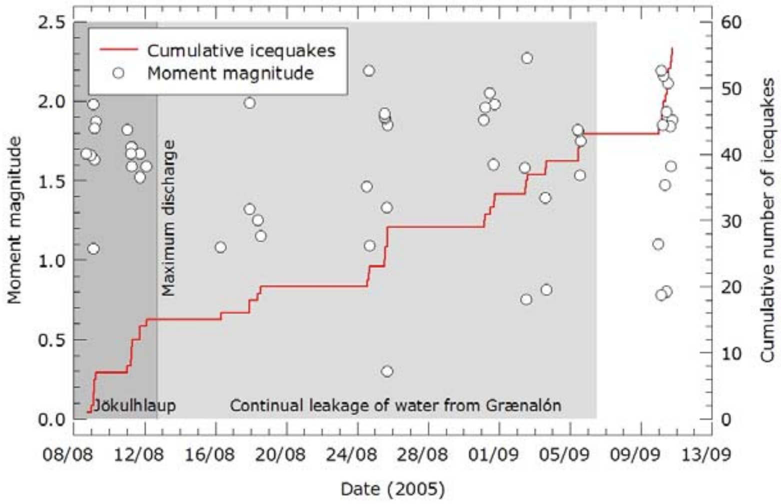

Figure 1. Combined plot of the number of icequakes located in Skeiðarárjökull during August and September 2005 and their corresponding moment-magnitude. Note that from mid-August until mid-September, water leaked almost continually from Grænalón, as observed from aerial photographs and reports of sustained, high discharge in Núpsvötn.

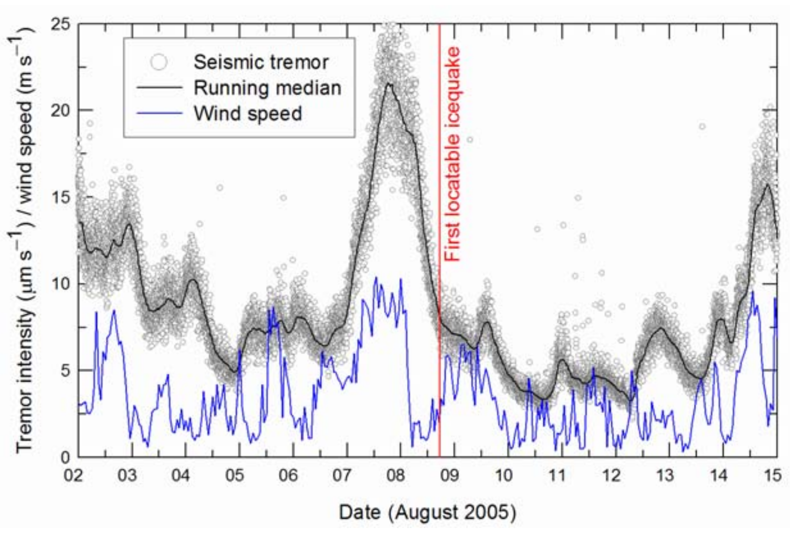

Figure 2. Time-series plot of tremor observations at Kálfafell and wind-speed measurements at the nearby Vegagerðin meteorological station, close to Lómagnúpar. Tremor data are based on the east component of measurements made in the 2–4 Hz frequency band. Each tremor value represents a one-minute average from a continuous, 100 Hz sampling rate. Note the sharp rise and concomitant peak in tremor velocity between ~12:00 GMT on 06 August and ~18:00 GMT on 07 August. The first locatable icequake – epicentre: 64.02°, -17.19° – occurred on 08 August at 17:28:32 GMT; this implies that the tremor pulse was caused by hydraulic resonance due to water flow within Skeiðarárjökull.

Between August and October 2005, icequakes occurred almost entirely within the Súla ice catchment, west of the glacier centreline (Björnsson *et al.*, 1999). The epicentral locations of icequakes recorded in Skeiðarárjökull during August, September, and October are shown in Figures 3, 4, and 5, respectively. In Figure 3, the two, poorly located icequakes near to the eastern tip of the glacier terminus were caused by the complete drainage of five interconnected, ice-marginal lakes in Norðurdalur on 17 August (Appendix 2).

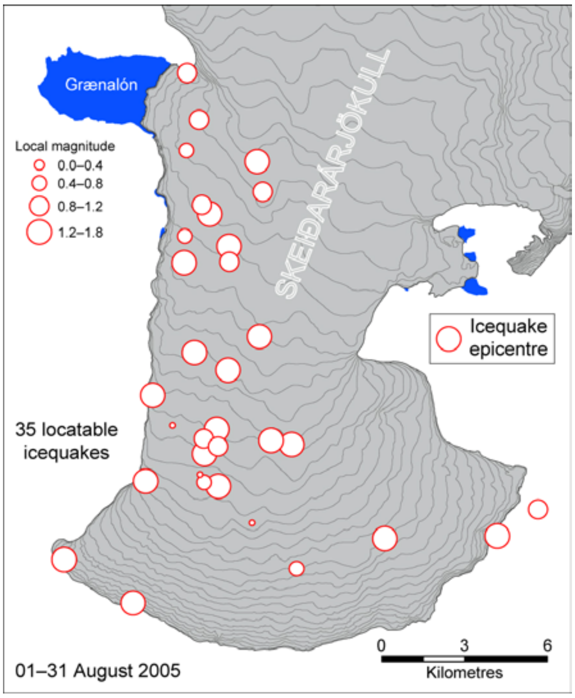

Figure 3. Plan view of the surface of Skeiðarárjökull and the location of icequake epicentres recorded during August 2005. The size of each symbol is proportional to the size of each icequake, as explained in the figure. Only epicentres derived from wave arrivals at three or more SIL stations are included. And within this dataset, the minimum epicentral accuracy is 1 km.

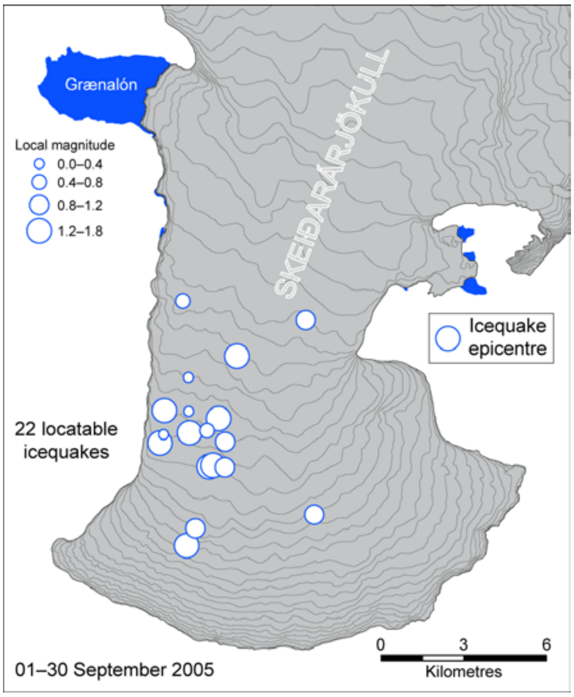

Figure 4. Plan view of the surface of Skeiðarárjökull and the location of icequake epicentres recorded during September 2005. The size of each symbol is proportional to the size of each icequake, as explained in the figure. For details about epicentral accuracy, see the caption to Figure 3.

Icequakes throughout September 2005 (Figure 1) were a consequence of three minor jökulhlaup that occurred following the removal of ice debris from the inlet for lake-water (see Figure 12). Repeated collapse of glacier ice from the sagging region of the inlet created a mechanical blockage, which allowed the elevation of Grænalón to rise by several metres.

In contrast, activity during October 2005 was forced solely by intense rainfall, which induced two icequake swarms that both persisted for ~12 hours, comprising ~60 icequakes each (Figures 5 and 6).

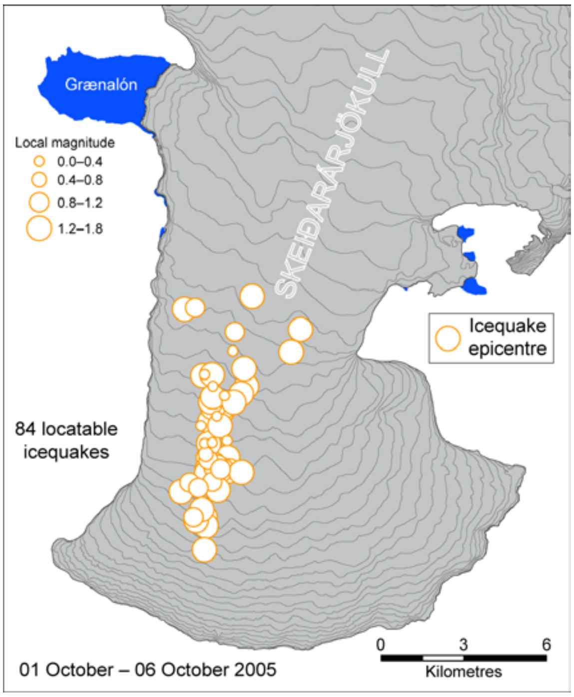

Figure 5. Plan view of the surface of Skeiðarárjökull and the location of icequake epicentres recorded during October 2005. The size of each symbol is proportional to the size of each icequake, as explained in the figure. See Figure 6 for a temporal view of the same data. For details about epicentral accuracy, see the caption to Figure 3.

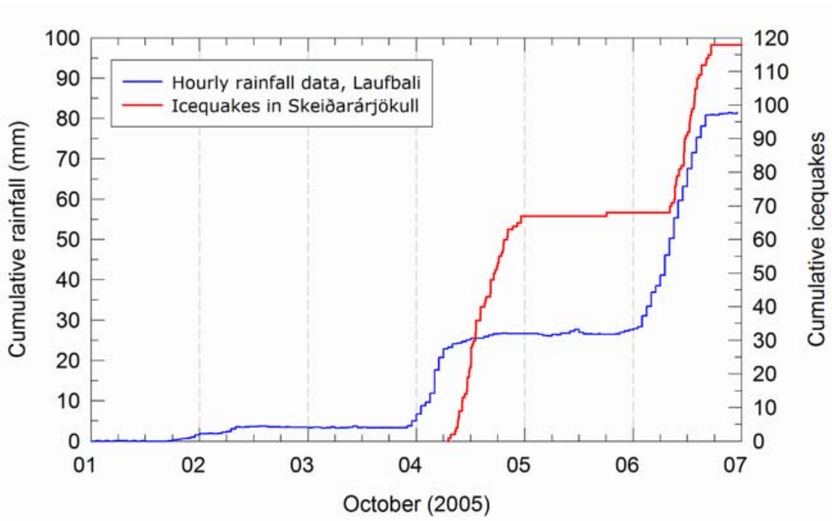

Figure 6. Temporal comparison between icequake activity in Skeiðarárjökull and rainfall observed at the Orkustofnun meteorological station at Laufbali (560 m a.s.l.), sited ~40 km southwest of Grænalón. Approximately nine hours of rain occurred, beginning at 21:00 GMT on 03 October, before the start of the icequake swarm. Using 10-minute data from Laufbali, the time-lag between the onset of intense rainfall and the first icequake is 9.36 hours (33,720 seconds). Additionally, the distance from the inlet (Figure 12) to the centre of the icequake swarm is 9,880 m (Figure 5). These values give a mean speed of 0.29 m s for the initial propagation of water beneath Skeiðarárjökull, assuming the icequakes were a consequence of water leaking from Grænalón.

Rainfall and temperature measurements from meteorological stations near to Skeiðarárjökull show that one month of warm, mostly dry weather preceded the beginning of the August 2005 jökulhlaup. During this period, the mean air temperature at Lómagnúpar was 10.9 °C (median 10.6 °C) and the maximum temperature was 19.5 °C (Figure 7); furthermore, high atmospheric pressure dominated, thus creating cloud-free sky that would have maximised incoming solar radiation. Such weather conditions would have caused large volumes of snow and glacier ice to melt within the catchment of Grænalón, thereby increasing the elevation of the lake by several metres. Additionally, between 01 and 08 August, Skaftafell – located ~25 km southeast of Grænalón – recorded ~83 mm of rainfall (Figure 7). It is likely that Grænalón received a similar amount of rain, and that this runoff further increased the volume of water in the lake.

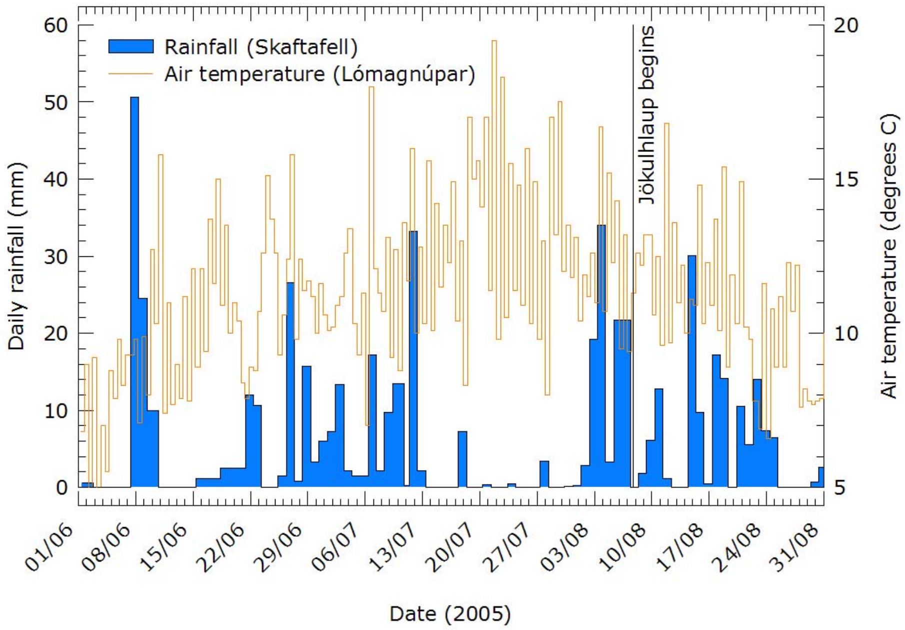

Figure 7. Daily record of rainfall at Skaftafell combined with hourly measurements of air temperature at Lómagnúpar between June and August 2005. The rain gauge at Skaftafell and the temperature sensor at Lómagnúpar are sited at an elevation of 160 m a.s.l. and 55 m a.s.l., respectively.

Aerial photographs taken two weeks' before and after the beginning of the jökulhlaup illustrate the reduction in the lake's surface-area (Figure 8).

Figure 8. Comparative photographs of Grænalón, taken 14 days before (A) and 13 days after (B) the August 2005 jökulhlaup. In both photographs the view is toward the west and the distant outlet glacier is Siðujökull. Photograph (A) was taken at a height of 300 m above Skeiðarárjökull, whereas photograph (B) was taken at a height of 500 m. Photographer: Matthew J. Roberts.

Núpsvötn is un-gauged; hence estimates of the rate of discharge-increase and the maximum discharge of the jökulhlaup rely on sparse observations from Skeiðarársandur and from the air. Figure 9A shows that midway through the rise of the jökulhlaup on 10 August, Núpsvötn was 357-m-wide at the bridge. (This figure is based on DGPS measurements of wash limits on 19 September 2005.) Assuming a mean cross-sectional depth of 1 m and an isotropic water-velocity of 2.5 m s^{-1}, the instantaneous discharge at the bridge was 893 m^3 s^{-1}.

As the jökulhlaup neared maximum discharge on 12 August, floodwater drained into Gígjukvísl from artesian vents that formed at the eastern edge of the Súla catchment (Ragnar Frank Kristjánsson, personal communication, 2005). This is illustrated by the two streams that appear from the lower right of Figure 9B; assuming a stream-width, -depth, and -velocity of 150 m, 1 m, and 1.5 m s^{-1}, respectively, floodwater entered Gígjukvísl at a rate of 225 m^3 s^{-1} at the time of the photograph. Notionally, the combined discharge of Núpsvötn and Gígjukvísl at the height of the jökulhlaup was ~1,200 m^3 s^{-1} (see Figure 15).

Figure 9. Oblique aerial photographs of Núpsvötn (A) and Gígjukvísl (B) during the rise of the August 2005 jökulhlaup. Photograph (B) was taken above the ice terminus and the view is toward the south. Note that photograph (A) was taken 15 hours before the jökulhlaup reached maximum discharge. Photographer: Jón G. Sigurðsson.

The first photographs of Grænalón since the beginning of the jökulhlaup were taken on 10 August (Figure 10). These photographs revealed that water was draining into Skeiðarárjökull via the inlet described to the "Mýrdalur" group on 25 July (Appendix 1).

Figure 11A shows a pool of meltwater on the glacier above the location of the inlet. This pool is interpreted as a sign of high water-pressure at the glacier base, created due to water seeping into Skeiðarárjökull from the spillway.

The pre-flood elevation of Grænalón was about 542 m a.s.l. – this figure is based on an extrapolation of a GPS measurement of the lake surface in October 2003; at that time, Grænalón had an elevation of 522 m a.s.l. (Roberts *et al.*, 2005). Figure 11C shows the spillway on 12 August, after at least 20 m of lake-surface lowering.

According to the hypsometry curve for Grænalón (Björnsson and Pálsson, 1989), 20 m of drawdown from 542 m a.s.l. equates to a water volume of ~200 × 10^6 m^3. Thus, given that the jökulhlaup lasted for a week, the mean rate of outflow from the lake would have been 331 m^3 s^{-1}.

Following the end of the initial jökulhlaup on 14 August, the inlet remained open (Figure 11D); additionally, swarms of icequakes occurred intermittently within Skeiðarárjökull throughout the autumn (see Figure 1). Considered together, these observations suggest the long-term maintenance of a leak from Grænalón.

Between 27 August and 02 September, the lake's elevation rose by ~12 m (cf. Figure 11D and E) – equivalent to a volumetric increase of ~120 × 10^6 m^3 (Björnsson and Pálsson, 1989) and, hence, a mean water influx of ~198 m^3 s^{-1} to Grænalón. At the Laufbali meteorological station, located ~40 km southwest of Grænalón, 63.7 mm of rainfall was recorded between 27 August and 02 September – with most rain occurring on 30 August. An equivalent amount of rainfall over a 2,000 km^2 region of southwest Vatnajökull would account for the ~120 × 10^6 m^3 increase in lake volume. Additionally, a larger-than-normal volume of water would have drained into Grænalón via the base of the ice dam; this is because a heightened water-pressure gradient would have persisted after the initial lowering of the lake.

Figure 10. Oblique aerial photographs of northwest Grænalón. (A) Pre-flood view of the lake 14 days before the beginning of the jökulhlaup; note the level of Grænalón in relation to the meltwater streams from Síðujökull. (B) Similar photograph to (A), but taken partway through the rise of the jökulhlaup; the formerly submerged meltwater channels from Síðujökull are now apparent. (C) Icebergs perched on the western shore of Grænalón. (D) View toward Síðujökull, illustrating the depleted size of Grænalón after the initial jökulhlaup. Photographers: Matthew J. Roberts (A, D) and Jón G. Sigurðsson (B, C).

Temporary blockage of the inlet is the prime reason for the observed cycles of water accumulation and drainage at Grænalón since the August 2005 jökulhlaup. Figure 12 illustrates the collapse of the ice-roof that spanned the inlet; it is possible that blocks of ice from the collapsed roof plugged the inlet repeatedly, thereby creating a mechanical blockage that enabled water to amass in the spillway.

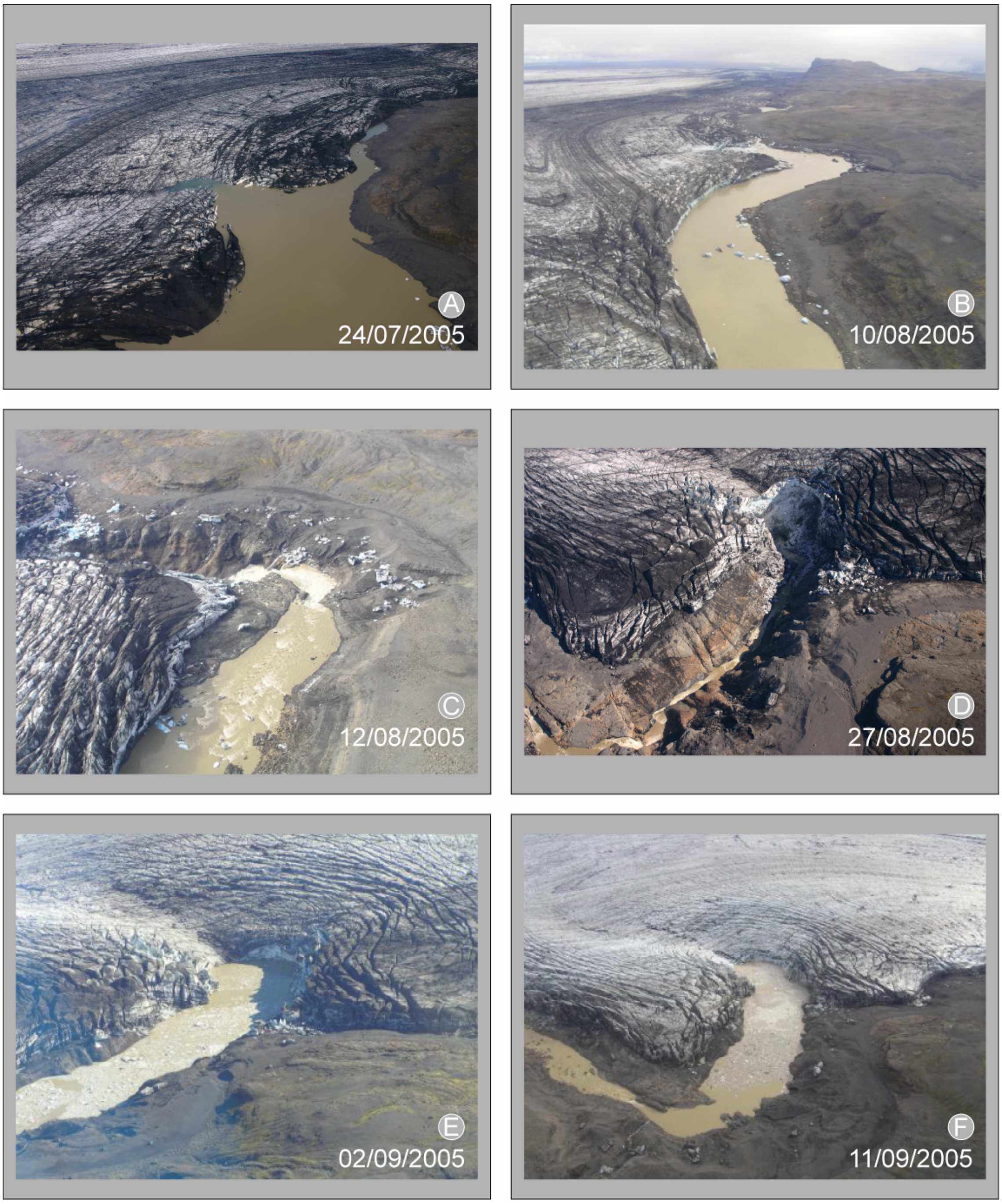

Figure 11. Aerial views of the spillway from Grænalón and the subglacial inlet to Skeiðarárjökull. (A) Pre-flood view of the southern tip of the spillway; the pool of water on the glacier surface demarcates the submerged inlet. (B) Southward-facing view of the spillway: the perched icebergs signify that the jökulhlaup is in progress. (C) Similar perspective as (A), but the photograph was taken at the height of the jökulhlaup. (D) Eastward-facing view of the subglacial inlet after the initial jökulhlaup; note the stream in the base of the spillway. (E) Similar perspective as (D) but, on this occasion, the spillway is full of water; note that the photograph was taken 19 days after the end of the initial jökulhlaup. (F) Same view as (E), illustrating that the level of Grænalón remained constant for a period of at least nine days; however, during the same interval, 23 icequakes were detected in Skeiðarárjökull (see Figures 1 and 4). The first kilometre of the subglacial path from the inlet is outlined by the sinuous depression in the glacier surface. Photographers: Matthew J. Roberts (A, D) and Jón G. Sigurðsson (B, C, E, F).

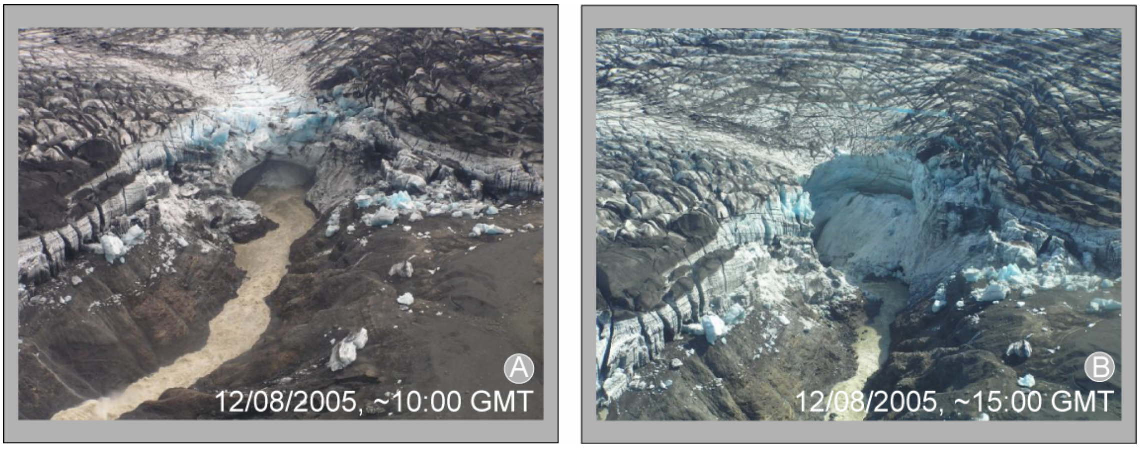

Figure 12. Comparative aerial photographs of floodwater draining into Skeiðarárjökull from Grænalón. Note that photograph (A) was taken about five hours before photograph (B). Photographer: Jón G. Sigurðsson.

Using oblique aerial photographs, an additional estimate of the amount of lake-surface lowering during the August 2005 jökulhlaup is possible. According to radar altimetry data collected over Grænalón between 2001 and 2003, the ice shelf typically has a 25–30-m-high freeboard (Magnús Tumi Guðmundsson, personal communication, 2004). It is likely that only the tip of the ice shelf is afloat because the present-day thickness of the ice dam exceeds the maximum depth of Grænalón (Björnsson and Pálsson, 1989; Roberts *et al.*, 2005).

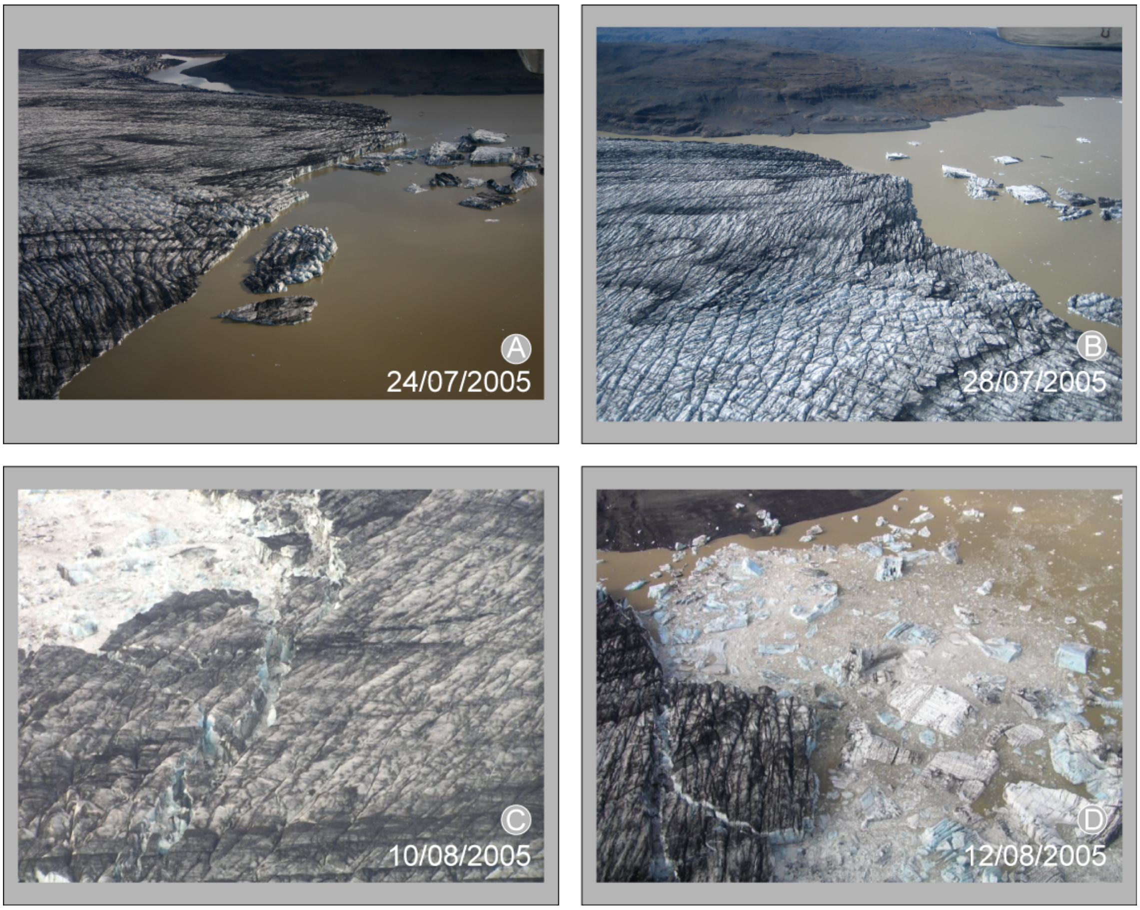

Figure 13. Successive aerial views of the southeast corner of Grænalón, illustrating the calving and grounding of icebergs during the drainage of the lake. After calving, the two tabular icebergs in (C) and (D) remained stationary – presumably due to grounding. Photographers: Matthew J. Roberts (A), Ragnar Frank Kristjánsson (B), and Jón G. Sigurðsson (C, D).

On 27 August 2005, the freeboard of the ice shelf cast a shadow onto Grænalón; figure 14B shows the shelf at 13:13 GMT, when the sun was in its zenith position at ~37.5° above the horizon (Almanak Háskólans, 2005). Assuming the length of the observed shadow was 30 m, the freeboard of the ice shelf on 27 August was ~23 m.

The same region of the shelf was photographed on 24 July 2005, 14 days before the beginning of the jökulhlaup (Figure 14A). At this point, a 3 m freeboard is visible, implying that the edge of the shelf was afloat (23 × 0.9 = 20.7 m). Consequently, Grænalón lowered by at least 20 m during the jökulhlaup; however, the photograph in Figure 14B was taken 12 days after the jökulhlaup peaked, and it is possible that the elevation of the lake was lower immediately after the jökulhlaup (Jón G. Sigurdsson, personal communication, 2005). In comparison, 24 m of drawdown occurred during the partial drainage of Grænalón in September 2001 (Roberts *et al.*, 2005).

Figure 14. Comparative aerial photographs of the central edge of the ice shelf that extends into Grænalón. The approximate coverage of (B) is depicted by the rectangle in (A). Photographer: Matthew J. Roberts.

Using firsthand accounts of the August 2005 jökulhlaup, combined with information gleaned from aerial photographs of Núpsvötn and Gígjukvísl, an approximation of the rate of discharge increase is possible (Figure 15).

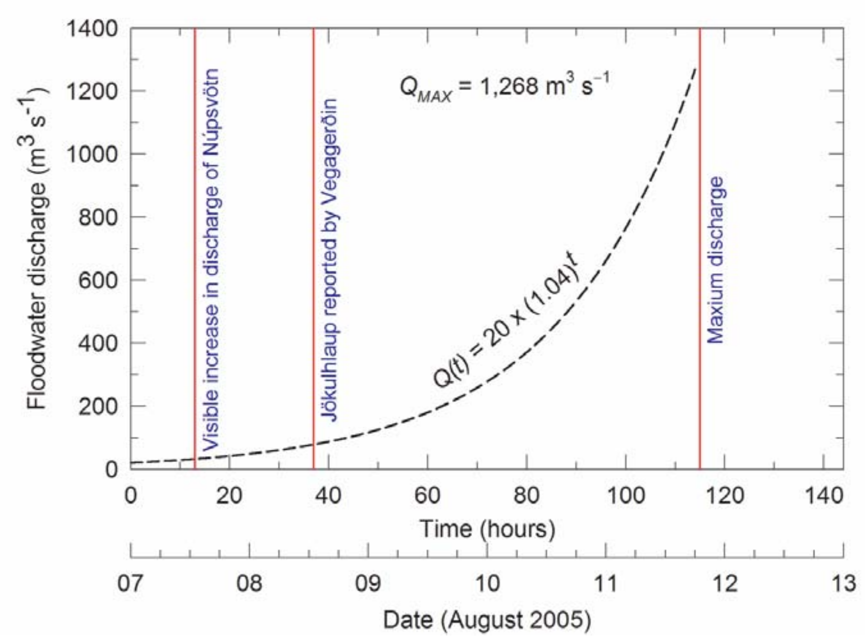

Figure 15. Inferred hydrograph for the rise of the August 2005 jökulhlaup in Núpsvötn. A base-flow of 20 $m^3 s^{-1}$ and an exponential function of 1.04 are assumed. The annotated, vertical lines represent field observations that were used to constrain the duration of flooding. The cut-off point for the rise of the jökulhlaup is derived from the estimate of maximum discharge described on page 6. Discharge was allowed to increase for a 115-hour period: from 00:00 GMT on 07 August to 18:00 GMT on 11 August. The hydrograph represents a volume of ~124 × 10^6 m^3.

Following the icequake swarm that accompanied the initial jökulhlaup, further icequake activity occurred in the western part of Skeiðarárjökull – often during periods of intense rainfall over southern Vatnajökull (e.g., Figure 6). Between 12 August and 15 October 2005, icequakes took place on 16 out of 23 days when at least 5 mm of rain was detected in Skaftafell. Figure 16 shows a strong, positive link between rainfall intensity and icequake activity; this relationship suggests that the seal at the base of the inlet was sensitive to minor increases in the surface-elevation of Grænalón after rainfall over southern Vatnajökull.

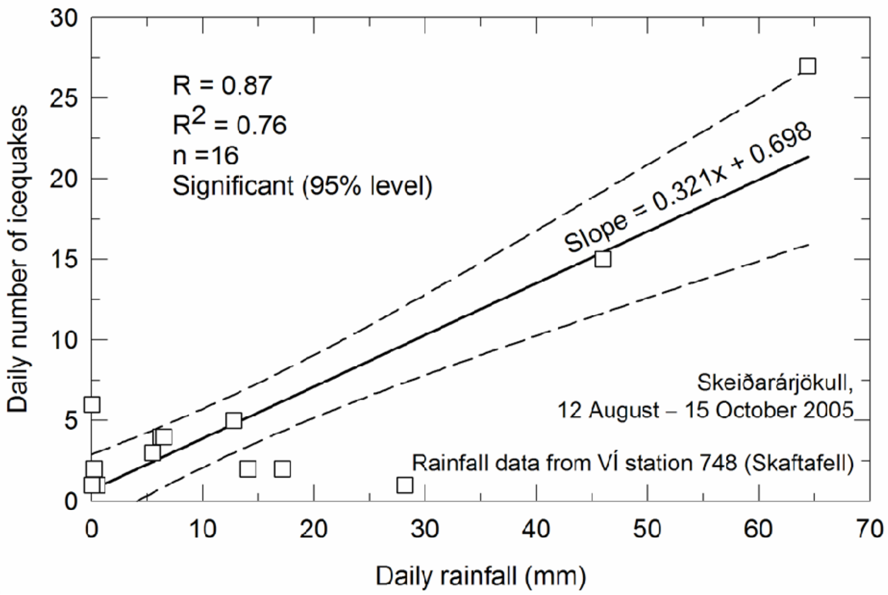

Figure 16. Relationship between daily rainfall and the corresponding number of daily icequakes in Skeiðarárjökull between 12 August and 15 October 2005. The dashed lines signify the 95% confidence limits. A strong, positive correlation between rainfall and icequake activity is apparent during episodes of intense rainfall (i.e. $\geq$ 45 mm d^{-1}).

CONCLUSIONS

The August 2005 jökulhlaup was the largest flood from Grænalón since 2001. Water entered Skeiðarárjökull via an inlet located at the head of the lake's spillway. The pre-flood elevation of Grænalón was about 542 m a.s.l., and two separate lines of reasoning indicate that at least 20 m of drawdown occurred during the August jökulhlaup. Approximately 200 × 10^6 m^3 of water drained from the lake over a seven-day period. On Skeiðarársandur, a discharge of ~1,200 m^3 s^{-1} was reached after five days; and at this point, floodwater affected Gígjukvísl as well as Núpsvötn.

It is likely that the present elevation of Grænalón is between 520 and 532 m a.s.l. Given the remarkably swift increase in lake volume between 27 August and 02 September 2005, the propensity for floods from Grænalón similar in size to the August 2005 jökulhlaup remains high.

ACKNOWLEDGEMENTS

I thank Jón G. Sigurðsson (Atlantsflug ehf.) and Ragnar Frank Kristjánsson (Warden, Skaftafell National Park) for kindly providing the photographs of Grænalón acknowledged in this report; I also thank Málfríður Ómarsdóttir for her assistance at Skeiðarárjökull.

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Roberts, M. J., F. Pálsson, M. T. Gudmundsson, H. Bjornsson, and F. S. Tweed. 2005. Ice-water interactions during floods from Grænalón glacier-dammed lake, Iceland, *Annals of Glaciology*, **40**, in press.

Appendix 1: Copy of e-mail message sent to "Mýrdalur" group on 25 July 2005

[Date Prev][Date Next][Thread Prev][Thread Next][Date Index][Thread Index]

Grænalón: Jökulhlaup Likely?

- *To*: myrdalur@vedur.is
- *Subject*: Grænalón: Jökulhlaup Likely?
- *From*: "Matthew J. Roberts" <matthew@vedur.is>
- *Date*: Mon, 25 Jul 2005 22:56:09 +0000
- *Organization*: Physics Department, Icelandic Meteorological Office
- *Reply-to*: matthew@vedur.is
- *User-agent*: Mozilla/5.0 (X11; U; Linux i686; en-US; rv:1.0.2) Gecko/20021120 Netscape/7.01

Sæl öll,

Yesterday, I took a sight-seeing flight to Grænalón and I saw that the lake had risen to its highest level since 2001.

I have enclosed two aerial photographs of the spillway from Grænalón. The photographs were taken two years apart and the circled boulder in each image is intended as a visual marker.

Since 2001, water from Grænalón has flowed into Skeiðarárjökull via an ice tunnel, which is visible in the 2003 photograph. In October 2003 I measured the elevation of the lake surface at 522 m a.s.l. The July 2005 photograph shows that Grænalón is at least 20 m higher than its 2003 elevation.

In the most recent photograph, a pool of light-coloured water is seen on Skeiðarárjökull above the location of the ice tunnel; additionally, several water-filled crevasses exist nearby. These water pockets are a sign of high water-pressure at the glacier base due to water seeping from the spillway.

The present elevation of Grænalón is unsustainable and a jökulhlaup seems likely before the end of the summer. Using previous events as a measure, Grænalón could lower by up to 20 m.

The last jökulhlaup from Grænalón occurred in May 2004.

I guess that the recent warm, sunny conditions are partly responsible for the healthy size of the lake!

Bestu kveðjur,

Matthew.

--
Matthew J. Roberts
Icelandic Meteorological Office (Veðurstofa Íslands)
Research Section, Physics Department
Bústaðavegur 9
150 Reykjavík
ICELAND

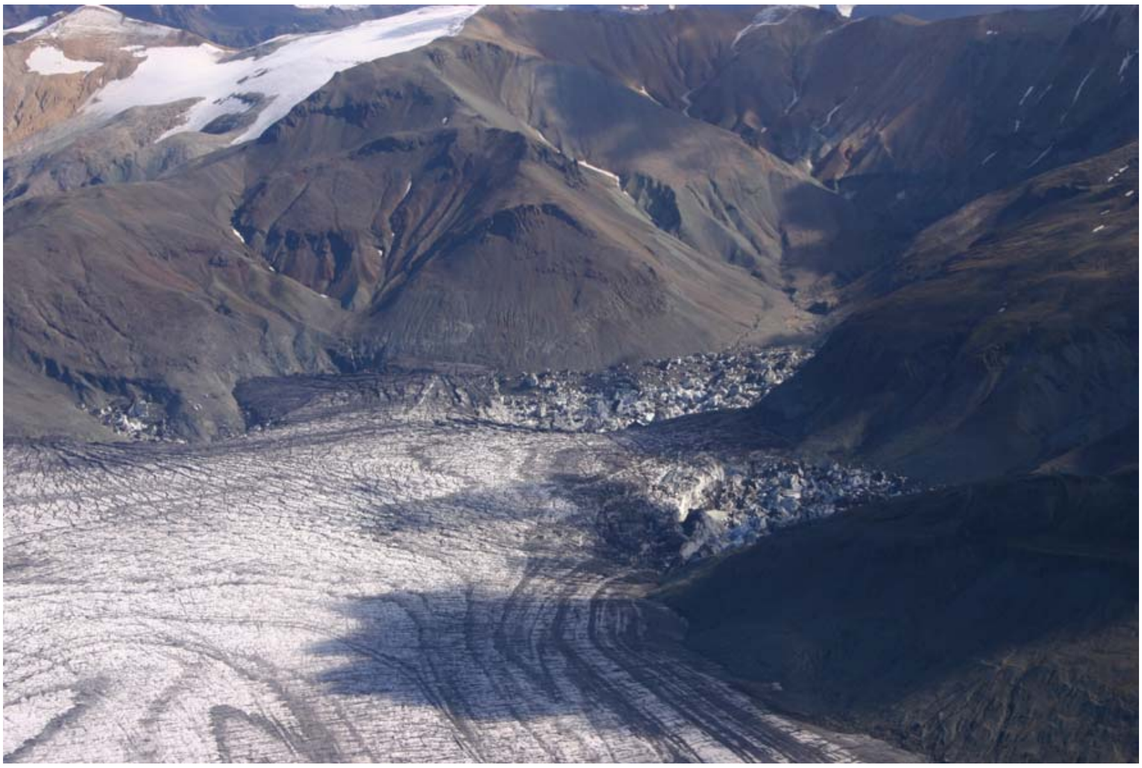
Direct: +354 522 6148

Spillway from Grænalón, 24 July 2005. Flight altitude: ~800 m a.s.l.
Photographer: Matthew J. Roberts

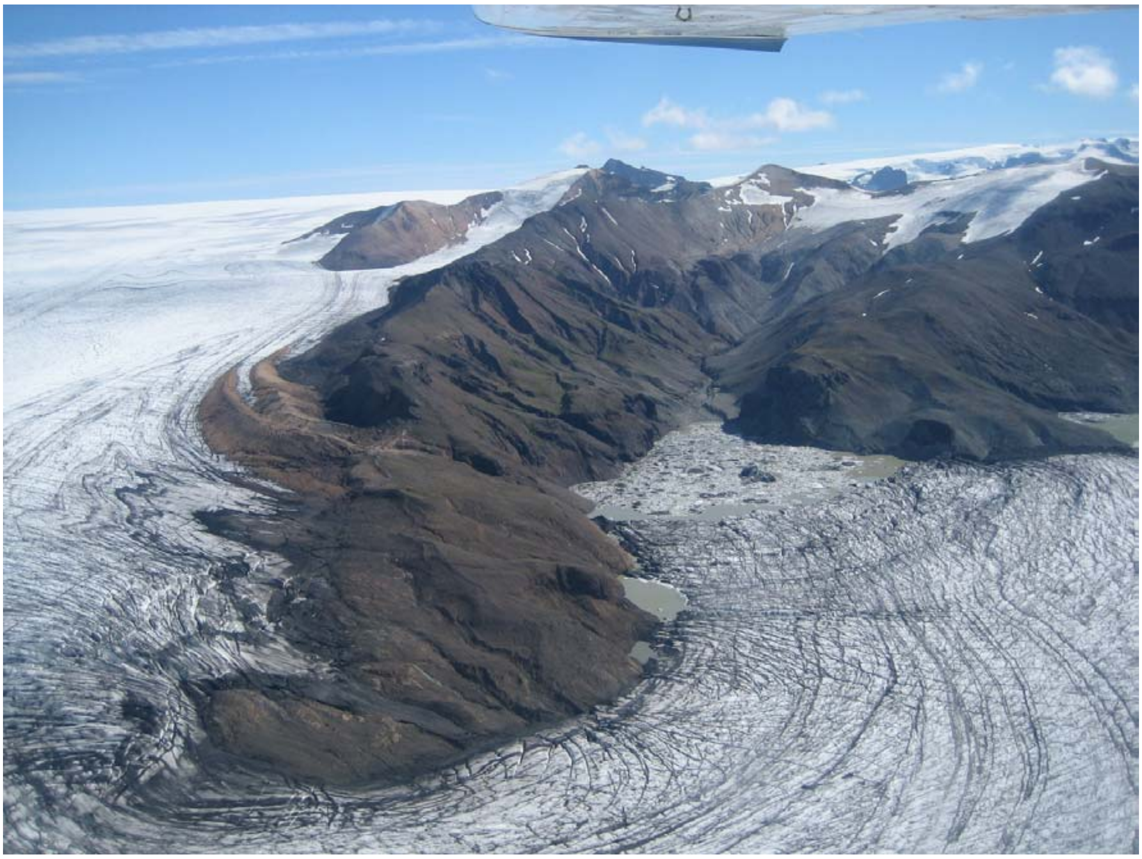
Spillway from Grænalón, 08 July 2003. Flight altitude: ~650 m a.s.l.
Photographer: Matthew J. Roberts

Appendix 2: Comparative photographs of Norðurdalur, eastern Skeiðarárjökull

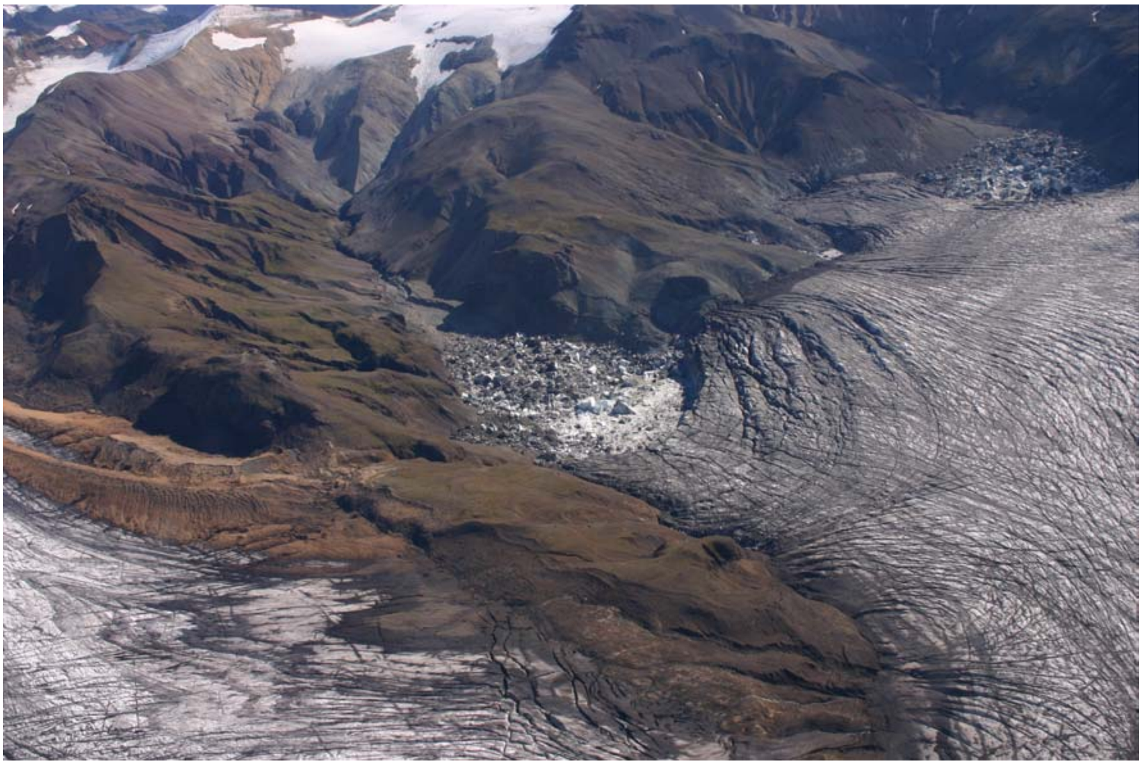
Photographer: Matthew J. Roberts; 18:46 GMT, 24 July 2005.



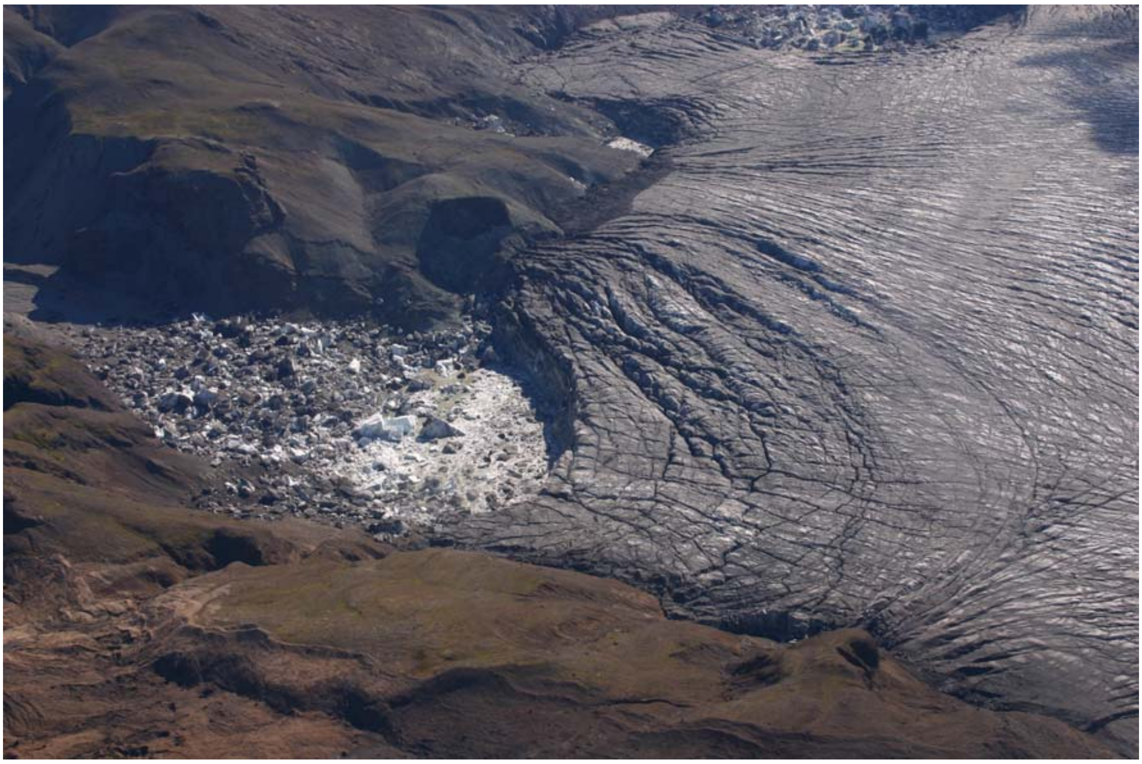
Photographer: Matthew J. Roberts; 12:59 GMT, 27 August 2005.



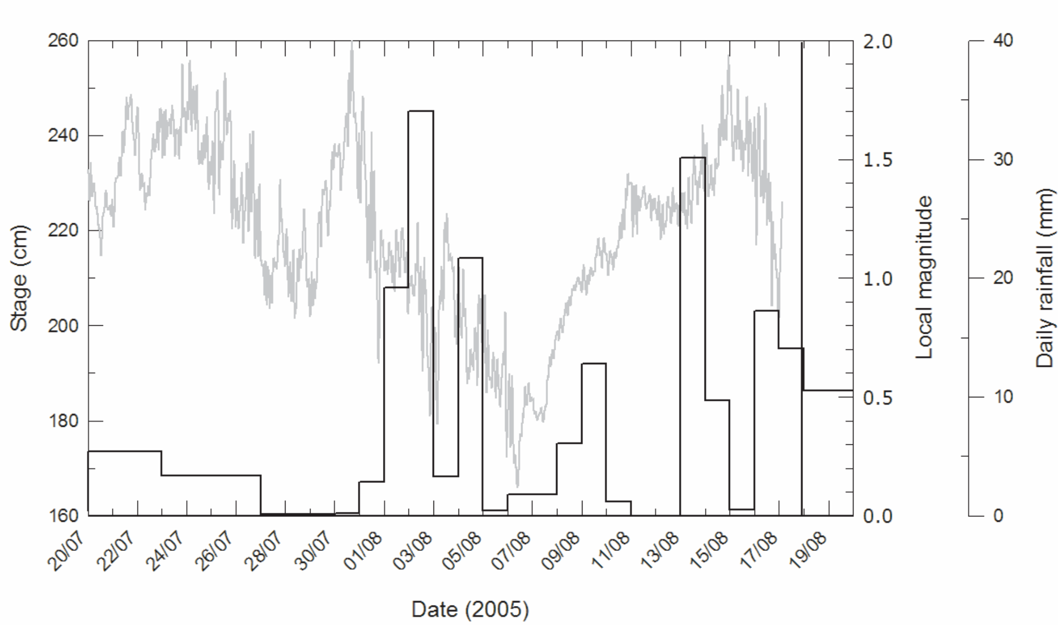
Photographer: Ragnar Frank Kristjánsson; 11:37 GMT, 28 July 2005.



Photographer: Matthew J. Roberts; 13:00 GMT, 27 August 2005.



Photographer: Matthew J. Roberts; 13:00 GMT, 27 August 2005.



Integrated, time-series plot of stage measurements on Skeiðará and daily rainfall in Skaftafell. (Stage measurements courtesy of Vatnamælingar.) The thick vertical line denotes icequake-magnitude; see Figure 3, and related text, for location details. From the stage record, the Norðurdalur lakes began to drain on 06 August 2005; however, it is not known if the lakes drained individually or simultaneously.