

# Lidar measurements of jökulhlaup source areas on Mýrdalsjökull in 2011 and on Hofsjökull in 2013: implications for jökulhlaup dynamics

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**Abstract** — Digital elevation models (DEMs) of several jökulhlaup source areas were measured during the mapping of Icelandic glaciers with aerial lidar in 2008–2013. This included i) the jökulhlaup in Múlakvísl from Mýrdalsjökull on 9 July 2011, which destroyed the bridge on the ring road, and ii) the jökulhlaup in Vestari-Jökulsá from Hofsjökull in late August 2013. Comparison of these DEMs with lidar measurements from before the jökulhlaups reveals valuable information about the volume of the floods and the nature of subglacial water flow from jökulhlaup source areas created by subglacial geothermal activity. DEM differencing shows lowering of the glacier surface of Mýrdalsjökull along several kilometres of the subglacial flood path from the main cauldrons that released the initial flash flood, which is most likely caused by melting of the glacier sole by warm flood water. It is not possible to derive an explicit estimate of the temperature of the flood water near the main cauldrons, but the DEM differencing indicates temperature on the order of 10 °C to tens of degrees Celsius. In recent years, three jökulhlaups have been observed from Hofsjökull and cauldrons have formed in the ice cap surface at three different locations. These measurements and observations of several other jökulhlaups in Iceland in recent years show that the initial temperature of jökulhlaup flood water may be quite variable from near the freezing point of water to tens of degrees Celsius. This variable temperature is likely to have important consequences for jökulhlaups dynamics and may be part of the explanation for the highly variable development of jökulhlaups. The jökulhlaup in Múlakvísl in 2011 and from Hofsjökull in 2013, as well as several other jökulhlaups from Mýrdalsjökull and some other glaciers and ice caps in Iceland, highlight the importance of improving the understanding of jökulhlaups and related natural hazards.

## INTRODUCTION

Jökulhlaups occur regularly in Iceland and are one of the most important natural hazard processes in the country (Björnsson, 2003). The dynamics of jökulhlaups are hard to observe as the floods typically take place under hundreds-of-metres-thick glacier ice and many aspects of the subglacial flood-path de-

velopment must be inferred by indirect observations (Björnsson, 2010; Einarsson *et al.*, 2016).

The dynamics of jökulhlaups from glaciers covering volcanoes and geothermal areas depend on the temperature of the flood water at the source (Björnsson, 2010). The thermodynamics of the floods are, furthermore, affected by variations in subglacial wa-

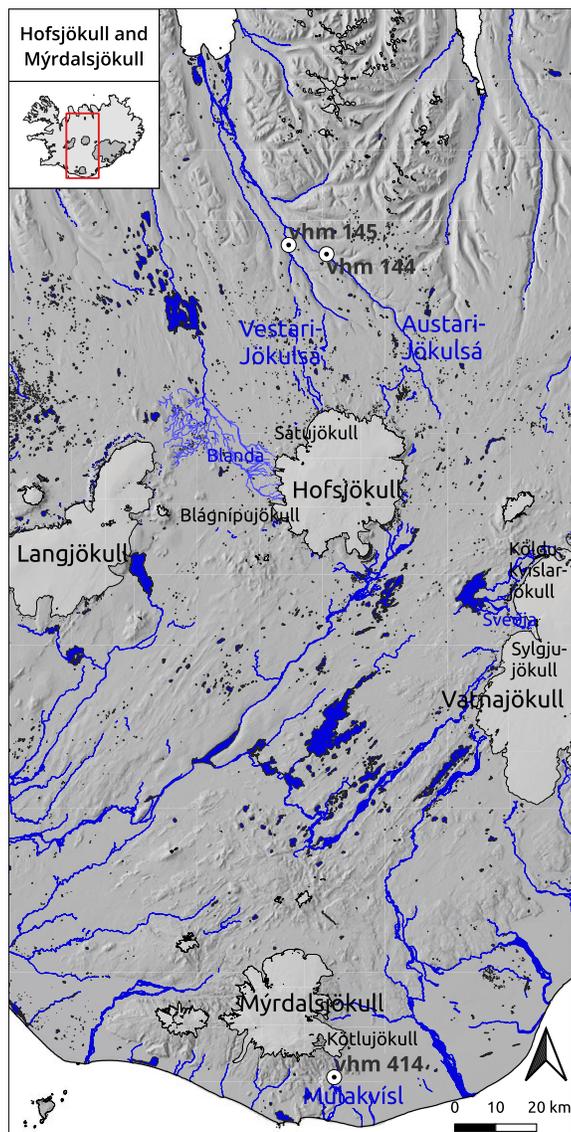


Figure 1. Location map showing the ice caps Mýrdalsjökull and Hofsjökull, the outlet glaciers Kötlujökull and Sátujökull, and Múlakvísl and Vestari-Jökulsá rivers where jökulhlaups occurred in 2011 and 2013, as well as locations of discharge and water-level gauging stations. The background shading is based on ÍslandsDEM (<https://dem.gis.is>). – *Yfirlitskort af Mýrdalsjökli og Hofsjökli, skriðjökklum og vatnsföllum sem koma við sögu í greininni, ásamt vatnshæðarmælistöðvum.*

suppression of the freezing point with increasing pressure. Less energy will, on the other hand, be available for melting of ice when flood water flows towards thinner ice and consequently lower water pressure because energy is needed to warm the water and maintain the temperature at the rising freezing point. Flow down a steep gradient in the ice thickness may even induce glaciohydraulic supercooling with freeze-on of basal ice from the flood water and a downstream reduction in the size of the subglacial flood path (Alley *et al.*, 1998).

Lowering of water pressure in subglacial lakes during a flood may also induce flash-boiling in an underlying geothermal system, which can intensify basal melting (Guðmundsson *et al.*, 2013; Einarsson *et al.*, 2023) and thereby increase the flood volume. These thermodynamic processes, which are governed by the phase diagram of water over large ranges of temperature and pressure, interact to create widely varying jökulhlaup dynamics that include slowly- and rapidly-rising floods (Einarsson *et al.*, 2016), depending on the initial flood-water temperature and the geometry of the subglacial flood path. These dynamics are poorly understood and it is important to expand observations of jökulhlaups beyond traditional measurements of flood discharge and water temperature at or near terminus outlets to improve understanding of subglacial floods. This is essential to adequately explain the main jökulhlaup characteristics such as flood duration and maximum discharge.

Changes in the elevation of the glacier surface associated with two jökulhlaups, from Mýrdalsjökull in 2011 and Hofsjökull in 2013, were observed during lidar mapping of the Icelandic glaciers that took place in 2008–2013 (Jóhannesson *et al.*, 2011, 2013). Surface-elevation profiling from aircraft, profiling using kinematic GNSS surveying and satellite mapping

ter pressure due to the dependency on pressure of the freezing point of water at the base of the glacier (Alley *et al.*, 1998) and the boiling point of water in the crust below the glacier (Guðmundsson *et al.*, 2013). Water flow at the base of glaciers takes place at a temperature near the pressure freezing point sufficiently far away from inlet locations of water from subglacial lakes that may be at a temperature above the pressure-dependent freezing point. More energy is available for the melting of ice and enlargement of the subglacial flood path when the flow is towards thicker ice because of the

were also used to analyse elevation changes related to the jökulhlaups. The observed lowering of the glacier surface in the source areas of the jökulhlaups reveals valuable information about the volume of the floods, the geometry of the subglacial water bodies that released them and the thermodynamics of the water flow in the uppermost part of the subglacial flood path. In this paper, lidar and satellite observations, as well as profile measurements, of lowering of cauldrons and neighbouring areas, where the jökulhlaups were released, are described and interpreted after general information about the jökulhlaups has been briefly summarized.

## THE JÖKULHLAUP IN MÚLAKVÍSL IN JULY 2011

A sudden jökulhlaup from Kötlujökull outlet glacier in SE Mýrdalsjökull ice cap occurred in the river Múlavísl on 9 July 2011 destroying the bridge on the main ring road of Iceland and causing disruption of traffic in S-Iceland until a temporary road connection was established a week later, see location maps in Figures 1 and 2.

The jökulhlaup in Múlavísl was remarkably sudden. The entire duration of the main flood was only a couple of hours at the water-level gauging station at Mt. Léreftshöfuð (named vhm 414 in Fig. 1) (Jónsson and Þórarinsdóttir, 2011), which is ca. 5 km downstream from the glacier margin, see Figure 3. The water level at Léreftshöfuð rose by 5 m within ca. 6 minutes and the flood wave propagated 8 km down to the ring road in 50 minutes. This allowed a warning to be announced on the basis of the continuously-transmitted measurements at Léreftshöfuð before the jökulhlaup reached the road. The maximum flood discharge on the sandur plain downstream from the gauging station at Léreftshöfuð was back-calculated with the HEC-RAS hydrodynamic model from measured flood marks along the river path near Léreftshöfuð and estimated as 3000 m<sup>3</sup>/s (Jónsson and Þórarinsdóttir, 2011). The maximum discharge was estimated ca. 6000 m<sup>3</sup>/s closer to the glacier, upstream of a lake of ponded flood water that formed north of Léreftshöfuð.

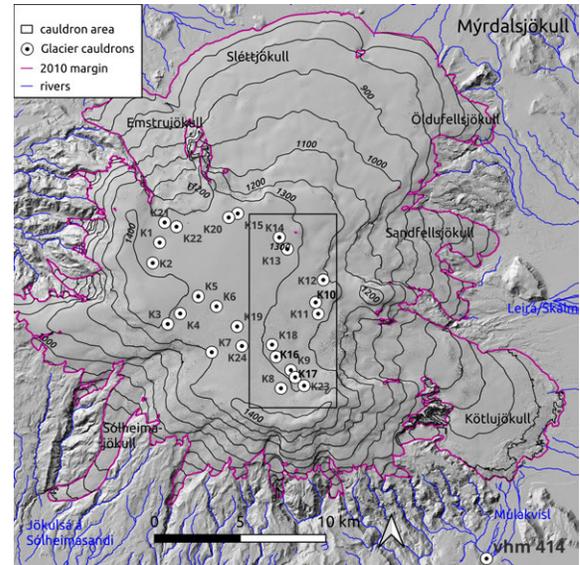


Figure 2. The surface of Mýrdalsjökull according to a lidar survey on 9 and 10 August 2010. The area resurveyed on 7 and 8 August 2011 is shown with a box on the eastern side of the summit area. The outline of the ice cap in 2010 is shown in red. Symbols show locations of cauldrons that have been identified by the Institute of Earth Sciences, University of Iceland. The shading outside the lidar DEM of the glacier is based on ÍslandsDEM. – *Yfirborð Mýrdalsjökuls skv. leysimælingu 9. og 10. ágúst 2010. Svæðið sem endurmælingin 7. og 8. ágúst 2011 náði til er sýnt með ramma á austanverðum hájöklinum. Útlína jökulsins árið 2010 er sýnd með rauðum ferli. Tákn sýna sigkatta sem skilgreindir hafa verið af Jarðvísindastofnun Háskólans.*

The source area of the jökulhlaup was investigated and photographed on 9 and 11 July 2011, on the same day and two days after the flood (Figs. 4, 5 and 6), revealing that the flood mainly originated from cauldrons no. 16, 9 and 10 in the numbered list of >20 cauldrons in Mýrdalsjökull from the Institute of Earth Sciences (IES), University of Iceland (Magnússon *et al.*, 2017, 2021). On 11 July, scientists from the IES measured several elevation profiles with an on-board C-band ground-clearance radar in the flight inspection aircraft TF-FMS, from the civil aviation service of Iceland (Isavia) (Gudmundsson *et al.*, 2007; Guð-

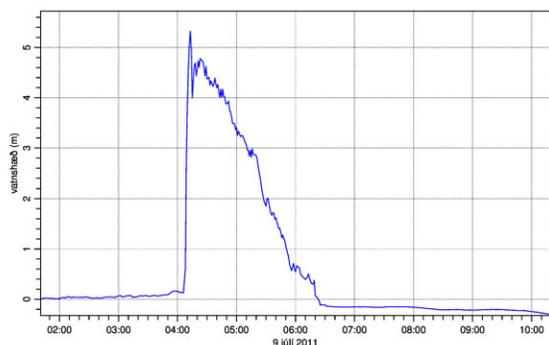


Figure 3. The water level in Múlakvísl at the gauging station Léreftshöfuð (vhm 414), ca. 5 km downstream from the terminus of Kötlujökull outlet glacier, in the night of 9 July 2011. The main flood lasted only for ca. 2 hours. – *Vatnshæð í Múlakvísl við Léreftshöfuð (vhm 414), um 5 km frá jaðri Kötlujökuls, aðfaranótt 9. júlí 2011. Flóðtoppurinn varði aðeins í u.þ.b. 2 klst.*

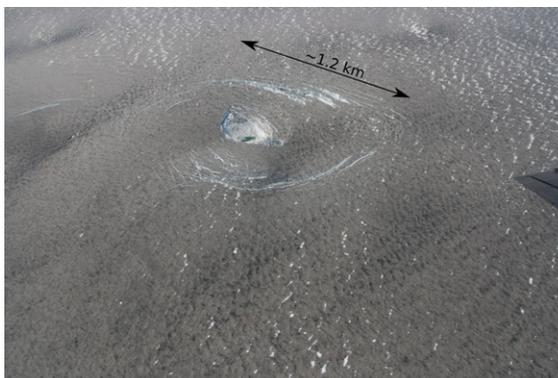


Figure 4. Cauldrons no. 16 (above the centre) and 9 (near the left margin) in Mýrdalsjökull seen from the north (see location map in Fig. 2). The gray colour of the glacier surface is caused by windborne tephra from the eruption in Grímsvötn in May 2011. – *Katlar 16 og 9 í Mýrdalsjökli séðir frá norðri. Yfirborð jökulsins er grátt vegna gjósku frá gosinu í Grímsvötnum í maí 2011.* Photo/ljósmynd: Oddur Sigurðsson, 11 July 2011.

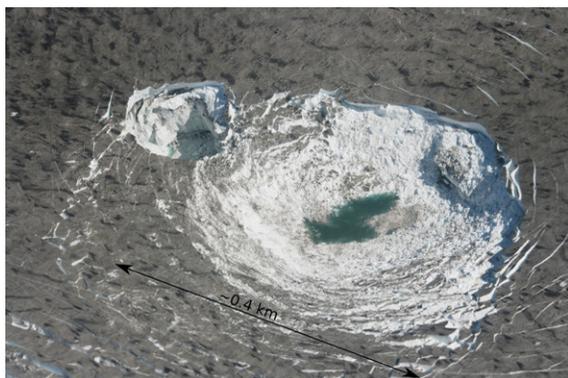


Figure 5. Cauldron no. 16 in Mýrdalsjökull seen from the southwest. The steep ice walls surrounding the collapsed shaft in northern part of the cauldron are clearly seen. There is ponded water on the surface near the middle of the main cauldron. – *Ketill 16 í Mýrdalsjökli séður frá suðvestri. Vel sést hversu brattar hliðarnar á strokknum í norðanverðum katlinum eru og að daginn sem myndin var tekin stendur uppi vatn í katlinum.* Photo/ljósmynd: Oddur Sigurðsson, 11 July 2011.

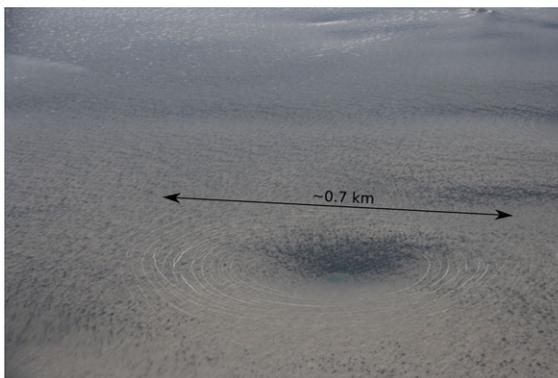


Figure 6. Cauldron no. 10 in Mýrdalsjökull seen from SSE. Circular crevasses can be seen in the area where cauldron no. 11 subsided further a month later. – *Ketill 10 í Mýrdalsjökli séður frá suðsuðaustri. Móta sést fyrir hringsprungum norðvestan ketilsins þar sem ketill 11 seig meira um mánuði síðar.* Photo/ljósmynd: Oddur Sigurðsson, 11 July 2011.

mundsson and Högnadóttir, 2011). Photographs taken on 11 July show circular crevasses indicating slight lowering of cauldron 18 that was not noticeable two days earlier.

The lowering revealed by the radar elevation-profile measurements of the IES/Isavia corresponds to a total volume of ca. 18 million m<sup>3</sup> released from the three cauldrons where the greatest lowering in the period 6 to 11 July was detected (Guðmundsson and Högnadóttir, 2011), whereas the water-level measurements at Léreftshöfuð and their model interpretation with HEC-RAS indicate a flood volume of ca. 7–8 million m<sup>3</sup> during the 2-hour-long flash flood in the early morning on 9 July (Jónsson and Þórarinsdóttir, 2011). A substantial amount of flood water, thus, appears to have been issued more slowly from the glacier in the two days that elapsed from the main flood until the flight measurements of IES/Isavia on 11 July (Guðmundsson and Högnadóttir, 2011; Larsen *et al.*, 2013), as evidenced by the lowering of cauldron 18 in this period that was mentioned above. This is in accordance with visual observations of the river and conductivity measurements in the river at the temporary bridge on the ring road during several weeks after the initial sudden outburst on 9 July, which indicate that irregular much smaller floods took place during this time period. Although unlikely, some water might have flowed from the cauldron area during the three days from the spring surveying of the cauldrons on 6 July until the flash flood occurred.

The formation mechanism of the subglacial water bodies that released the Múlakvísl flood is not well known. Geochemical analysis has been interpreted to indicate subglacial geothermal melting with water–rock interaction for at least a year before the flood (Galeczka *et al.*, 2014). Seismic tremor that was observed in connection with this and some other similarly-sized jökulhlaups from Mýrdalsjökull and Vatnajökull ice caps has also been viewed as an indication of small subglacial eruptions or shallow intrusions (Sgattoni *et al.*, 2017, 2019; Einarsson *et al.*, 2023). Guðmundsson *et al.* (2013) and Einarsson *et al.* (2023) interpret some types of tremor during jökulhlaups as a consequence of flash-boiling in the subglacial geothermal system, which could greatly intensify

basal melting during the flood. Sgattoni *et al.* and Einarsson *et al.* note that in some cases the tremor may also be caused by small subglacial eruptions or shallow intrusions.

## THE JÖKULHLAUP FROM HOFSJÖKULL IN AUGUST 2013

On 21 August 2013, a smell of sulphur was noticed from the river Vestari-Jökulsá in Skagafjörður. The river seemed to carry an unusual amount of suspended sediments and appeared silver-gray in colour. Hydrologists from the Icelandic Meteorological Office took water samples from the river and confirmed by field observations that the flood water originated from the northwestern margin of Hofsjökull ice cap where it entered the easternmost branch of Vestari-Jökulsá, which issues from the outlet glacier Sátujökull (Jóhannesson *et al.*, 2014), see location map in Figure 1. The jökulhlaup discharge reached a maximum of ~40 m<sup>3</sup>/s on 24 August at Goðdalabrú, beyond the discharge at the gauging station during the days before and after the flood, and then receded over the following ca. three days (IMO, 2014), see Figure 7. Comparison with the discharge in neighbouring Austari-Jökulsá, which was not affected by the jökulhlaup, shows that the background discharge in other watersheds in this area was most likely somewhat higher during the jökulhlaup than in the days immediately before and after the flood. Taking this into account, the maximum additional discharge in Vestari-Jökulsá due to the jökulhlaup can be estimated as ~30–35 m<sup>3</sup>/s. The total volume of flood water was estimated as 4.3 million m<sup>3</sup> by comparison of the measured discharge in Austari-Jökulsá at Skatastaðir (vhm 144, Figure 1) and Vestari-Jökulsá at Goðdalabrú (vhm 145, Figure 1), (IMO, 2014), but differences in precipitation between the watersheds in question during the flood leads to substantial uncertainty in this estimate. The jökulhlaup did not cause any damage or disruption.

Besides the jökulhlaup in Vestari-Jökulsá described here, jökulhlaups from Hofsjökull are uncommon with only three other such floods reported from the ice cap. Eyþórsson (1961) described a jökulhlaup from Hofsjökull in Blanda in 1903 or 1904.

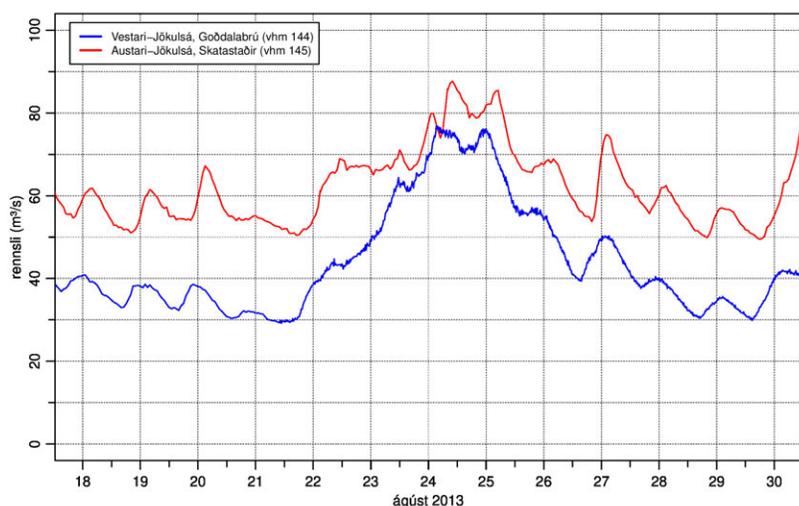


Figure 7. River discharge in Vestari- (blue) and Austari-Jökulsá (red) in Skagafjörður 18–30 August 2013 at Goðdalabrá (vhm 145) and Skatastaðir (vhm 144) gauging stations. The flood in Vestari-Jökulsá reached maximum on 24 August. – *Rennslí í Vestari- (blár ferill) og Austari-Jökulsá (rauður ferill) í Skagafirði 18.–30. ágúst 2013 við Goðdalabrá (vhm 145) og Skatastaði (vhm 144). Jökulhlaupið í Vestari-Jökulsá náði hámarki 24. ágúst.*

The outlet location is unknown but Eyþórsson mentioned that the flood might have originated near the mountain Blágnípa at the SW margin of the ice cap. In the fall of 2017, a small jökulhlaup appears to have emerged from beneath the Blágnípujökull outlet glacier on the western side of the ice cap (see Fig. 1), breaking up the ice near the terminus and transporting large chunks of glacier ice several hundred meters downstream (IMO, 2018). In September 2021, a second smaller jökulhlaup in Vestari-Jökulsá was detected at the Goðdalabrá gauging station, coming from the same summit cauldron as the 2013 flood.

A Landsat 8 satellite image of Hofsjökull from 24 September 2013 (Fig. 8) shows an elongated dark spot or depression at 1700 m a.s.l. at the northern margin of the summit of the ice cap. A depression had not been noticed before in this area. The depression appeared composed of two connected cauldrons. In the autumn 2013 mass-balance expedition to Hofsjökull, it was confirmed that a 20–30-m-deep, WNW–ESE elongated, depression had formed at this location,  $\sim(64^{\circ}49.5'N; 18^{\circ}52'V)$ , with a long axis of 500–1000 m (Þ. Þorsteinsson, pers. comm., October 2013). Concentric, circular, partly snow-filled crevasses were observed at the margin of the depression.

On 14 October 2013, scientists from the IES flew over the cauldron area in Hofsjökull in the same TF-FMS aircraft as was used for profile measurements of

Mýrdalsjökull in July 2011. They took photographs (Figure 9) and measured two elevation profiles with the on-board C-band radar. The profiles show a ca. 800 m long, 500 m wide and 20 m deep depression, which was not noticeable at this location when the glacier surface was mapped by aerial lidar in the year 2008 (Jóhannesson et al., 2013).

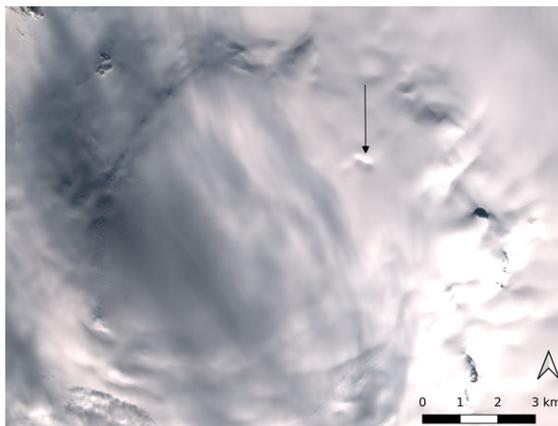


Figure 8. Landsat 8 satellite image of NW Hofsjökull from 24 September 2013. A newly formed cauldron is marked with a black arrow. – *Landsat 8 gervihnattarmynd af norð-vestanverðum Hofsjökli, 24. september 2013. Nýmyndaður sigketill við öskjubrúnina er auðkenndur með svartri ör.*

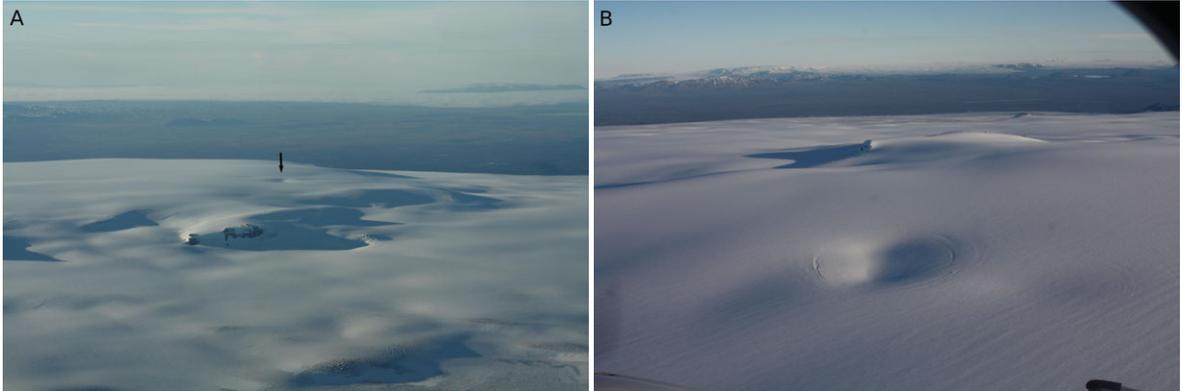


Figure 9. Cauldron near the northern margin of the summit caldera of Hofsjökull ice cap formed in August 2013 seen from east (A) and west (B). The cauldron is marked with a black arrow on the photo to the left. – *Horft frá austri (A) og vestri (B) yfir sigketil í norðurbrún Hofsjökulsöskjunnar sem myndaðist í ágúst 2013. Sigketillinn er auðkenndur með svartri ör á myndinni til vinstri.* Photos/ljósmyndir: Magnús T. Guðmundsson, 14 October 2013.

## Data and methods

Lidar measurements are an accurate method for mapping ice-surface elevations independently of surface texture and external light sources (Favey *et al.*, 1999; Abermann *et al.*, 2010) and were for this reason chosen for a national survey of Icelandic glaciers that took place in 2008–2013. The measurements were carried out by the German mapping company TopScan GmbH with an Optech ALTM 3100 laser scanner operated from  $\sim 2500$  m above ground, with 60 m/s flight speed,  $\sim 1200$  m distance between flight-lines, swath width of  $\sim 1800$  m and swath overlap of 600 m. The wavelength of the ALTM lidar is 1064 nm, and the laser scan rate was 33 kHz. GNSS base stations from the Icelandic ISGPS station network (Geirsson *et al.*, 2010) operated by the National Land Survey of Iceland and temporary base stations operated at ISN2004 triangulation network points were used for kinematic correction of the on-board GNSS instrument, ensuring a distance of  $<50$ – $100$  km from the survey areas to the nearest base station. The average measurement point density was  $\sim 0.3$ – $0.4$  per  $m^2$ , i.e. approximately one measurement every  $3 m^2$ . The measurements were averaged and interpolated onto a regular  $5 \times 5$  m grid (DEM) using a linear prediction method implemented in in-house software of TopScan. On average, approximately ten lidar measurements from the randomly distributed point clouds are available to de-

termine each point in the  $5 \times 5$  m regular grid. For specialized applications, higher-resolution  $2 \times 2$  m DEMs may be derived from the original point clouds.

Two measurements are obtained from each reflected laser pulse, corresponding to the first and the last returned pulse. The measurements corresponding to the first-pulse were used to calculate the regular DEMs, as these are considered more likely to originate from the ‘smooth’ ice surface that the DEM is intended to represent. The last-pulse measurements, which may be expected to be more affected by surface irregularities (e.g. crevasses and melt channels), may be used together with the first-pulse measurements in special-purpose studies such as digital delineation of crevasses or geomorphological analysis (Jóhannesson *et al.*, 2011; Staines *et al.*, 2015).

GNSS validation measurements on ice-free land and on the glaciers, taken on a day close to the lidar surveying, and comparison of lidar results in overlap areas indicate that the vertical accuracy of the lidar measurements  $<0.5$  m (Jóhannesson *et al.*, 2011).

Table 1 summarizes the lidar surveys of Mýrdalsjökull and Hofsjökull in 2008, 2010, 2011 and 2013 that are used in this paper.

TanDEM-X DEMs of Mýrdalsjökull used for comparison with other surface-elevation data about the jökulhlaup in Múlakvísl in 2011 were deduced from interferometric synthetic aperture radar (InSAR) data acquired during the TanDEM-X satellite mission

Table 1. Dates of lidar surveys and total survey area (km<sup>2</sup>), including adjacent ice-free areas and overlapping regions for each survey. The date of the main survey is given in bold in case several efforts were needed to map the entire glacier in question, in which case data from the other surveys may have been adjusted in altitude to create a composite DEM corresponding to the time of the main survey. Such patching did not affect the jökulhlaup source areas that are analysed here. – *Dagsetning leysimælinga og flatarmál mældra svæða.*

Glacier	Survey dates (area)
Hofsjökull	<b>3/4.9.2008</b> (760 km <sup>2</sup> ), 18/19.7.2010 (347 km <sup>2</sup> )
Hofsjökull	<b>13/14.10.2013</b> (994 km <sup>2</sup> )
Mýrdalsjökull	16/21.7.2010 (51 km <sup>2</sup> ), <b>9/10.8.2010</b> (748 km <sup>2</sup> )
Mýrdalsjökull	<b>7/8.8.2011</b> (57 km <sup>2</sup> , cauldrons)

on 23 March and 4 September 2011. The DEMs are processed by extracting the topographic information from the InSAR data in the same manner as described by Rossi *et al.* (2012).

Pléiades stereo images of Hofsjökull, collected in four acquisitions between 1–5 October 2020, and ArcticDEM strips (Porter *et al.*, 2022) of the glacier, from 11 July 2021 and 2 July 2022, were used for comparison with the 2013 lidar DEM. The Pléiades stereo images were processed using the Ames StereoPipeline (Shean *et al.*, 2016), following the processing strategy described in Deschamp-Berger *et al.* (2020). Each of the resulting Pléiades DEMs was co-registered with respect to the 2013 lidar DEM with the co-registration algorithm of Nuth and Kääb (2011), and a 2-m resolution mosaic was created with the routine DEM mosaic in the Ames StereoPipeline for early October 2020. We assessed a relative vertical uncertainty of the Pléiades DEM mosaic of 1 m. The Normalized Mean Absolute Deviation (NMAD) of elevation between the Pléiades DEM mosaic and the lidar DEM was in all cases lower than this value outside the glacier (Berthier *et al.*, 2024). Pléiades data have been widely used for monitoring glacier changes (Berthier *et al.*, 2014, 2024).

Glacier surface-elevation profiles were measured with kinematic differential GNSS using base stations from the Icelandic ISGPS station network and with airborne radar altimetry with the flight inspection aircraft TF-FMS (Gudmundsson *et al.*, 2007; Magnússon *et al.*, 2021).

## RESULTS

### Surface elevation changes of Mýrdalsjökull in July and August 2011

The source area of the July 2011 jökulhlaup in Múlakvísl from Mýrdalsjökull ice cap was resurveyed by lidar approximately one month after the flood on 7 and 8 August 2011 (Jóhannesson, 2012) (see Table 1). The resurveyed area spanned roughly the elevation range 1200–1400 m a.s.l. and measured ca. 5 km W–E and 11 km S–N (Fig. 2). Shadings of this area from the 2010 and 2011 DEMs are presented side-by-side in Figure 10 and clearly show four main subsidence areas that were formed during and after the jökulhlaup. The main cauldron that subsided was no. 16 and cauldron no. 9, 1–2 km to the SE was simultaneously emptied (see Figs. 11 and 12, as well as Figs. 4 and 5). Cauldrons no. 10 and 11, ca. 4 km NE of cauldron 16, also show substantial lowering (see Figs. 11 and 13, as well as Fig. 6). The surface lowering of cauldron 11 was not as large in the reconnaissance flight and radar-profile measurements on 11 July described above as the lowering of the other three cauldrons. These cauldrons are part of a system >20 cauldrons in Mýrdalsjökull ice cap with substantial variations in surface elevation with time that are regularly monitored by the IES (Gudmundsson *et al.*, 2007; Magnússon *et al.*, 2021) as mentioned above.

The elevation difference between the 2010 and 2011 surveys (Fig. 11), after a correction for a ~0.28 m elevation difference between the surveys outside the main subsidence areas, shows the four main subsidence cauldrons mentioned above. It also

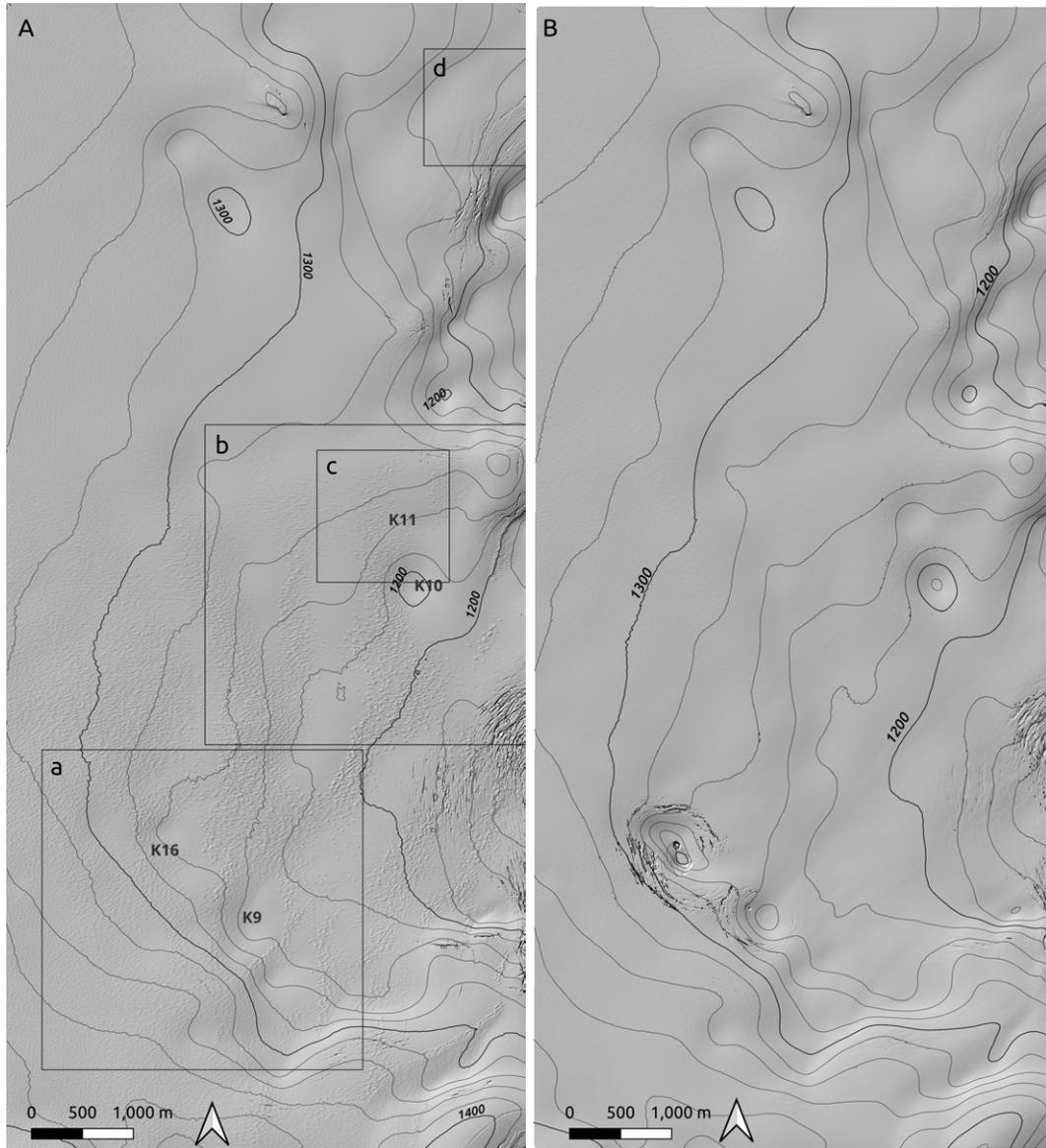


Figure 10. Shadings of the lidar surveys of Mýrdalsjökull in 2010 (left) and 2011 (right) with 100 m (bold) and 20 m (thin) contour lines. The large boxes (marked a and b) on the 2010 map to the left identify areas where the resurvey in 2011 shows lowering of the glacier surface from the year before, which is shown in more detail on maps in following figures. The smaller boxes (marked c and d) identify areas where overlapping survey lines on 7 and 8 August 2011 show a lowering of the glacier surface between those two days in August 2011. *Skyggðar yfirlitsmyndir af mælingunum 2010 (til vinstri) og 2011 (til hægri) á Mýrdalsjökli ásamt 100 m (breiðum) og 20 m (mjóum) hæðarlínunum. Stóru rammarnir (merktir a og b) á myndinni til vinstri afmarka svæði þar sem endurmælingin 2011 sýnir að yfirborð jökulsins seig frá árinu áður og sýnd eru á myndum hér á eftir. Minni rammar (merktir c og d) afmarka skörunarsvæði þar sem fluglínur frá 7. og 8. ágúst 2011 sýna að jökulyfirborðið seig milli þessara tveggja mældidaga í ágúst 2011.*



shows extended areas with several-metre lowering downstream of the cauldrons, where the flow of flood water presumably caused melting of the glacier sole and release of ponded water outside the main cauldrons. The surface lowering was possibly also to some degree caused by erosion of the glacier bed. This >500-m-wide path of lowering is initially towards ESE from cauldrons 16 and 9 for a distance of ~2 km and abruptly turns towards NE for another ~2–3 km. The path of lowering from cauldron 10 is narrower and not as distinct and extends ~1 km towards S. The difference map also shows >10 m lowering of cauldron 11, about 1 km NNW of cauldron 10, which appears to have released additional flood water after the IES radar profile measurements were carried out on 11 July, as further discussed in a separate subsection below.

The lowering of the cauldron areas is shown in more detail in Figures 12 and 13. The elevation change was by far greatest in cauldron 16, which was lowered by ca. 75 m over a 50×200 m SE–NV-oriented area. A distinct shaft with near-vertical ice walls and ca. 50 m diameter was formed by the collapse of a part of the cauldron bottom where the lowering exceeded 100 m. The centre of cauldron 18 was lowered by ca. 5 m. The centre of cauldron 9 was lowered by ca. 30 m, the centre of cauldron 10 by ca. 14 m and the centre of cauldron 11 by ca. 20 m, respectively, between the 2010 and 2011 lidar surveys.

Figure 10A and Figure 11 have an irregular or “orange-peel” texture on a length scale of ~10 m that is caused by inhomogeneous snow melting due to the Eyjafjallajökull 2010 eruption. Tephra deposited on the winter snowpack on Mýrdalsjökull and other glaciers in Iceland in the spring of 2010 caused preferential melting in a strikingly regular pattern of 1–2 m deep depressions over extended areas. This surface roughness is not present in the 2011 lidar DEM of the glacier surface. The roughness in the 2010 shadings and irregularities in the 2011 minus 2010 difference maps is, therefore, not due to errors in the 2010 lidar DEM, which shows this interesting surface characteristic in remarkable detail.

The lowering of the flood path towards SE downstream of cauldrons 9 and 16 shown in Figure 11 is

typically in the range 2–5 m. There is, furthermore, similar-magnitude lowering in several areas or side branches that strike out from the main flood path (see Fig. 11). There, meltwater may have been ponded before the jökulhlaup and released when the main cauldrons emptied, or perhaps in the period after the flood but before the August 2011 lidar survey, or alternatively, basal melting in these areas may have been intensified by flash-boiling in the geothermal system induced by the lowering of water pressure associated with the jökulhlaup.

#### *The volume corresponding to the lowering of the glacier surface*

The volume corresponding to the lowering of the glacier surface between the lidar surveys in August 2010 and August 2011 was calculated within five areas (see Fig. 11) that were delineated around the four cauldrons, no. 16, 9, 10 and 11 and the downstream flood path, where surface lowering was detected as described above, see Table 2.

The elevation difference between the 2010 and 2011 lidar DEMs within a 200-m-wide buffer outside of the cauldrons and inferred flood paths is mostly within –1 and +2 metres with a median of +0.28 m, so that the surface was a little higher in 2011 than in 2010. This median value was subtracted from the elevation difference shown in figures discussed above (and added to the computed lowering) in order to eliminate a bias that would otherwise have affected volume estimates and other derived quantities. After this bias correction has been made, the geometries of the glacier surface in 2010 and 2011 within the 200-m-wide buffer are quite close, with an interquartile range of –0.57 to +0.55 m and NMAD of 0.83 m.

The volume corresponding to the surface lowering between the lidar surveys in 2010 and 2011 is potentially affected by inflow of ice into the cauldrons and basal melting within the cauldrons themselves and neighbouring areas in the intervening period, in addition to the emptying of the subglacial water body associated with the jökulhlaup. Indeed, monitoring of the cauldrons by the IES indicates that the bottom of cauldrons 16, 9, 10 and 11 rose by ~6, ~5, ~8, and ~1 m, respectively, from August 2010 until shortly before the jökulhlaup on 9 July 2011 (Guðmundsson and

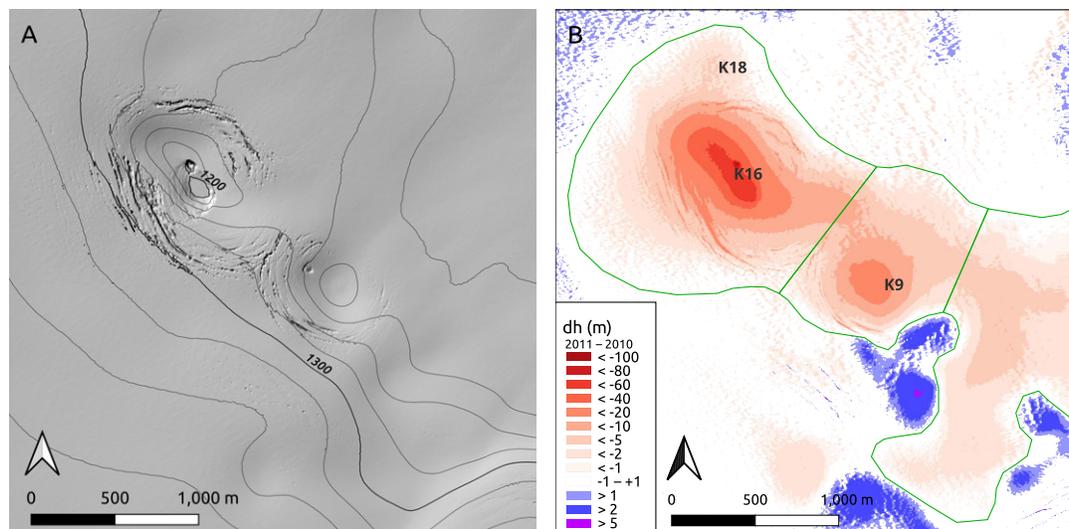


Figure 12. Shading (left) and the change in the elevation of the glacier surface (right) at cauldrons 16 and 9 in Mýrdalsjökull from August 2010 to August 2011 (box a on the map in Figure 10 shows the location of the area). The lowering near the centre of cauldron 16 was ca. 75 m over an extended area and reached a maximum of over 100 m in the shaft to the NW of the centre. The centre of cauldron 9 was lowered by ca. 30 m. – *Skygging (til vinstri) og breyting á yfirborðshæð (til hægri) katla 16 og 9 í Mýrdalsjökli milli leysimælinganna 2010 og 2011 (rammi a á mynd 10 sýnir svæðið). Í miðju ketils 16 var lækkinin ca. 75 m á nokkuð stóru svæði en náði hámarki yfir 100 m í strokknum skammt norðvestan við miðju ketilsins. Miðja ketils 9 lækkaði hins vegar um ca. 30 m.*

Table 2. Volume corresponding to the lowering of the glacier surface between August 2010 and August 2011 of cauldrons and jökulhlaup paths on Mýrdalsjökull associated with the jökulhlaup in Múlakvísl in July 2011. The five areas used for the volume computations are shown with green outlines identified with Roman numerals on the map in Fig. 11. *Rúmmál sem svarar til lækkunar yfirborðs Mýrdalsjökuls milli ágúst 2010 og ágúst 2011 sem tengist jökulhlaupinu í Múlakvísl í júlí 2011. Fimm svæði sem notuð voru við rúmmálsreikningana eru afnörkuð með grænum ferlum á kortinu og merkt rómverskum tölustöfum.*

Cauldron/area	Volume (10 <sup>6</sup> m <sup>3</sup> )
Cauldron 16 (I)	20.5
Cauldron 9 (II)	6.2
Jökulhlaup path from cauldrons 16 and 9 as well as side branches (V)	9.6
Cauldron 10 and jökulhlaup path (III)	4.1
Cauldron 11 (IV)	3.5
Cauldrons 16, 9 and 10, total	30.7
Cauldrons 16, 9 and 10 and jökulhlaup path, total	40.4
<b>All cauldrons and jökulhlaup path, total</b>	<b>43.9</b>

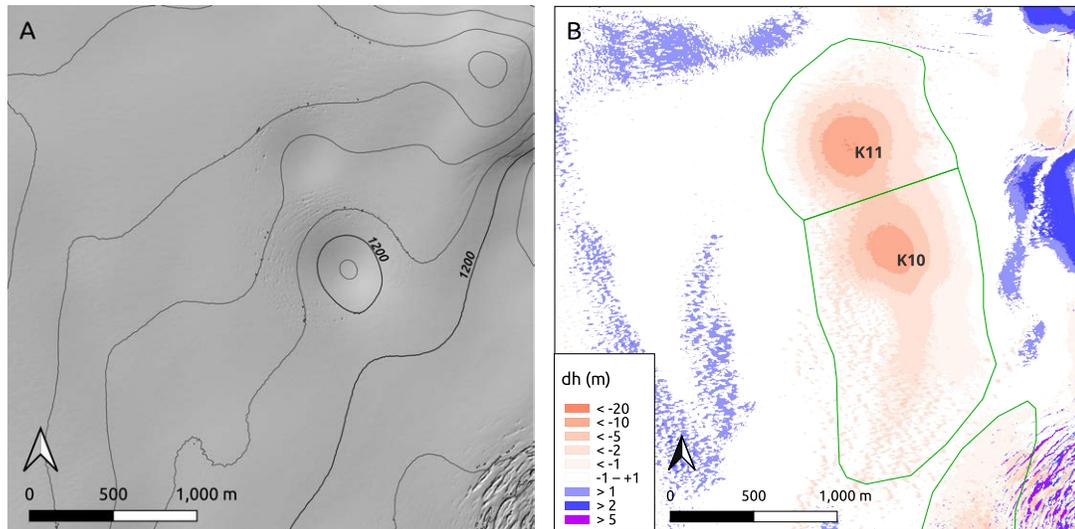


Figure 13. Shading (left) and the change in the elevation of the glacier surface (right) at cauldrons 10 and 11 in Mýrdalsjökull from August 2010 to August 2011 (box b on the map in Figure 10 shows the location of the area). The lowering near the centre of cauldron 10 was ca. 14 m and ca. 20 m near the centre of cauldron 11. – *Skygging (til vinstri) og breyting á yfirborðshæð (til hægri) katla 10 og 11 í Mýrdalsjökli milli leysimælinganna 2010 og 2011 (rammi b á mynd 10 sýnir svæðið). Í miðju ketils 10 var lækkunin ca. 14 m og um 20 m í miðju ketils 11.*

Högnadóttir, 2011) (Figs. 14 and 15). The volume corresponding to these surface elevation changes from 2010 to 2011 may be roughly estimated as  $\sim 1$ ,  $\sim 0.3$ ,  $\sim 0.4$  and  $\lesssim 0.05$  million  $\text{m}^3$  for these cauldrons, respectively. This needs to be borne in mind when the volume changes tabulated in Table 2 are interpreted.

*Lowering of the glacier surface between 7 and 8 August 2011*

There is ca. 600 m overlap between adjacent swaths in the aerial lidar mapping. During the processing of the lidar data from 7 and 8 August 2011, the glacier surface was found to have been lowered between those two adjacent days in two several-hundred-metres-wide areas. One of the areas is cauldron 11 (marked c in Fig. 10A), which seems to have emptied separately from the other three cauldrons about a month after the main jökulhlaup on 9 July. The other area (marked d in Fig. 10A) is ca. 4 km farther to the NNE. The 2011 lidar DEM was created from lidar data from 8 August in these areas and separate smaller DEMs created from the measurements from 7 August.

The centre of cauldron 11 was lowered by ca. 8 m between 7 and 8 August (out of a total of 20 m total lowering between the 2010 and 2011 DEMs) (Fig. 16, see also Fig. 15). The serendipitously discovered lowering of this cauldron in August had a remarkably regular cylindrically-symmetric geometry (Fig. 16A). A 500–1000-m-long and 100–200-m-wide area farther to the north was lowered by ca. 0.5 m during the same time period (Fig. 16B). It is possible that the total volume of water that was released from cauldron 11 during the summer of 2011 was larger than indicated in the fifth row of Table 2 since the cauldron may have subsided further after 8 August in view of the substantial subsidence over only ca. 24 hours between the 2011 surveys. The TanDEM-X DEM from 4 Sept. 2011 shows, however, that this possible additional lowering was comparatively small ( $\sim 2$ – $3$  m, see Fig. 15). The other area (marked d in 10A) with surface-elevation changes between the surveys in August 2011 (Fig. 16B) is not known for such elevation changes. The shape of the lowered area is rather irregular and it seems unlikely that the lowering is caused

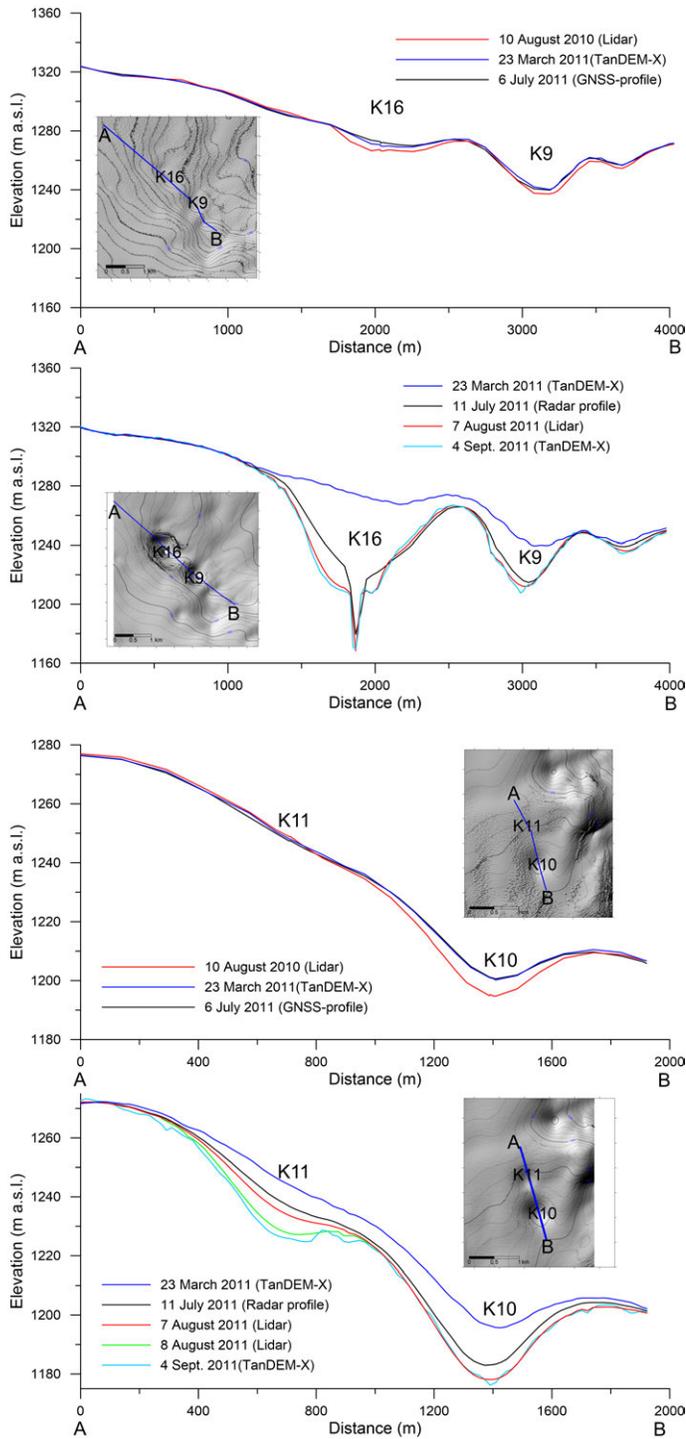


Figure 14. Surface-elevation profiles over cauldrons 16 and 9 before (top) and after (bottom) the jökulhlaup from Mýrdalsjökull on 9 July 2011. The figure with profiles after the jökulhlaup also shows a TanDEM-X profile from 23 March 2011 for comparison. – Hæðarsnið yfir katla 16 og 9 fyrir (til vinstri) og eftir (til hægri) jökulhlaupið úr Mýrdalsjökli þ. 9. júlí 2011. Myndin sem sýnir snið eftir hlaupið sýnir einnig TanDEM-X snið frá 23. mars 2011 til samanburðar.

Figure 15. Surface-elevation profiles over cauldrons 10 and 11 before (top) and after (bottom) the jökulhlaup from Mýrdalsjökull on 9 July 2011. The figure with profiles after the jökulhlaup also shows a TanDEM-X profile from 23 March 2011 for comparison. Note that there is no difference in elevation on 7 and 8 August for cauldron 10. – Hæðarsnið yfir katla 10 og 11 fyrir (til vinstri) og eftir (til hægri) jökulhlaupið úr Mýrdalsjökli þ. 9. júlí 2011. Myndin sem sýnir snið eftir hlaupið sýnir einnig TanDEM-X snið frá 23. mars 2011 til samanburðar. Athugið að enginn munur er á hæðinni sem mælist 7. og 8. ágúst fyrir ketil 10.

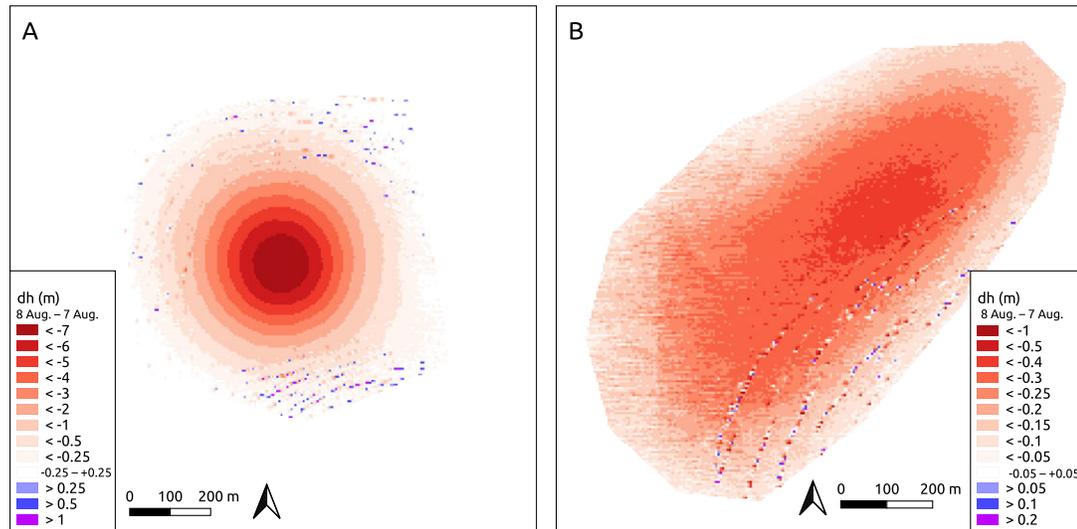


Figure 16. The change in the elevation of the glacier surface of Mýrdalsjökull over a single day at two locations within the overlap area of two survey lines on 7 and 8 August 2011 (boxes c and d on the map in Fig. 10A show the locations of the areas). Map A on the left (box c in Fig. 10A) shows that substantial lowering of cauldron 11 took place during the two-day lidar survey in 2011, with a maximum lowering of almost 8 m near the centre of the cauldron. Map B on the right (box d in Fig. 10A) shows that an area of similar size farther north was lowered by ca. 0.5 m between the two days. Note the difference in the colour scale of the maps. – *Breyting á yfirborðshæð á skörunarsvæði mælilína á Mýrdalsjökli á einum degi milli 7. og 8. ágúst 2011 (rammar c og d á mynd 10A sýna svæðin). Mynd A til vinstri (rammi c) sýnir að ketill 11 myndaðist einmitt þegar leysimælingarnar í ágúst 2011 fóru fram og lækkaði miðja ketilsins mest um tæpa 8 metra á rúmum sólarhring. Mynd B til hægri (rammi d) sýnir svæði af svipaðri stærð sem lækkar u.þ.b. 0,5 m milli mælidaganna. Athugið mun á litakvarða myndanna.*

by spatial variations in surface melting or induced by changes in the flow of the glacier. Thus, release of ponded water at the base is the most likely cause for the lowering, as for cauldron 11, although this is uncertain.

#### *Thermodynamics of the subglacial water flow*

Table 2 shows that the volume corresponding to the ice-surface lowering over the subglacial flood path (area V in Fig. 11) from cauldrons 16 and 9 is approximately one third of the combined volume corresponding to the lowering of those two cauldrons (areas I and II in Fig. 11). The 2011 lidar DEM does not cover the flood path below ca. 1150 m a.s.l. but the TanDEM-X DEM from 4 Sept. 2011 shows that there is rather irregular lowering of similar magnitude over a ~1–2 km-wide area extending down to at least 800 m a.s.l.

It is hard to say to what extent this extensive lowering is caused by melting of the glacier sole by warm flood water and subsequent sinking of the glacier into the space previously occupied by the melted ice. The lowering of a side branch towards S in the southernmost part of area V in Figure 11 is likely to be caused by emptying of cauldron 17 during and/or after the flood on July 9, and similarly, the lowering of a side branch towards SE from the main flood path is also likely to be caused by emptying of ponded water at the base during or after the main flood.

The longitudinal geometry of the lowering along the main flood path (see Fig. 11), with greatest lowering near the cauldrons and tapering off with distance from the cauldrons, indicates basal melting due to warm flood water. The steep glacier surface below ca. 1150 m a.s.l. could also have been lowered due to

ice dynamics induced by hydro-jacking during the initial phase of the jökulhlaup, as the glacier may be expected to have been near floatation then because of high water pressure along the flood path. The flood water would need to have had a temperature of 20–30 °C to melt out the flood path from cauldrons 16 and 9 down to ca. 1150 m a.s.l. if a substantial part of the volume corresponding to the lowering in this area (area V in Fig. 11) is due to melting of basal ice. This estimate is computed as the ratio of the heat needed to melt the ice volume  $V_V$  corresponding to the flood-path lowering,  $L \rho_i V_V$ , to the heat released by cooling the water that flowed from cauldrons 16 (volume  $V_I$ ) and 9 (volume  $V_{II}$ ) by one degree  $C_p \rho_w (V_I + V_{II})$ , where  $L = 3.335 \cdot 10^5 \text{ J kg}^{-1}$  and  $C_p = 4,218 \text{ J kg}^{-1} \text{ K}^{-1}$  are the heat of fusion and specific heat of water, respectively, and  $\rho_i = 900 \text{ kg m}^{-3}$  and  $\rho_w = 1000 \text{ kg m}^{-3}$  are the density of ice and water, respectively. The uncertainty of this estimate is due to a possible error of  $\pm 0.5 \text{ m}$  in the bias-corrected DEM difference, as well as uncertainty in the small correction made to take the elevation increase of cauldrons 16 and 9 from the lidar survey in August 2010 to the flood in July 2011 into account, and uncertainties arising from possible erosion of the glacier bed and release of potential energy. The estimated water temperature also depends slightly on whether the water released from the cauldrons is mainly melted before or after the initial lidar survey. If substantial ice melting extended farther downglacier than to ca. 1150 m a.s.l., the water temperature would need to be even higher, and correspondingly lower if ice-dynamics and emptying of ponded basal water caused part of the lowering above ca. 1150 m a.s.l. The lowering along the main flood path could also to some extent be caused by temporarily increased basal melting after the main flood, see the discussion section below, which would tend to lower the estimated initial water temperature.

On the basis of the available measurements it is not possible to derive an explicit estimate of the initial flood-water temperature. It seems likely from the geometry of the surface lowering downstream of the cauldrons, that ice melting due to warm flood water is partly responsible for this lowering and, therefore,

that the temperature of the flood water was on the order of 10 °C to tens of degrees Celsius when the water flowed out of the cauldrons. It is of course also possible, and perhaps more likely than not, that flood water from cauldron 16 was warmer and the water from cauldron 9 colder than this estimate. The flood path from cauldrons 10 and 11, on the other hand, has proportionally a much smaller volume relative to the volume of the cauldrons, indicating colder flood water released from those cauldrons. This order of magnitude estimate for the temperature of the flood water from cauldron 16, and possibly also cauldron 9, is of a similar magnitude as has been suggested by for the 2011 jökulhlaup from Köldukvíslarjökull in Sveðja (Magnússon *et al.*, 2016) and the 2024 jökulhlaup from Mýrdalsjökull in Leirá/Skálm (Magnússon *et al.*, 2024), which was  $>15 \text{ °C}$  and  $\sim 40 \text{ °C}$ , respectively.

#### Surface elevation changes of Hofsjökull in connection with the jökulhlaup in August 2013

Hofsjökull ice cap (Fig. 17) was resurveyed by lidar on 13 and 14 October 2013 (see Table 1), one month and three weeks after the August jökulhlaup in Vestari-Jökulsá, as part of a collaboration between the IMO, the University of Innsbruck and the Austrian company alpS GmbH.

Comparison of the 2013 lidar DEM in the summit area of the ice cap, where the cauldron formed in late August, with the earlier 2008 lidar DEM of the same region (see Fig. 19) makes it possible to study the size and geometry of the cauldron and to accurately calculate the volume corresponding to the subsided area.

The glacier surface near the cauldron, but outside the area that subsided, had lowered between the 2008 and 2013 surveys. As for the 2011 cauldrons in Mýrdalsjökull, this difference was corrected by subtracting the median elevation difference within a 200-m-wide buffer outside of the cauldron, which was found to be  $-2.0 \text{ m}$ . The geometries of the glacier surface in 2008 and 2013 after the bias correction within the buffer are again quite close, with an interquartile range of  $-0.24$  to  $+0.40 \text{ m}$  and NMAD of  $0.44 \text{ m}$ . After correcting for the general lowering, one finds that the lowering near the centre of the cauldron reached a maximum of  $19 \text{ m}$  (see a map of the bias-corrected DEM difference in Fig. 19). The total volume corre-

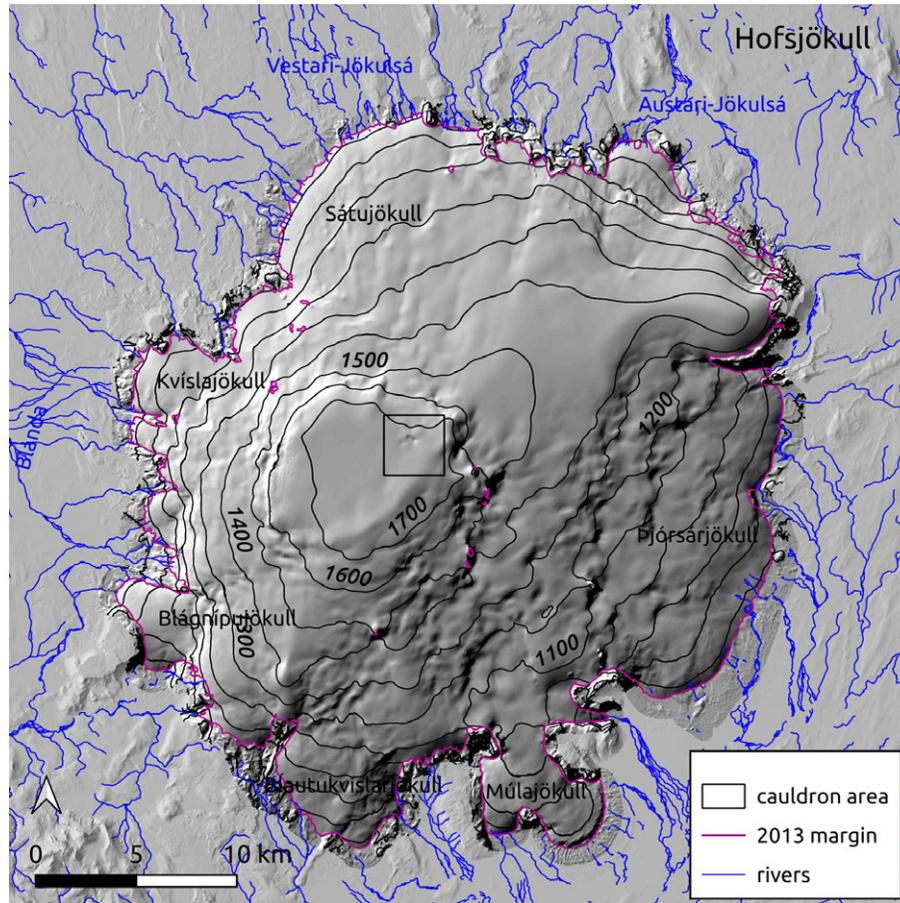


Figure 17. The surface of Hofsjökull according to a lidar survey on 13 and 14 October 2013. The area near the northern margin of the summit caldera, where a cauldron was formed in August 2013, is shown with a black box. The outline of the ice cap in 2010 is shown in red. The shading outside the lidar DEM of the glacier is based on ÍslandsDEM. – *Yfirborð Hofsjökuls skv. leysimælingu 13. og 14. ágúst 2013. Svæðið þar sem sigketill myndaðist í ágúst 2013 á norðanverðum hájöklinum er sýnt með ramma. Útlína jökulsins árið 2010 er sýnd með rauðum ferli.*

sponding to the lowering was 4.1 million m<sup>3</sup> of ice, which corresponds to 3.7 million m<sup>3</sup> of water if a sudden, localized increase in subglacial geothermal heat flow caused increased melting of ice from the glacier sole that then led to the jökulhlaup. However, if the cauldron was formed by geothermal heat flow over a longer time period, possibly in part over a larger area than subsided in connection with the jökulhlaup, so that water accumulated below the cauldron without much lowering at the surface there, then the total volume of water released from the cauldron would be

ca. 4.1 million m<sup>3</sup>. The former possibility must be considered more likely for a jökulhlaup from an area without previous history of jökulhlaups or surface elevation changes due to glacier floods. This estimate for the volume of water released from the glacier is in as good agreement as can be expected with the estimated volume of the jökulhlaup in Vestari-Jökulsá by Goðdalabrú, 4.3 million m<sup>3</sup>, presented earlier, when uncertainties in the estimated flood discharge at Goðdalabrú are considered.

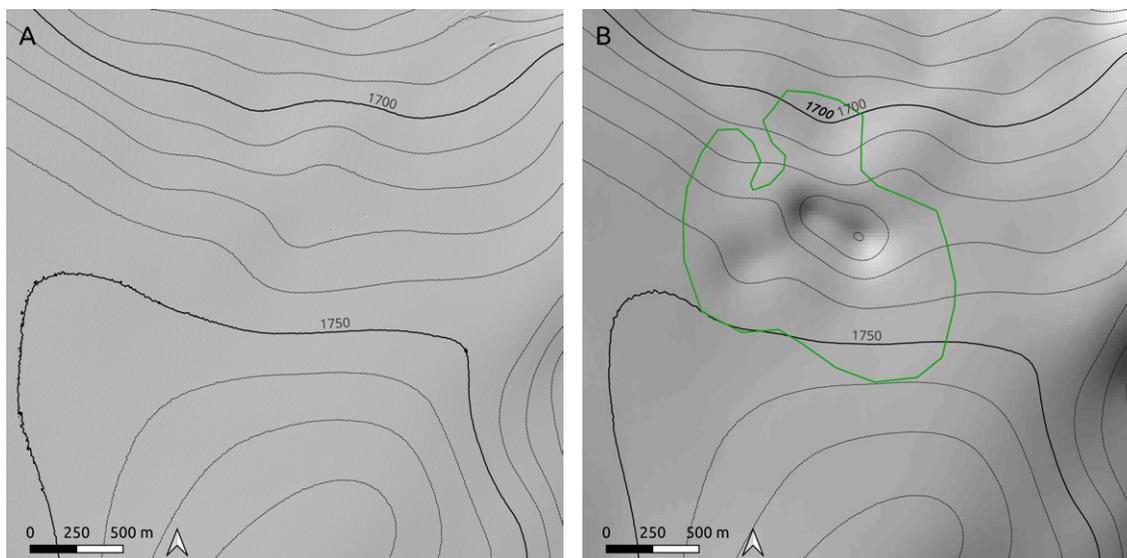


Figure 18. Shadings of the cauldron area near the northern margin of the summit caldera of Hofsjökull ice cap. The location of the area is shown with a black box on Fig. 17. The map to the left shows the results of the lidar survey of TopScan/IMO on 3 October 2008 and the map on the right the TopScan/UIBK survey on 13 and 14 October 2013. A green curve on the 2013 map shows the area used to compute the volume corresponding to the lowering of the glacier surface from 2008 to 2013. The maps show 10-m contours in addition to the shadings. – *Skyggingar af sigketilssvæði í norðurbrún Hofsjökuls-öskjunnar. Svæðið er sýnt með ramma á mynd 17. Myndin til vinstri sýnir leysimælingu TopScan/VÍ frá 3. október 2008 en myndin til hægri mælingu TopScan/UIBK frá 13. og 14. október 2013. Grænn ferill á 2013 kortinu afmarkar svæðið sem notað er til þess að reikna rúmmál ketilsins. Sýndar eru 10 m hæðarlínur auk skyggingar.*

As for Mýrdalsjökull in 2011, the volume corresponding to the surface lowering between the lidar surveys of Hofsjökull in 2008 and 2013 is, in addition to the emptying of the subglacial water body associated with the jökulhlaup, potentially affected by inflow into the cauldron and basal melting within the cauldron itself in the 5-year intervening period. Spatial variations in surface mass balance or surface-elevation changes induced by changes in the flow of the glacier in the vicinity of the cauldron are also possible. The estimated volume change must, therefore, be considered the consequence of various potential processes acting over this comparatively long period. However, repeated mapping of glaciers typically reveals that spatial variations in the glacier-surface geometry are quite stable over extended periods, when large-scale elevation changes due to interannual mass-balance and ice-flow variations are subtracted.

Pléiades satellite photogrammetric mapping of Hofsjökull in the fall of 2020 shows that the surface geometry in the 2013 cauldron area had largely recovered (see Fig. 20). The glacier surface had approached the 2008 geometry within 1–2 m when an overall elevation change outside the cauldron was subtracted. Thus, it seems likely that the measured surface-elevation changes of the cauldron between 2008 and 2013 are mostly caused by subglacial melting induced by a localized increase in geothermal heat flow and the subsequent collapse of the glacier surface due to the emptying of the basal water body, despite the long period between the lidar surveys. The 2021 and 2022 ArcticDEM strips show 4–5 m lowering of the centre of the cauldron area between July 2021 and July 2022, which is likely caused by the jökulhlaup in September 2021 that was mentioned above. Since the 2022 ArcticDEM strip dates from almost a year after the jökulhlaup, the initial lowering of the cauldron as

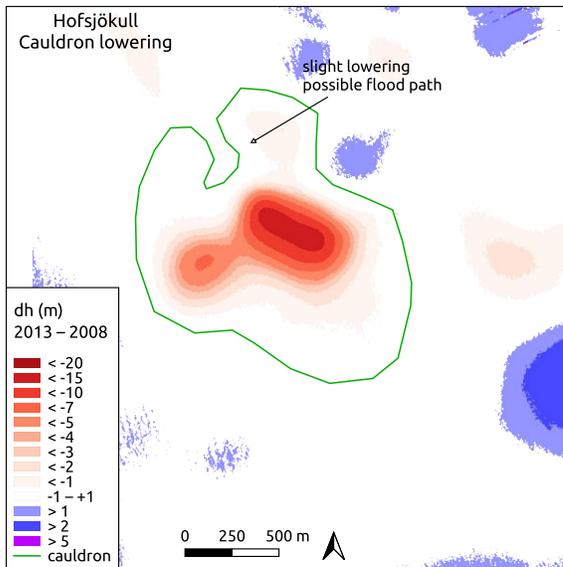


Figure 19. The elevation difference between lidar surveys on 13 and 14 October 2013 and 3 October 2008 in the area of a subsidence cauldron near the northern margin of the summit caldera of Hofsjökull ice cap. The difference is corrected for a  $\sim 2$  m general lowering of the area near the cauldron between the surveys in 2008 and 2013. – *Sigketill í norðurbrún Hofsjökulsöskjunnar, mismunur leysimælinga TopScan 13. og 14. október 2013 og 3. október 2008. Leiðrétt er fyrir  $\sim 2$  m lækkun á svæðinu nærri katlinum milli mælinganna 2008 og 2013.*

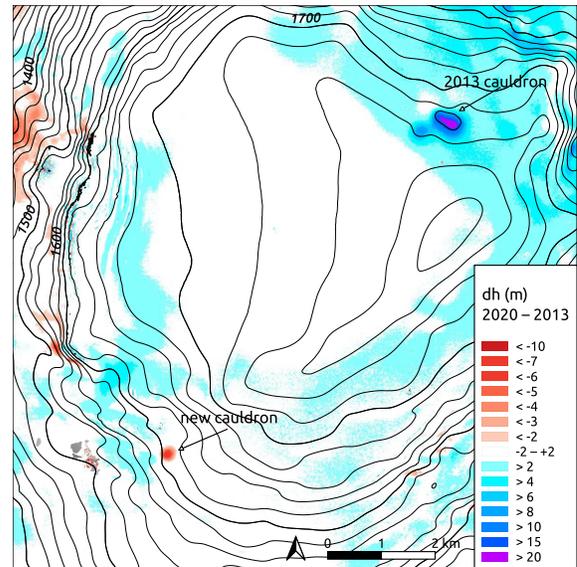


Figure 20. The elevation difference between a Pléiades DEM derived from images taken in early October 2020 and the lidar survey in October 2013 on the summit of Hofsjökull ice cap. The elevation of the upper accumulation area of Hofsjökull generally increased by a few metres in this time period, whereas the ablation area (not shown here) was lowered by 10 to 30 m. – *Mismunur Pléiades landlíkans sem byggt er á fjarvídarljósmyndum í byrjun október 2020 og leysimælinga í október 2013.*

a consequence of the release of the flood must have been greater than the elevation difference computed from the DEMs, perhaps in the range 5–10 m. Interestingly, further comparison of the 2020 Pléiades and 2013 lidar DEMs reveals a  $\sim 300$ -m diameter and  $\sim 7$ -m-deep cauldron on the SW side of the ice-cap summit (see Fig. 20 near the lower left corner) that must have formed sometime in the period 2013 to 2020.

There is not much indication of glacier-surface lowering along a possible flood path from the 2013 Hofsjökull cauldron. There is some lowering towards N from the main cauldron, approximately  $\sim 200$  m long and  $\sim 100$  m wide with 1–2 m lowering (see Fig. 19). If this feature is formed by basal melting due to the temperature of the flood water, the water would be rather cold compared with flood water from cauldron

16 in Mýrdalsjökull in 2011, that is presumably colder than  $1^\circ\text{C}$ .

## DISCUSSION AND CONCLUSIONS

The cauldron-volume estimates derived above are based on DEMs spanning a  $\sim 1$ -year period in the case of Mýrdalsjökull and  $\sim 5$ -year period for Hofsjökull. The time interval from the jökulhlaup to the latter DEM is almost one month in case of Mýrdalsjökull and almost two months for Hofsjökull. Ice flow into the newly formed depression from the time of the flood to the lidar survey will tend to make the cauldron shallower, but since ice is incompressible the reduction in the depth of the cauldron centre over this short interval will be compensated by lowering of adjacent

areas and those two changes may be assumed to cancel in the volume computations. Additional floods and enhanced basal melting after the jökulhlaup but before the latter lidar survey may also have an effect on the volume estimate. In combination, the GNSS and aerial radar-profile measurements, lidar and TanDEM-X elevation measurements, show that flood water was released from the cauldron source area over an extended period of time such that the initial sudden flood only amounted to  $\sim 20\%$  of the total amount of released water. Subglacial accumulation of water, ice flow, interannual variations in snow drift patterns and spatial variations in surface mass balance in the interval from the initial lidar survey to the flood may also affect the volume estimates. In spite of these uncertainties, the geometric similarity of spatial variations in the glacier-surface elevation outside of cauldron and flood path areas makes it possible to derive good estimates of the volume of floods released from subglacial water bodies with the satellite and aerial DEMs and elevation-profile measurements that have become increasingly available in recent years.

For the 2011 jökulhlaup from Mýrdalsjökull, the large difference between the estimated volume of the flood at Léreftshöfuð (7–8 million  $\text{m}^3$ , Jónsson and Þórarinsdóttir, 2011), the volume of cauldrons 16, 9 and 10 based on aerial profile measurements (18 million  $\text{m}^3$ , Guðmundsson and Högnadóttir, 2011), and the total volume corresponding to the elevation difference of the 2011 and 2010 lidar DEMs (44 million  $\text{m}^3$ , Table 2) is interesting. As mentioned before, the most likely explanation for the comparatively low volume of the 2-hour-long flood peak on 9 July compared with the other volume estimates is that smaller floods after the abrupt flash flood account for the difference (Larsen *et al.*, 2013). The factor-of-two difference between the volumes estimated from profile measurements and the lidar DEMs is partially explained by the lowering of cauldron 18 shortly after the main flood on 9 July ( $\lesssim 0.4$  million  $\text{m}^3$ ), that was not included in the analysis of the profile measurements, further outflow from cauldron 11 after the profile measurements were carried out ( $\sim 3$  million  $\text{m}^3$ ) and the volume corresponding to the surface lowering over the subglacial jökulhlaup path ( $\sim 10$  million  $\text{m}^3$ ). This

shows the importance of taking into account the melting of ice along the subglacial flood path for jökulhlaups of the type that occurred in Múlakvísl in 2011 where the initially warm flood water released from the cauldron melts a substantial volume of ice on its way downglacier. Cauldrons 16 and 9, as well as 10 and 11, also subsided further after the profile measurements on July 11 (Figs. 14 and 15), which is likely to explain part of the remaining  $\sim 10$  million  $\text{m}^3$  volume loss. The difference may also be to some extent explained by differences in integration methodology between the calculations based on profiles, on the one hand, and DEMs, on the other, but other uncertainties discussed above related to the accuracy of the DEMs and the timing of the different measurements are also possible explanations. It is, furthermore, possible that part of the glacier-surface lowering along the flood path, particularly in the steep part of the glacier below ca. 1150 m a.s.l., is caused by ice dynamics, as discussed above, and should not be counted as part of the flood volume at all. These large differences show that different methods to estimate the size of jökulhlaups may be associated with larger errors or inconsistencies than would perhaps be expected beforehand.

If flash-boiling in the geothermal system below the glacier due to lowering of water pressure in the subglacial hydraulic system during the 2011 jökulhlaup caused enhanced basal melting (Guðmundsson, 2013; Sgattoni *et al.*, 2019; Einarsson *et al.*, 2023), it seems likely that such enhanced melting would last longer than the jökulhlaup because of thermal inertia in the crust. Continued lowering of the cauldron source area and possibly also the downstream jökulhlaup path would then be expected until closure of subglacial conduits by ice-flow has had time to seal off the subglacial lakes so that they can again start collecting water.

### Jökulhlaup dynamics

Crude estimates of initial water-temperature have been derived above for floods from subglacial water bodies in Mýrdalsjökull and Hofsjökull that released jökulhlaups in 2011 and 2013. Similar estimates have been derived for floods from Köldukvíslarjökull in 2011 and Mýrdalsjökull in 2024 (Magnússon *et al.*, 2016, 2024). These estimates indicate that tempera-

ture of water bodies above subglacial geothermal areas can vary substantially between cauldrons and presumably also between years for the same cauldron. Direct water-temperature measurements have been carried out for the 100-m-deep Skaftá cauldron subglacial lakes through ~300-m-long boreholes showing temperature around 4 °C on several occasions (see Jóhannesson *et al.*, 2007). Flood-water temperature in the catastrophic jökulhlaup in Skeiðará in November 1996, which reached a maximum discharge of ~50 000 m<sup>3</sup> s<sup>-1</sup> on Skeiðarársandur (Snorrason *et al.*, 1997; Björnsson, 2003), was estimated 8 °C at the subglacial outflow location from Grímsvötn, based on thermodynamic considerations (Björnsson, 2003). The rather large range in temperature spanned by all those estimates and measurements indicates that local, and perhaps transient, conditions determine temperature in subglacial water bodies when jökulhlaups are released, and that highly varying flood development (e.g. rapidly- vs. slowly-rising jökulhlaups, see Einarsson *et al.*, 2016) for different floods may be partly determined by the widely varying initial temperature of the flood water.

### **Jökulhlaups from Hofsjökull**

The formation of the cauldron near the northern margin of the summit caldera of Hofsjökull ice cap indicates the existence of a subglacial geothermal area at this location, presumably a high-temperature geothermal area. It is unclear whether the activity of a pre-existing subglacial geothermal area increased prior to the 2013 jökulhlaup or whether new activity started in this area of the subglacial volcano that is known to exist under the summit of Hofsjökull (Hjartarson, 2013). Hofsjökull is not mentioned in the review of subglacial volcanic activity in Iceland by Gudmundsson (2005). Travellers and field workers have several times reported sulphuric smell in the air near the northern margin of Hofsjökull (Hjartarson, 2013; O. Sigurðsson, pers. comm., December 2025), but traces of geothermal fluids have until recently not been observed in rivers issuing from this part of Hofsjökull in spite of high-quality analysis of water samples (S. R. Gíslason, pers. comm., December 2025). Subglacial geothermal areas have, furthermore, not been detected in this part of the glacier by resistivity soundings (K.

Árnason, pers. comm., December 2025). The small jökulhlaup in 2018 from Blágnípujökull on western side of the ice cap mentioned above was associated with reports of sulphuric smell from ice caves at the glacier margin indicating the existence of an active geothermal area beneath Blágnípujökull. At this same location, a ~20-m-wide and >10-m-deep melt cauldron had been observed on 8 October 2004, during the autumn mass-balance expedition on Hofsjökull (Þ. Þorsteinsson, pers. comm., January 2026). A strong stench of sulphur was noticed around that cauldron.

Glaciologists from the IMO and the Hydrological Service of the National Energy Authority have since 1988 carried out annual mass-balance measurements on Hofsjökull with expeditions in the spring and autumn. They did not encounter cauldrons with notable variations in surface elevation between these expeditions until 2004 and 2013, again in 2021 at the same location as in 2013, and then most recently in the autumn expedition in November 2025, when another small cauldron was discovered north of the margin of the summit caldera, ca. 1.3 km N of the 2013 cauldron (H. Hannesdóttir, pers. comm., November 2025). This most recent cauldron has not released a noticeable jökulhlaup so far but leakage of geothermal water entering Vestari-Jökulsá has been detected by increased electric conductivity in the river at Goðdala-brú between August and December 2025 (B. Einarsson, pers. comm., December 2025).

It is not possible to say whether the jökulhlaups in Vestari-Jökulsá in 2013 and 2021, and at Blágnípujökull in 2018, as well as the formation of the cauldrons discovered from the Pléiades 2020 DEM and in the field expedition in November 2025, are isolated events or the first floods and cauldron formations in a new phase of geothermal and hydrological activity in this or other parts of Hofsjökull. It is also not possible to say whether the recovery of the ice surface geometry in the 2013 cauldron area is due to ice flow towards the cauldron or refilling of a subglacial lake over several years. The size and abruptness of possible future jökulhlaups from Hofsjökull is uncertain but it is clear that they could be much larger than the jökulhlaup in 2013, as evidenced by a jökulhlaup from a “new” location at Köldukvíslarjökull outlet glacier

in W-Vatnajökull into Hágöngulón reservoir on 13 July 2011, which reached a maximum discharge of  $2200\text{ m}^3\text{ s}^{-1}$  (Magnússon *et al.*, 2016).

### Jökulhlaup hazard

The jökulhlaup from Mýrdalsjökull in July 2011 in Múlakvísl was similar to sudden jökulhlaups from Mýrdalsjökull in 1955 in Múlakvísl and Skálm (Þórarinnsson, 1957), in 1999 in Jökulsá á Sólheimasandi (Sigurðsson *et al.*, 2000), and in 2024 in Leirá and Skálm (Magnússon *et al.*, 2024; IMO, 2024) in terms of abruptness and peak discharge. As for the small jökulhlaups from Hofsjökull and the medium-sized jökulhlaup from Köldukvíslarjökull in Vatnajökull in Sveðja, none of these jökulhlaups, apart from the 2011 jökulhlaup in Múlakvísl, were predicted and, thus, no warnings were issued before the floods reached roads or a hydropower reservoir. The hazard potential of sudden jökulhlaups from subglacial water bodies created by glacier-covered geothermal areas has received increasing attention in recent years (cf. Hákonardóttir, 2018), among other things because important infrastructure might be endangered. These floods highlight the importance of improving the understanding of jökulhlaups and related flood hazards and implementing appropriate warning systems where this is practical, as well as showing caution and being aware of jökulhlaup hazard in areal planning and in the design of infrastructure and other constructions near glacier rivers. Crevasses formed during the subsidence of cauldrons as a consequence of jökulhlaups are hazardous for travellers on glaciers and require continuous updating of crevasse maps that are available for the Icelandic glaciers (<https://safetravel.is/is/-outdoors/crevasse-maps>).

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### ÁGRIP

Jöklar Íslands voru kortlagðir með leysimælingum á árunum 2008–2013. Þann 9. júlí 2011 varð jökulhlaup í Múlakvísl sem rennur úr Kötlujökli í Mýrdalsjökli. Tók það brúna á ánni og rauf þar með hringveginn. Um mánuði eftir hlaupið var unnið landlíkan af upptakasvæði þess. Undir lok ágúst 2013 varð jökulhlaup í Vestari-Jökulsá í Skagafirði sem kom úr Sátujökli í Hofsjökli. Tæpum tveimur mánuðum síðar var unnið landlíkan af upptakasvæði hlaupsins. Samanburður þessara landlíkana við leysimælingar frá því fyrir hlaupin veitir áhugaverðar upplýsingar um rúmmál hlaupanna og eðli vatnsrennslis frá upptakasvæðunum undir jöklinum. Landlíkanið af Mýrdalsjökli eftir Múlakvíslarhlaupið 2011 bendir til þess að rúmmál hlaupvatns sem frá jöklinum rann í júlí og ágúst 2011 hafi verið mun meira en í flóðtoppinum sjálfum þ. 9. júlí. Þessi mismunur stafar annars vegar af vatnagangi í Múlakvísl frá 9. júlí fram í ágúst þegar katlar og ýmis önnur svæði, sem ekki komu við sögu í aðalhlaupinu, virðast hafa hlaupið, og hins vegar af vatni sem rann frá svæðum utan katlanna sem lækkuðu í aðalhlaupinu og eftir það. Landlíkónin sýna víðtæka lækkun yfirborðs jökulsins marga kílómetra niður eftir hlaupfarveginum frá aðalkötlunum, sem líklegast stafar af bráðnun íss við botn jökulsins af völdum snarþeitis hlaupvatns frá kötlunum. Ekki er unnt að meta hita hlaupvatnsins með nákvæmni en landlíkansamanburður bendir til þess að hitinn í útrennsli frá meginkötlunum þ. 9. júlí hafi verið á stærðarþrepinu  $10\text{ }^{\circ}\text{C}$  til tugir gráða á Celsius. Á síðustu árum hafa þrjú jökulhlaup átt upptök í Hofsjökli og þrjár katlar hafa myndast í yfirborði jökulsins. Hofsjökull var ekki á árum áður þekktur að því að þar ættu umtalsverð

jökulhlaup upptök. Þessi þróun er tilefni til þess að fylgjast með jökulhlaupum frá Hofsjökli og gæta að flóðahættu í vatnsföllum sem frá jöklinum falla. Mat á rúmmáli jökulhlaupsins í Vestari-Jökulsá, sem kom undan Sátujökli í ágúst 2013, með samanburði landlíkana er í góðu samræmi við mat á rennsli hlaupsins við Goðdalabrá í Skagafirði. Landlíkansamanburðurinn sýnir ekki mikla lækun yfirborðs jökulsins niður eftir flóðfarvegi frá katlinum í norðurbrún öskjunnar undir Hofsjökli þar sem hlaupið átti upptök. Það bendir til þess að útrennslið úr katlinum hafi verið nærri frostmarki. Þessar mælingar og ýmsar athuganir á öðrum jökulhlaupum hér á landi síðustu ár benda til þess að hiti hlaupvatns sem rennur frá jarðhitaköttlum undir jökulum geti verið mjög mismunandi, allt frá frostmarki upp í tugi gráða á Celsius. Þessi mismunandi hiti getur haft mikil áhrif á þróun jökulhlaupanna og kann að vera hluti skýringarinnar á því að jökulhlaup virðast geta þróast á mjög mismunandi veg í mismunandi tilfellum. Sum koma mjög snögg fram, jafnvel á innan við klukkustund, en önnur vaxa mun hægar yfir nokkurra daga tímabil eða á einni til tveimur vikum. Jökulhlaupið í Múlakvísl árið 2011 er að mörgu leyti svipað nokkrum öðrum skyndilegum jökulhlaupum frá Mýrdalsjökli árin 1955, 1999 og 2024 og einnig jökulhlaupinu árið 2011 frá Köldukvíslarjökli, en þessi hlaup komu öll, nema Múlakvíslarhlaupið 2011, fyrirvaralaust fram og án þess að við þeim væri varað. Hlaup þessi eru áminning um að gæta að hættu af völdum jökulhlaupa í sambandi við skipulag og hönnun innviða í grennd við farvegi jökuláa og koma upp viðvörðunarbúnaði vegna jökulhlaupa þar sem honum verður við komið.

## REFERENCES

- Abermann, J., A. Fischer, A. Lambrecht and T. Geist 2010. On the potential of very high-resolution repeat DEMs in glacial and periglacial environments. *Cryosph.* 4(1), 53–65 <https://doi.org/10.5194/tc-4-53-2010>
- Alley, R.B., D. E. Lawson, E. B. Evanson, J. C. Strasser and G. J. Larson 1998. Glaciohydraulic supercooling: a freeze-on mechanism to create stratified, debris-rich basal ice: II. Theory. *J. Glaciol.* 44(148), 563–569. <https://doi.org/10.3189/S0022143000002070>
- Berthier, E., C. Vincent, E. Magnússon, A. Gunnlaugsson, P. Pitte, E. Le Meur, M. Masiokas, L. Ruiz, F. Pálsson, J. M.-C. Belart and P. Wagnon 2014. Glacier topography and elevation changes derived from Pléiades sub-meter stereo images. *Cryosph.* 8(6), 2275–2291. <https://doi.org/10.5194/tc-8-2275-2014>
- Berthier, E., J. Lebreton, D. Fontannaz, S. Horsford, J. M.-C. Belart, F. Brun, L. M. Andreassen, B. Menounos and C. Blondel 2024. The Pléiades Glacier Observatory: high-resolution digital elevation models and ortho-imagery to monitor glacier change. *Cryosph.* 18(12), 5551–5571. <https://doi.org/10.5194/tc-18-5551-2024>
- Björnsson, H. 2003. Subglacial lakes and jökulhlaups in Iceland. *Glob. Planet. Change* 35(3–4), 255–271. [https://doi.org/10.1016/S0921-8181\(02\)00130-3](https://doi.org/10.1016/S0921-8181(02)00130-3)
- Björnsson, H. 2010. Understanding jökulhlaups: from tale to theory. *J. Glaciol.* 56(200), 1002–1010. <https://doi.org/10.3189/002214311796406086>
- Deschamps-Berger, C., S. Gascoïn, E. Berthier, J. Deems, E. Gutmann, A. Dehecq, D. Shean and H. Dumont 2020. Snow depth mapping from stereo satellite imagery in mountainous terrain: evaluation using airborne laser-scanning data. *Cryosph.* 14, 2925–2940. <https://doi.org/10.5194/tc-14-2925-2020>
- Einarsson, B., E. Magnússon, M. J. Roberts, F. Pálsson, Th. Thorsteinsson and T. Jóhannesson 2016. A spectrum of jökulhlaup dynamics revealed by GPS measurements of glacier surface motion. *Ann. Glaciol.* 57(72), 47–61. Cambridge Core. <https://doi.org/10.1017/aog.2016.8>
- Einarsson, P., F. Pálsson, M. Pálsson, E. Magnússon, B. Brandsdóttir and T. Winder 2023. Sources of continuous tremor associated with jökulhlaups and eruptions of Grímsvötn volcano, Iceland. *Jökull* 73, 55–74. <https://doi.org/10.33799/jokull2023.73.055>
- Eyþórsson, J. 1961. Úr ýmsum áttum. Jökulhlaup í Blöndu. [Jökulhlaup in Blanda.] *Veðrið* 6, 41.
- Favey, E., A. Geiger, G. H. Guðmundsson and A. Wehr 1999. Evaluating the potential of an airborne laser-scanning system for measuring volume changes of glaciers. *Geogr. Ann. A* 81(4), 555–561. <https://doi.org/10.1111/1468-0459.00083>
- Galeczka, I., E. H. Oelkers and S. R. Gíslason 2014. The chemistry and element fluxes of the July 2011 Múlakvísl and Kaldakvísl glacial floods, Iceland. *J. Volcanol. and Geoth. Res.* 273, 41–57. <https://doi.org/10.1016/j.jvolgeores.2013.12.004>
- Geirsson, H., Th. Árnadóttir, S. Hreinsdóttir and 13 others 2010. Overview of results from continuous GPS

- observations in Iceland from 1995 to 2010. *Jökull* 60, 3–22. <https://doi.org/10.33799/jokull2010.60.003>
- Guðmundsson, M. T. 2005. Subglacial volcanic activity in Iceland. In: Caseldine, C., A. Russell, J. Harðardóttir, Ó. Knudsen (eds.), *Developments in Quaternary Sciences* 5, 127–151. [https://doi.org/10.1016/S1571-0866\(05\)80008-9](https://doi.org/10.1016/S1571-0866(05)80008-9)
- Guðmundsson, M. T., Th. Högnadóttir, A. B. Kristinsson and S. Guðbjörnsson 2007. Geothermal activity in the subglacial Katla caldera, Iceland, 1999–2005, studied with radar altimetry. *Ann. Glaciol.* 45, 66–72. <https://doi.org/10.3189/172756407782282444>
- Guðmundsson, M. T., and Þ. Högnadóttir 2011. *Uppþök og stærð jökulhlaups í Múlakvísl – niðurstöður flugmælinga [The source area and the size of the jökulhlaup in Múlakvísl – results of aerial surveys]*. Inst. Earth Sci., University of Iceland, memo dated 13 July 2011.
- Guðmundsson, M. T., Th. Thórðarson, G. Larsen, P. Einarsson, Á. Höskuldsson and P. Imsland 2013. Undir Vatnajökli [Below Vatnajökull]. In: Sólnes, J., F. Sigmundsson and B. Bessason (eds.): *Náttúruvá á Íslandi*. Viðlagatrygging Íslands/Háskólaútgáfan, 263–277.
- Hákonardóttir, K. M. 2018. *Jökulhlaup og gjóskubrotsfloð. Náttúruvá á Þjórsár–Tungnaásvæði [Jökulhlaups and tephra-dam-break floods. Natural hazards in the Þjórsá–Tungnaá region]*. Rep. LV-2018-097, Landsvirkjun, Reykjavík, 72 pp.
- Hjartarson, Á. 2013. Hofsjökull. In: Sólnes, J., F. Sigmundsson and B. Bessason (eds.): *Náttúruvá á Íslandi*. Viðlagatrygging Íslands/Háskólaútgáfan, 313–317.
- IMO 2014. *Rennslisskýrsla vatnsárið 2012/2013, V145, Vestari-Jökulsá, Goðdalabré [River discharge at V145, Vestari-Jökulsá, Goðdalabré, in hydrological year 2012/2014]*. Techn. Rep., Icel. Meteorol. Office, Reykjavík, 4 pp. [In Icelandic]
- IMO 2018. *Ice cave in Hofsjökull – a warning*. News report and warning on the web of the Icel. Meteorol. Office, Reykjavík. <https://en.vedur.is/about-imo/news/ice-cave-in-hofsjokull-a-warning>
- IMO 2024. *Jökulhlaup í Skálm 27. júlí 2024 [Jökulhlaup in Skálm 27 July 2024]*. News report on the web of the Icel. Meteorol. Office, Reykjavík. <https://www.vedur.is/um-vi/frettir/hlaup-ur-myrdalsjokli-hlaupid-hefur-ekki-nad-hamarki>
- Jóhannesson, T., Th. Thorsteinsson, A. Stefánsson, E. J. Gaidos and B. Einarsson 2007. Circulation and thermodynamics in a subglacial geothermal lake under the Western Skaftá cauldron of the Vatnajökull ice cap, Iceland. *Geophys. Res. Lett.*, 45, L19502. <https://doi.org/10.1029/2007GL030686>
- Jóhannesson, T., H. Björnsson, F. Pálsson, O. Sigurðsson and Th. Thorsteinsson 2011. LiDAR mapping of the Snæfellsjökull ice cap, western Iceland. *Jökull*, 61, 19–32. <https://doi.org/10.33799/jokull2011.61.019>
- Jóhannesson, T. 2012. *Jökulhlaup í Múlakvísl 9. júlí 2011: Sigkatlar í Mýrdalsjökli mældir með leysimælingu úr flugvél [Jökulhlaup in Múlakvísl on July 9th, 2011: Lidar survey of cauldrons in Mýrdalsjökull]*. Techn. Rep. T6J/2012-01, Icel. Meteorol. Office, Reykjavík, 19 pp.
- Jóhannesson, T., H. Björnsson, E. Magnússon, S. Guðmundsson, F. Pálsson, O. Sigurðsson, Th. Thorsteinsson and E. Berthier 2013. Ice-volume changes, bias estimation of mass-balance measurements and changes in subglacial lakes derived by lidar mapping of the surface of Icelandic glaciers. *Ann. Glaciol.* 54(63), 63–74. <https://doi.org/10.3189/2013AoG63A422>
- Jóhannesson, T., O. Sigurðsson, H. B. Hróðmarsson and Bergur Einarsson 2014. *Jökulhlaup úr Hofsjökli í ágúst 2013 [Jökulhlaup from Hofsjökull in August 2013]*. Techn. Rep. 2014-287, 28.11.2014, Icel. Meteorol. Office, Reykjavík, 6 pp.
- Jónsson, G. Þ., and T. Þórarinsdóttir 2011. *Hlaup í Múlakvísl 8.–10. júlí 2011 [Jökulhlaup in Múlakvísl 8–10 July 2011]*. Techn. Rep. GThJ-TTh/2011-01, Icel. Meteorol. Office, Reykjavík, 10 pp.
- Larsen, G., M. T. Guðmundsson and O. Sigmarsson 2013. Katla. In: Sólnes, J., F. Sigmundsson and B. Bessason (eds.): *Náttúruvá á Íslandi*. Viðlagatrygging Íslands/Háskólaútgáfan, 211–233.
- Magnússon, E., F. Pálsson, M. T. Guðmundsson and Þ. Högnadóttir 2016. *Jökulhlaup í Sveðju í júlí 2011: Íssjarmælingar við Hamarsketil vorin 2013, 2014 og 2015 og yfirborðshæðarbreytingar í katlinum og nágrenni hans 1998–2015 [Jökulhlaup in Sveðja in July 2011: Radio-echo sounding of a cauldron near Hamarinn in spring 2013, 2014 and 2015 and surface-elevation changes in the cauldron and neighbouring areas 1998–2015]*. Rep. LV-2016-30, Landsvirkjun, Reykjavík, 34 pp.
- Magnússon, E., F. Pálsson, M. T. Guðmundsson, J. M. C. Belart and Þ. Högnadóttir 2017. *Hvað sýna íssjarmælingar undir sigkötum Mýrdalsjökuls [Results of radio-echo sounding below the cauldrons of Mýrdalsjökull]*. Techn. rep., Inst. Earth Sci., University of Iceland, 40 pp.

- Magnússon, E., F. Pálsson, A. Jarosch, T. Boeckel, H. Hannesdóttir and J. M. C. Belart 2021. The bedrock and tephra layer topography within the glacier filled Katla caldera, Iceland, deduced from dense RES-survey. *Jökull* 71, 39–70. <https://doi.org/10.33799/jokull2021.71.039>
- Magnússon, E., J. M. C. Belart and F. Pálsson 2024. *Jökulhlaup í Leirá–Skálm, 27. júlí 2024 [Jökulhlaup in Leirá–Skálm, 27 July 2024]*. Techn. rep./Presentation, Inst. Earth Sci., University of Iceland, 31 pp.
- Nuth, C., and A. Kääb 2011. Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change. *Cryosph.* 5, 271–290. <https://doi.org/10.5194/tc-5-271-2011>
- Porter, C., and 17 others 2022. ArcticDEM – Strips, Version 4.1. *Harvard Dataverse, V1*, (accessed Dec. 2025). <https://doi.org/10.7910/DVN/C98DVS>
- Rossi, C., F. R. Gonzalez, T. Fritz, N. Yague-Martinez and M. Eineder 2012. TanDEM-X calibrated raw DEM generation. *ISPRS Journal of Photogrammetry and Remote Sensing* 73, 12–20, <https://doi.org/10.1016/j.isprsjprs.2012.05.014>
- Sgattoni, G., Ó. Guðmundsson, P. Einarsson, F. Lucchi, K.L. Li, H. Sadeghisorkhani, R. Roberts and A. Tryggvason 2017. The 2011 unrest at Katla volcano: characterization and interpretation of the tremor sources. *J. Volcanol. Geotherm. Res.* 338, 63–78. <https://doi.org/10.1016/j.jvolgeores.2017.03.028>
- Sgattoni, G., F. Lucchi, P. Einarsson, G. De Astis and C. A. Tranne 2019. The 2011 unrest at Katla volcano: seismicity and geological context. *Jökull* 69, 53–70. <https://doi.org/10.33799/jokull2019.69.053>
- Shean, D.E., O. Alexandrov, Z.M. Moratto, B.E. Smith, I.R. Joughin, C. Porter and P. Morin 2016. An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very high-resolution commercial stereo satellite imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* 116, 101–117. <https://doi.org/10.1016/j.isprsjprs.2016.03.012>
- Sigurðsson, O., S. Zóphóníasson and E. Ísleifsson 2000. Jökulhlaup úr Sólheimajökli 18. júlí 1999 [Jökulhlaup from Sólheimajökull 18 July 1999]. *Jökull* 49, 75–80. <https://doi.org/10.33799/jokull2000.49.075o>
- Snorrason, Á., P. Jónsson, S. Pálsson, S. Árnason, O. Sigurðsson, S. Víkingsson, Á. Sigurðsson and S. Zóphóníasson 1997. Hlaupið á Skeiðarársandi haustið 1996: Útbreiðsla, rennsli og aurburður [The jökulhlaup on Skeiðarársandur in 1996: flood extent, discharge and sediment transport]. In: Haraldsson, H. (ed.): *Vatnajökull: gos og hlaup 1996 [Vatnajökull: eruption and jökulhlaup in 1996]*. Reykjavík, Vega-gerðin, 79–137.
- Staines, K. E. H., J. L. Carrivick, F. S. Tweed, A. J. Evans, A. J. Russell, T. Jóhannesson and M. J. Roberts 2015. A multi-dimensional analysis of pro-glacial landscape change at Sólheimajökull, southern Iceland. *Earth Surf. Processes Landf.* 40(6), 809–822. <https://doi.org/10.1002/esp.3662>
- Þórarinnsson, S. 1957. The jökulhlaup from the Katla area in 1955 compared with other jökulhlaups in Iceland. *Jökull* 7, 21–25. <https://doi.org/10.33799/jokull1957.-07.021>