Reviewed research article

A national glacier inventory and variations in glacier extent in Iceland from the Little Ice Age maximum to 2019

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Abstract — *A national glacier outline inventory for several different times since the end of the Little Ice Age (LIA) in Iceland has been created with input from several research groups and institutions, and submitted to the GLIMS (Global Land Ice Measurements from Space, nsidc.org/glims) database, where it is openly available. The glacier outlines have been revised and updated for consistency and the most representative outline chosen. The maximum glacier extent during the LIA was not reached simultaneously in Iceland, but many glaciers started retreating from their outermost LIA moraines around 1890. The total area of glaciers in Iceland in 2019 was approximately 10,400 km^2, and has decreased by more than 2200 km^2 since the end of the 19th century (corresponding to an 18% loss in area) and by approximately 750 km^2 since ∼2000. The larger ice caps have lost 10–30% of their maximum LIA area, whereas intermediate-size glaciers have been reduced by up to 80%. During the first two decades of the 21st century, the decrease rate has on average been approximately 40 km^2 a^{-1}. During this period, some tens of small glaciers have disappeared entirely. Temporal glacier inventories are important for climate change studies, for calibration of glacier models, for studies of glacier surges and glacier dynamics, and they are essential for better understanding of the state of glaciers. Although surges, volcanic eruptions and jökulhlaups influence the position of some glacier termini, glacier variations have been rather synchronous in Iceland, largely following climatic variations since the end of the 19th century.*

INTRODUCTION

Most glaciers in the world have retreated from their advanced positions of the Little Ice Age (LIA, ∼1450–1900 in Iceland), which they reached at different times (e.g. Grove, 2004). There is a robust trend of shrinkage and volume loss of glaciers in all glacierized regions of the Earth (Paul and Bolch, 2019; Zemp *et al.*, 2019). The LIA outer boundary is often marked by terminal and lateral moraines as well as trimlines, which have been used to reconstruct the maximum LIA extent of glaciers (e.g. Paul and Bolch, 2019). Reconstructions of glacier extents from a variety of sources such as historical documents, pictorial sources, delineation and dating of moraines and lacustrine records have revealed a detailed timeline of glacier variations during the LIA for many glaciers in the Alps (e.g. Zemp *et al.*, 2008), South America (e.g. Masiokas *et al.*, 2009; Zalazar *et al.*, 2020), Norway (e.g. Nesje *et al.*, 2008; Nussbaumer *et al.*, 2011) and Iceland (e.g. Þórarinsson, 1943; Björnsson and Pálsson, 2004; Bradwell *et al.*, 2006; Sigurðsson, 2010; Aðalgeirsdóttir *et al.*, 2011; Pálsson *et al.*, 2012; Hannesdóttir *et al.*, 2015a,b; Harning *et al.*, 2016; Guðmundsson *et al.*, 2017; Fernández-Fernández *et al.*, 2017, 2019). The ongoing glacier retreat leads to the disintegration of large glaciers into smaller ice bodies, the formation of terminus lakes and increased debris cover. This is increasingly challenging for glacier monitoring, for example the delineation of glacier boundaries and length-change measurements (e.g. Fischer *et al.*, 2016; Paul and Bolch, 2019).

Glaciers currently cover approximately 10% of Iceland. They are large freshwater reservoirs and contain the equivalent of $\sim$3400 km^3 of water (Björnsson, 2009, 2017), corresponding to the precipitation in the entire country over $\sim$20 years (e.g. Crochet, 2007). The glaciers influence the hydrology of the country through the annual mass-balance cycle and changes in ice volume due to variations in the climate, with important implications for the hydropower industry and other water users. The glaciers are dynamic and highly responsive to changes in climate and have high annual mass-turnover rates (1.5–3.0 m_{we} a^{-1}, Pálsson *et al.*, 2012). Several of the larger ice caps and glaciers in Iceland cover active volcanic and geothermal zones, causing subglacial eruptions and frequent jökulhlaups (Guðmundsson and Larsen, 2013). They are affected by geothermal melting, which is a substantial component in the glacier mass balance (Björnsson *et al.*, 2013; Jóhannesson *et al.*, 2020), as they are located in areas of high geothermal heat flux, including the neovolcanic zone.

This paper describes a national glacier outline inventory for Iceland for the period after the LIA maximum in the late 19^{th} century, which has been submitted to GLIMS (Global Land Ice Measurements from Space, nsidc.org/glims). Hitherto only the glacier outline from around the year 2000 has been available in digital form at the international snow and ice database. The outlines were collected by several research groups and institutions and are described in more detail in other scientific papers. They have been reviewed and updated for consistency, and the most reliable or representative outline chosen, from several available outlines for the same glacier. This paper provides general information about the glacier outlines, as well as a simple interpretation of the glacier variations that they represent, but readers are referred to the original papers for more detailed information. The paper is not intended as a comprehensive review paper about post-LIA glacier variations in Iceland. Rather, it provides background information about the updated, multi-temporal GLIMS glacier variations data set for Iceland in order to make it more useful for other studies of glacier variations and related research.

STUDY AREA

The largest ice caps in Iceland are located in the southern and central highlands (Figure 1), where prevailing southerly winds deliver a large amount of precipitation, on average 4000–5000 mm a^{-1} in the upper accumulation area of Vatnajökull and Mýrdalsjökull, reaching a maximum of $\sim$7000 mm a^{-1}, and ca. half of that on Langjökull and Hofsjökull (Björnsson and Pálsson, 2008; Björnsson, 2009, 2017). The balanced-budget equilibrium line altitude (ELA) of Vatnajökull ice cap lies on average around 1000 m a.s.l. on the southern outlet glaciers, compared with 1350 m a.s.l. on the inland outlet glaciers (Pálsson *et al.*, 2019). The balanced-budget ELAs of the ice caps in central Iceland are at ca. 1100–1300 m a.s.l. on Hofsjökull and 1000–1200 m a.s.l. on Langjökull (Thorsteinsson *et al.*, 2017; Pálsson *et al.*, 2012, respectively). The ELA of Mýrdalsjökull has been estimated from satellite images (from the location of the firn line) and is at ca. 1000 m a.s.l. on the east- and southeast-flowing glaciers vs. 1200 m a.s.l. on the inland and southern outlets (unpubl. data from the IMO). Typically, only 10–20% of the bed of the glaciers lies above the current ELA; thus, the larger ice caps exist mainly due to their own thickness (Björnsson and Pálsson, 2008). Several mountains reaching over 1400 m a.s.l. maintain small glaciers in the central highlands. A few ice-capped volcanoes exist outside the neovolcanic zone, including Snæfellsjökull and Mt. Snæfell. Drangajökull in Vestfirðir, the fifth largest ice cap, has the lowest ELA (600–700 m a.s.l.) of glaciers in Iceland (Björnsson, 2009, 2017). An overview of the ice caps and glaciers analysed in this paper is found in Table 1, including the elevation range and the area span in $\sim$1890–2019.

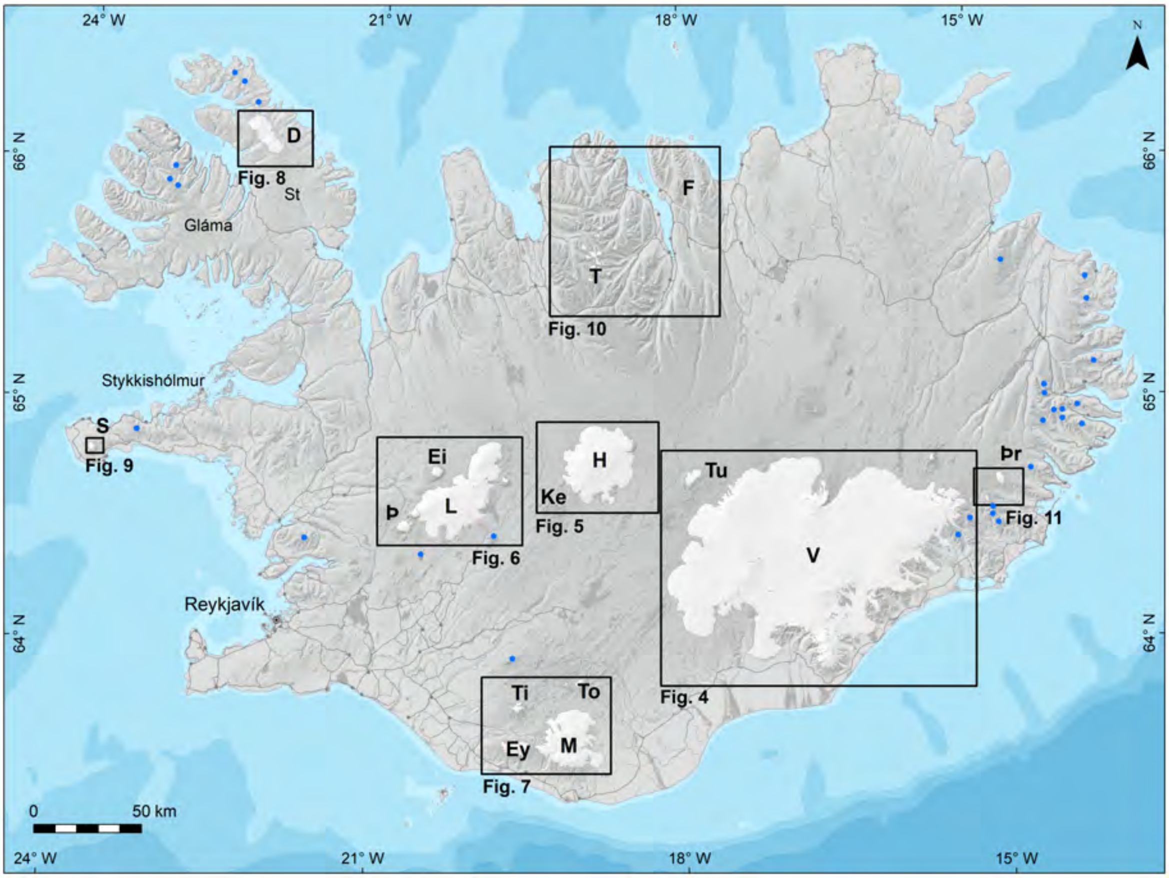

Figure 1: Glaciers and ice caps in Iceland. Each ice cap or glacier group is indicated with boxes and figure numbers. Small glaciers < 3 km^2 (belonging to regional glacier groups) are shown with blue dots, referred to as East, Southeast, Kerlingafjöll, Northwest, South and West Iceland glaciers in Table 1. D=Drangajökull, T=Tröllaskagi glaciers, F=Flateyjarskagi glaciers, S=Snæfellsjökull, Ei=Eiríksjökull, L=Langjökull, Þ=Þórisjökull, H=Hofsjökull, Ke=Kerlingarfjöll, Tu=Tungnafellsjökull, V=Vatnajökull, Þr=Þrándarjökull, Ti=Tindfjallajökull, To=Torfajökull, Ey=Eyjafjallajökull, M=Mýrdalsjökull, St=Steingrímsfjarðarheiði mountain pass. – *Jöklar á Íslandi. Útmörk kortanna sem fylgja á eftir eru sýnd með svörtum kössum og myndanúmerum. Litlir jöklar eru sýndir með bláum punktum og eru nefndir Austurlandsjöklar, Suðausturlandsjöklar, Kerlingarfjallajöklar, Vestfjarðarjöklar, Suðurlandsjöklar og Vesturlandsjöklar í töflu 1.*

Approximately 170 glaciers are found on the Tröllaskagi peninsula, N-Iceland, covering an area of approximately 130 km^2 in total (in 2019) (Björnsson, 1991; Sigurðsson *et al.*, 2017). Most of them are located on north-facing cirques and valleys, and range in size from 0.1–7 km^2. The precipitation is relatively low, arrives mainly with northerly winds and varies from 400 mm a^{-1} in some lowland areas to 2000–3000 mm a^{-1} near the summits (Crochet *et al.*, 2007). Most of the glaciers are partly debris-covered (due to frequent avalanches and rockfalls from steep head walls), although a few of them are debris-free (Björnsson, 1991; Wangensteen *et al.*, 2006; Kellerer-Pirklbauer *et al.*, 2007; Björnsson and Pálsson, 2008). The insulating effect of the debris cover makes them less sensitive to climate variations than most other glaciers in Iceland (e.g. Martin *et al.*, 1991).

Table 1: Glacier name, GLIMS ID, elevation span and area range for the ice caps, intermediate-size glaciers and small glaciers (< 3 km^2) for different regions in Iceland. All glaciers in Tröllaskagi are included in the small-glaciers group although a few of them are in the intermediate-size category in terms of their size. *The LIA maximum of Drangajökull is dated to 1850. – *Nafn jökuls, GLIMS auðkenni, hæðarbil og flatarmálsbil jöklanna. Allir jöklar á Tröllaskaga eru flokkaðir með litlum jöklum, þó að nokkrir þeirra séu stærri en 3 km^2. Drangajökull náði mestri útbreiðslu á litlu ísöld um 1850.*

Glacier	**GLIMS-ID**	**Elevation span** (m a.s.l.)	**Area range** (∼1890–2019, km^2)
Main ice caps			
Vatnajökull	G343222E64409N	0–2100	8789–7720
Langjökull	G339764E64629N	400–1400	1093–836
Hofsjökull	G341164E64838N	600–1800	1038–810
Mýrdalsjökull	G340925E63656N	100–1500	736–520
Drangajökull	G337738E66173N	100–900	270*–137
Eyjafjallajökull	G340399E63622N	200–1700	116–66
Intermediate-size glaciers (< 40 km^2)			
Tungnafellsjökull	G342097E64755N	950–1500	49–32
Þórisjökull	G339290E64537N	700–1300	44–23.8
Eiríksjökull	G339601E64772N	1000–1500	37–20.5
Þrándarjökull	G345090E64698N	950–1200	35–14.2
Tindfjallajökull	G340403E63790N	1000–1450	22.6–12.4
Snæfellsjökull	G336220E64811N	700–1450	25–8.8
Torfajökull	G340991E63899N	850–1200	22.8–8.1
Hrútfellsjökull	G340262E64742N	700–1400	10.8–4.4
Hofsjökull eystri	G344949E64616N	1000–1150	11.6–3.1
Ok glacier	G339116E64609N	1100–1200	10.3–0.07
Kaldaklofsjökull	G340860E63893N	1000–1100	8–1.6
Snæfell (Tindsjökull)	G344437E64800N	1200–1800	8–4.4
Small glaciers (< 3 km^2)			
Tröllaskagi glaciers	–	700–1300	201–127
Flateyjarskagi glaciers	–	500–1200	18.4–9.7
East Iceland glaciers	–	650–1200	10.8–4.1
Southeast Iceland glaciers	–	950–1200	12.6–4.5
Kerlingarfjöll glaciers	–	1000–1450	13.6–1.7
Vestfirðir glaciers	–	400–850	5.5–0.6
South Iceland glaciers	–	950–1400	2.5–0.5
West Iceland glaciers	–	1000–1200	4.1–0.2
Total	–	0–2100	12,594–10,371

Glacier surges are responsible for a large proportion of the total mass transport by the larger outlet glaciers of the main ice caps. Up to 75% of the area of the Vatnajökull ice cap has been affected by surges, and many outlet glaciers have a history of regular surges (Björnsson *et al.*, 2003). For the 20th century as a whole, surges contributed at least 10% to the total ice transport to the ablation areas of Vatnajökull (Björnsson *et al.*, 2003). Typical advances are in the range of ∼0.3–2 km, with the exception of the 10 km advance of Brúarjökull during the surges in 1890 and in 1963–1964 (Þórarinsson, 1969). The timing and duration of recorded surges that have caused advances of the glacier terminus are summarized in Björnsson *et al.* (2003).

HISTORICAL AND GLACIOLOGICAL BACKGROUND

Widespread glacier advances manifest the LIA cooling in Iceland, and most glaciers reached their greatest historical (that is after 874 CE in Iceland) extent during the LIA, with a maximum recorded in the late 19th century (e.g. Þórarinsson, 1943; Eyþórsson, 1935, 1981; Guðmundsson, 1997; Sigurðsson, 2005; Flowers *et al.*, 2007; Kirkbride and Dugmore, 2008; Geirsdóttir *et al.*, 2009, 2019; Larsen *et al.*, 2011; Hannesdóttir *et al.*, 2015a; Björnsson 2009, 2017), although some glaciers reached a similar extent already during the 18th century (e.g. Þórarinsson, 1943; Thoroddsen, 1958; Bradwell *et al.*, 2006; Kirkbride and Dugmore, 2008; Harning *et al.*, 2016). The maximum LIA extent is the largest post-Preboreal extent of many glaciers, in particular the larger outlet glaciers of the main ice caps (Þórarinsson, 1943; Eyþórsson, 1981; Flowers *et al.*, 2008; Geirsdóttir *et al.*, 2009, 2019). Mapping and dating of Neoglacial moraines have revealed glacier advances of similar extent as during the LIA in a few locations (e.g. Guðmundsson, 1997; Kirkbride and Dugmore, 2006). However, pre-LIA moraine remnants are found tens to hundreds of metres outside the LIA limit of some glaciers – for example the Stóralda moraines of Svínafellsjökull (Þórarinsson, 1956), the outermost moraines of Sólheimajökull (e.g. Schomacker *et al.*, 2012) and in front of Fjallsjökull and Kvíárjökull (Björnsson, 1998), Kaldalónsjökull (Brynjólfsson *et al.*, 2015) and Kötlujökull (Schomacker *et al.*, 2003). The maximum Neoglacial extent of glaciers in Tröllaskagi is typically only slightly beyond the maximum LIA extent indicating that the glacier dimensions during the LIA largely reflect the post-Preboreal Holocene maximum extent (Stötter *et al.*, 1999). Nevertheless, the Neoglacial advances for some glaciers were more extensive than those of the LIA (e.g. Kirkbride and Dugmore, 2001; Kellerer-Pirklbauer *et al.*, 2007; Fernández-Fernández *et al.*, 2019).

Studies on glacier variations of the LIA have been based on dating landforms in the proglacial area, by tephrochronology, radiocarbon dating and lichenometry (e.g. Guðmundsson, 1997; Sigurðsson, 2005). In recent decades, more continuous records on glacier fluctuations have been obtained from sediment cores from lakes proximal to the glaciers or affected by glacial meltwater (e.g. Striberger *et al.*, 2011; Larsen *et al.*, 2015; Harning *et al.*, 2016; Geirsdóttir *et al.*, 2019).

Many glaciers started retreating from their LIA terminal moraines in the last decades of the 19th century. The retreat accelerated in the 1930s, as a result of rapid warming starting in the 1920s (Figure 2). Due to cooler summers after the 1940s, the glacier retreat slowed down, and most glaciers advanced or halted their retreat in the period 1960 to 1990. Almost all glaciers in Iceland started retreating again in the mid-1990s, and the retreat has been particularly rapid since the year 2000. Figure 3 shows the relative proportion of advance and retreat of non-surging glacier termini since the start of regular observations of terminus variations in Iceland in the 1930s (Sigurðsson, 1998).

Glacier variations in Iceland show a clear relationship with variations in climate. In-situ glacier mass-balance measurements, geodetic mass-balance estimates, degree–day mass balance and energy balance models of selected glaciers, indicate that the mass balance is mainly governed by variation in summer temperature and winter precipitation (Jóhannesson and Sigurðsson, 1998; Aðalgeirsdóttir *et al.*, 2006; Flowers *et al.*, 2007; Björnsson and Pálsson, 2008; Guðmundsson *et al.*, 2009, 2011; Pálsson *et al.*, 2012; Björnsson *et al.*, 2013; Schmidt *et al.*, 2017; Belart *et al.*, 2019, 2020). There is a strong spatial mass-balance gradient over Iceland. Glaciers located close to the south and west coast experience higher decadal mass-balance oscillations, and they have higher mass-balance sensitivity to changes in summer temperature and winter precipitation, than the more inland, eastern and northern glaciers (e.g. Magnússon *et al.*, 2016; Belart *et al.*, 2020). This difference can probably be explained by differences in local climate, related to the pattern of oceanic currents surrounding Iceland (Hock and others, 2005; Björnsson *et al.*, 2013; Belart *et al.*, 2020).

DATA AND METHODS

The outlines of Icelandic glaciers at different times have been drawn by several research groups in re-

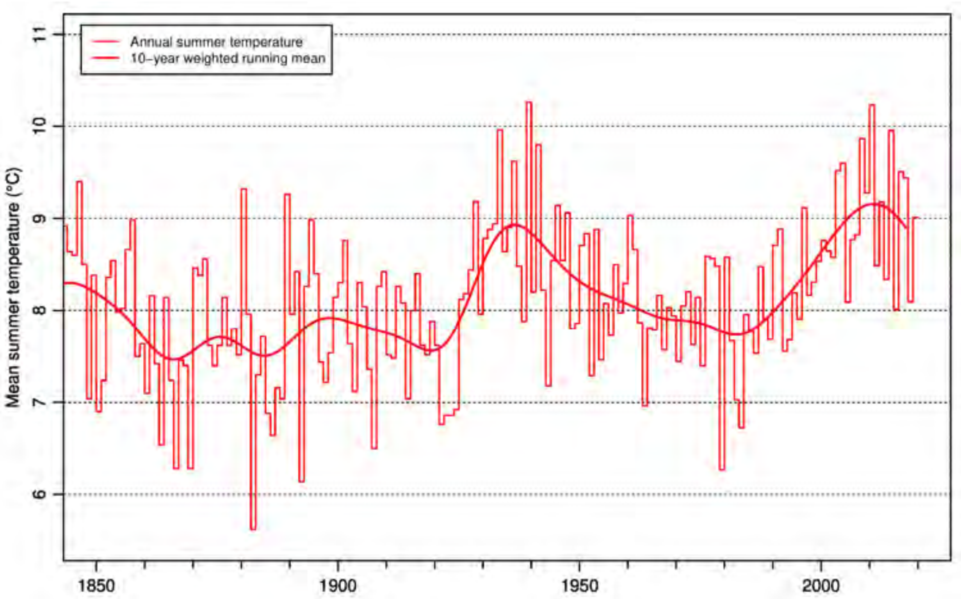

Figure 2: Mean annual summer (MJJAS) temperature at Stykkishólmur in W-Iceland from the 19th century to 2019 together with the 10-year weighted running mean (Gaussian smoothing). – *Meðalsumarhiti (MJJÁS) í Stykkishólmi frá 19. öld til 2019 ásamt 10 ára vegnu meðaltali (Gaussvægi).*

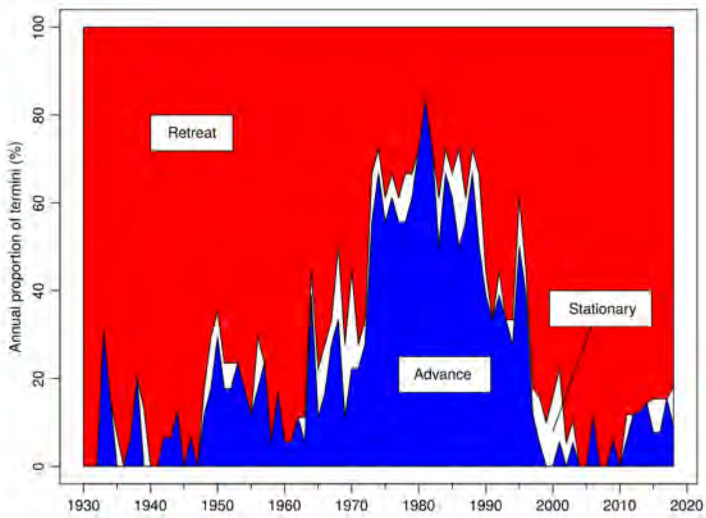

Figure 3: The annual proportion of monitored non-surging Icelandic glacier termini that advanced (blue) or retreated (red) in the period 1931–2018. The figure is based on data from 10–20 glaciers for most years, and is created with data from the terminus variations database of the Iceland Glaciological Society, available at spordakost.jorfi.is. – *Árlegt hlutfall íslenskra jökla sem gengu fram eða hopuðu á árunum 1931–2018. Framhlaupsjöklar eru ekki taldir með. Myndin sýnir gögn frá 10–20 jökulsporðum fyrir flest ár. Gögnin eru fengin hjá Jöklarannsóknafélagi Íslands og má nálgast þau á spordakost.jorfi.is.*

cent decades from maps, aerial and satellite images, as well as field measurements, of various resolution and quality, the accuracy of which is detailed in each subsection below. A majority of these glacier outlines were available in digital format, although a few of them had to be digitized from maps in order to be included in our data set. Table 2 gives an overview of the data used for delineation of the glacier margins and the corresponding references. These data have hitherto not been gathered systematically, but are published in numerous scientific papers, theses and reports, and many are not in digital format. The most complete glacier extent data sets are from the LIA maximum (here denoted with "$\sim$1890" although the LIA maximum may have been reached earlier for some glaciers), 1945–1946, 1970–1980, $\sim$2000, 2007–2013, 2014, 2017 and 2019. Some glaciers have a higher number of outlines than others (see the caption of Figure 12 for references). We have chosen the years with most complete glacier coverage to be included in the data set and omitted years with data covering only a single or a few glaciers.

Several different definitions of a glacier exist. The GLIMS definition is as follows (Raup and Khalsa, 2010, p. 4): "A glacier or perennial snow mass, identified by a single GLIMS glacier ID, consists of a body of ice and snow that is observed at the end of the melt season. . . . This includes, at a minimum, all tributaries and connected feeders that contribute ice to the main glacier, plus all debris-covered parts of it. Excluded is all exposed ground, including nunataks." The International Association of Hydrological Sciences (IAHS) glossary definition (Cogley *et al.*, 2011, p. 45) is: "A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow."

Although the Icelandic glacier outline data set is intended for GLIMS it was not possible to fully adhere to the GLIMS definition since the outlines are based on existing delineations of glacier margins using data of many different origins. In particular, outlines based on glacial geomorphological evidence (to delineate the maximum LIA extent) may be assumed to be closer to the IAHS rather than GLIMS definition, because terminal and lateral moraines are formed in areas affected by "past or present flow" of ice. Outlines from the map of Icelandic glaciers (Sigurðsson *et al.*, 2017) are partly based on oblique aerial photographs from several different times where an effort was made to exclude perennial and seasonal snow, thus these outlines are also closer to the IAHS than the GLIMS definition.

It is a challenge to determine the glacier boundary for debris-covered glaciers (e.g. Paul *et al.*, 2013), which should according to the GLIMS definition be included within the glacier polygon. The main areas where debris-covered glacier snouts are no longer connected with the active glacier front are Rjúpnabrekkujökull and the outlets north of Köldukvíslarjökull of northwestern Vatnajökull, covering 25 km^2 in 2019, the north and east flowing outlets of Kverkfjöll (northern Vatnajökull), covering 5 km^2 in 2019 and Klofajökull (northern outlet of Eiríksjökull), covering 2 km^2 in 2019. These areas show little surface lowering in recent decades.

When these debris-covered glacier parts become detached from the active glacier, flat proglacial areas characterized by sandur plains, sometimes crossed by glacier rivers, may emerge and the adjacent ice margin on the inside of these can be considered the "active" margin of the glacier in question. These debris-covered parts have been delineated separately and submitted to GLIMS as polygons of debris-covered glacier. They are also delineated within the main outline of the respective glacier, as required by the GLIMS definition and are, therefore, included in the calculated glacier area reported here. We have only defined such debris-covered-glacier polygons for moraine or dead-ice fields that do not seem to be part of the active glacier and not for dirty or debris-covered glacier snouts that participate in the terminus variations and thickness changes of the respective glacier. Ice-cored terminus moraines and debris-covered dead-ice buried in sandur plains or completely detached and located far from the glacier are, however, not included within our glacier outline database. We have not systematically mapped such areas in the neighbourhood of glaciers in Iceland, which is beyond the scope of this work. The area of polygons showing debris-covered glacier within the glacier outlines may be subtracted from the total area of the glacier in question to obtain the area of the active glacier. This smaller glacier area may be more appropriate to use in some analyses of glacier area changes than the total area including moraine or dead-ice fields, see for example the analysis of Aðalgeirsdóttir *et al.* (2020) of glacier changes in Iceland since $\sim$1890 based on volume–area scaling.

Table 2: Area of glaciers in Iceland since the LIA, see data sources and references in footnotes. See Table 1 for information about GLIMS-ID and elevation range. The area of glaciers smaller than 25 km^2 is given with one decimal place, whereas the area of larger glaciers is rounded to the nearest integer. The column headings indicate the type of data on which the outlines are based. GE: LIA geomorphological evidence. If no reference is cited, the outline has been created or revised in this study. The area of the smaller glaciers (regional glacier groups) in the last 8 rows is presented in parenthesis since it is calculated by statistical regression based on the known area of five small glaciers in different regions in Iceland, between ~1890 and 1945 (*), 1945 and 1973 (**), and ~2000 and ~2010 (***). Note that the area of many glaciers is slightly different from previously published values for the same years, such as by Björnsson and Pálsson (2008) and Sigurðsson *et al.* (2017), because of our inclusion of dead-ice areas to be consistent with the GLIMS definition of a glacier and due to our revision of some glacier margins. The last column specifies the area remaining in 2019 with respect to the maximum LIA area (%).

Glacier	~1890 GE	1945/1946 AMS		1973–1980 Landsat 1/A.img.		~2000 Remote sensing		2007–2013 Lidar		2014 A.img./Landsat 8	2017 Sentinel-2	2019 Sentinel-2	2019 Remain.
	A (km^2)	Year	A (km^2)	Year	A (km^2)	Year	A (km^2)	Year	A (km^2)	A (km^2)	A (km^2)	A (km^2)	w.r.t. LIA
Vatnajökull	8789[1,4,5,17,21−25]	1945/1946[a,b]	8326[1,3,17]	1973[c]	8215	2000[d]	8122[1]	2010–2012	7881	7814[i,j]	7754	7720[(i)]	88%
Langjökull	1093[2,19,20,25]	1945[a,b]	992[2]	1973[c]	931	2000[d]	921[2]	2007	896[16]	862[j]	845	836[(i)]	76%
Hofsjökull	1038[7,25]	1945/1946[a,b]	948[7]	1980[i]	923	1999[i]	892[1]	2008	852[7]	825[j]	813	810	78%
Mýrdalsjökull	736[1,25]	1945/1946[b]	652[1]	1980[h]	607[3]	1999[i]	596[3]	2010	562[3]	539[i]	525	520	71%
Drangajökull	270[6,10]	1946[b]	161[8]	1975[b]	148[8]	2005[i]	146[8]	2011	144[8]	144[k]	138	137	51%
Eyjafjallajökull	116[1,25]	1945[b]	87[3]	1980[h]	82[3]	2000–2003[i]	81[1]	2010	72[9]	70[k]	66	66[i]	57%
Tungnafellsjökull	49[12]	1946[b]	40[12]	1980[h]	40[3]	2004[e]	38[1]	2011	34[12]	34[j]	33	32	66%
Þórisjökull	44[14]	1945/1946[a]	30[1]	1973[c]	31	2000[d]	30[1]	2007	26	24.4[j]	23.8	23.8[i]	54%
Eiríksjökull	37[15]	1945[b]	25.4 [9]	1978[b]	25.3[9]	2000[d]	24.1[1]	2008	22.7[9]	21.3[j]	20.9[i]	20.5	55%
Þrándarjökull	35[25]	1945/1946[a]	27[1]	1976[b]	21.1[9]	2004[e]	17.0 [9]	2012	14.9[9]	14.9[j]	14.6[i]	14.2	41%
Tindfjallajökull	22.6[25]	1945/1946[b]	16.8[9]	1978[b]	16.1	2004[e]	15.6[9]	2011	13.2[9]	12.7[j]	12.4	12.4	55%
Snæfellsjökull	25[13]	1945[b]	13.9[9]	1979[b]	13.9[9]	2002–2003[g]	12.5[1]	2008	9.9[18]	9.0[l]	9.0	8.8	35%
Torfajökull	22.8[1,25]	1945[b]	16.0[9]	1970[b]	14.2[9]	1999[i]	11.4[1]	2011	9.3[9]	8.8[j]	8.1	8.1	36%
Hrútfellsjökull	10.8[1,25]	1946[b]	7.7[9]	1980[h]	7.9[9]	2004[e]	5.8[9]	2013	5.0	4.[l]9	4.5	4.4	41%
Hofsjökull E	11.6[1,25]	1946[b]	7.1[9]	1976[b]	5.9[9]	2004[e]	5.0[1]	2012	3.5[9]	3.4[j]	3.4[i]	3.1	26%
Ok glacier	10.3[1,25]	1945/1946[a]	7.4[1]	1975[b]	5.2[11]	2000[d]	3.7[1]	2008[i]	1.5[11]	0.6[j]	0.07	0.07[g]	1%
Kaldaklofsjökull	8.0[1,25]	1945/1946[a]	3.9[1]	1973[c]	3.3	1999[i]	2.5[1]	2011	1.8	1.8[j]	1.6	1.6	21%
Snæfell (Tindsj.)	8.0[1,25]	1945[b]	5.3[9]	1976	5.2	1993[b]	5.0[9]	2012	4.3[9]	4.2[j]	4.4	4.4	55%
Tröllaskagi gl.	201[1]	1945/1946	(192)	1973**	(190)	2000[f]	168[1]	2010***	(144)	138[i,j]	127	(127)	63%
Flateyjarskagi gl.	18.4[1]	1945/1946*	(15.2)	1973**	(15.1)	2000[f]	13.3[1]	2010***	(11.4)	9.9[i,j]	9.7	(9.7)	53%
E-Iceland gl.	10.8[1]	1945/1946*	(6.7)	1973**	(6.4)	2003[e]	5.6[1]	2010***	(4.8)	4.5[j]	4.1	(4.1)	38%
SE-Iceland gl.	12.6[1]	1945/1946*	(8.5)	1973**	(8.4)	2003[e]	7.4[1]	2010***	(6.4)	4.9[j]	4.5	(4.5)	38%
Kerlingarfjöll gl.	13.6[1]	1945/1946*	(5.8)	1973**	(5.8)	1998[i]	5.1[1]	2010***	(4.4)	1.9[j]	1.7	(1.7)	13%
Vestfirðir gl.	5.5[1]	1945/1946*	(0.9)	1973**	(0.9)	2004[f]	0.8[1]	2010***	(0.7)	0.7[j]	0.6	(0.6)	11%
S-Iceland gl.	2.5[1]	1945/1946*	(0.7)	1973**	(0.7)	1999–2003[b,d,e]	0.6[1]	2010***	(0.5)	0.6[j]	0.5	(0.5)	16%
W-Iceland gl.	4.1[1]	1945/1946*	(0.7)	1973**	(0.7)	2000[d]	0.6[1]	2010***	(0.5)	0.3[j]	0.2	(0.2)	5%
Total	12594	NA	11595	NA	11323	NA	11129	NA	10726	10550	10424	10371	82%

[a] AMS map; [b] Aerial images NLSI; [c] Landsat 1 ; [d] Landsat 7; [e] SPOT5; [f] stereo images; [g] GPS measurements; [h] declassified Hexagon KH9. [i] Aerial images Loftmyndir ehf;[j] Landsat8;[k] Pleiades;[l] ArcticDEM. [1] Sigurðsson *et al.* (2017); [2] Pálsson *et al.* (2012) [3] Belart *et al.* (2019); [4] Hannesdóttir *et al.* (2015a); [5] Guðmundsson *et al.* (2017); [6] Brynjólfsson *et al.* (2014); [7] Thorsteinsson *et al.* (2017); [8] Magnússon *et al.* (2016); [9] Belart *et al.* (2020); [10] Harning *et al.* (2016); [11] Helgadóttir (2017); [12] Gunnlaugsson (2016); [13] Evans *et al.* (2016a); [14] Evans *et al.* (2006); [15] Evans *et al.* (2016b); [16] Pope *et al.* (2013); [17] Magnússon *et al.* (2005); [18] Jóhannesson *et al.* (2011); [19] Geirsdóttir *et al.*, 2009; [20] Larsen *et al.*, 2011; [21] Björnsson and Pálsson, 2004; [22] Aðalgeirsdóttir *et al.*, 2011; [23] Benediktsson *et al.*, 2008; [24] Schomacker *et al.*, 2014; [25] Guðmundsson unpubl. data.

Tafla 2, frh. – Flatarmál jökla á mismunandi tímum frá lokum litlu ísaldar, upplýsingar um gögn sem notuð eru til þess að draga útlínur jöklanna og heimildir eftir því sem við á. Dálkhausar gefa til kynna gögn sem notuð eru í hverju tilviki. GE: jökulummerki frá litlu ísöld. Ef engra heimilda er getið, þá hefur útlína þess jökuls verið dregin eða endurtúlkuð í þessari grein. Flatarmál minnstu jöklanna (átta neðstu línurnar) er innan sviga í þeim tilfellum sem flatarmálið er áætlað út frá þekktum flatarmálsbreytingum fimm jökla af svipaðri gerð/stærð. Athugið að í sumum tilfellum er flatarmál jökla frábrugðið fyrri útgefnum tölum, eins og til dæmis þeim sem birtust í grein Helga Björnssonar og Finns Pálssonar (2008) sem og á Jöklakortinu (Oddur Sigurðsson o.fl., 2017) vegna þess að urðarkápur jökla eru samkvæmt GLIMS skilgreiningu hluti af jöklinum en einnig hafa útlínur verið endurtúlkaðar í einhverjum tilfellum. Síðasti dálkurinn sýnir hlutfallslega stærð jökuls árið 2019 miðað við hámarksstærð hans á litlu ísöld.

Digital elevation model (DEM) differencing can help identifying the active part of the glacier terminus, as distinct from stagnant ice, isolated from the surroundings and not moving, which is thus practically not a part of the glacier (e.g. Vincent *et al.*, 2016; Mölg *et al.*, 2018; Tanarro *et al.*, 2019). For glaciers, that terminate at higher elevation, snow often makes the glacier margin hard to distinguish in many areas, for example on the Fimmvörðuháls mountain pass and on the south side of Drangajökull. Small, perennial or late-summer seasonal snow patches are sometimes difficult to distinguish from glacier ice on satellite and aerial images (e.g. Sigurðsson *et al.*, 2014; DeVisser and Fountain, 2015; Selkowitz and Forster 2016; Leigh *et al.*, 2019, and references therein). Ice patches are ice bodies without movement by flow or internal motion (e.g. Serrano *et al.*, 2011). Distinguishing seasonal snow patches from glaciers or perennial snow based on one-time photography is impossible. Only by tracking the features over a number of years can the seasonal or perennial nature of each feature be determined. The large ice caps dominate the area covered by glaciers in Iceland so uncertainty about small snow or ice patches, or perennial and seasonal snow, does not have a large effect on the estimate of the total area of the glaciers in a relative sense.

The area of some of the small glaciers (< 3 km^2) (Figure 2 and Table 1) is known from the mapping of the glacier outline $\sim$1890, around 2000, in 2014 and 2017. Their areal extent in 1945, 1973, $\sim$2010 and 2019 is estimated with statistical regression based on the known area of other small glaciers at those times (Snæfellsjökull, Hrútfellsjökull, Kaldaklofsjökull, Snæfell, Ok glacier). For all maps presented below, a combination of elevation hillshades from three main sources, ArcticDEM mosaic tiles (Porter *et al.*, 2018), lidar data sets from the Icelandic IPY glacier mapping campaign (Jóhannesson *et al.*, 2013), and an elevation data set from the National Land Survey of Iceland published in 2016, was used as a background.

The reconstructed Little Ice Age maximum extent

In many areas, well preserved glacial geomorphological features, including terminal and lateral moraines, trimlines and glacier erratics, delineate the maximum LIA extent of the glaciers. Glacially eroded and sculptured landscapes and differences in vegetation cover also give an indication of the possible extent of the glaciers during the LIA. Reconstruction of the maximum LIA glacier extent has been based on glacial geomorphological features identified on oblique and vertical aerial photographs and satellite images as well as by detailed field investigations (e.g. Þórarinsson, 1943; Sigurðsson, 2005; Pálsson *et al.*, 2012; Hannesdóttir *et al.*, 2015a; Evans, 2016a, 2016b; Guðmundsson *et al.*, 2017). In some cases, the LIA terminal moraines are shown on the oldest reliable maps from 1905 (surveyed in 1902–1904), which were based on the geodetic surveys of the Danish General Staff (Nørlund, 1944; Böðvarsson, 1996). These maps do not cover the whole country, but they include the southern stretch of Vatnajökull, a few outlets of Mýrdalsjökull, Eyjafjallajökull, Snæfellsjökull and Drangajökull. Additionally, historical documents, maps and photographs from the 19$^{\text{th}}$ century to the early 20$^{\text{th}}$ century have been used in previous studies to constrain the maximum LIA extent (e.g. Thoroddsen, 1911, 1958; Þorkelsson, 1918; Bárðarson, 1934; Magnússon, 1955; F. Björnsson, 1993, 1998; Guðmundsson *et al.*, 2012). The maximum LIA extent of some glaciers has been studied in more detail by glacial geomorphological mapping in the field.

These studies are referred to in Table 2.

The age of glacial geomorphological features, including moraines, may often be estimated from historical accounts, surface texture, vegetation cover and lichenometry, but remains uncertain in many cases, as further discussed below. A (subjective) estimate of the horizontal accuracy of the LIA glacier outline, as derived mainly on the basis of glacial geomorphological evidence, is on the order of 50–100 m, based on the width of the geomorphological features. Problems in identifying the crest or the outermost part of the moraines from remote sensing imagery affect the accuracy of the $\sim$1890 glacier outline. The accuracy of the age of the terminal moraines, that is the time when the glacier margin was last adjacent to the moraine, where available from the above mentioned sources, is presumably in the range of 10–50 years.

The smaller and thinner glaciers, often leave only vague traces of their former extent, which results in an uncertain LIA maximum glacier outline. The different types of bedrock of the various glacierized areas also affect the preservation of the moraines, trimlines and glacier erratics. The glacial erosion is, for example, different in the neovolcanic zone than within the Tertiary basaltic bedrock in East and West Iceland. This applies to the glacier outlets on the eastern side of Vatnajökull, where glacial geomorphological evidence is sparse on the eroded bedrock characteristic of this area. This applies also to parts of the Drangajökull ice cap and the northeastern side of Langjökull. The total length of the uncertain LIA outline is estimated to be a few km for eastern Vatnajökull and negligible for Langjökull. The reconstruction of the maximum LIA glacier outline of Drangajökull is covered in a separate section.

LIA glacial geomorphological evidence is not available in some areas where repeated jökulhlaups and braided glacial rivers have sculptured the landscape, washed away moraines or buried them with sediments. In these areas and others were detailed geomorphological evidence is ambiguous, we have drawn a qualitatively estimated LIA maximum outline based on the geometry of younger outlines at these locations.

For simplification, the timing of the LIA maximum is here referred to as "$\sim$1890". However, there is firm evidence from historical documents (e.g. Þórarinsson, 1943) and lacustrine records (Harning *et al.*, 2016), that Drangajökull started receding already around 1850. Also, it is worth noting that Skeiðarárjökull, the large southern outlet glacier of Vatnajökull, reached its maximum extent during a surge in 1929 (Sigurðsson, 2005). An estimated maximum LIA or $\sim$1890 extent of virtually all glaciers in Iceland is shown on the map of Icelandic glaciers published by the IMO (Sigurðsson *et al.*, 2017). The delineation of this outline is mostly based on satellite and aerial imagery, oblique aerial photographs and lidar DEMs, as well as on historical information, used to identify a "recent" maximum glacier extent visually, but without field observations or dating of the identified features. In this paper (see Figures 4–10), the LIA glacier outline has been updated in certain areas, taking into account more detailed mapping of the glacial geomorphological landforms where available (see references cited in Table 2). Thus, the maximum LIA glacier areas have changed slightly from the values presented on the map of Icelandic glaciers (Sigurðsson *et al.*, 2017).

Glacier extent in 1945/1946

The US Army Map Service (AMS) created topographic maps of Iceland at a scale of 1:50,000. These were based on aerial photographs taken in 1945 and 1946 and had contour lines drawn at 20 m intervals. During recent years, the original AMS aerial photographs, that are now stored at the National Land Survey of Iceland (NLS), have been scanned, georectified and processed to create DEMs and orthoimages utilizing the 60% acquisition overlap (Magnússon *et al.*, 2016; Belart *et al.*, 2019). These DEMs have been used to digitize glacier outlines more accurately than those displayed on the original topographic maps (see for example Belart *et al.*, 2019, and Andreassen *et al.*, 2020). In Table 2, a distinction is made between 1945/1946 glacier outlines digitized from the original maps and outlines derived more recently from the scanned aerial photographs. Two-thirds of the 1945/1946 outline for Vatnajökull (from Skeiðarárjökull to the west and north to Lambatungnajökull, except Öræfajökull for which the aerial images have been scanned and re-processed) is based on the AMS maps with some corrections; by georeferencing the scanned maps individually, and fitting each map segment to the surrounding valley walls, using lidar DEMs as reference topography (for more details see Pálsson *et al.*, 2012, and Hannesdóttir *et al.*, 2015b).

Glacier extent in 1970–1980

Glacier outlines for the decade 1970–1980 have been digitized from early Landsat 1 (previously known as ERTS-1) images acquired in the summer of 1973, with a Ground Sampling Distance (GSD) 60×60 m and aerial images from the National Land Survey of Iceland from the 1970s (with a GSD of 0.7×0.7 m). The aerial images have been processed for creation of orthoimages and DEMs, and they were used to create additional glacier outlines in areas not covered by the 1973 Landsat imagery, and improve outlines in a few areas. This includes glacier margins for the smaller ice caps and glaciers (see Table 2 for details). The outlines of a few glaciers are based on declassified Hexagon KH9 satellite images aquired in 1980 (Belart *et al.*, 2019, 2020).

Glacier extent in ∼2000

Multiple imagery sources were used to delineate the glacier margin for ∼2000. These included orthorectified aerial images from the company Loftmyndir ehf. (GSD of 1×1 m), satellite images from both Landsat 7 (GSD of 15×15 m) and SPOT-5 (GSD of 2.5×2.5 m and 5×5 m) and georeferenced oblique images taken from an airplane. The year of acquisition varies between sources from 1998 to 2004. The orthoimages (airborne and spaceborne) also have different GSD. For information relating to each glacier or glacierized area see Table 2.

Glacier extent in 2007–2013

During 2008–2012, starting during the International Polar Year, accurate and detailed DEMs of the glaciers in Iceland were produced with airborne lidar. The lidar DEMs have a GSD of 5×5 m and hillshades were created from them for delineation of glacier outlines (Jóhannesson *et al.*, 2011, 2013). More than 90% of the glaciers were surveyed in this effort, including Vatnajökull, Hofsjökull, Mýrdalsjökull, Drangajökull, Eyjafjallajökull and several smaller glaciers. Approximately 70% of Langjökull was surveyed by the Scott Polar Research Institute (SPRI) in late summer 2007, and almost the whole glacier again in 2013, including Þórisjökull (Pope *et al.*, 2013). Hofsjökull was also resurveyed by lidar in 2013. The lidar mapping generally includes a 500–1000 m wide ice-free buffer zone around the ice margins which contains many glacial geomorphological features, and therefore the new DEMs have proved to be useful in geological investigations of proglacial areas.

Glacier extent in 2014

Glacier outlines of 2014 based on aerial images from Loftmyndir ehf. and Landsat 8 satellite images are part of the glacier inventory presented here and submitted to GLIMS. Many of the smaller glaciers, particularly on Tröllaskagi, were snow-covered in late summer in 2014, and the glacier margin is hard to delineate in some areas for this reason. The outlines from 2014 are not shown on the maps in this paper for clarity because they are hard to distinguish from the outlines from ∼2010 and 2019. Data from 2014 are, however, included in the time series of glacier area shown in the Results section.

Glacier extent in 2017

During the summer and autumn of 2017, Sentinel-2 satellites acquired images (GSD of 10×10 m) of all the major glaciers in Iceland. To fill in the missing patches a mix of Landsat 8 and orthorectified aerial images from the company Loftmyndir ehf. were used. Kääb *et al.* (2016) noted lateral offsets in the geolocation of Sentinel-2 data. We found this offset to be quite small for the Icelandic glaciers and it is neglected here for simplicity since it does not affect calculations of glacier area. The outlines from 2017 are not shown on the maps in this paper for clarity because they are hard to distinguish from the outlines from ∼2010 and 2019.

Glacier extent in 2019

During the summer and autumn of 2019, Sentinel-2 satellites acquired images (GSD of 10×10 m) of all the major glaciers in Iceland. The warm spring and summer of 2019 enhanced melting of seasonal snow, exposing glacier margins, and enabled the delineation of the actual ice margin for the first time in several years at many locations. Orthorectified aerial images from the company Loftmyndir ehf. were also used in some areas. The smallest glaciers ($<3\,km^2$, shown in blue in Figure 1) and the groups listed in Table 1 were not digitized from those images and changes in their extent were assumed to be negligible compared with 2017.

Glacier surges

Changes in the extent of Icelandic glaciers not only depend on variations in mass-balance driven by climate change, but also on factors such as surge activity (Björnsson *et al.*, 2003), subglacial volcanic eruptions (Guðmundsson, 2005), and jökulhlaups (e.g. Guðmundsson and Larsen, 2013). The largest surges of glaciers, such as the one of Brúarjökull in 1890 and 1963–1964, that resulted in an advance of the terminus of the entire outlet glacier by $\sim$10 km with an increase in the glacier area by $>160\,km^2$ (Þórarinsson, 1969; Guðmundsson *et al.*, 1996), have a large effect on the glacier extent. The 1963–1964 surge of Brúarjökull is the only surge in Iceland of this magnitude since the end of the LIA; other surges in Iceland in this time period typically being in the range $\sim$0.3–2 km as noted before. Most known surge-type outlet glaciers of the main ice caps, including all the main outlet glaciers of western Vatnajökull, surged during the 1990s. The largest surges affecting the variations of glacier termini are discussed for each glacier in the corresponding subsections in the Results section below.

Area calculations

In this paper, area calculations are, as is commonly used in Iceland, made with the national ISN93 coordinate system, which utilizes the Lambert conformal conic projection with two standard parallels (EPSG:3057). This is slightly different from area calculations in the GLIMS glacier database where area calculations are carried out in the NSIDC EASE-Grid that uses the WGS-84 datum and a cylindrical equal-area projection (EPGS:3975). The differences are, however, not noticeable, except for Vatnajökull, where the difference amounts to a couple of km^2. Users of the dataset do, however, need to be aware that area calculations will give different results based on the coordinate systems they choose to use. For the glacier area calculations, ice patches that have become detached from the main body of each glacier since the LIA are included in the glacier area.

RESULTS

The retreat and advance history of glaciers in Iceland since the end of the LIA is fairly consistent across the country according to the outline data set. Most glaciers started to retreat from the outermost terminal LIA moraines in the 1880s and 1890s. The retreat accelerated after 1900 and almost all glacier termini retreated rapidly in the 1930s and 1940s, with occasional exceptions due to surges (Figure 3). The retreat slowed down, most termini stagnated and many glaciers readvanced after 1960. The glaciers started to retreat again due to increased temperatures after 1995 (Figure 2). The retreat rate of many glaciers since 2000 has been similar to that in the 1930s and the 1940s, although a few glaciers show up to double retreat rates during the latter period compared with the earlier one (see spordakost.jorfi.is).

In the following subsections, maps of the main ice caps and glaciers are presented with the outlines of the maximum LIA glacier extent in $\sim$1890 (except for Drangajökull at $\sim$1850), in 1945–1946, 1970–1980, $\sim$2000, 2007–2013 and 2019, see Table 2 for information about each outline and the corresponding area.

Vatnajökull and Tungnafellsjökull

Vatnajökull ice cap lost $1069\,km^2$ during the period $\sim$1890–2019, equal to 12% of its maximum LIA extent, whereof close to half of the area loss ($460\,km^2$) occurred during the period $\sim$1890–1945 (Table 2). The main area loss occurs at the large outlet glaciers to the south, Breiðamerkurjökull and Skeiðarárjökull, Tungnaárjökull to the west, and Brúarjökull and Eyjabakkajökull to the north (Figure 4). They are all surge-type glaciers. The rate of area change was highest during the first 2 decades of the 21st century, on the order of $-36\ km^2\ a^{-1}$ to $-44\ km^2\ a^{-1}$.

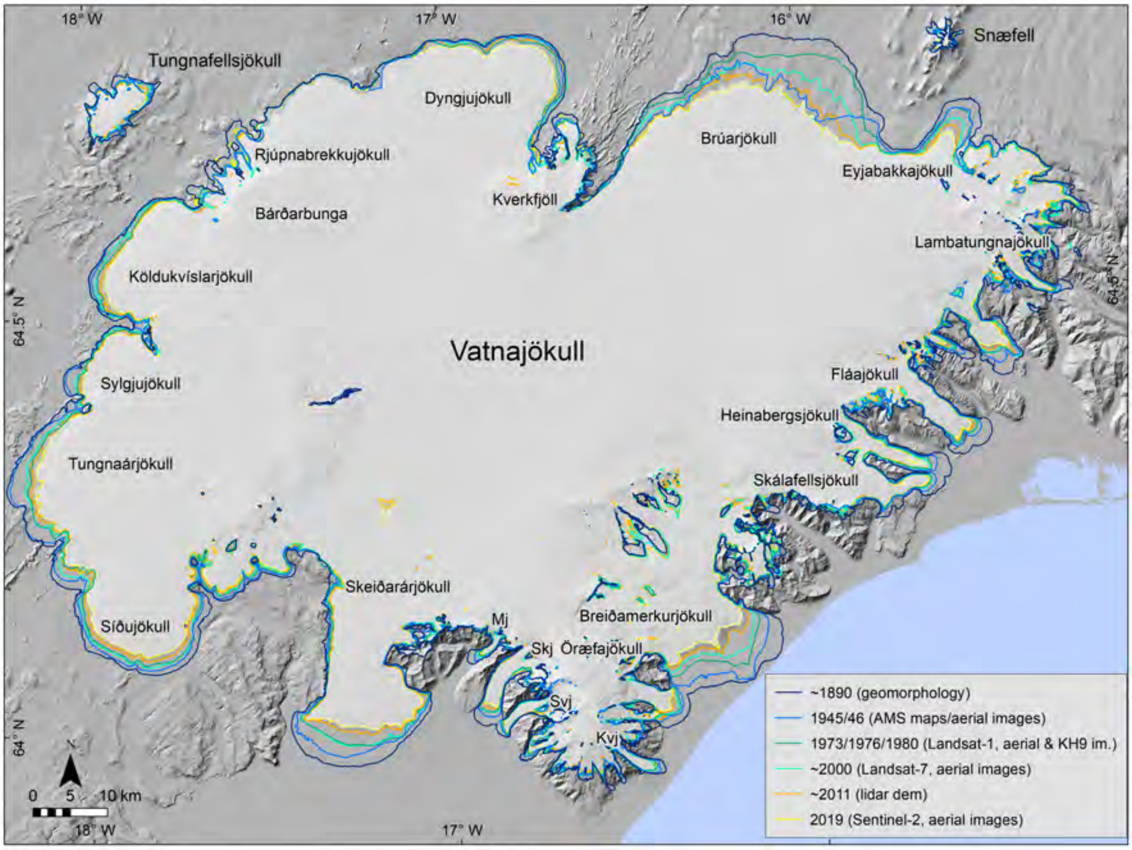

Figure 4: The extent of Vatnajökull ice cap, Tungnafellsjökull and the glaciers of Mt. Snæfell at several times since the LIA maximum in ∼1890. Mj=Morsárjökull, Skj=Skaftafellsjökull, Svj=Svínafellsjökull, Kvj=Kvíárjökull. – *Útlínur Vatnajökuls, Tungnafellsjökuls og jöklanna á Snæfelli á mismunandi tímum frá því um 1890.*

Breiðamerkurjökull calves into Jökulsárlón glacier lagoon, which started to form in the mid-1930s because of the retreat of the glacier in a subglacial valley that reaches below sea level. This ∼900 km^2 outlet glacier retreats and thins due to negative surface mass balance in a warming climate, but calving causes approximately one-third of the mass loss (Pálsson, 2018). The southern outlet glaciers have retreated up to several km since the end of the 19th century (Figure 4), with the maximum retreat of more than 8 km of Breiðamerkurjökull.

Surges of Dyngjujökull and Brúarjökull (Björnsson *et al.*, 2003) have influenced the configuration of the northern glacier margin, with the most extensive advance of 10 km during the surge of Brúarjökull in 1890 (Þórarinsson, 1964). Brúarjökull retreated 11 km between 1890 and 1963, and the glacier again advanced close to 10 km during the surge in 1963–1964 (Guðmundsson *et al.*, 1996). Thus, the glacier outline in 1973 was close to the outermost moraines of ∼1890 (Figure 4).

The LIA extent of the southern outlet glaciers of Vatnajökull has been traced in detail (Bradwell *et al.*, 2006; Guðmundsson *et al.*, 2012, 2017; Hannesdóttir *et al.*, 2015a; Everest *et al.*, 2017). Less detailed information about the LIA extent is available for other parts of the ice cap; however, a few notes from travellers and natural scientists visiting the glacier termini give some indications. Skeiðarárjökull fluctuated near it maximum LIA extent until ca. 1890. A surge in 1929 brought at least parts of the terminus beyond the previous maximum extent

(Sigurðsson, 2005). Tungnaárjökull reached its LIA maximum around 1890 (Thoroddsen, 1933; Tómasson and Vilmundardóttir, 1967; Magnússon *et al.*, 2005), and its forefield has been mapped in detail (Evans *et al.*, 2009; Molewski *et al.*, 2016). Skaftárjökull was slowly retreating from its outermost moraines when Thoroddsen visited the area in 1893 (Thoroddsen, 1893, 1906), and so was Síðujökull (Sigurðsson, 2005). These glaciers are both prone to surges and so is Dyngjujökull, which was receding when Thoroddsen inspected that part of the Icelandic highlands in 1884 (Thoroddsen, 1906). The maximum LIA glacier extent of the northwestern (Köldukvíslarjökull–Dyngjujökull) and eastern parts of the margin (east of Eyjabakkajökull) of Vatnajökull ice cap have not been studied in detail, and the LIA outline relies solely on the geomorphological imprint detectable on aerial photos and satellite images. The LIA extent of Brúarjökull and Eyjabakkajökull has been mapped in detail by Benediktsson *et al.* (2008) and Schomacker *et al.* (2014), respectively.

The debris-covered snouts of Dyngjujökull, Rjúpnabrekkujökull and the smaller outlets west of Bárðarbunga were presumably connected to the ice-cored LIA moraines during most of the 20$^{\text{th}}$ century. In the last 10–20 years, the glacier terminus has been retreating from the ice-cored moraine field, which marks its maximum LIA extent according to our interpretation. Further work on the glacier outlines in this area is in progress. A DEM and orthoimage will be created based on aerial images of 1945/1946 and from the 1960s. This will enable a more thorough evaluation of the terminus variations since the maximum LIA by DEM differencing which makes it possible to detect the active glacier margin.

Tungnafellsjökull, a small ice cap to the northwest of Vatnajökull, decreased by 17 km^2 during the period ∼1890–2019, equal to 34% decrease relative to its maximum LIA extent. The LIA extent of Tungnafellsjökull has been traced by identifying moraines and other geomorphological evidence on satellite and aerial images (Gunnlaugsson, 2016). Historical data are sparse; however, Hans Reck visited Tungnafellsjökull in 1907 and noted that the outlet glaciers were receding at that time (Þórarinsson, 1943).

Hofsjökull, Langjökull and smaller neighbouring glaciers

Hofsjökull ice cap decreased by 228 km^2 during the period ∼1890–2019, and similar to Vatnajökull, close to half of the area loss occurred in the period ∼1890–1945. The rate of area change is highest during the first 2 decades of the 21$^{\text{st}}$ century, in the range $-3\,\text{km}^2\,\text{a}^{-1}$ to $-4.5\,\text{km}^2\,\text{a}^{-1}$ (Table 3). The larger outlet glaciers of Hofsjökull have retreated by approximately 2–3 km from the maximum LIA extent and the retreat is fairly uniform around the glacier (Figure 5).

The maximum LIA extent of Hofsjökull has been drawn based on geomorphological evidence detected on aerial photos and satellite images. Hermann Stoll (1911) travelled in the area in 1910 and mentioned that the outlet glaciers of Hofsjökull were receding from their outermost moraines at that time. Sigbjarnarson (1981) reviewed available information about the retreat of the northwestern part of the ice margin (Sátujökull) from the LIA maximum to 1981. He concludes that the outermost moraines must have been built up during surges.

Langjökull ice cap has during the period ∼1890–2019 lost 257 km^2. The rate of area change since 2000 is in the range of $-3.5\,\text{km}^2\,\text{a}^{-1}$ to $-5.3\,\text{km}^2\,\text{a}^{-1}$ (Table 3). The outlet glaciers that have experienced the greatest area loss are on the eastern and southern side of the ice cap, with their termini retreating 3–4.5 km from the maximum LIA extent (Figure 6). The eastern Hagafellsjökull glacier surged in 1974, 1980, 1999 (Björnsson *et al.*, 2003), and the terminus advanced by approximately 1 km each time. Leaving its terminus in a more advanced position in 2000 than in 1973 for example (Figure 6).

The LIA extent of Langjökull has been delineated from geomorphological field evidence, with support from historical documents, maps and photographs from the 19$^{\text{th}}$ century to the early 20$^{\text{th}}$ century, along with field observations (e.g. Geirsdóttir *et al.*, 2008). Detailed oblique and aerial photographs support the estimated maximum LIA extent (see Pálsson *et al.*, 2012, for further description).

The smaller glaciers in the vicinity of Langjökull, namely, Þórisjökull, Eiríksjökull and Hrútfellsjökull have lost 20 km^2, 17 km^2 and 6 km^2, respec-

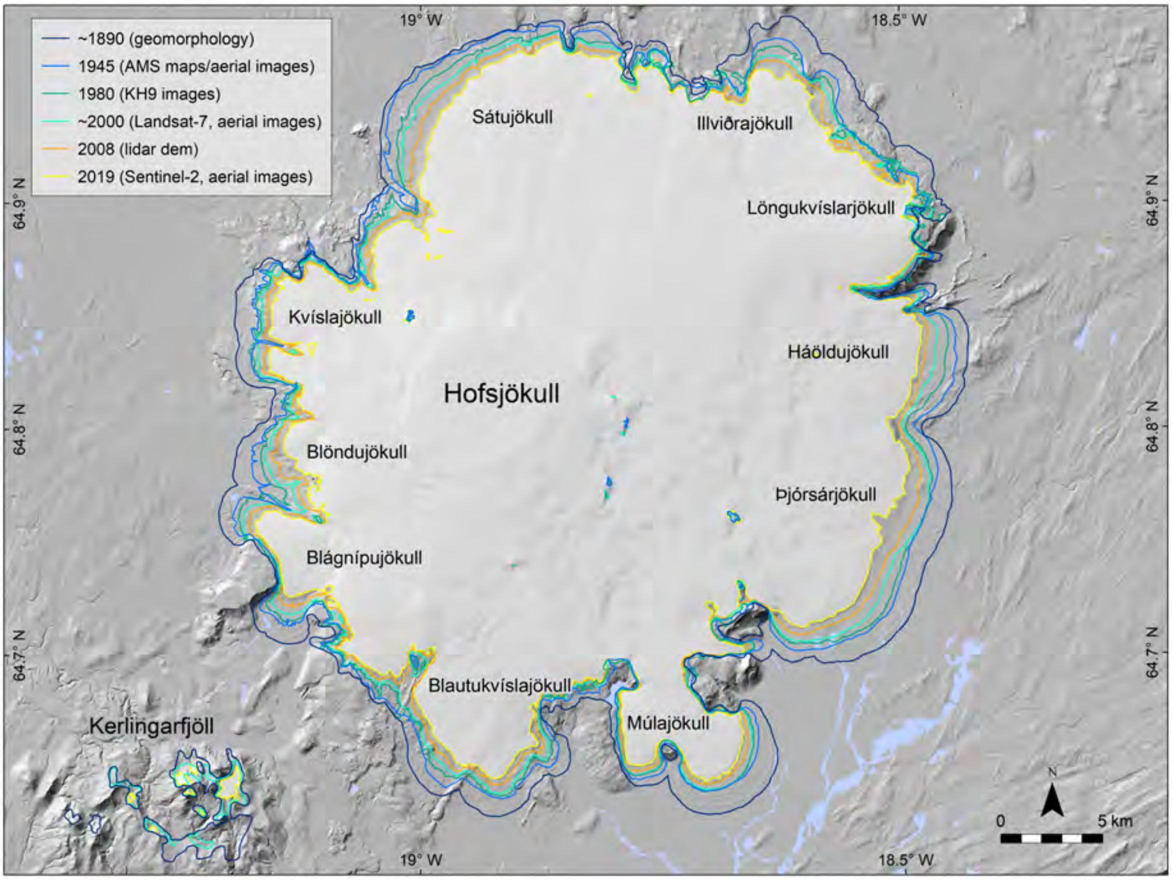

Figure 5: The extent of Hofsjökull ice cap and the small glaciers in Kerlingarfjöll mountains southwest of the ice cap at several times since the LIA maximum in ∼1890. – *Útlínur Hofsjökuls og smájöklanna í Kerlingafjöllum á mismunandi tímum frá því um 1890.*

tively, during the time period ∼1890–2019, or 46%, 45% and 59% of their maximum LIA size. However, Ok glacier, which had an area $>10\,km^2$ at the end of the LIA, has almost disappeared. It was declared to no longer exist as a dynamically active glacier in the year 2014, although a few small, thin patches of a disintegrated glacier ice (in total $0.07\,km^2$ in 2019, $<0.03\,km^2$ each) can still be found in the area.

Mýrdalsjökull, Eyjafjallajökull and smaller southern glaciers

Mýrdalsjökull ice cap lost $216\,km^2$ during the period ∼1890–2019, amounting to 29% of its maximum LIA size. The main area loss has taken place on the northern and eastern sides of the ice cap, where the termini have retreated between 2.5 and 3.5 km from their maximum LIA extent (Figure 7). The rate of area change since 2000 is in the range of $-3.1\ km^2\,a^{-1}$ to $-5.7\ km^2\,a^{-1}$ (Table 3). The highest area loss occurred during 2010–2014, when Kötlujökull retreated several hundred metres. However, it is worth noting, that the delineation of the glacier terminus from the lidar DEM (of 2010) is rather problematic at the terminus, due to the debris cover, which is hard to differentiate from the proglacial area.

The forefield of the outlet glacier Sólheimajökull from Mýrdalsjökull ice cap (Figure 7) has been studied in detail (e.g. Schomacker *et al.*, 2012, and

Table 3: Comparison of area change and rates of area change for the main ice caps and glaciers and groups of intermediate-size glaciers (divided according to their ∼2000 area), excluding the small glaciers (shown in blue in Figure 1). The rates of area change for each time interval is based on the actual time period, which varies between the ice caps and glaciers (see Table 2). The maximum LIA of Drangajökull is dated to ∼1850. Although a few glaciers on Tröllaskagi belong to the intermediate-size category in terms of their size, their outlines are only available for a limited number of years, and they are therefore not included here. – *Samanburður á flatarmálsbreytingu og hraða flatarmálsbreytingar fyrir stærri jökla landsins (jöklum minni en 3 km^2 er sleppt). Hraði flatarmálsbreytingar er reiknaður samkvæmt árafjölda hvers tímabils sem er mismunandi eftir hverjum jökli fyrir sig (sjá töflu 2). Drangajökull náði hámarksútbreiðslu um 1850. Þrátt fyrir að nokkrir jöklar á Tröllaskaga falli í miðlungs stærðarflokkinn eru þeir ekki teknir með hér þar sem útlínur þeirra eru ekki tiltækar á mörgum mismunandi árum.*

	∼1890–1945/46	**1945/46–∼1973**	**∼1973–∼2000**	**∼2000–∼2010**	**∼2010–∼2014**	**2014–2019**
Total glacier area						
Total area change (km^2)	−999	−272	−194	−404	−175	−179
Total area change (%)	−7.93	−2.35	−1.71	−3.63	−1.63	−1.70
Rate of change (km^2 a^{-1})	−18.2	−9.72	−7.19	−40.4	−43.8	−35.9
Rate of change (% a^{-1})	−0.14	−0.08	−0.06	−0.36	−0.41	−0.34
Vatnajökull						
Total area change (km^2)	−463	−112	−93	−241	−67	−94
Total area change (%)	−5.27	−1.34	−1.13	−2.97	−0.85	−1.20
Rate of change (km^2 a^{-1})	−8.42	−3.98	−3.43	−21.9	−22.3	−18.8
Rate of change (% a^{-1})	−0.10	−0.05	−0.04	−0.27	−0.28	−0.24
Langjökull						
Total area change (km^2)	−101	−61	−10.4	−24.6	−34	−26.4
Total area change (%)	−9.24	−6.15	−1.12	−2.67	−3.79	−3.06
Rate of change (km^2 a^{-1})	−1.84	−2.18	−0.39	−3.51	−4.86	−5.28
Rate of change (% a^{-1})	−0.17	−0.22	−0.04	−0.38	−0.54	−0.61
Hofsjökull						
Total area change (km^2)	−90	−25	−31	−40	−27	−15.1
Total area change (%)	−8.67	−2.59	−3.40	−4.50	−3.13	−1.83
Rate of change (km^2 a^{-1})	−1.64	−0.88	−1.65	−4.46	−4.45	−3.02
Rate of change (% a^{-1})	−0.16	−0.07	−0.18	−0.50	−0.52	−0.37
Mýrdalsjökull						
Total area change (km^2)	−84	−45	−10.9	−34.4	−22.7	−18.8
Total area change (%)	−11.4	−6.90	−1.80	−5.77	−4.04	−3.49
Rate of change (km^2 a^{-1})	−1.53	−1.61	−0.57	−3.13	−5.68	−3.76
Rate of change (% a^{-1})	−0.21	−0.20	−0.09	−0.52	−1.01	−0.70
Drangajökull						
Total area change (km^2)	−109	−12.9	−1.9	−2.4	0.05	−6.3
Total area change (%)	−40.4	−8.02	−1.28	−1.64	0.08	−4.38
Rate of change (km^2 a^{-1})	−1.1	−0.46	−0.07	−0.34	0.03	−1.26
Rate of change (% a^{-1})	−0.43	−0.27	−0.04	−0.23	0.02	−0.88
Eyjafjallajökull						
Total area change (km^2)	−29.4	−4.6	−1.4	−8.2	−2.9	−3.4
Total area change (%)	−25.3	−5.31	−1.71	−10.2	−4.01	−4.89
Rate of change (km^2 a^{-1})	−0.53	−0.16	−0.07	−0.91	−0.73	−0.68
Rate of change (% a^{-1})	−0.46	−0.15	−0.08	−1.13	−1.00	−0.98
Intermediate-size glaciers (∼10–40 km^2, n=7)						
Total area change (km^2)	−10.0	−0.95	−1.87	−2.65	−0.65	−0.75
Total area change (%)	−29.4	−4.49	−7.69	−9.41	−13.76	−4.28
Rate of change (km^2 a^{-1})	−0.17	−0.03	−0.07	−0.30	−0.15	−0.15
Rate of change (% a^{-1})	−0.95	−0.16	−0.37	−1.55	−1.09	−0.83
Intermediate-size glaciers (∼3–10 km^2, n=5)						
Total area change (km^2)	−3.46	−0.78	−1.10	−1.19	−0.22	−0.28
Total area change (%)	−36.1	−12.3	−19.8	−29.4	−12.8	−5.34
Rate of change (km^2 a^{-1})	−0.06	−0.03	−0.05	−0.13	−0.06	−0.06
Rate of change (% a^{-1})	−0.78	−0.37	−0.83	−3.21	−2.50	−1.07

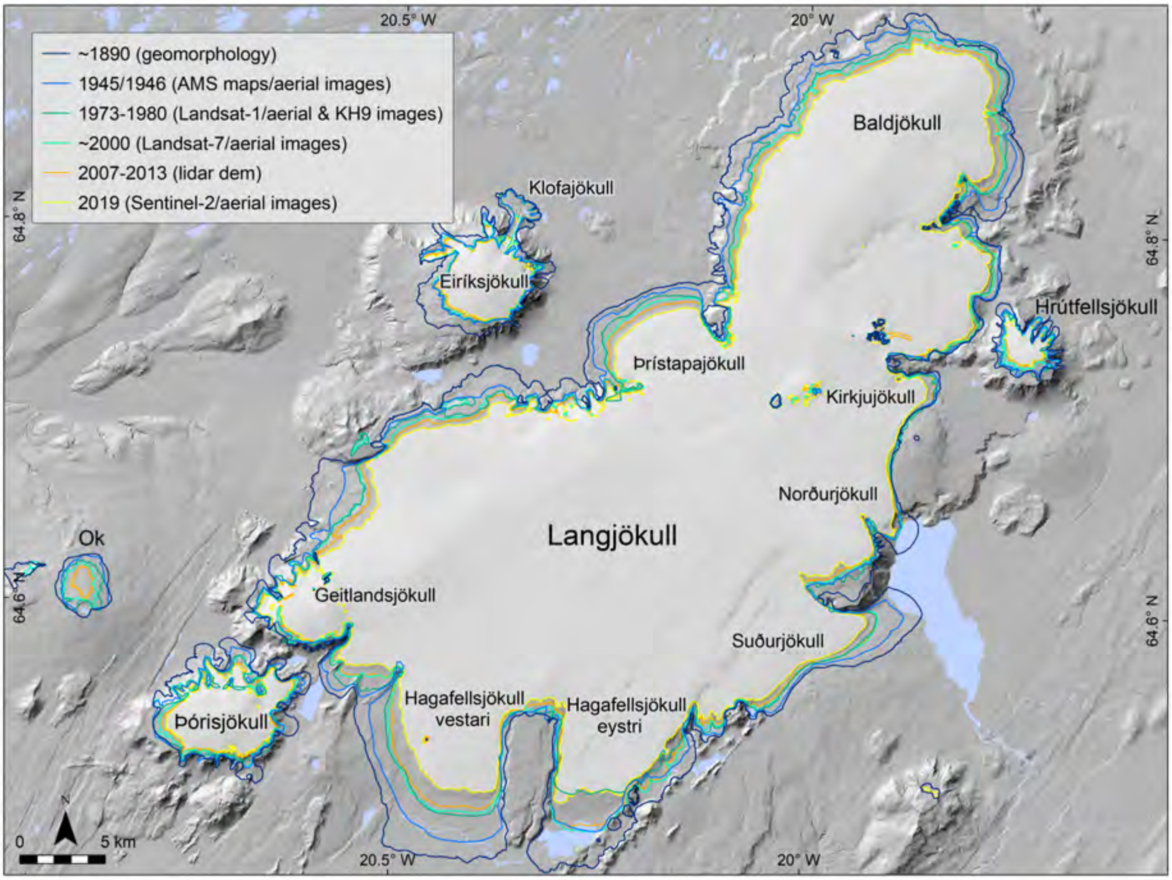

Figure 6: The extent of Langjökull ice cap, Eiríksjökull, Þórisjökull, Ok glacier and Hrútfellsjökull at several times since the LIA maximum in $\sim$1890. – *Útlínur Langjökuls, Eiríksjökuls, Þórisjökuls, Oks og Hrútfellsjökuls á mismunandi tímum frá því um 1890.*

references therein). This outlet glacier reached its Holocene maximum extent approximately 2000 years ago, whereas the LIA maximum moraines are located some tens of metres outside the 1904 margin, which is depicted on the map of the Danish General Staff from 1907 (Danish Geodetic Institute, 1941b). The forefield of the eastern margin of Mýrdalsjökull (Sandfellsjökull and Öldufellsjökull) has been mapped by Evans *et al.* (2018), providing a high-resolution delineation of the glacier margin at the LIA maximum, and the forefield of Kötlujökull was mapped by Kjær and Krüger (2001). Thoroddsen (1906) noted that Kötlujökull was in an advanced state in 1893, and no terminal moraines have been found farther from the glacier. The outermost moraines of Sléttjökull were formed around the turn of the 20^{th} century, supported by a photograph taken by Karl Sapper in 1906 (Krüger *et al.*, 2010). Jökulhlaups due to subglacial eruptions or released from subglacial geothermal areas may have washed away or buried moraines in the forefield. Terminus variations of Mýrdalsjökull may have been affected by volcanic eruptions of Katla (Larsen, 2010) that may melt several km^3 of ice and change the subglacial topography of the Mýrdalsjökull ice cap.

Mýrdalsjökull and Eyjafjallajökull may have been connected during the maximum LIA stage (H. Björnsson, 1993) but it is uncertain whether the Fimmvörðuháls ridge (Figure 7), between the two ice caps, was covered by dynamically moving glacier ice or thick firn (Sigurðsson, 2004). The LIA extent of Eyjafjalla-

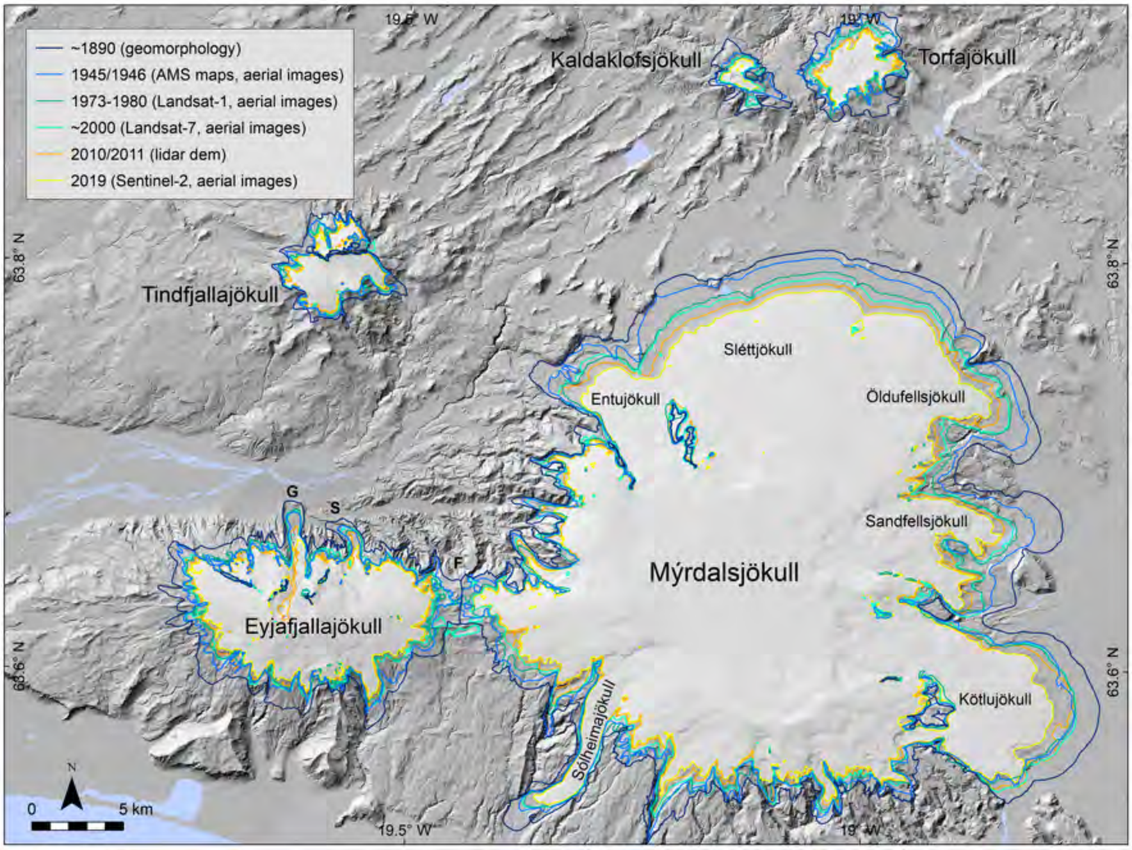

Figure 7: The extent of Mýrdalsjökull ice cap, Eyjafjallajökull ice cap, Tindfjallajökull, Kaldaklofsjökull and Torfajökull at various years since the LIA maximum in ∼1890. G: Gígjökull, S: Steinsholtsjökull, F: Fimmvörðuháls. – *Útlínur Mýrdalsjökuls, Eyjafjallajökuls, Tindfjallajökuls, Kaldaklofsjökuls og Torfajökuls á mismunandi tímum frá því um 1890.*

jökull has not been traced by detailed geomorphological mapping in the field, except for the proglacial area of Gígjökull and Steinsholtsjökull (Kirkbride and Dugmore, 2008). Eyjafjallajökull ice cap decreased by 50 km^2 during the period ∼1890–2019, corresponding to 43% loss in area compared with its maximum LIA extent. The rate of area change since 2000 is in the range of $-0.7\,km^2\,a^{-1}$ to $-0.9\,km^2\,a^{-1}$ (Table 3).

Tindfjallajökull, Torfajökull and Kaldaklofsjökull have lost 10 km^2, 15 km^2 and 16 km^2, respectively, in the ∼1890–2019 period (Table 2), corresponding to 45%, 74% and 80% area loss, relative to their maximum LIA extent. Their maximum LIA extent has not been mapped by field surveys, and the glacial geomorphologic evidence is rather sparse in the rhyolitic mountains north of Mýrdalsjökull ice cap. When Karl Sapper visited Torfajökull in 1906, its southwest margin had recently receded up to 150 m (Þórarinsson, 1943). The extent of Tindfjallajökull in 1907 is shown on the map of the Danish General Staff, as well as some moraines in front of the glacier snouts, presumably from the LIA (Danish Geodetic Institute, 1908).

Drangajökull, Gláma and Snæfellsjökull

Drangajökull ice cap has decreased by 133 km^2 during the time period ∼1850–2019, which amounts to a 49% reduction in area relative to its maximum LIA size (Table 2, Figure 8). The rate of area change was highest during the time period 2014–

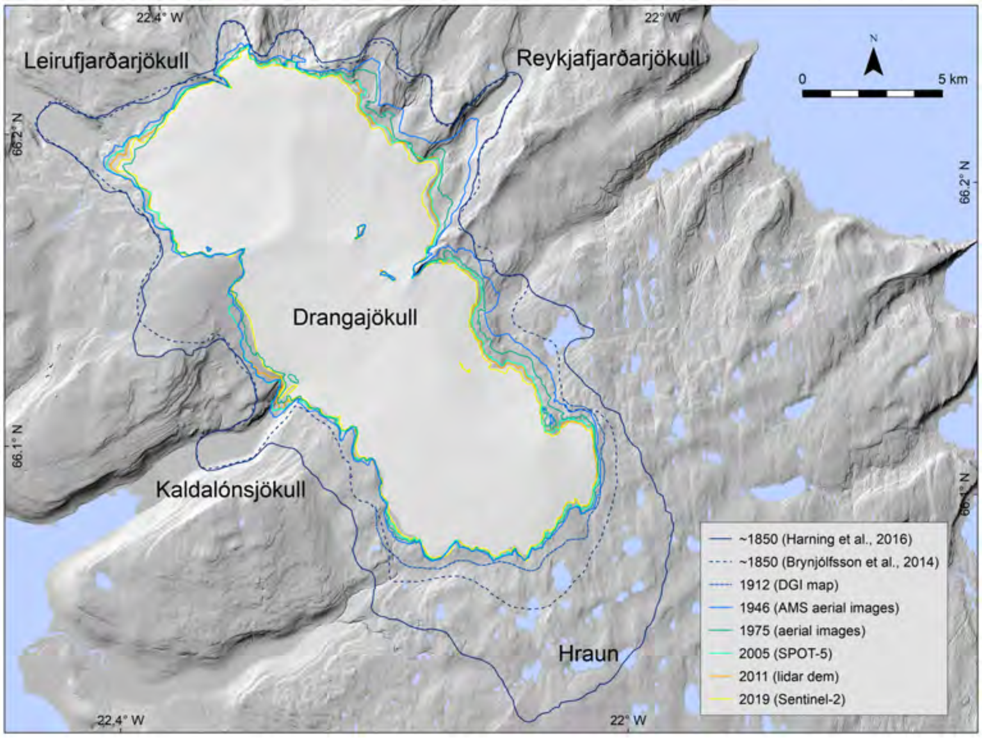

Figure 8: The extent of Drangajökull ice cap at several times since the LIA maximum. Drangajökull reached the maximum LIA extent a few decades earlier than most glaciers in Iceland, around 1850 (Þórarinsson, 1943; Brynjólfsson *et al.*, 2015; Harning *et al.*, 2016). Two ~1850 extents are presented, published by Harning *et al.* (2016) (chosen as the maximum LIA extent and sent to GLIMS) and Brynjólfsson *et al.* (2014). The 1912 outline from the map of the Danish General Staff (Danish Geodetic Institute, 1941a) for the southeastern part of the glacier is shown for comparison. – *Útlínur Drangajökuls á mismunandi tímum frá hámarki litlu ísaldar. Drangajökull náði mestri útbreiðslu á litlu ísöld um 1850, nokkrum áratugum fyrr en flestir jöklar á Íslandi (Þórarinsson, 1943; Brynjólfsson o.fl., 2015; Harning o.fl., 2016). Tveir möguleikar á hámarksútbreiðslu jökulsins eru sýndir, annars vegar skv. grein Harning o.fl. (2016) og hins vegar skv. grein Skafta Brynjólfssonar o.fl. (2014). Sú fyrrnefnda var valin til þess að senda til GLIMS. Útlína jökulsins suðaustanmegin frá 1912 er fengin af korti danska herforingjaráðsins og sýnd til samanburðar við hámarksútbreiðslu um 1850.*

2019, $-1.3\,\mathrm{km^2\,a^{-1}}$, and similar during the time period ~1850–1945, $-1.1\,\mathrm{km^2\,a^{-1}}$ (Table 3).

The recent retreat history of Drangajökull is described in Magnússon *et al.* (2016) and Belart *et al.* (2020). The LIA glacier history has been extracted from historical accounts (Þórarinsson, 1943), the analysis of moraines, lake sediments and exposed dead vegetation emerging from beneath the ice cap (Brynjólfsson *et al.*, 2014, 2015; Harning *et al.*, 2016; Anderson *et al.*, 2018). From these records, it is known, that the different outlet glaciers, as well as other parts of the ice cap did not reach the maximum LIA extent simultaneously. Sigurður Þórarinsson concluded, based on historical accounts about destruction of farmland, that the outlet glaciers of Drangajökull reached their maximum LIA extent around the middle of the 18$^{\mathrm{th}}$ century (Þórarinsson, 1943; Þórarinsson, 1974). They reached almost the same extent shortly before the middle of the 19$^{\mathrm{th}}$ century, thereafter slowly retreating to the end of the century. This is similar to the conclusions of Harning *et al.* (2016), that the final expansion to the peak LIA extent was most likely reached around the middle of 17$^{\mathrm{th}}$ or the 18$^{\mathrm{th}}$ centuries.

From the study of Brynjólfsson *et al.* (2015) it is known that the surges of the outlet glaciers of Drangajökull (Reykjafjarðarjökull, Leirufjarðarjökull and Kaldalónsjökull, see Figure 8) were non-synchronous. Therefore, the ice margin reached its farthermost position at different times at different locations. Each of these glaciers has surged several times since 1700 and they then extended 3–4 km farther down-valley than at present.

Þórarinsson's (1943) analysis was carried out before understanding of the effect of surges on glacier variations. Some of the conclusions of his analysis may reflect the effect of a surge on individual outlet glaciers rather then a general expansion of the entire ice margin. It is possible that further examination of historical information about travel routes over and near the ice cap in recent centuries will provide more clues to delineate the maximum LIA extent of the ice cap with more certainty.

The glacier reconstructions of the LIA extent by Brynjólfsson *et al.* (2014) and Harning *et al.* (2016) (Figure 8), differ mainly in the southeastern part of the ice cap (in the highland area called Hraun), resulting in a LIA maximum area difference of 50 km^2 (220 km^2 reported in Brynjólfsson *et al.*, 2014, and 270 km^2 published by Harning *et al.*, 2016). Our LIA maximum outline of Drangajökull is based on the reconstruction of Harning *et al.* (2016), which is supported by data from lake sediments and detailed field observations.

Measurements by the Danish General Staff in 1912 (Danish Geodetic Institute, 1941a) show Drangajökull with an area of 200 km^2 and a smaller extent of the southeastern part of the ice cap, compared with the maximum LIA extent of both Brynjólfsson *et al.* (2014) and Harning *et al.* (2016) (see Figure 8). The geological map by Þorvaldur Thoroddsen (1901), based on his own field observations in 1886 (Thoroddsen, 1887), indicates an even larger ice cap near the end of the 19th century with an area of ca. 350 km^2, and Björn Gunnlaugsson's map from 1844 shows a much larger ice cap still, with an area >550 km^2 extending all the way to the Steingrímsfjarðarheiði mountain overpass (see Figure 1) towards southeast (Þórarinsson, 1943, 1974). It should be born in mind that neither Gunnlaugsson nor Thoroddsen visited the area in question on the south side of Drangajökull.

A highland area at 700–800 m a.s.l. on the northwest of Drangajökull, north of Kaldalón (Figure 8), is included within the LIA maximum extent of the ice cap and contributes with $\sim$10–15 km^2 to the LIA maximum area of Drangajökjull in Tables 2 and 3. It is uncertain whether this part of the ice cap was ever dynamically connected to the main Drangajökull ice cap. The same may apply to parts of the larger area on the highland on the southeast side of the ice cap (in Hraun), discussed in the previous paragraph. These areas may have been partly or largely covered with perennial snow and firn rather than glacier ice. This may be the explanation that there is proportionally a larger change in area for Drangajökull between LIA maximum and 1945 than for any other of the main ice caps. The above mentioned earlier LIA maximum of Drangajökull, around the middle of the 19th century, compared with $\sim$1890 for the other main ice caps, may also partly explain this proportionally larger area change which, thus, took place over a longer time interval for Drangajökull.

The so-called Glámujökull "ice cap" south of Ísafjarðardjúp in Vestfirðir (see Gláma highland in Figure 1) is not included in our list of glaciers during the LIA in Iceland, as it was observed to be merely disconnected snow patches in 1893 and is, therefore, unlikely to have been a substantial ice body during the LIA (Sigurðsson, 2004). The Glámujökull "ice cap" is, however, mapped as a glacier on several maps of Iceland dating from the 18th and 19th centuries and described as a glacier in many historical documents.

Snæfellsjökull (located near the western end of the Snæfellsnes peninsula) has lost 16 km^2, and currently has only 35% of its maximum LIA extent. The main area loss occurred on the northern side, where the outlet glaciers have retreated 1.5–2 km; this is where the glacier reached the lowest elevation (Figure 9).

The maximum LIA extent of Snæfellsjökull has been delineated from detailed mapping (Evans *et al.*, 2016a). The average thickness of Snæfellsjökull in 2003 was only 30 m according to radio-echo soundings (Davíðsdóttir, 2003). Between 1999 and 2008,

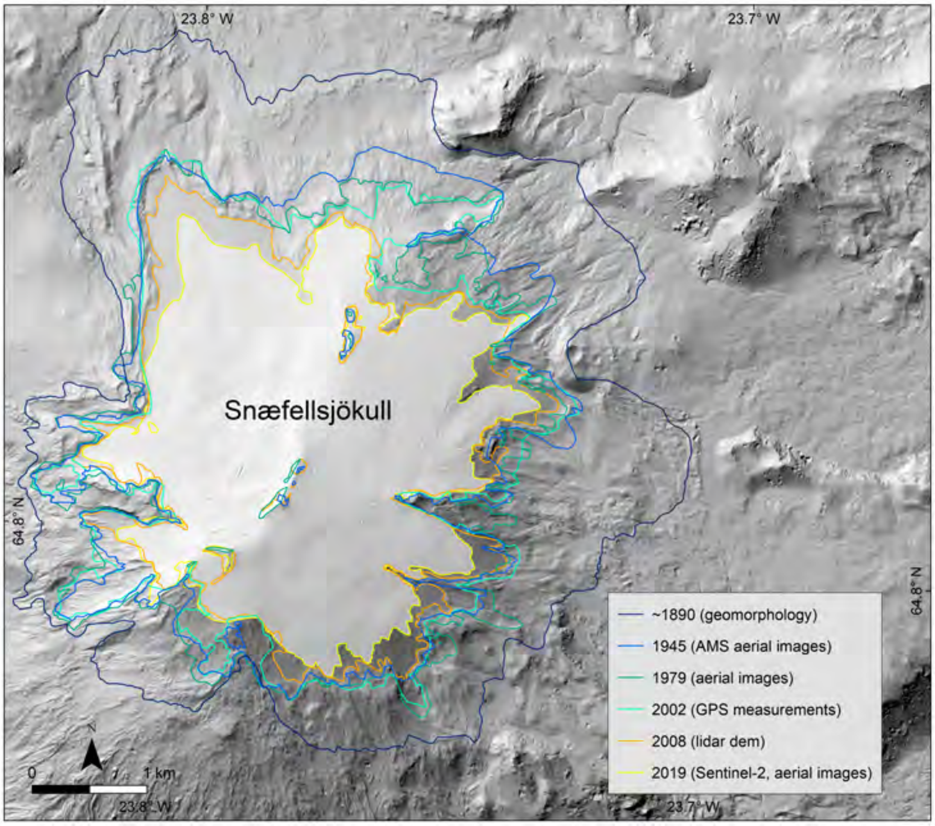

Figure 9: The extent of Snæfellsjökull ice cap at several times since the LIA maximum in ∼1890. – *Útlínur Snæfellsjökuls á mismunandi tímum frá því um 1890.*

the average surface lowering was approximately 15 m (Jóhannesson *et al.*, 2011), and Snæfellsjökull is expected to lose proportionally more mass in the near future than most other well-known Icelandic glaciers (Jóhannesson *et al.*, 2011), although it may not disappear entirely since the bed reaches > 1400 m a.s.l., well above the local ELA (unpubl. data).

Þrándarjökull and Hofsjökull eystri

Þrándarjökull and Hofsjökull eystri have decreased by 20 km^2 and 9 km^2, respectively, loosing approximately 59% and 73% of their maximum LIA size (Table 2). Their maximum LIA extent of was delineated from remote sensing data and is based on sparse glacial geomorphological landforms around the glaciers (Figure 10). The outlines since the mid-20th century have been mapped in more detail from aerial images (Belart *et al.*, 2020).

Glaciers on Tröllaskagi and Flateyjarskagi

The total area of glaciers on Tröllaskagi decreased by 74 km^2 during ∼1890–2019 (Table 2), which is close to 40% of their cumulative maximum LIA area. However, as mentioned previously, the maximum LIA glacier outline has not been traced in detail except for few glaciers on the peninsula. The maximum LIA extent for most of the glaciers on Tröllaskagi peninsula has been derived from remote sensing data only; only a few glaciers have been studied in detail (Caseldine, 1985; Caseldine and Stötter, 1993; Stötter *et al.* 1999; Wastl *et al.*, 2001; Brynjólfsson *et al.*, 2012; Fernández-Fernández *et al.*, 2017, 2019; Tanarro *et al.*, 2019). Reliable information about the age of the LIA moraines comes mainly from radiocarbon dating and tephrochronology (Häberle, 1991, 1994; Stötter, 1991; Stötter *et al.*, 1999; Wastl and Stötter, 2005).

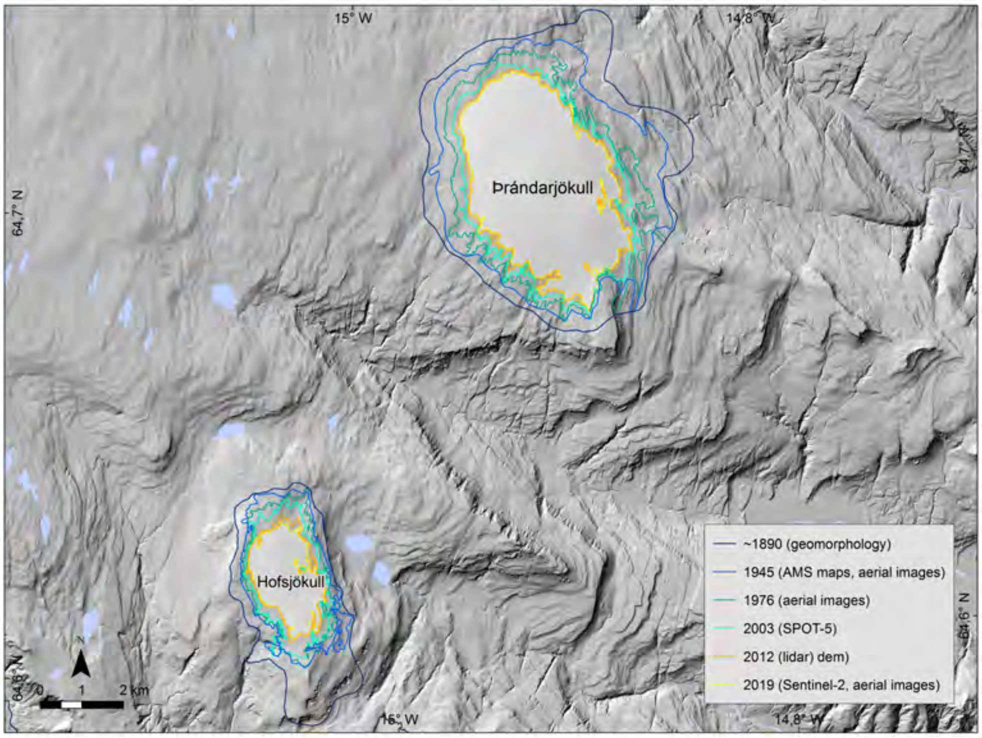

Figure 10: The extent of Þrándarjökull and Hofsjökull eystri in East-Iceland at several times since ∼1890. – *Útlínur Þrándarjökuls og Hofsjökuls eystri á mismunandi tímum frá því um 1890.*

The ∼1890 glacier outline presented here (Figure 11) is a first attempt to delineate the maximum LIA extent for most of the glaciers on the peninsula. The origin and formation of the glaciers is diverse, and the area includes many rock glaciers and ice-cored moraines (e.g. Lilleøren *et al.*, 2013). Work is ongoing to refine the LIA glacier extent of some glaciers with detailed fieldwork and further analysis of remote sensing data (e.g. Fernández-Fernández *et al.*, 2019; Tanarro *et al.*, 2019). Apparently, many of the debris-covered glaciers have not retreated much since the LIA maximum, as the LIA outline overlies the more recent outlines at several locations (Figure 11), although considerable thinning has been observed (Brynjólfsson, unpubl. data). Many of the debris-free glaciers have retreated, as evidenced for example by the frontal measurements of Gljúfurárjökull and Tungnahryggsjökull (spordakost.jorfi.is).

The total area of glaciers on Flateyjarskagi decreased by 9 km^2 in ∼1890–2019 (Table 2), close to 50% of their maximum LIA area. However, as for the Tröllaskagi glaciers, the maximum LIA glacier outline has not been traced in detail by field measurements, and the moraines have not been dated.

Other small glaciers

Glaciers in the 0.01–3.0 km^2 size range (in the year 2000), are found in East, Southeast, South, West and Northwest Iceland as well as in Kerlingarfjöll mountains in central Iceland (see Figure 1, Sigurðsson and Williams, 2008, and Sigurðsson *et al.*, 2017, for further information). The LIA maximum glacier outline has only been traced from remote sensing data (without detailed field mapping). These small glaciers were systematically mapped in ∼2000 and again in 2017.

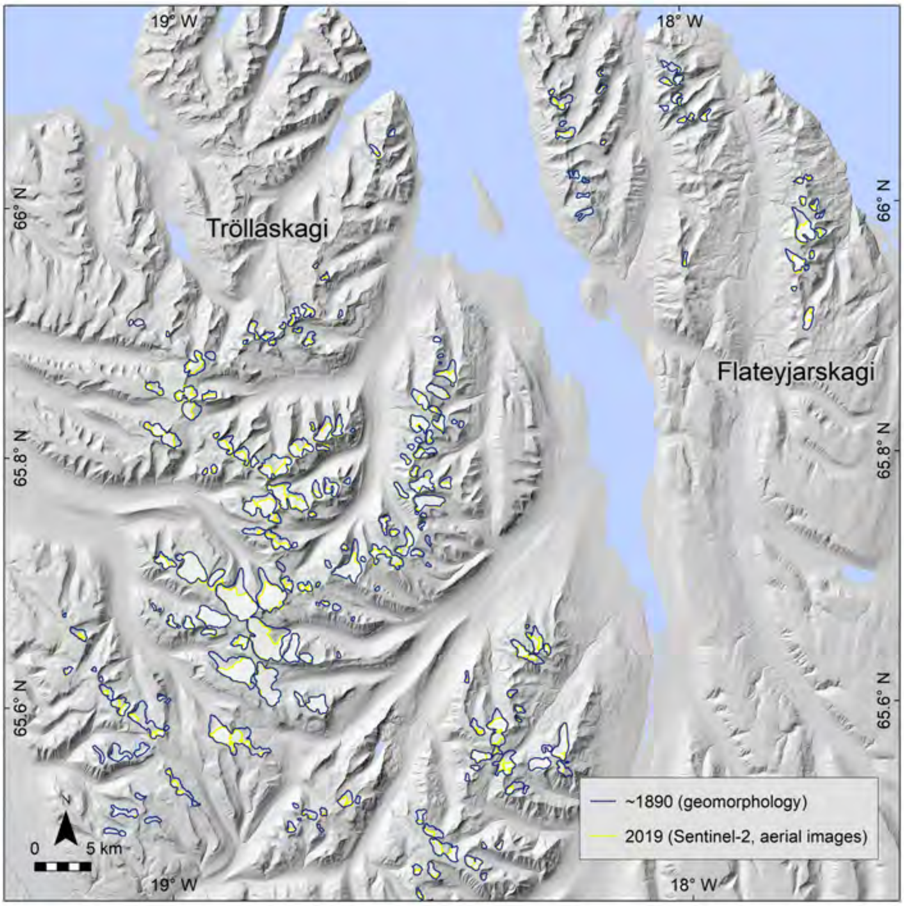

Figure 11: The extent of the glaciers on Tröllaskagi and Flateyjarskagi is only shown in ∼1890 and 2019. Their outlines for ∼2000 has also been mapped but is not shown as it is close to the 2019 outlines. – *Útlínur jökla á Trölla- og Flateyjarskaga um 1890 og 2019. Útlínur þeirra frá árinu 2000 hafa einnig verið kortlagðar, en eru ekki sýndar hér vegna þess að þær falla nánast saman við útlínurnar frá árinu 2019.*

Variations in glacier area since the end of the 19$^{\mathrm{th}}$ century

The variation in the area of glaciers in Iceland since the late 19$^{\mathrm{th}}$ century shows that the larger ice caps (Vatnajökull, Hofsjökull, Langjökull and Mýrdalsjökull) have lost approximately 10–30% of their maximum LIA area, whereas intermediate-size glaciers have lost 35–85%, in general, with larger relative area loss the smaller the glacier (Figure 12). There is, however, a larger error in the estimated maximum LIA extent of the smaller glaciers, due to the scarcity of moraines and other glacial geomorphological evidence. Slight errors in the maximum LIA extent of the smaller glaciers, considerably affect the relative area curve for the whole time series.

The (absolute) area changes of the ice caps and glaciers considered in this paper are shown in Figure 13. The surge of Brúarjökull in 1963–1964 is the only surge that considerably affected the area of an entire ice cap or glacier since the end of the 19$^{\mathrm{th}}$ century. During that surge, this outlet glacier increased in area by 160 km^2 due to the advance of the terminus (Guðmundsson *et al.*, 1996).

Data on glacier area from additional sources have been included in Figure 12 to increase the temporal detail – these are derived from glacier outlines not

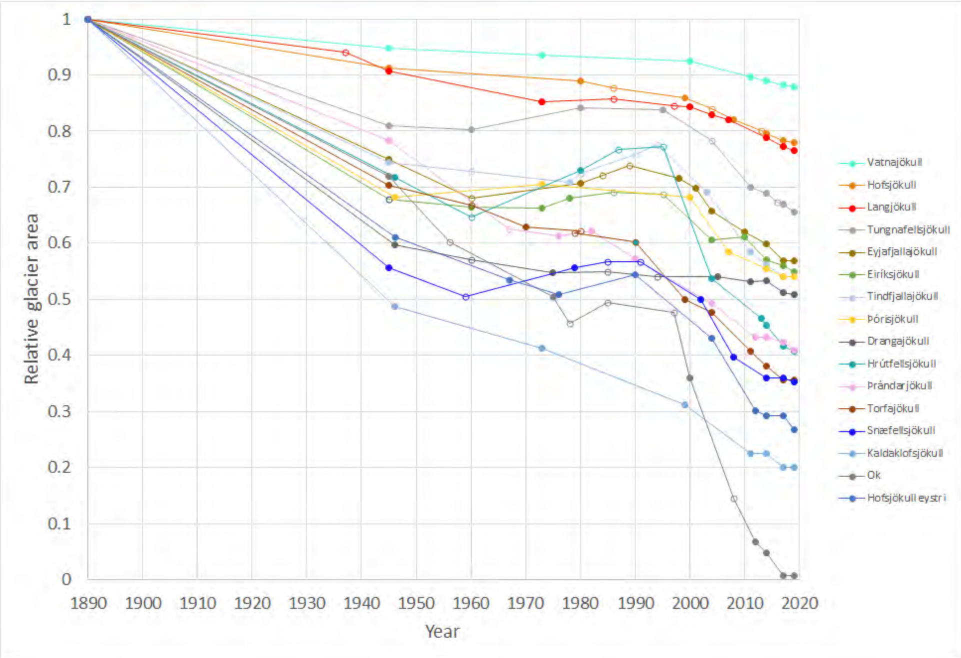

Figure 12: The area change of the ice caps and glaciers in Iceland relative to their extent at the LIA maximum from ∼1890 until 2019, excluding the smallest glaciers (< 3 km^2 in 2000). The LIA maximum for Drangajökull is dated to ∼1850 but plotted starting in ∼1890 for simplicity. Glacier area derived from outlines not included in the GLIMS data set have been added to increase the temporal resolution (open circles). They are based on Pálsson *et al.* (2012), Helgadóttir (2017), Belart *et al.* (2020), and unpublished data from the IES-UI and IMO. – *Hlutfallsleg flatarmálsbreyting jökla (að undanskildum litlum jöklum minni en 3 km^2). Þrátt fyrir að Drangajökull hafi náð hámarksútbreiðslu um 1850 miðast línuritið við 1890 til einföldunar. Flatarmál jökla skv. öðrum gögnum en gerð er grein fyrir hér og send hafa verið til GLIMS, er sýnt með opnum hringjum. Þessi viðbótargögn eru frá Finni Pálssyni o.fl. (2012), Maríu Jónu Helgadóttir (2017), Joaquin Belart o.fl. (2020) auk óbirtra gagna frá Jarðvísindastofnun háskólans og Veðurstofu Íslands.*

shown on the glacier maps (see references in the figure caption). The smaller glaciers and ice caps with steep outlets responded more rapidly to the cooler climate after 1960 than the larger glaciers, and gained enough mass to advance 100–500 m, for example Snæfellsjökull, Tindfjallajökull, Eyjafjallajökull and Hrútfellsjökull, as can be seen from the more detailed time series of those glaciers shown in Figure 12.

Glaciers with termini reaching down to low elevations experience larger relative area loss than glaciers at high elevation. When the lower-lying glaciers/outlet glaciers have lost a substantial proportion of their ablation area, the rate of area loss tends to slow down. Recently, dead ice lobes have been observed becoming detached from some glacier tongues, for example in 2018 when the snout of eastern Hagafellsjökull was shortened by 700 m due to this process (Einarsson, 2019, spordakost.jorfi.is), which may lead to an abrupt change in glacier area for individual glaciers.

Some tens of small, named glaciers have essentially disappeared since the year 2000. The first well-known Icelandic glacier to be declared "dead" or non-existing as a dynamically moving ice body, was Ok glacier, which had a narrow elevation span (1100–1200 m). Less than 1% of the maximum LIA area of Ok glacier remain in the form of several thin, disintegrating ice patches in local depressions.

A comparison of area change and rates of area change for the main ice caps and glaciers and for groups of smaller glaciers for different time periods is presented in Table 3. The rate of total area change, which is dominated by Vatnajökull,

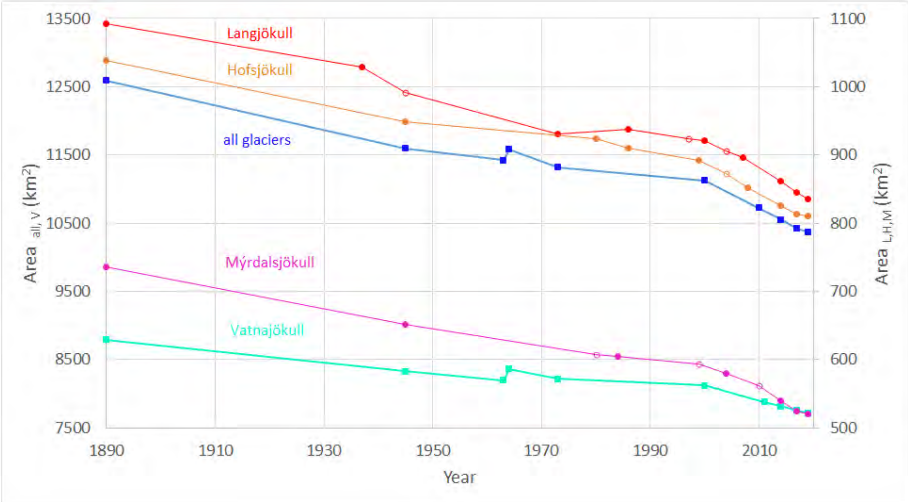

Figure 13: Area (with respect to the maximum LIA extent) of the main Icelandic ice caps and all the glaciers in total since the end of the 19th century. Open circles denote additional data points that are not derived from outlines in the GLIMS data set (see caption of Figure 12). The step rise in the curves for Vatnajökull and all glaciers is due to the surge in Brúarjökull in 1963–1964. The left y-axis applies to the area of Vatnajökull (V) and all glaciers (blue line), whereas the right y-axis applies to the smaller ice caps (L=Langjökull, H=Hofsjökull, M=Mýrdalsjökull). – *Flatarmál meginjökla landsins og einnig allra jökla landsins samtals. Skyndileg aukning í flatarmáli Vatnajökuls árið 1964 kemur til vegna framhlaups Brúarjökuls 1963–1964. Vinstri y-ásinn á við Vatnajökul og alla jökla (blá lína), en hægri y-ás á við Langjökul, Hofsjökul og Mýrdalsjökul.*

varies between $-7.2\,\mathrm{km}^2\,\mathrm{a}^{-1}$ ($\sim$1973 to $\sim$2000) and $-44\,\mathrm{km}^2\,\mathrm{a}^{-1}$ ($\sim$2010 to $\sim$2014). The rate of relative area change is in general inversely related to the size of the glacier. It is greatest in magnitude for the smaller intermediate-size glaciers (3–10 km^2) and varies between $-0.37\,\%\,\mathrm{a}^{-1}$ ($\sim$1945 to $\sim$1973) and $-2.5\,\%\,\mathrm{a}^{-1}$ ($\sim$2010 to 2014). This may for example be compared with $-0.07\,\%\,\mathrm{a}^{-1}$ (in $\sim$1945 to 1973) and $-0.52\,\%\,\mathrm{a}^{-1}$ ($\sim$2010 to 2014) for Hofsjökull.

DISCUSSION

The general pattern of glacier area changes reflects the fluctuations in the climate in Iceland since the end of the 19th century, as seen in variation in the summer temperature in Stykkishólmur (Figure 2), with occasional exceptions due to surges. This temperature record may be considered representative of the rather spatially uniform decadal temperature variations in Iceland (Crochet, 2011), in agreement with model studies of the response of Icelandic glaciers to climate variations (Aðalgeirsdóttir *et al.*, 2011; Flowers *et al.*, 2007, 2008; Schmidt *et al.*, 2017). Areal changes are not an unequivocal indicator of climate changes, as glacier response to climate change depends on several non-climatic factors. But area changes are more easily extracted from various remote sensing data and historical information about glacier variations than glaciological or geodetic mass balance. Information about variations in glacier extent can be useful to complement available data about mass-balance variations in analyses of glacier–climate interactions, and past changes in ice volumes can be derived from glacier extent variations with the volume–area scaling method (Bahr *et al.*, 2015; Aðalgeirsdóttir *et al.*, 2020).

Glacier-area changes and outlet-length variations are related, as the main area changes generally take place in the ablation area. The terminus variation measurements of the Iceland Glaciological Society (collected since the 1930s, see spordakost.jorfi.is) reflect the general pattern of area changes of glaciers in Iceland. The in-situ length-change observations can now be extended back in time and compared with changes in terminus position derived from the glacier outline inventory. The retreat rates were highest during the most recent time periods (2000–2010, 2010–2014 and 2014–2019, see Table 3), and the maximum rates for most ice caps and glaciers observed in 2010–2014. The rapid retreat during the 1930s and 1940s, as documented in the terminus variations database of the Iceland Glaciological society, is not well represented in the outline inventory, due to poor temporal resolution during the first half of the 20th century. The rate of area decrease may during this time have been similar as in the first two decades of the 21st century. The frontal measurements are an important source of information about glacier variations and complement other data about glacier change.

Multi-temporal glacier outline inventories are important for large-scale (i.e. regional) studies of geodetic mass balance and glacier variations, where the outlines are needed as input data but require tedious work of digitization, clear aims and detailed workflow (e.g. Brun *et al.*, 2017; Dussaillant *et al.*, 2019). Areal changes can also easily be analysed and compared globally on the basis of multi-temporal glacier-outline inventories. The total area of glaciers in Iceland has decreased by 18% since ∼1890. The four largest ice caps (Vatnajökull, Langjökull, Hofsjökull and Mýrdalsjökull) have lost 12–30% since the end of the 19th century, whereas the intermediate-size glaciers have decreased by 35–80%. For comparison, most glaciers worldwide outside Antarctica and Greenland have experienced an area loss of about 30–60% since their mapped maximum LIA extent (Paul and Bolch, 2019), although time periods, climatic regimes, glacier characteristics and sample sizes differ globally.

An increasing number of terminal lakes that are formed as the glaciers retreat, enhance melting of ice and increase glacier retreat, and they have caused rapid changes in the proglacial area of many glaciers in Iceland in the past two decades (Guðmundsson *et al.*, 2020). The development of the terminus lakes will in the future be monitored as part of the monitoring of glacier variations in Iceland and their extent will be submitted to GLIMS as part of the next verion of the Icelandic glacier outline database. Also, individual flow basins will be delineated and submitted to GLIMS, thus the area changes of individual outlet glaciers can then be extracted.

One possible explanation of the widely different extents of Drangajökull ice cap according to different historical sources and field investigations described in a previous section, is that perennial snow may have covered large areas of the plateau near the glacier for several decades during the cold climate of the 18th and 19th centuries. Such areas should be included within the glacier outline according the GLIMS definition (Raup and Khalsa, 2010), but this definition is not easy to apply for LIA glacier extents when the location of the glacier margin is partly based on geomorphological evidence such as moraines. Large areas on the highland to the southeast from Drangajökull may have been covered by perennial snow during parts of the 18th and 19th centuries and these areas are not included within our LIA maximum outline. Brynjólfsson *et al.* (2014) describe that negligible glacial geomorphological imprints in specific areas at elevations 500–600 m around Drangajökull, suggest a thin and not very dynamic glacier ice.

In this paper, we have described the new Icelandic glacier inventory that has been sent to GLIMS. The glacier outline database will be updated with more detailed information based on DEMs and orthoimages that are being created from the historical aerial images of NLSI from the 1940s and 1960s, as well as images from declassified Hexagon KH9 satellites from 1977–1980. Work is ongoing to refine the maximum LIA glacier extent in some areas, where detailed studies of the forefields has not yet been undertaken, for example on Tröllaskagi and Þrándarjökull and Hofsjökull eystri. Complications regarding the maximum LIA extent of glaciers on Tröllaskagi and in some other areas, where glaciogenic landforms are influenced by permafrost (rock glaciers and ice-cored moraines), need to be more thoroughly considered (e.g. Wangensteen *et al.*, 2006; Lilleøren *et al.*, 2013; Tanarro *et al.*, 2019).

The digital outlines provide a baseline for future monitoring of glacier changes and a reference against which changes can be compared. Since the outline data set will be made openly available at GLIMS, for distribution to various other global glacier and open access mapping inventories and archives, it will be available to other researchers and also for various mapping purposes where this type of data is useful, for example for science outreach projects.

CONCLUSION

Glacier-area variations in Iceland since ∼1890 show a clear response to variations in climate. They have been rather synchronous over the country, although surges and subglacial volcanic activity influence the position of some glacier margins.

Glaciers in Iceland have decreased by 18% in area since ∼1890. The main ice caps have lost between 10% and 30% of their maximum LIA size, whereas intermediate-size glaciers have been reduced by up to 80%.

The glacier area in 2019 was approximately 10,400 km^2, and has decreased by more than 2200 km^2 since the end of the 19^{th} century and by approximately 750 km^2 since ∼2000. Some tens of small glaciers have disappeared entirely during the first two decades of 21^{st} century. During that time period, the rate of decrease in area has been approximately $40\,km^2\,a^{-1}$.

The area decrease rates since the late 19^{th}century were highest during the most recent time periods (2000–2010, 2010–2014 and 2014–2019). The glacier retreat rate may have been similar in the 1930s and 1940s; the temporal resolution of the inventory is, however, not sufficient to estimate this.

Glacier inventories are important for climate change studies, for calibration of glacier models and for studies of glacier surges and glacier dynamics and for science outreach projects. It is now possible to extend the terminus variations database of the Iceland Glaciological Society back to the end of the 19^{th} by comparison with the outlines of our inventory.

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Ágrip

Gögnum um útbreiðslu íslenskra jökla hefur verið safnað saman frá nokkrum rannsóknarhópum og stofnunum og nemendaverkefnum, þau samræmd og yfirfarin og send til alþjóðlegs gagnasafn fyrir slík gögn (GLIMS, sjá nsidc.org/glims). Jöklar á Íslandi náðu ekki hámarksútbreiðslu á sama tíma en flestir þeirra tóku að hörfa frá ystu jökulgörðum um 1890. Heildarflatarmál jökla árið 2019 var um 10.400 km^2 og hafa jöklarnir minnkað um meira en 2200 km^2 frá lokum 19. aldar, sem samsvarar 18% flatarmálsins um 1890. Jöklarnir hafa tapað um 750 km^2 frá aldamótunum 2000. Stærri jöklarnir hafa tapað 10–30% af flatarmáli sínu en miðlungsstóru jöklarnir (3–40 km^2 árið 2000) hafa tapað allt að 80% flatarmálsins. Á fyrstu tveimur áraugutum 21. aldar hafa jöklarnir minnkað um u.þ.b. 40 km^2 á ári. Á þessu tímabili hafa margir litlir jöklar horfið með öllu. Gagnasöfn um útbreiðslu jökla eru mikilvæg fyrir rannsóknir á loftslagsbreytingum, til þess að stilla af jöklalíkön, til rannsókna á framhlaupum og á eðli jökla. Þó að framhlaup, eldgos undir jökli og jökulhlaup hafi áhrif á stöðu einstakra jökulsporða hafa jöklabreytingar á Íslandi verið fremur samstíga og fylgt að mestu leyti veðurfarsbreytingum frá lokum 19. aldar.

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