Reviewed research article

Little Ice Age advance of Kvískerjajöklar, Öræfajökull, Iceland. A contribution to the assessment of glacier variations in Iceland since the late 18$^{\rm th}$ century

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Abstract — *We describe the changes of the Kvískerjajöklar outlet glaciers in SE Iceland (presently ranging 600–1600 m a.s.l.), from their Little Ice Age maximum (LIA$_{max}$) to the present. We assume that glacier extent of the late 19th century approximately describes LIA$_{max}$ although the glaciers already reached their peak extent in the 18th century. The former glacier margins were delineated from moraines, historical descriptions, topographical maps, aerial and oblique photographs, Landsat images and a lidar DEM. Along the previous glacier margins, elevation differences with respect to the lidar DEM of 2011 were estimated and contour maps of the glacier drawn at selected dates, maintaining the shape of the glacier surface as available maps. During the period ∼1890 to 2011, the outlets lost -0.4 m a^{-1} water equivalent evenly distributed over their surface and their area was reduced by 37% (from ∼10 km^2 to 6.4 km^2, 0.03 km^2 a^{-1}, 0.43 km^3 water equivalent in total, i.e. 0.003 km^3 w.e. a^{-1}).*

INTRODUCTION

The Kvískerjajöklar outlet glaciers (6.4 km^2 in 2011) drain the steep, eastern flanks of Öræfajökull stratovolcano, SE-Vatnajökull ice cap. The outlets are divided in two segments, the North and South glacier by a volcanic fissure ridge which can be traced up to the caldera rim of the volcano (1800 m a.s.l.), containing the prominent nunataks of Hellutindar (1142 m a.s.l.) and Rótarfjallshnúkur (1026 m a.s.l.), Figure 1. The North glacier was 4.3 km long in 2011, terminating at 580 m a.s.l. whereas the South glacier was 2.8 km long, ending at 700 m a.s.l. The estimated total volume of the glaciers is approximately 2 km^3 (Magnússon *et al.*, 2012). Like other outlets of Vatnajökull, they have retreated considerably since their maximum extent during the Little Ice Age (LIA$_{\rm max}$).

Most of the larger outlet glaciers in Southeast Iceland reached their LIA$_{\rm max}$ in the 1880s to 1890s, whereas some of the small and steepest glaciers already may have reached their outermost position in the 18$^{\rm th}$ century and thereafter remained close to that location until the late 19$^{\rm th}$ century. Based on written and oral records about marginal moraines of Kvískerjajöklar, we contribute to the discussion on of glacier variations in Iceland since the late 18$^{\rm th}$ century to the present.

Synopsis of glaciers and climatic variations during the Little Ice Age

The climate in Iceland was relatively cold from the 13$^{\rm th}$ century to the 1920s, a period often called the Little Ice Age (LIA), but was however, interrupted by frequent warm spells. The account of the climate

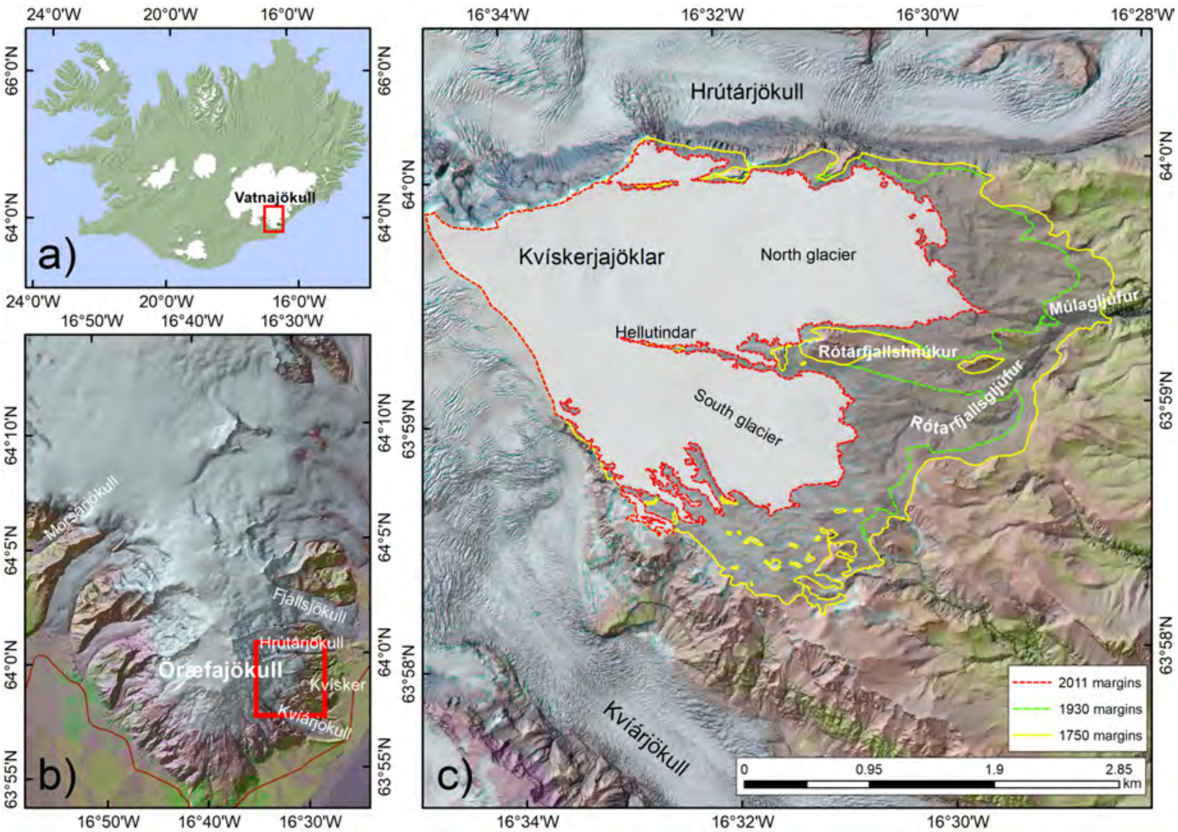

Figure 1. a) Iceland and the location of Vatnajökull and Öræfajökul. b) Öræfajökull with outlet glaciers and the location of Kvísker farm. c) The South and North Kvískerjajöklar glaciers (white area), the ice margins at $\mathrm{LIA}_{\mathrm{max}}$ (yellow line), in 1930 (green broken line) and 2011 (red broken line). Map based on data from the National Land Survey of Iceland, the Icelandic Meteorological Office and the Institute of Earth Sciences, University of Iceland. – *a) Ísland, Vatnajökull. b) Öræfajökull, Kvískerjajöklar innan rauðs ramma. c) Kvískerjajöklar, hámarksstaða á litlu ísöld (gul lína), um 1930 (græn brotin lína) og 2011 (rauð brotin lína).*

is based on written reports on weather, sea ice and glacier variations (Annálar 1400–1900; Thoroddsen, 1911, 1916–1917; Thorarinsson, 1939, 1943, 1956; Grove, 1988; Ogilvie and Jónsson, 2000; Björnsson, 2017; Miles *et al.*, 2020). The deteriorating climate in the late Middle Ages led to a general glacier advance and the major outlet glaciers in Iceland reached their $\mathrm{LIA}_{\mathrm{max}}$ extent at the end of the extremely cold period of the 1880s; soon thereafter they started on a retreat which has continued to the present day, with temporary short advances or near standstill in the 1970s to the early 1990s (Thorarinsson, 1939, 1943, 1956; Eyþórsson, 1981; Sigurðsson, 1998; Jóhannesson and Sigurðsson, 1998; Magnússon, 1955; Ólafsson and Pálsson, 1978; Pálsson, 1945; Björnsson, 1998; Guðmundsson, 1998; Bradwell *et al.*, 2008; Björnsson and Pálsson, 2008; Björnsson, 2009, 2017; Chenet *et al.*, 2010; Hannesdóttir, 2014; Evans, 2016; Evans *et al.*, 2017). However, the glacier changes were variable in detail during the LIA. Some of the steepest outlets may have reached their largest extent near the middle of the 18^{th} century and alternately retreated and advanced until the end of the 19^{th} century. For instance, in 1894, Thoroddsen (1911) noted two series of moraines in front of the terminus of Morsárjökull, implicating the outlet had reached maximum extent earlier than in the end of the Little Ice Age. Thorarinsson (1943) pointed out that two severely cold periods after 1600 led to advanced position of the outlets of Drangajökull ice cap, in Northwestern Iceland, and of the Southern Vatnajökull ice cap; moreover, during the particularly cold 1750s and 1760s at least two major outlets of Öræfajökull, the Fjallsjökull and Hrútárjökull glaciers (Figure 1) reached their LIA_{max}. Twice in the 19^{th} century, Hrútárjökull glacier dammed the mouth of Múlagljúfur gorge and thereby the river Múlakvísl draining the Kvískerjajöklar, creating an ice-dammed lake (Figure 2; Henderson 1957; Thoroddsen, 1959; Björnsson 1958; Björnsson 1998; Hannesdóttir, 2014).

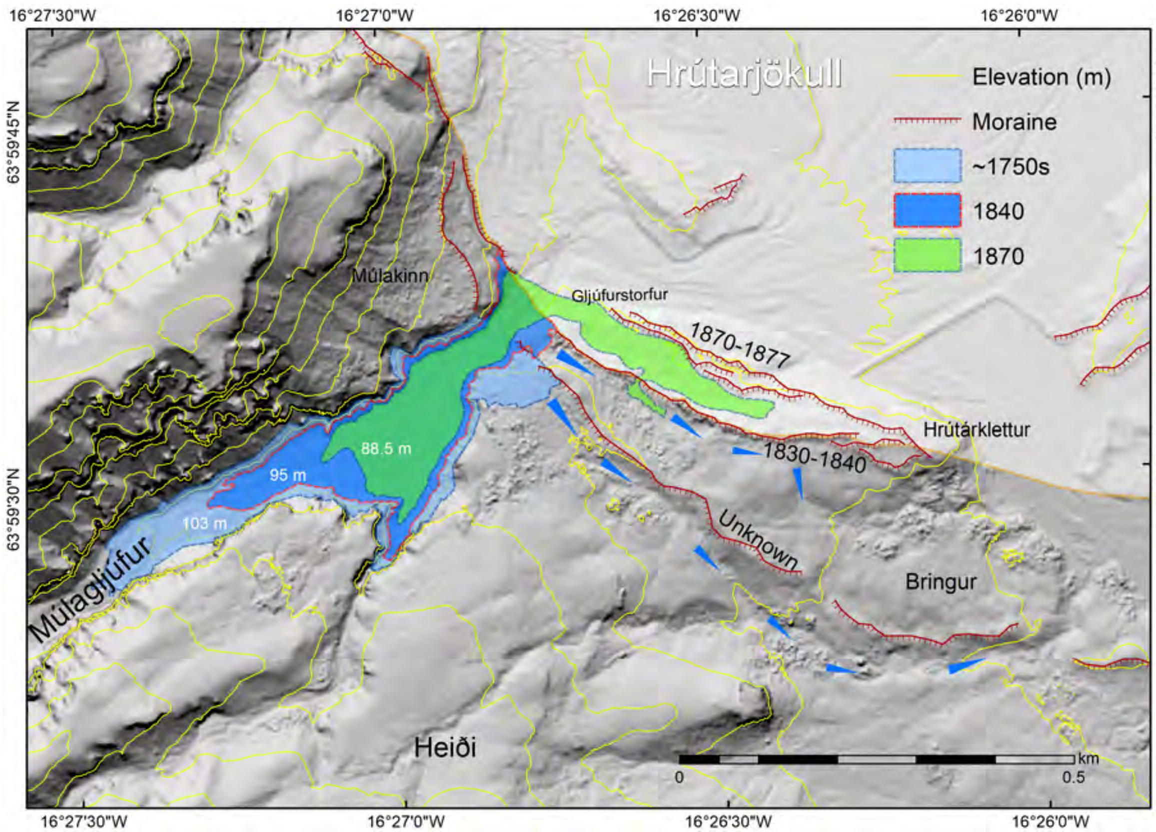

Figure 2. Series of moraines built up by Hrútárjökull in the 19^{th} century (1830–1840, 1870–1877, Björnsson, 1958) and one of an unknown earlier age. The glacier dammed up a lake in Múlagljúfur, whose various levels are shown, based on the overflow elevation at the moraines at $\sim$103 m (blue arrows indicate the direction of runoff), $\sim$95 m and $\sim$88.5 m a.s.l. Local farmers managed to bypass the lake inside the gorge to access the Múlakinn. The largest lake would have closed this route. – *Raðir jökulgarða sem Hrútárjökull ýtti upp við mynni Múlagljúfurs (1830–1840, 1870–1877, Sigurður Björnsson, 1958) og einn eldri garður benda til þess að jökullinn hafi náð hámarksstærð fyrr en í lok 19. aldar. Jökullinn stíflaði mynni Múlagljúfurs svo að jökullón mynduðust í því. Stærð lóna er sýnd miðað við að vatnsborð þeirra hafi ráðist af hæð yfirfalls meðfram jökulgörðunum í um $\sim$103 m, $\sim$95 m og $\sim$88.5 m y.s.. Þó komst vinnufólk á Kvískerjum fyrir lónið í gljúfrinu inn í Múlakinn. Sú leið hefði verið ófær hefði jökullinn legið á fremsta garði og jökullónið verið í hæstu stöðu.*

VARIATIONS OF KVÍSKERJAJÖKLAR IN THE 18$^{\text{th}}$, 19$^{\text{th}}$ and 20$^{\text{th}}$ CENTURIES

Geomorphological records of the terminal positions of Kvískerjajöklar are distinct but scattered. Conspicuous terminal moraines in the canyon foreland indicate two main glacier advances during the LIA. The moraines lie largely parallel, separated by tens to >140 m, although the two outermost moraines sporadically merge. We suggest the end moraine might be named after the Icelandic naturalist Sveinn Pálsson, who described it when scaling the easternmost peaks of the Öræfajökull caldera rim in 1794. He pointed out that the glacier had retreated a few fathoms from this moraine (Pálsson, 1945, 2004). Moreover, Pálsson noted that the canyon west of the farm Kvísker leads up to the glacier margin. To do so the glacier tongue had to occupy the gorge Rótarfjallsgljúfur and reach over its outer rim (Figure 3), otherwise it would not have been spotted from the farm site. A series of moraines on the outer rim of the Rótarfjallsgljúfur gorge, as well as shallow streambeds, most likely incised by glacial water, reflect at least six glacier advances or short standstills of the glacier front during the post-LIA$_{\max}$ retreat (Figure 3). This observation is in accordance with information reported by the late Flosi Björnsson (1957, 1965, 1998), forwarded orally to him by his ancestors who lived at Kvísker. Further, Björnsson states that in the late 1880s the Kvískerjajöklar glaciers almost reached the outermost "Pálsson moraine" and the inner moraine was most likely formed at this time, he commented. The Kvísker farmers and the 19$^{\text{th}}$ century documents indicate that through the 18$^{\text{th}}$ to the late 19$^{\text{th}}$ century glaciers submerged the inner part of Múlagljúfur gorge (Figures 1 and 3) and still remained there until 1930. Series of moraines indicate several advances between the 1880s and the 1930s. In the 1880s, the glacier was still at the outer rim of Rótarfjallsgljúfur but receded some distance into the gorge near the end of the 19$^{\text{th}}$ century. In the 1930s, the glacier retreated from the deepest section of the gorge and gradually vanished (Henderson 1957; Thoroddsen, 1959; Björnsson, 1998). Based on this information, we can conclude that Kvískerjajöklar had already reached their LIA$_{\max}$ in the 18$^{\text{th}}$ century and more or less maintained that advanced extent until the late 19$^{\text{th}}$ century. Therefore, in our discussion of the glacier changes we use information dating to the late 19$^{\text{th}}$ century to describe the glacier extent at the end of the Little Ice Age, but the glacier most likely reached its largest in the 18$^{\text{th}}$ century.

The post-LIA$_{\max}$ glacier extent of Kvískerjajöklar can be traced from a few geodetic maps. The maps of the Danish General Staff (DGS), based on a triangulation survey of SE-Iceland in 1903–1938, describe the topography in the early 20$^{\text{th}}$ century. However, the map of Kvískerjajöklar lacks details, as the surveyors never entered this rugged terrain. No trace is shown of the Rótarfjallsgljúfur gorge, indicating that it may still have been occupied by ice at the beginning of the 20$^{\text{th}}$ century.

A few photographers, including the Englishman F. W. W. Howell (1857–1901) and the Icelander Magnús Ólafsson (1862–1937), captured several glaciers in Southeast Iceland in the 1890s and the first decades of the 20$^{\text{th}}$ century, recording the position of the ice margin at several locations around the time of the LIA$_{\max}$ extent or shortly after the glaciers started to retreat. However, only one photograph exists of the upper part of Kvískerjajöklar, taken in 1890 or 1891 by Howell.

Mapping of glacier variations

The positions of the termini were recorded in the field by GPS, digitized on topographical maps, aerial photographs, satellite (Landsat) and airborne lidar images and then all digitized into ArcMap. The area changes of Kvískerjajöklar since the LIA$_{\max}$ extent to 2016 are shown in Figure 4.

The DGS (1905) maps depict the 1904 extent of the outlet glaciers of Vatnajökull but they are not accurate for Kvískerjajöklar. The C762 maps of the US Army Map service (AMS), based on photogrammetry, and the underlying aerial photographs taken in 1945 (AMS 1951) show the mid-20$^{\text{th}}$ century ice margin. The AMS maps have been proven to be accurate to $\pm$5 m elevation after co-registration with the lidar DEMs. Recently, improved DEMs and georectified images of Öræfajökull have been created by digital processing of the original AMS stereo imagery (Belart *et al.*, 2019).

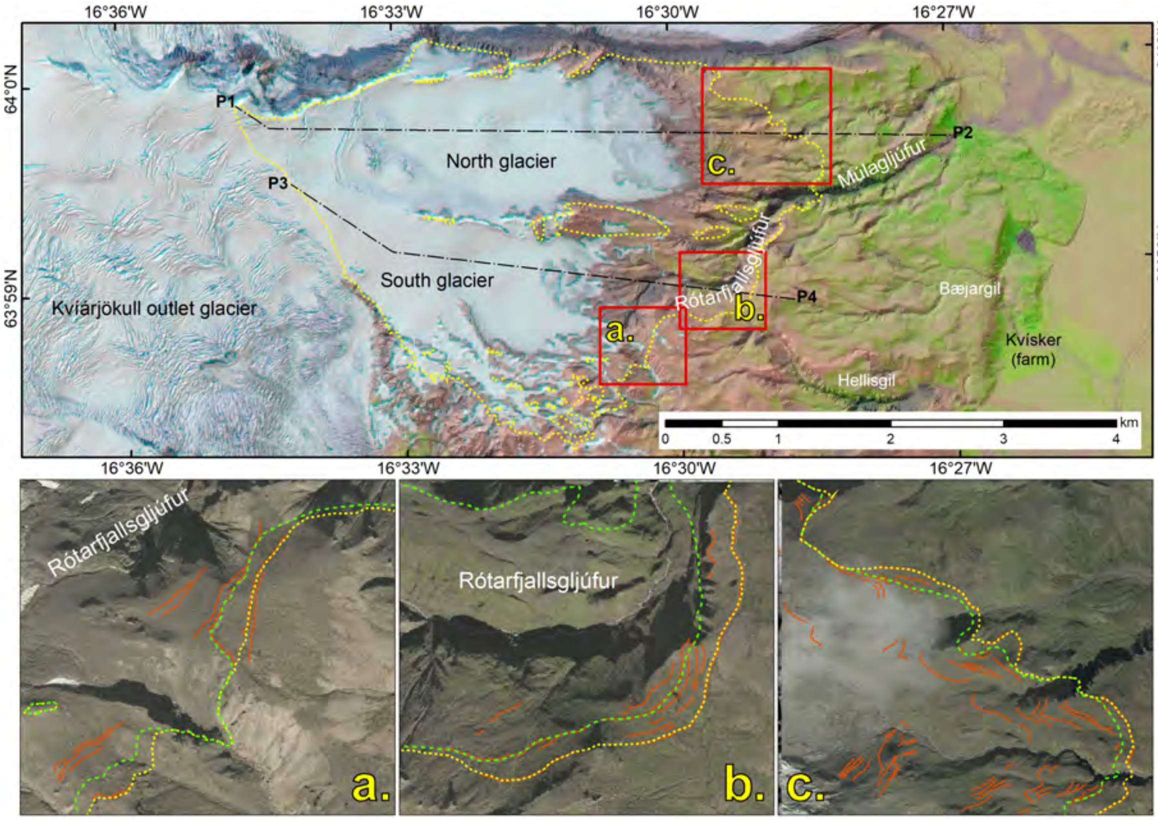

Figure 3. Series of moraines in the steep terrain of Kvískerjafjöll indicate several stages of glacier advance in the 18^{th} to 20^{th} century. The yellow broken line traces the outermost end-moraine: a) The end moraine noted by Sveinn Pálsson, 1794. b) The location of the glacier snout as viewed by Pálsson in 1794. c) The two prominent terminal moraines of the north glacier (yellow and green broken lines) indicating the outermost LIA advances. Several younger moraines occur in the foreland. Lines P1–P2 and P3–P4 show the location of profiles used to examine post-$\mathrm{LIA}_{\mathrm{max}}$ surface lowering. – *Raðir jökulgarða í brattlendi Kvískerjafjalla. Garðarnir benda til að jöklarnir hafi hopað og gengið fram á víxl á síðustu öldum. Gul brotalína rekur fremstu garða: a) Endagarður sem Sveinn Pálsson náttúrufræðingur segir frá þegar hann gekk á Öræfajökul árið 1794. b) jökuljaðarinn, sem Sveinn sá neðan frá Kvískerjum og ályktaði að gilið (Hellisgil) næði upp að jöklinum. c) Tvær fremstu raðir jökulgarðanna (gul og græn brotalína) sýna hámarksútbreiðslu nyrðri jökultungunnar á síðustu öldum. Línur merktar P1–P2 og P3–P4 sýna legu sniða þar sem yfirborðsbreytingar voru metnar með líkanreikningum.*

The aerial photographs and images were collected from the database of the National Land Survey of Iceland (NLSI), the company Loftmyndir ehf., and the US Geological Survey (Landsat 1–5 and 7–8). Lidar DEMs of Vatnajökull and its foreland, were surveyed in 2010–2012 in connection with the International Polar Year 2007–2008, Jóhannesson *et al.*, 2011, 2013). The lidar DEMs were used to georectify aerial images and to reproject and correct the horizontal positioning of older maps.

The $\mathrm{LIA}_{\mathrm{max}}$ margin was digitized in ArcGIS by delineating glacio-geomorphological features, identified from orthorectified aerial photographs and field observations. Moraines formed by the $\mathrm{LIA}_{\mathrm{max}}$ out-

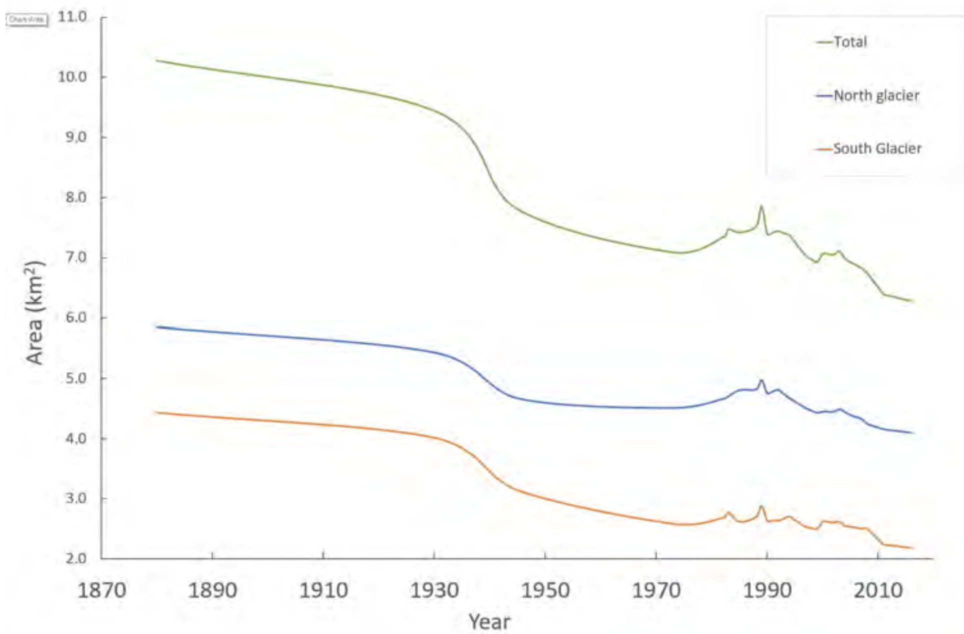

Figure 4. Area changes of Kvískerjajöklar outlets since the LIA_{max}, the North glacier (blue line), the South glacier (orange line) and total area changes of both glaciers (green). – *Flatarmálsbreytingar á Kvískerjajöklum frá lokum litlu ísaldar, nyrðri (blá lína) og syðri (rauðgul lína) tungurnar og báðar saman (græn lína).*

let glaciers were outlined, but inside the gorges and adjacent gullies, no signs of moraines are found and the outlines were interpolated between the neighbouring identified features with the aid of the lidar DEM elevation contours. The glacier terminal position in Múlagljúfur gorge was based on Thoroddsen's (1959) description from the late 19^{th} century, who noted that a narrow ice tongue occupied the inner part of the gully. Flosi Björnsson (1998) describes a steep glacier tongue reaching down to the gully in the first decades of the 20^{th} century.

The delineation of the 1930 ice margin was done by examination of a handful of photographs from this year, taken on land and from the air, using the QGIS Pic2Map plugin. Several landforms were identified on high-resolution photographs captured from the airship Graf Zeppelin on July 17, 1930 (Figure 5). The ice margin and the landforms were traced to identify several points that indicated the ice-surface elevation at the lateral glacier margin.

The ice divides of Kvískerjajöklar are well defined by mountain ridges. In the present study we assumed that the glacier surface at high elevations remained approximately the same during the period 1890 to 2011, as was proven to be the case for the neighbouring Kotárjökull, another outlet of Öræfajökull by Guðmundsson *et al.*, 2012, 2017; Hannesdóttir *et al.*, 2014, 2015, who noted that the ice surface above 1600 m altitude on Öræfajökull might only have lowered by $\sim$5 m since the 1890s.

CONSTRUCTION OF ICE SURFACE DEMS

Three digital elevation models were constructed of the past ice surface elevation, representing: a) the LIA_{max} extent in the mid-18^{th} century; b) the 1880s; and c) 1930. This involved vertically shifting the lidar 2011 DEM, a method previously applied for reconstructing outlet glacier elevation in Southeast Iceland by Guðmundsson *et al.* (2012, 2017) and Hannesdóttir

Figure 5. An oblique aerial photograph of Kvískerjajöklar, taken from the airship Graf Zeppelin on July 17, 1930. The photographer was possibly Rolf Hermann Carl, who worked for the "Graphische Abteilung der Luftschiffbau Zeppelin GmbH" from 1929 to 1934. *Flugmynd af Kvískerjajöklum sem tekin var frá loftskipinu Graf Zeppelin 17. júlí 1930. Ljósmyndari var líklega Rolf Hermann Carl, sem starfaði fyrir „Graphische Abteilung der Luftschiffbau Zeppelin GmbH" frá 1929 til 1934.*

et al. (2014). The elevation difference between the LIA_{max}, 1880s and 1930 ice surface with respect to the 2011 lidar DEM was estimated at several locations along the lateral 2011 ice margin, expressed by a least-squares relationship (Figure 6) for elevations between 650 m a.s.l. and 1600 m a.s.l., assuming insignificant elevation changes at higher elevations. The LIA_{max} elevation at the glacier margins was derived by the equations $z_{LIA} = 0.895z_{2011}+157$ and $z_{LIA} = 0.920z_{2011}+121$ (in metres; Figure 6a), for the South and North glaciers, respectively. The form of the contour lines of the AMS map of 1945 was used to create a DEM at LIA_{max} with a similar shape. A photograph captured by the English traveler F. W. W. Howell (1857–1901) from the nearby Breiðamerkurjökull outlet glacier, in 1891, supports our assumed shape of the glacier surface in the accumulation area. The 1930 glacier marginal elevations were estimated by the equations $z_{1930} = 0.910z_{2011}+136$ and $z_{1930} = 0.948z_{2011}+78$, for the South and North glaciers (Figure 6b), respectively, and a surface map was drawn in a similar manner based on the geometry depicted by the contours of the 2010 map.

The glacier surface at elevations below the present day glacier terminus was evaluated by simple ice-flow modelling constrained by moraines (Glacier Reconstruction Tool (GlaRe) in ESRI ArcGIS, Pellitero *et al.*, 2016). The model constructs glacier surface profiles along flow lines, assuming perfect plasticity of ice, a basal shear stress of 100 kPa, and neglects shape factors for the basal geometry. Seven flowlines were modelled the North glacier which widens in the lower

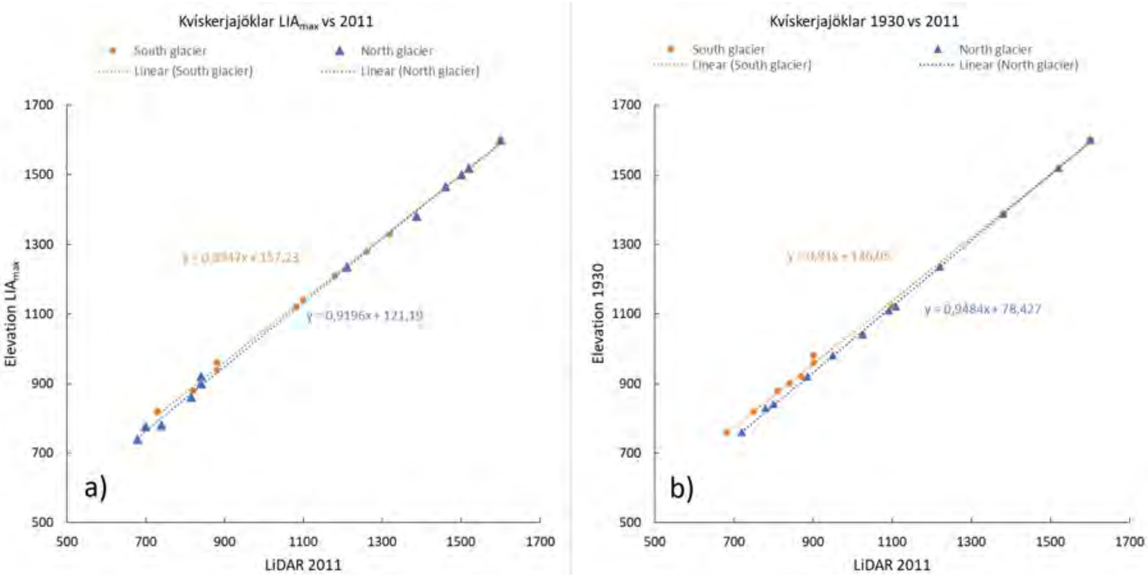

Figure 6. Glacier elevation along the lateral margins of the North (blue triangles) and South (yellow circles) Kvískerjajöklar at $\mathrm{LIA}_{\mathrm{max}}$ (a) and in 1930 (b) with respect to the elevation in 2011. The least-squares linear relationship between 650 m a.s.l. and 1600 m a.s.l., assuming insignificant elevation changes at higher elevations, is shown with a dotted line. – *Yfirborðshæð á jöðrum nyrðri (bláir þríhyrningar) og syðri (gulir hringir) Kvískerjajökla, í hámarksstöðu á litlu ísöld (t.h.) og 1930 (t.v.) samanborið við árið 2011.*

ablation area. During the $\mathrm{LIA}_{\mathrm{max}}$ it extended beyond a steep vertical drop of the narrow Múlagljúfur gorge. The South glacier was modelled by four flow lines, overflowing the Rótarfjallsgljúfur gorge during the LIA and merging with the North glacier farther downstream. Figure 7a–b shows the surface lowering over the period from 1880 to 2011, along the profiles P1–P2 for the North glacier and P3–P4 for the South glacier (see Figure 3). Area and volume changes are given in Table 1. The computed DEMs did not account for rock buttresses that shape the northern rim of Múlagljúfur, as described by historical records (Pálsson, 1945; Henderson, 1957; Thoroddsen, 1959; Björnsson, 1998). The final DEMs of the upper and lower parts of the glacier were merged at an elevation of ∼600 m with some smoothing of the ice-surface geometry at the coalescence zone.

Uncertainty of the DEMs

The DEMs of the $\mathrm{LIA}_{\mathrm{max}}$, 1880s and 1930 are partly constructed by subjective assessments and hence the uncertainty in elevation is difficult to quantify. In the elevation range 650–1600 m a.s.l. (∼6 km^2) we assume an uncertainty of ±10 in the elevation. The altitude of the LIA ice surface near the lateral ice margins, estimated from geomorphological evidence, is assumed accurate to ±5 m. The elevation error in the 2011 lidar DEM is <0.5 m. This is much less than other sources of error and has negligible effect on the final error estimate. In the range 260–650 m a.s.l. (∼3 km^2) we estimate the error to be ±20 m. In the lower part of the 1930 glacier area, outside the 2011 DEM (∼3 km^2) where the elevation is based on the GlaRe model, we estimate an error of ±30 m, mainly due to misaligned contours and near-margin connection to contours outside the glacier. Joining the two DEMs will also introduces some error. Volume changes were calculated by subtracting DEMs in Surfer. The uncertainties of the volume change between $\mathrm{LIA}_{\mathrm{max}}$ and 1880 DEM is estimated as ±0.15 km^3 and for the period 2011 and 1930 DEMs as ±0.12 km^3 (error contributions from differ-

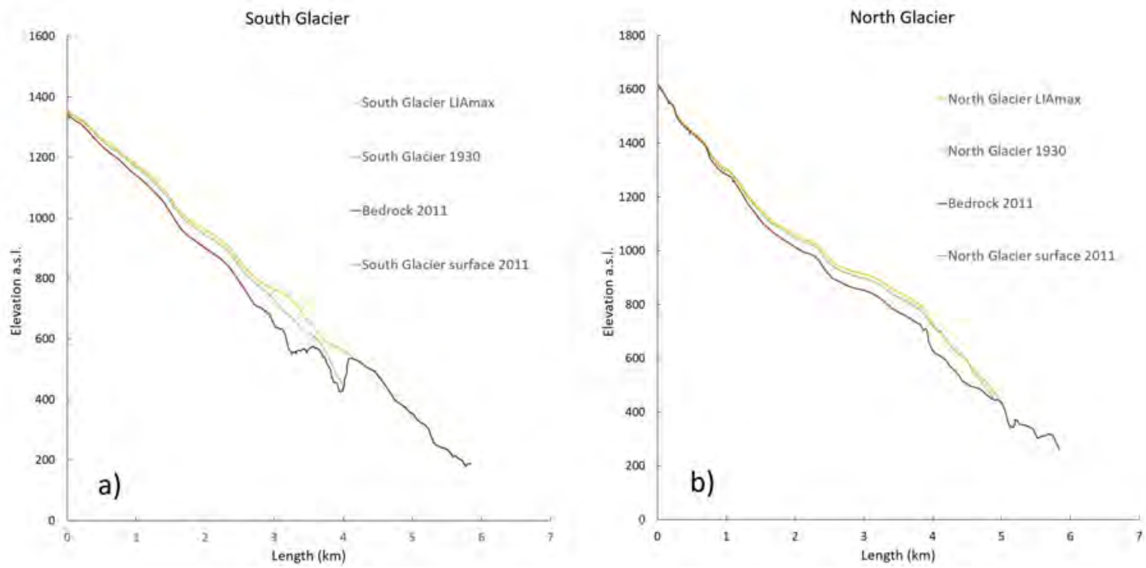

Figure 7. Surface elevation changes from LIA_{max} to 1930 and 2011 of a) South glacier and b) North glacier. – *Snið af yfirborðsbreytingum (3. mynd) frá hámarksstöðu á litlu ísöld til 2011, a) nyrðri og b) syðri jökulinn.*

Table 1. Changes of Kvískerjajöklar since the LIA_{max}. Period, number of years, area changes (A) and area loss (ΔA) in km^2. Volume loss (ΔV) as water equivalent (w.e.), annual average volume loss (AAVL) and annual average specific mass balance in w.e. – *Flatar- og rúmmálsbreytingar frá hámarki litlu ísaldar. Tímabil og fjöldi ára, flatarmálsbreyting (A) og flatarmálstap (ΔA) á umræddum tímabilum, rúmmálsrýrnun (ΔV) í vatnsgildi (w.e.), árleg meðaltalsrýrnun (AAVL) og afkoma.*

Period	Years	A (km^2)	ΔA (km^2)	ΔV (w.e. km^3)	AAVL (ice km^3 a^{-1})	m a^{-1} (w.e.)
LIAmax*–1880	130	10.5–10.1	0.4	0.02±0.1	0.003	-0.01
1880–1930	50	10.1–9.5	0.6	0.13±0.1	0.012	-0.27
1930–2011	81	9.5–6.4	3.1	0.3±0.08	0.039	-0.47
1750–2011	261	10.5–6.4	4.1	0.45±0.1	0.016	-0.2
1880–2011	131	10.1–6.4	3.7	0.43±0.1	0.029	-0.4

*Here assumed to be in 1750s, with an area of 10.5 km^2.

ent elevation ranges to the total volume changes are combined as root mean square).

CONCLUDING REMARKS

Kvískerjajöklar are among the smallest outlet glaciers draining the Öræfajökull ice cap and respond swiftly to climate variations. These outlets reached their maximum extent in the 18th century and remained at an advanced position throughout the 19th century, producing a series of moraines indicating a number of readvances before they eventually started retreating during the relatively warmer 20th century. Both outlets gradually receded during the 20th century until the 1980s when their snouts started to oscillate for two decades: the North glacier terminus at elevations 500–600 m a.s.l. and that of the South outlet at 600–680 m a.s.l. In this period, the North glacier advanced > 300 m beyond its position in 1945 and to a point

$\sim$100 m lower in elevation. Since the turn of the 21st century, both outlets have retreated considerably, at a varying rate. A recent thickening of their snouts was noted in 2015–2017 (Belart, pers. comm. 2019).

From 1880 to 2011, Kvískerjajöklar lost 37% of their area. The average annual specific mass loss was -0.4 m a^{-1} w.e., almost two times higher than for the neighbouring Kotárjökull, which lies 200 m higher on the slopes of Öræfajökull, and 2/3 of the specific loss of Breiðamerkurjökull, of 0,58 km^3 a^{-1} w.e. in the period 1890–2010 or -0,64 m a^{-1}, which extends down to sea level (Guðmundsson *et al.*, 2012, 2017).

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Ágrip

Lítið hefur verið tekið saman um breytingar á jöklunum í hlíðum Öræfajökuls ofan við bæinn Kvísker. Í þessari grein, þar sem þeir eru nefndir Nyrðri- og Syðri-Kvískerjajöklar, rekjum við hvernig jökultungurnar hafa breyst, auk þess að áætla flatarmáls- og rúmmálsbreytingar frá hámarksstöðu á litlu ísöld til 2011. Af nokkrum rituðum heimildum má álykta að þessir jöklar hafi þegar verið búnir að ná hámarksstærð á 18. öld. Þar er stuðst við lýsingar í skrifum Sveins Pálssonar, náttúrufræðings, en einnig legu fremstu jökulgarða.

Sveinn Pálsson gekk á Öræfajökul við þriðja mann í ágúst 1794 og lýsir jökulgarði utan á hól sem jökullinn hafði þá hopað örfáa faðma frá (Sveinn Pálsson, 1945; Flosi Björnsson, 1957). Garður þessi er í um 750 m hæð vestan í Sveinshöfða og mætti kalla „jökulgarð Sveins“. Sveinn segir einnig í dagbók sinni að gilið vestan við Kvísker nái upp að jöklinum. Til þess að svo megi vera þurfti jökullinn að fylla Rótarfjallsgljúfur og ná yfir syðri brún þess því annars hefði Sveinn ekki séð til hans frá láglendi. Á brún gljúfursins í um 550 m hæð eru jökulgarðar og grunnir vatnsfarvegir sem geta stutt athugasemd Sveins. Má ætla að jökullinn hafi hvílt nokkuð tíma á brúninni en jafnframt gengið þar fram og aftur nokkrum sinnum. Fjalllendið ofan Kvískerja er giljótt og til þess að komast að jöklinum ráða gljúfrin leiðarvali. Sveinn Pálsson minnist hins vegar hvorki á gljúfur eða hindranir á leið hans á Öræfajökul 1794. Það gæti bent til þess að Rótarfjallsgljúfur hefi verið undir ís og því ekki sú hindrun og það varð eftir að jökull hvarf úr því. Ystu jökulgarðar við Múlagljúfur eru í 360–380 m hæð y.s.

Venjulega eru íslenskir jöklar sagðir hafa náð hámarksstærð um 1890. Á það almennt við um stærstu jöklana en ýmislegt bendir til að brattir jöklar hafi náð hámarksstöðu fyrr. Nefna má frásagnir um að Hrútárjökull hafi verið stærri um 1830–1840 en síðar á 19. öld, en þeim fróðleik héldu bræðurnir á Kvískerjum til haga og birtu m.a. í Jökli. Þó að lýsingar á legu Kvískerjajökla á 19. öld séu fáar má ætla að jökultungurnar hafa verið af svipaðri stærð fram á síðustu áratugi hennar og náð niður í Rótarfjallsgljúfur og Múlagljúfur. Af lýsingu enska trúboðans Ebeneser Henderson, sem fór um Öræfasveit árið 1815, er ljóst að þá lá ísinn í gljúfrunum. Þorvaldur Thoroddsen (1894) segir mjallhvíta, mjóa jökultungu ná í botn Múlagljúfurs. Talsverðar breytingar urðu á syðri tungunni nálægt 1900 og samkvæmt Flosa Björnssyni (1957) geta honum eldri menn þess að jökullinn hafi enn verið við brún Rótarfjallsgljúfurs um 1870–1880 en ekki náð að fremstu jökulöldunni. Jökullinn mun hafa eyðst hratt nálægt aldamótunum 1900 en hopað alveg úr gljúfrinu um 1930. Jökultotan í Múlagljúfri tók einnig að eyðast upp úr 1930 og hvarf þaðan á fáum árum.

Kort danska herforingjaráðsins af Öræfajökli frá árinu 1904 sýnir Múlagljúfur en ekki Rótarfjallsgljúfur. Þar verður ekki annað séð en að sléttur jökull hafi náð niður í $\sim$500 m hæð. Landmælingamennirnir fóru hins vegar ekki um Kvískerjafjöllin, heldur drógu þeir landslagið upp eftir bestu ágiskun. Það gerðist víðar meðan landmælingarnar fóru fram (Ágúst Böðvarsson, munnleg heimild, árið 1994). Flosi Björnsson (1998) segir jökulinn hafa teygt sig niður í botn Múlagljúfurs á fyrstu áratugum 20. aldar. Ljósmyndir í safni Kvískerjasystkina frá um 1930 og frá Graf Zeppelin loftfarinu (31. júlí 1930) sýna að á þeim tíma var enn jökultota í Múlagljúfri en slitin sundur við gljúfurbrúnina. Flosi segir að jökullinn fremst á Múla hafi enn ekki verið farinn að hopa að ráði um 1930 og styður ljósmyndin sem var tekin frá Zeppelin loftfarinu þá frásögn. Helgi (1925–2015) og Hálfdán (1927–2017) Björnssynir sögðu greinarhöfundi (Sn. G.) að í þeirra minni var jökultungan enn í gljúfurbotninum en mikið tekin að þynnast. Þá hafi fólk velt fyrir sér hvort foss leyndist á bak við hana og þegar jökullinn síðan hvarf reyndist svo vera (munnleg frásögn Hálfdáns og Helga Björnssonar, árið 2015).

Kvískerjajöklar eru á meðal minnstu skriðjökla sem falla frá Öræfajökli. Þeir svara ört breytingum í loftslagi. Þeir hopuðu töluvert fram yfir miðja 20. öldina en tóku að vaxa í kringum 1980. Á þeim tíma voru gervitunglagögn orðin aðgengileg svo unnt var að fylgjast með jöklabreytingum á hverju ári. Áratugina á eftir gengu tungurnar ýmist fram eða hopuðu. Lengst fram munu þeir hafa náð um 1992 en þá var jaðar nyrðri tungunnar meira en 300 m framar en árið 1945 og 100 m neðar. Eftir síðustu aldamót tóku þessar jökultungur að hopa ört en nýverið varð vart við að fremstu hlutar þeirra höfðu þykknað eilítið (Joaquin Belart, munnleg heimild 2019).

Til þess að áætla flatarmáls- og rúmmálsbreytingar Kvískerjajökla voru búin til stafræn yfirborðslíkön (Digital Elevation Model, DEM) af jöklunum í hámarksstöðu á litlu ísöld (LIA) og þau borin saman við nákvæmt yfirborðslíkan af sama svæði frá árinu 2011, sem er gert eftir lidar-flugmæligögnum. Upplausnin var 5x5 m/díl og lóðrétt nákvæmni um 0,5 m (Tómas Jóhannesson o.fl, 2013). Efri hluti kortanna var gerður þannig að yfirborðslíkaninu frá 2011 var hliðrað lóðrétt. Við mat á hæðarbreytingum var stuðst við samanburð á hæð við jökulröndina, nú og fyrri ummerki. Hækkað landlíkan heldur sömu lögun yfirborðsins og á þekktum kortum (1905, 1945, 2011). Sú aðferð hefur áður verið notuð til að endurgera yfirborð fjölda jökla á Suðausturlandi (Snævarr Guðmundsson, Hrafnhildur Hannesdóttir og Helgi Björnsson, 2012; Hrafnhildur Hannesdóttir, 2014; Snævarr Guðmundsson, Helgi Björnsson og Finnur Pálsson, 2017). Við gerð neðri hluta kortanna (neðan við núverandi jökulsporð) var stuðst við einfalt ísflæðilíkan (hluti af ESRI ArcGIS hugbúnaði, Pellitero o.fl., 2016).

Niðurstöður flatarmálsmælinga benda til þess að Kvískerjajöklar hafi minnkað úr $\sim$10 km^2 frá því að þeir voru í hámarksstöðu á litlu ísöld í 6.4 km^2 árið 2011, þ.e. um 37%. Árlegt meðaltalshop telst því um 0.03 km^2. Hopið var hins vegar mun hægara á árunum fyrir 1930 en síðar. Á tímabilinu 1880–1930 (50 ár) töpuðu jöklarnir $\sim$1 km^2 að flatarmáli en frá 1930–2011 (81 ár) 3 km^2. Flatarmálsstap á fyrra tímabilinu var <0.012 km^2 a^{-1} að meðaltali en 0.039 km^2 a^{-1} á því síðara. Árið 2011 var ákomusvæðið (m.v. jafnvægislínu í 1100 m h.y.s.) 1,7 km^2 en leysingarsvæði 4,7 km^2. Hlutfall ákomusvæðis af heildarflatarmáli var 0.27. Þorvaldur Thoroddsen (1915) taldi að snælína hafi verið í 1020 m hæð við lok 19. aldar. Þá var ákomusvæði 3,5 km^2 og 0,35 af heildarflatarmáli. Hefur því safnsvæði á litlu ísöld verið talsvert stærra og afkomulíkur bjartari en nú er.

Við áætlum rúmmálsrýrnun frá um 1880 til 2011 nærri 0.43 km^3 að vatnsgildi. Það samsvarar að árleg rúmmálsrýrnun væri að meðaltali 0.003 km^3 að vatnsgildi og meðaltalsleysing -0.4 m a^{-1} í vatnsgildi yfir tímabilið 1880–2011. Áætlum við að rúmmálsrýrnun á fyrra tímabili hafi verið um 0.13 km^3 a^{-1} en 0.3 km^3 a^{-1} á því síðara. Meðaltalsleysing reyndist -0.27 m a^{-1} frá 1880 til 1930 en -0.4 m a^{-1} frá 1930 til 2011. Til samanburðar reyndist rúmmálsrýrnun Kotárjökuls, í suðvesturhlíðum Öræfajökuls, vera 0.4 km^3 eða 21% yfir tímabilið 1880–2011 (Snævarr Guðmundsson o.fl., 2012). Meðaltalsleysing Breiðamerkurjökuls var 0,58 km^3 a^{-1} að vatnsgildi á tímabilinu 1890–2010 eða -0,64 m a^{-1}. Rúmmálsrýrnun reyndist svipuð (Kvískerjajöklar 0.43 km^3 en Kotárjökull 0.4 km^3) en flatarmálsrýrnun Kvískerjajökla 1880–2011 er hins vegar 37% en Kotárjökuls um 21% á svo til sama tímabili. Safnsvæði Kotárjökuls er bæði stærra að flatarmáli og nær upp í meiri hæð (nær 1800 m) ásamt því að bera ís úr öskju Öræfajökuls. Safnsvæði Kvískerjajökla er lægra en 1600 m og minna að flatarmáli.

Þakkir Kvískerjabræðrum, Flosa, Sigurði, Helga og Hálfdáni Björnssonum, eru þakkaðar margar fróðlegar samræður um efni greinarinnar. Verkefnið var styrkt af Kvískerjasjóði og vinum Vatnajökuls. Við þökkum Tómasi Jóhannessyni og David Evans fyrir yfirlestur og góð ráð.

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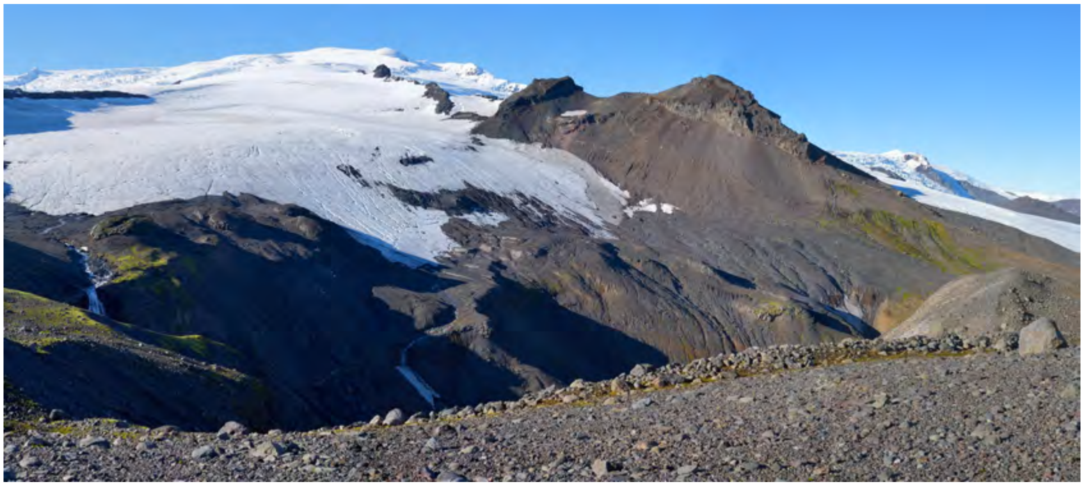

Top: A view from Sveinshöfði across the Rótarfjallsgljúfur gorge, in front of the South Kvískerjajökull glacier, towards Rótarfjallshnjúkur Mt. (right) and Hellutindar ridge. The "Pálsson's moraine" is in the foreground. Below: By the "Pálsson's moraine". A view over the lower Rótarfjallsgljúfur gorge, which was covered by the glacier during the Little Ice Age. – *Ofar: Horft frá Sveinshöfða yfir Rótarfjallsgljúfur framan við Syðri-Kvískerjajökul, til Rótarfjallshnjúks (hægra megin) og Hellutinda. Fremst er "jökulgarður Sveins". Neðar: "Jökulgarður Sveins" og neðri hluti Rótarfjallsgljúfurs baðaður sólskini. Gljúfrið var undir jökli á litlu ísöld.* Photos/*Ljósm.* Snævarr Guðmundsson, September 29, 2016.