Testing lichenometric techniques in the production of a new growth-rate (curve) for the Breiðamerkurjökull foreland, Iceland, and the analysis of potential climatic drivers of glacier recession

David J A Evans[1], Snævarr Guðmundsson[2], Jonathan L. Vautrey[1], Kate Fernyough[1] and W. Gerard Southworth[1]

1. Department of Geography, Durham University, South Road, Durham DH1 3LE, UK

2. Nature Research Center of Southeast Iceland, Höfn í Hornafirði, Iceland

Abstract

Independent dating of closely-spaced moraines on the west Breiðamerkurjökull foreland is used to test the accuracy of the size frequency (SF) and largest lichen (5LL) lichenometric dating techniques. The 5LL technique derived the most accurate ages for three undated moraines within the dated sequence but growth rates and lag times produced by the two methods (5LL = 0.71 mm yr^{-1} and 11 years; SF = 0.64 mm yr^{-1} and 7 years) were not significantly different. We therefore reject previous conclusions that any one technique is demonstrably inferior to the other, at least for dating glacial landforms created over the last 130 years in SE Iceland. Comparisons of climate trends and recession rates indicate that air temperature anomalies, particularly those of the summer, are the strongest driver of glacier retreat. No clear relationship between NAO trends and glacier retreat were identified, although a positive and/or rising trend in NAO is associated with the slowing of ice retreat overall, and the marked readvances of the mid-1950s, mid-1970s and mid-1990s are all coincident with positive and/or rising NAO 5yr moving averages. Summer and annual temperature trends, not the NAO, clearly show that recent accelerated global warming is driving the marked recession of the period 1995-2015. Over the last 100 years temperature has been the major driver of glacier terminus oscillations at west Breiðamerkurjökull but it is clear that extreme decreases in winter precipitation (i.e. 1960-73) have the potential to increase retreat rates significantly even during times of below average annual temperatures.

Key words: Lichenometry; glacier retreat; Breiðamerkurjökull; historical glacier-climate relations

Introduction

Despite recent declarations of levels of uncertainty on its robustness as a dating technique (e.g. Loso et al. 2014; Osborn et al. 2015; Rosenwinkel et al. 2015), lichenometry remains one of the most popular techniques for dating surfaces less than ~300-400 years old (Bradwell, 2001, 2018), and is based simply on the premise that the age of a surface can be calculated by measuring the size of lichen with a known growth rate. It has proven particularly successful in high-latitude and high-altitude environments (e.g. Andrews & Webber 1964; Benedict 1967; Beschel 1973; Matthews 1974, 1994; Bickerton & Matthews 1992; Evans et al. 1994; McCarthy 2003; Bradwell, 2004a; Bull 2018), and has therefore been preferred to other techniques in dating moraines on many recently deglaciated glacier forelands (e.g. Evans *et al.* 1999, Bradwell, 2001, 2004a; McKinzey et al. 2004; Matthews, 2005), thereby facilitating assessments of glacier-climate relationships over the period of historical climate change since the last Little Ice Age maximum (Bradwell 2004b; Bradwell et al. 2006; Chandler et al. 2016a, b). This has been exercised in southern Iceland in particular because the active temperate outlet lobes of Vatnajökull are sensitive to climatic changes over short timescales due to the cold-temperate climate of the region and its proximity to both polar and oceanic fronts (cf. Chandler et al. 2016a, b). Moreover, glacier terminus oscillations are recorded annually by recessional push moraines and consequently there is an unusually high resolution geomorphic signature of climate change and concomitant glacier response (Evans 2003, 2005, 2013; Bradwell *et al.*, 2006; Bradwell *et al.*, 2013, Evans & Twigg, 2002; Evans & Orton 2015; Chandler et al. 2016a, b, c; Evans et al. 2016, 2017). Hence glacier forelands with good moraine preservation and a strong chronological control on ice recession are prime sites to develop both lichenometric dating curves (more precisely, age-size plots) and consequently an understanding of glacier response to short timescale climate drivers.

Previous applications of lichenometry to the glacial landform record in southern Iceland have predominantly targeted the same yellow-green *Rhizocarpon* lichens but have been restricted by the lack of substrate ages, despite the high resolution record of terminus oscillations encoded in the moraines, and hence the inability to construct a local lichen growth rate curve (Gordon & Sharp 1983; Thompson & Jones 1986; Evans et al. 1999; Dabski 2002, 2007; Bradwell 2009; Bradwell et al. 2006, 2013). Additionally, Bradwell (2018) highlights three further problems in isolating growth rates or age-size relationships for these lichens, including: a) the different field techniques employed; (b) the range of techniques employed in data analysis; and (c) the differences in climatic conditions between study sites (cf. Jochimsen 1973; Evans et al. 1999; Bradwell 2009; Chenet et al. 2010; Osborn et al. 2015; Rosenwinkel et al., 2015; Decaulne 2016). This has given rise to the production of a range of growth rates dictated specifically by the lichen dimension measured (short or long axis, although the long axis predominates), data handling employed (predominantly largest lichen, average of 5 largest lichens or size frequency analysis of large populations) and search area (whole landforms, specific aspects and/or restricted sample areas). In an attempt to deliver a lichen growth rate for the region that they claim has greater statistical rigour (cf. Jomelli et al., 2007; Osborn et al., 2015), the moraine dating projects of Bradwell (2001, 2004a), McKinzey et al. (2004, 2005) and Bradwell et al. (2006) moved away from the more traditional methods of earlier Icelandic lichenometric dating studies and employed instead the size-frequency (SF) approach. This has resulted in a general increase in the age estimates of moraines dating to the Little Ice Age (LIA) maximum on some forelands, some of which are calculated to be up to 100 years older than previously proposed. But not all such lichenometrically-derived ages appear to reconcile with those delivered through historical archives, especially for moraines relating to events at the extreme age limits of the technique (cf. Kirkbride & Dugmore 2001; Bradwell 2004a, b; McKinzey et al. 2004, 2005). It is the uncertainty of the veracity of such archives that is central to the general lack of independent substrate age controls for lichenometry in southern Iceland.

In order to address this fundamental shortfall, we here develop an age-size plot, to be employed as a lichen growth rate for the western half of the Breiðamerkurjökull foreland (Mávabyggðajökull and Esjufjallajökull ice flow units; Figure 1), which is based upon the first accurate independent derivation of moraine ages using historical archives and orthorectified aerial photography applied to a digital elevation model of the area. Importantly, this exercise reveals that the traditional exercise of employing the 5 largest lichens on whole moraine surfaces to derive a lichen growth rate, regardless of critiques of its statistical validity, delivers more accurate historical ages than the size-frequency approach for the Breiðamerkurjökull LIA maximum and recessional moraines. We speculate that this is likely due to the tendency for the size-frequency approach to utilize only partial moraine surfaces and hence a greater potential for it to miss the larger lichens on a moraine than the more traditional techniques. Nevertheless, the occurrence of older end moraines lying immediately beyond those dating to the late 19th Century likely explains larger lichens on some other glacier forelands (e.g. Bradwell 2004b; McKinzey et al. 2004, 2005; Bradwell et al. 2006) and that therefore the regional moraine record contains evidence of a two-phase LIA glacier maximum in SE Iceland. The concept of multiple glacier advances in the late Holocene is recognised in the classification of Little Ice Age Type Events (LIATE) proposed by Matthews and Briffa (2005) and termed Periods (LIATP) in Iceland by Kirkbride and Dugmore (2006). Climate-glacier interactions since the attainment of the more recent (late 19th Century) LIA maximum are assessed using our refined moraine dating procedure, the broad framework of which is constrained by historical archive; a more detailed ice recession chronology is compiled using a new lichen growth rate calibrated by the independently derived moraine dates.

Historical ice recession and climate trends in the study area

Since the 1930s glacier termini variations in SE Iceland, as documented by direct ice margin measurements, broadly correlate with air temperature variations, with warming and cooling trends coinciding with periods of glacier retreat and advance respectively (Sigurðsson et al., 2007). During the period 1931–1960, rapid ice-front retreat was initiated by relatively high air temperatures, particularly during the decade of the 1930s. This was reversed after 1965 in response to climate cooling, with a number of glacier termini advancing during the 1975–1990 period and culminating in the mid 1990's readvance (Sigurðsson et al., 2007). Since 1995 the SE Iceland glaciers have been in marked recession mode and this is clearly a response to rapidly rising air temperatures (Figure 2). Breiðamerkurjökull has shown a more marked recession history, having undergone continued recession since the 1930s, with readvances in the mid-1950s and in the period of the mid-1970s through to the early 1990s (Evans & Twigg 2002).

Breiðamerkurjökull is one of the most active outlet glaciers on the Vatnajökull ice cap, and retreat since the LIA maximum has produced a highly detailed geomorphological record of active snout recession, driven by seasonal climatic drivers, in the form of recessional push moraines (Price, 1969; Boulton, 1986; Evans & Twigg 2002). Recessional push moraines are particularly good geomorphic forms of climatic change archive because they are formed when winter readvances of the glacier margin construct ridges, thereby recording the ice-marginal position for the year during which they were deposited (Price 1970; Boulton 1986; Krüger 1995; Matthews et al. 1995;

Chandler et al. 2016a, b, c). Superimposition of ridges and the construction of larger composite push moraines occurs when ice margins are quasi-stationary, for example as occurred during the early to mid-1990s in southern Iceland in response to a prominent and relatively sustained positive North Atlantic Oscillation (NAO) index (Evans & Hiemstra 2005; Evans et al. 2009, 2016, 2017; see below).

The rate of glacier marginal recession can be calculated using recessional push moraine spacing, with the critical assumption that one moraine is constructed each year (Boulton 1986; Beedle et al. 2009; Lukas 2012). On the SE Iceland glacier forelands, the reconciliation between ice-margin retreat rates calculated in this way and annual summer air temperature anomalies demonstrates a clear correlation (Bradwell, 2004b; Bradwell et al., 2013; Chandler et al., 2016a). This indicates that the outlet glaciers have very rapid reaction times and respond to summer temperature variations (i.e. at annual timescales). In addition to the dominant role of summer air temperatures on glacier recession, it has been proposed that periods of more sustained glacier advance may be linked to a negative NAO Index (Bradwell et al., 2006). It is possible that a shift to more zonal atmospheric circulation and a weaker Icelandic Low may have triggered climatic cooling and glacier advances during the 19th and early 20th centuries (Bradwell et al., 2006). Alternatively, Evans and Chandler (2018) highlight the role of a peak in positive NAO during the early to mid-1990s as potentially influential in increasing winter precipitation and creating a period of positive glacier mass balance (cf. Björnsson et al., 2013), thereby leading to the mid-1990s re-advance of the SE Iceland outlet glaciers. Nevertheless, this period of positive NAO followed on from a sustained period of low temperatures, as highlighted above (Sigurðsson et al., 2007), and hence the mid-1990s re-advance could be the culmination of longer-term cooling. Additional complications in the use of recessional moraines as climate proxies have been identified by Chandler et al. (2016a, b, c). For example, more than one push moraine has been constructed per year along some parts of certain glacier snouts, specifically where reverse slopes and poor drainage conditions have given rise to localised till squeezing into multiple ridges. Uncertainties also arise in the age derivations for moraines that were created before the first aerial photography in 1945; in these cases there is a reliance on lichenometric dating and historical archive. Clearly more refined chronological controls (i.e. lichenometry calibrated by historical documentation and aerial imagery) are required in order to better resolve our assessments of glacier-climate interactions as recorded in moraine archives.

A comprehensive database of ice-front measurements already exists for Icelandic glaciers, but within the records of many glaciers, including Breiðamerkurjökull, there are extended periods for which measurements are only sporadic. Moreover, the age assignments on many moraines in the detailed recession sequence are patchy, despite the many glacier maps that have been compiled for the area since the first survey by the Danish General Staff in 1904 (see Evans & Twigg 2002 for a review). In order to compile a more detailed recession chronology we employ a range of historical archives and aerial photography to date a number of the push moraines on the Breiðamerkurjökull foreland and thereby facilitate: 1) a compilation of a dated moraine sequence; and 2) the comparative testing of the accuracy of different lichenometric techniques and the calculation of a new lichen growth-rate, from which a higher resolution dated moraine sequence is compiled. From these procedures we then derive glacier recession rates based on moraine spacing and evaluate the potential climatic controls on glacier terminus activity.

Methods

The range of lichen growth rates derived from various lichenometric methods employed in SE Iceland (i.e. lichen dimension measured, data handling employed and search area used) is compiled in Table 1 (c.f. Evans et al. 1999; Bradwell 2018). The first lichen growth curve in SE Iceland was produced for Solheimajökull by Jaksch (1970, 1975) and there has since been extensive use of this technique in the region (e.g. Gordon & Sharp 1983; Maizels & Dugmore 1985; Thompson & Jones 1986; Evans et al. 1999; Bradwell 2001, 2004a, b; Dabski 2002, 2007; McKinzey et al. 2004, 2005). In most cases this has involved using the average size of the five largest lichens (5LL) or largest lichen (LL) to compile lichen growth curves (age-size plots) and obtain a substrate age. More recently, Bradwell (2001, 2004a) established the alternative method of the size-frequency (SF) approach (cf. Innes 1983; Caseldine 1991; Caseldine & Baker 1998), which employs the best-fit slope of the size-frequency ($\log_{10}$) distribution to estimate the relative age of a landform (Bradwell 2001, 2004a). A growth rate (curve) can be produced by either using the largest lichen from each population, or by plotting the gradient of the regression line against the age of the surface. The wide range of derived growth-rates presented in Table 1 is the inevitable outcome of using the different lichenometric procedures as well as differences in the effective precipitation at different sites; the latter was used by Evans et al. (1999) as a surrogate for moisture conditions, to which lichen growth is particularly susceptible (cf. Hamilton 1995). Also significant is the accuracy of historically documented ages for the oldest moraines on the glacier forelands, with some late-19th Century dates being questioned and regarded as too young, for example by Kirkbride and Dugmore (2001), Bradwell (2004b), McKinzey et al. (2004, 2005) and Bradwell et al. (2006).

Notwithstanding the point highlighted above, it is most likely that the larger outlet glaciers in SE Iceland, including Breiðamerkurjökull, attained their maximum extent in the late 19th century (Þorarinsson 1943; Grove 1988; Evans et al. 1999; Evans & Twigg 2002; Hannesdottir et al. 2015). However, exact ages for moraines developed prior to the first aerial photographs in 1945 are difficult to verify. Hence we have identified ice marginal positions over this period of time by researching a range of historical archives (especially contemporary notes and documents of the local farmers; F. Björnsson, 1993, 1996, 1998), expedition records, old ground photographs and maps as well as pre-1945 oblique aerial views. In combination with more recent aerial and satellite imagery, this has facilitated the identification of eight independently dated moraine ridges on the foreland between Jökulsárlón and Breiðárlón which could be employed as lichenometric dating control substrates. This develops the findings of Guðmundsson et al. (2017), who assessed the changes of Breiðamerkurjökull since the end of the Little Ice Age based on topographic maps, aerial vertical and oblique photographs and more recent airborne LiDAR surveys and satellite images. Glacier terminus positions over time were then compiled on high-resolution digital elevation models (DEMs) produced from an airborne LiDAR survey in 2010–2011 with a point cloud density of ~0.33 m^2 and a vertical elevation accuracy of 0.5 m (Jóhannesson et al. 2013).

The SF lichenometric technique was undertaken on the eight dated substrates by measuring the long axes of 300 thalli of *Rhizocarpon* species in fixed 100m^2 areas on the ice-proximal sides of push moraines. Elongate and irregular thalli were measured regardless of shape (cf. Bradwell 2001), but coalescent lichen were disregarded because competition for moisture and light between the neighbouring thalli can compromise growth rates (cf. Bradwell 2001; Dabski 2007). The largest five average (5LL) lichenometric technique involved searching and measuring lichens on the whole proximal surface of each moraine and then using the average of the largest five thalli as a representative lichen size for the substrate (e.g. Evans et al. 1999).

For the SF technique, lichen data were compiled on a size frequency graph with lichen axis (diameter) plotted against the logarithm of the percentage frequency. Following the procedures of Bradwell (2001, 2004a), a class size of 3 mm was used and lichen below the modal class of each population were excluded. A regression line was plotted for each lichen population, and the gradient of this line was plotted against the moraine age to produce a SF lichen age-size plot. Additionally, a largest lichen (LL) growth curve or age-size plot was created by plotting the largest lichen in each population against the moraine age. An alternative 5LL growth curve (age-size plot) was then constructed by plotting the mean axis of the five largest lichens, measured along the entirety of each moraine ridge, against the moraine age.

Three further undated moraines that lie between the eight independently dated moraines were allocated ages based upon the application of the alternative lichen growth curves or age-size plots to their lichen populations. These locations are identified as “lichen dated sites” as they are used to assess the applicability of the lichen growth rates by deriving ages that must lie between those of their bracketing moraines of known age. The lichen dated sites are LD1 (located between the 1904 and 1930 moraines), LD2 (between 1945 and 1951 moraines) and LD3 (between 1951 and 1955 moraines) and allow the addition of further dated ice marginal positions to the recession sequence.

Once the moraine sequence was dated (a procedure that is not reliant on lichenometric dating *per se*), the glacial marginal recession rates were calculated by measuring the distance between the dated moraines along a defined flowline, as defined by the orientation of flutings (Evans & Twigg 2002), and then dividing by the age difference between the two moraines. Retreat rates were then plotted along a time series with annual and winter precipitation anomalies, annual and summer temperature anomalies and the NAO index, in order to facilitate the analysis of the potential climatic drivers of glacier recession. Temperature and precipitation data were obtained from Veðurstofa Íslands (2016) and the NAO data from the station-based Hurrell NAO database (Hurrell and NCAR, 2014).

Results

i) Dating glacier marginal recession using historical archives and aerial imagery

The map of the Breiðamerkurjökull foreland and Breiðamerkursandur (Figure 3) displays the glacial geomorphology and the demarcation of the glacier terminus at fifteen time intervals, eight of which correspond to identifiable moraines in the study area. The geomorphological mapping constitutes a continuation and refinement of previous maps by Howarth and Welch (1969a, 1969b) and Evans and Twigg (2000, 2002) for the years 1945, 1965 and 1998. Ice marginal recession is clearly documented by the inset sequences of push moraines on the Breiðamerkurjökull foreland but few individual moraines have been previously dated precisely. Uncertainties in both the ice marginal positions and the ages of moraines are summarised in Table 2, which vary respectively from 1 m to 60 m and from ± 1 year to ± 10 years, but these calculations are related to maximum errors over the whole glacier foreland as depicted in the spatial recession graph in Figure 4. This graph depicts the variable recession patterns of the glacier margin, including the role of the developing Jökulsárlón proglacial lake in increasing the recession rate due to calving and the contrast of this with the relatively more steady recession of the Mávabyggðajökull and Esjufjallajökull ice flow units. The dating of the formation of the terminal end moraine along the Breiðamerkursandur to the 1890s LIA maximum is a simplification of a more complex spatial and temporal evolution (Figure 4). In places west of Jökulsárlón lagoon it developed after the outlet had reached its maximum LIA extent in the period 1870-1880s. The terminus then stabilised at that position for several years, perhaps up to a decade. Near the mouth of the Jökulsárlón lagoon the moraine developed after 1906 and not later than 1933 (F. Björnsson, 1996). These age variations reflect the contrasting behaviour of the major ice flow units, surge events in the Norðlingalægðarjökull, and pulsed advances by ice protected beneath the Esjufjallarönd medial moraine prior to 1933. The 1904 margin of the glacier was delineated from the oldest maps, based on triangulation surveys of the Danish General Staff in 1904 in this region of SE-Iceland (DGS, 1905). At that time the terminus had already retreated a short distance. Being reasonably accurate, the DGS maps often need horizontal corrections by tens or even a few hundreds of meters (in the Esjufjöll region) but are estimated to be accurate within +/-20m after the correction on the glacier forelands. The 1904 map depicts the glacier terminus at a distance of only 100-200 m inside the maximum LIA moraine arc, thereby allowing a precise age allocation to the moraine at that location once the map is draped onto the LiDAR-derived DEM (Guðmundsson et al. 2017; Figure 3).

Further age allocations on recession positions are possible using maps depicting the ice margin from a variety of sources. These include recession maps for 1894-1954 by Todtmann (1960), glacier maps for 1945 and 1965 by Howarth and Welch (1969a, b), for 1951 by Durham University (1951), for 1960, 1964 and 1980 by Price and Howarth (1970) and Price (1982) and for 1998 by Evans & Twigg (2002). Additional margins were captured on expedition ground and oblique photographs which were orthorectified and draped on the DEM. The 1930 margin is based on an oblique aerial photograph captured from the airship Graf Zeppelin during a flyby on July 17, 1930 (Guðmundsson

& Björnsson, 2017) as well as photographs taken in the 1930s and notes from the local farmer Flosi Björnsson (F. Björnsson, 1993, 1996, 1998). The 1945 margin is based on the aerial photographs of the AMS C762 map series of the US Army, taken on 30th of August 1945 from an elevation of 7000 m (Army Map Service, 1951). Digital scanned copies provided fair resolution but limited contrast range, but they provide the first highly accurate delineation of the glacier margin. After the mid-20th century, maps along with series of unrectified aerial photographs were georectified and corrected in terms of horizontal positioning using the LiDAR DEMs of Vatnajökull, which were surveyed in 2010–2012 in connection with the International Polar Year 2007–2008 (Jóhannesson and others, 2011, 2013). The process was carried out by identifying 30–50 common control points in the images or maps and the LiDAR DEMs for each glacier and using ArcGIS tools for reprojection and warping. Additionally, for the first two decades of the 21st century, orthorectified Landsat images (Landsat 1–5 and 7–8, image courtesy of the US Geological Survey), the aerial image database of Loftmyndir ehf and LiDAR DEMs of the Vatnajökull ice cap and its foreland (Jóhannesson and others, 2013) have been used to delineate the retreating terminus.

Of the fifteen time intervals identified for the ice margin position, eight (1904, 1930, 1951, 1960, 1964, 1970, 1973 and 1982) correspond to identifiable moraines in the study area on the foreland between Jökulsárlón and Breiðárlón, where the moraines were constructed by the actively receding margins of the Mávabyggðajökull and Esjufjallajökull ice flow units (Figure 1). These moraines thereby constitute independently dated substrates and therefore suitable targets for the establishment of lichenometric dating control.

Our knowledge of glacier marginal recession rates prior to this study is collated in Table 3, which summarises Guðmundsson's (2014) analysis of the dated margins depicted in Figures 3 and 4. This demonstrates that recession rates vary between the flow units, with Esjufjallajökull and Norðlingalægðarjökull (central and eastern flow units) having undergone similar retreat (~5.2 km) but at slightly different rates (58 and 66 m yr^{-1} respectively) and Máfabyggðajökull (west flow unit) having retreated significantly less (4.1 km) and at a noticeably slower rate of 45 m yr^{-1}. The faster recession rate for Norðlingalægðarjökull is driven by the inherent instability of its calving margin in the Jökulsárlón proglacial lake (Bjornsson et al. 2001; Evans & Twigg 2002). The smaller total and slower recession of Máfabyggðajökull likely relates to its accumulation zone being located in the higher topography of Öræfajökull and hence less susceptible to the rising ELAs of the historical period (H. Björnsson 1996, 2009). The identification of additional dated ice margins to those in Table 3, especially the 1930 margin, facilitates the reconstruction of a more refined pattern of recession. This is enhanced further by the employment of the new lichen growth curve outlined below to date additional marginal positions (LD1-3).

ii) Lichen growth curves (age-size plots) for the Breiðamerkurjökull foreland

The lichen data for the independently dated moraines is presented in Figure 5 as graphs depicting the size-frequency distributions. Both the histograms of lichen size frequency and the linear regression plots of the logarithm of the frequency against lichen axis clearly display age-related trends and hence can be confidently used in the derivation of growth rates (curves). The linear regression plots reveal that the lichens in each moraine population lie on a straight line with the largest thallus falling below the predicted 1 in 1000 threshold. Therefore, the lichens are not anomalous and comprise a single population (Andersen & Sollid 1971; Caseldine 1991; Cook-Talbot 1991; Locke *et al.* 1979).

Using the largest lichen from each moraine sample, the LL size-frequency growth plot (Figure 6a, upper) produces a regression line with a strong positive linear correlation and an R^2 value of 0.96. This yields a lichen growth rate of 0.64mm yr^{-1} with a lag time of 7 years. Using the gradient of the regression line from each size-frequency distribution in Figure 5 allows the construction of a size-frequency gradient growth curve (Figure 6a, lower), which has a high correlation, with an R^2 value of 0.95. Although this curve can be used to date substrates, it cannot be used to calculate lichen growth rates.

An age-size plot of the average of the five largest lichens (5LL) measured across the entirety of the moraine reveals a strong positive linear correlation, with a high R^2 value of 0.98 (Figure 6b). The predicted growth-rate and lag time are both higher than those derived from the size-frequency method, being 0.71mm yr^{-1} and 11 years respectively. The standard deviations of the five largest lichen are low, ranging from 1.4-3.8 mm with an average of 2.4 mm (Table 4).

Outcomes of the application of the three curves depicted in Figure 6 to dating the lichen populations of the undated moraines (LD 1-3; Figure 3) are collated in Table 5 and allow an assessment of the suitability of each technique for lichenometric dating of the Breiðamerkurjökull moraine sequence. The size-frequency gradient growth rate (Figure 6a, lower) significantly overestimates the age of moraine LD 2 and slightly underestimates the age of moraine LD 3. The LL size-frequency curve (Figure 6a, upper) overestimates the age of moraine LD 2 and underestimates the age of moraine LD 3 but only on the order of 2-3 years. The 5LL technique produces the only growth-rate curve to correctly predict the age of all three LD moraines to within their known age range. Hence the 5LL technique is hereon employed to derive the ages of the undated moraines.

iii) Glacier marginal recession rates at Breiðamerkurjökull

The improved resolution of dated ice marginal positions derived from a combination of our new mapping (Figures 3 & 4) and lichenometrically aged moraines using the 5LL technique (Table 5) facilitates the re-calculation of recession rates presented in Table 3, specifically for the Mávabyggðajökull and Esjufjallajökull ice flow units of Breiðamerkurjökull (Table 6). Remarkable in this output is the somewhat unsteady recession indicated for this part of the glacier terminus, as depicted in Figure 8, with some significant but short-lived peaks in relatively rapid retreat (e.g. 133-137m yr^{-1}) but a prominent phase of moderate retreat (30-36 m yr^{-1}) in the mid-1970s to mid-1990s, herein called the late 20th Century stabilization. Until 1926 the recession from the LIA (1890) maximum moraine was also slow at 7-11 m yr^{-1}, but this was terminated abruptly by an increase to 80 and then 65 m yr^{-1} for the periods 1926-30 and 1930-1945 respectively. There then began a phase of highly oscillating recession rates with 35 m yr^{-1} from 1945-48, 98 m yr^{-1} from 1948-51, 42 m yr^{-1} from 1951-54, the single year of 1954-55 with a remarkable rate of 133 m yr^{-1}, and then 13 m yr^{-1} from 1955-60, before a return to a period of more sustained fast retreat for 1960-64 (84 m yr^{-1}) and 1964-70 (70 m yr^{-1}). The fastest retreat rate of 137 m yr^{-1} occurred over the period 1970-73, immediately prior to the late 20th Century stabilization of 1973-94. This was followed by the modern era of marked glacier terminus recession in southern Iceland, with rates of 63, 100 and 102 m yr^{-1} characterizing the periods 1994-2004, 2004-2010 and 2010-2015 respectively.

Discussion

The dating of a relatively closely-spaced moraine sequence on the foreland of the Esjufjallajökull flow unit of Breiðamerkurjökull has facilitated a comparative test of the applicability and accuracy of different lichenometric techniques, from which the 5LL technique emerges as the most accurate in the derivation of ages for undated moraines in the sequence. Previous arguments proposing the preferred use of the SF technique were justified by referring to its capability to statistically assess the distribution of the representative lichen population and potentially detect outliers and anomalously large thalli, and hence it was regarded as more accurate and statistically robust than the 5LL technique (Bradwell, 2001, 2004a; Bradwell *et al.*, 2013). Importantly, the SF technique clearly indicates that all the log transformed lichen populations in this study approximate a straight line with a strong negative correlation (R^2 ranging from 0.88-0.99), showing that the lichens at each site are from single undisturbed populations. It has been proposed that the derivation of such statistical trends allows easy identification of anomalous data points but this can also be assessed, and more simply, by calculating the standard deviation of the five largest lichens over whole moraines rather than fixed sample plots and where standard deviations are relatively small; in this study such standard deviations averaged only 2.4 mm for each site. Moreover, unlike the 5LL technique, the SF technique failed to calculate an age that was within the date ranges of two of the undated moraines (LD 2 & 3), albeit by small margins. Therefore, we see little advantage in using the SF technique as an exclusive replacement for the traditional and simpler 5LL method. Hence the 5LL lichen growth rates and lag times of 0.71 mm yr^{-1} and 11 years respectively are preferred for this SE Icelandic glacier foreland. Nevertheless, there is not a particularly large difference between the growth rates and lag times of the two alternative techniques, with the SF approach yielding a growth rate of 0.64 mm yr^{-1} and a growth lag of 7 years, and therefore previous indications that any one technique is demonstrably inferior to the other (e.g. Osborn et al. 2015; Bull 2018) are unfounded, at least over the period of the last 130 years; significantly longer periods of time are likely to involve increasingly non-linear growth curves (Bradwell & Armstrong 2007) but the 5LL technique has not been fully tested over such longer timescales in SE Iceland.

The lag times and growth rates calculated here using the 5LL technique compare well to those of other studies in the area that derived their own site-specific growth-rate curves (Jaksch 1970, 1975; Gordon & Sharp 1983; Maizels & Dugmore 1985; Thompson & Jones 1986; Bradwell 1998; Evans et al. 1999), although only Maizels and Dugmore

(1985), Thompson and Jones (1986) and Evans et al. (1999) used a 5LL approach rather than only the largest lichen (LL). The range of these growth rates is 0.56-0.99 mm yr^{-1} (Table 1) but more importantly the rate calculated for the Breiðamerkurjökull foreland is 0.8 mm yr^{-1} by Evans et al. (1999). The LL technique on a sample population was used by Gordon and Sharp (1983) to derive a growth rate for the foreland of 0.68 mm yr^{-1}, which compares equally well with our SF/LL-derived rate of 0.64 mm yr^{-1}, and 5LL-derived rate of 0.71 mm yr^{-1}, further demonstrating the lack of inferiority of any one technique. This is an especially significant finding considering the potential for missing the largest lichens in SF/LL sample populations and hence delivering a slower growth rate than the 5LL technique, which here is not particularly problematic when we consider the small range in growth rates derived from the alternative approaches (i.e. 0.64-0.71 mm yr^{-1}). As outlined above, we simply advocate the 5LL technique because it delivered the most accurate ages for the three undated moraines (LD 1-3).

Further confidence in our new lichen growth rate is instilled by the fact that it is the product of the first study that uses closely-spaced and independently dated moraines over the full time period since the abandonment of the LIA maximum at 1890 and all from the same glacier foreland. Previously reported growth rates have either used moraines that have an uncertain age or independently dated surfaces from a number of different locations (e.g. Gordon & Sharp 1983; Evans *et al.* 1999; Bradwell 2001, 2004a), the latter often being disputed due to perceived inaccuracies in historical documentation (cf. McKinzey et al. 2004, 2005). Additionally, the employment of independently dated surfaces from different locations can result in lichens from different microclimates (especially moisture-related) being used inappropriately to produce a single growth rate (curve) for one region. The range of growth rates compiled by Evans *et al.* (1999) demonstrated that this was significant not just for an area as large as the whole of Iceland but also for SE Iceland, where precipitation is highly variable over small spatial scales. For example, there is a 400 mm difference in the 1961-1990 average annual precipitation between Hólar í Hornafirði and Fagurhólsmýri, located ~100km apart, to the east and west of Breiðamerkurjökull respectively (Chrochet et al. 2007; Veðurstofa Íslands 2016). Moreover, Bradwell (2001) estimates that the mean annual precipitation of the sites used to produce his growth curve between these two stations are up to 1000 mm due to further variation induced by orographic effects. Clearly this level of variation causes differences in lichen growth rates, as can be seen in the variable lichen growth curves produced for a range of locations in Iceland (see Evans *et al.* 1999 for a compilation). Consequently, the use of surfaces from a transect on the west Breiðamerkurjökull foreland in this study ensures the smallest possible range in precipitation and hence moisture conditions than those inherent within Bradwell's (2001) more regionally-derived lichen growth curve.

Compatible trends in recession rates since the 1890 LIA maximum at Breiðamerkurjökull are apparent in the moraine records for the Esjufjallajökull, Norðlingalægðarjökull and Máfabyggðajökull ice flow units (cf. Guðmundsson 2014), but our higher resolution chronology identifies some significant peaks and troughs in recession rates that can be compared to climate data trends in order to assess glacier-climate relationships for the last 100 years. Previous research (e.g. Bradwell, 2004b; Sigurðsson et al., 2007; Bradwell et al., 2013; Chandler et al., 2016a) has demonstrated that recession rates and annual summer air temperature anomalies are clearly correlated. The persistently fast retreat rate of Esjufjallajökull in particular during the 1930s and 1940s is similar to those of other Icelandic glaciers in the region (Bradwell *et al*., 2013; Sigurdsson *et al.*, 2007), and this clearly coincides with a period of sustained above average summer temperatures (Figure 8).

Readvances previously recorded for Breiðamerkurjökull in the mid-1950s and the mid-1970s through to the early 1990s (Evans & Twigg 2002) are coincident with phases of moderate and slow retreat in Figure 8. The latter, more substantial period was related by Sigurðsson et al. (2007) to post 1965 climate cooling, with the construction of the early 1990s composite push moraines around SE Iceland being a signature of the prominent and relatively sustained positive NAO index at that time. The NAO trends in Figure 8, particularly the 5 yr moving average, reveal some pattern in terms of more sustained styles of ice recession behaviour for Esjufjallajökull, most clearly in the gradual rise from extreme negative to extreme positive through 1970-1995, which corresponds with the sustained phase of moderate retreat (late 20th Century stabilization) but has not culminated in a marked mid-1990s readvance as it has elsewhere in the region. Despite the apparent linkages between the gradually rising NAO trend and the late 20th Century stabilization, with its culmination in the mid-1990s readvance, this period also clearly follows on from, and partially coincides with, Sigurðsson et als. (2007) sustained period of low temperatures (Figure 8). Therefore, the mid-1990s re-advance in particular could be the culmination of that longer-term cooling, a glacier-climate relationship that is clearly demonstrated on the foreland of Skaftafellsjökull for example (cf. Þórarinsson 1956; Thompson 1988; Marren 2002; Evans et al. 2017) but not demonstrated in the geomorphology at Esjufjallajökull.

Other correlations between NAO and glacier recession patterns include an increasingly negative 5yr moving average coinciding with fast retreat in 1960-1970 and culminating in rapid retreat in the early 1970s. Prior to this, a low variability and slightly positive mode coincided with 1945-1960 period of oscillating rapid to moderate and then slow retreat. These trends indicate that sustained negative NAO may have been influential in fast or rapid retreat after the 1950s but the opposite trend occurred in the preceding 1926-1945 fast retreat period (Figure 8). In summary, the NAO trends in Figure 8 reveal that a positive (e.g. Evans & Chandler 2018) rather than a negative (e.g. Bradwell et al. 2006) NAO is capable of slowing ice recession (i.e. post-1950s trends), presumably by increasing the winter precipitation (evident in Figure 8 for the early-mid 1990s) and creating a period of positive glacier mass balance. However, this relationship breaks down during the pre-1950s period, where a positive NAO is most commonly associated with fast ice retreat; interestingly, however, a peak in the positive NAO yearly mean in the mid-1920s does coincide with slow retreat. Predominantly, therefore, a positive and/or rising trend in NAO is associated with the slowing of ice retreat overall and the marked readvances of the mid-1950s, mid-1970s and mid-1990s are all coincident with positive and/or rising NAO 5yr moving averages.

After its peak positive mode in the mid-1990s, the NAO 5yr moving average dropped sharply to slight negative and has oscillated around that slight negative mode ever since, coinciding with a fast retreat phase in 1995-2005 followed by a rapid retreat phase since 2005. This flattening of the NAO signal indicates that it has no role in recent rapid retreat even though the post-2005 period contains the largest fluctuations in NAO yearly mean of the last 100 years. In contrast, it is very clear from the summer and annual temperature curves in Figure 8 that recent accelerated global warming is driving the marked recession pattern from 1995-2015 (see below). A previous assessment undertaken by Kirkbride (2002) on the potential correlations between glacier retreat rates and seasonal NAO values similarly indicated no clear relationship between the two, but rather a shift in the position of the Icelandic Low appeared to be the main driver of rapid ice retreat.

The curves in Figure 8 show particularly clear correlations between ice-margin retreat rates and annual summer air temperature anomalies, as predicted by previous studies in the region (cf. Bradwell 2004b; Bradwell et al. 2013; Chandler et al. 2016a) and further afield (e.g. Beedle et al. 2009). Hence it appears that the SE Iceland outlet glaciers respond rapidly to summer temperature variations. The importance of temperature anomalies is illustrated by numerous coincident trends with glacier retreat rates (Figure 8). Firstly, a steep rise from the negative values of the slow retreat phase of the early 1920s up to a sustained plateau of above average annual and summer temperatures coincides with the 1926-45 fast retreat phase. The subsequent oscillating rates of 1945-60 are related to a lower positive trend in both annual and summer temperatures, but also continued highly oscillatory summer temperatures in particular. This terminates at the sustained fast retreat of 1960-70, the early part of which appears related to rises in both annual and summer temperatures to well above average. Their significant fall to values well below average marks the beginning of the sustained low temperatures of the late 20th Century stabilization, but this is difficult to reconcile with continued fast recession culminating with the rapid retreat of 1970-73. The only trend that coincides with the rapid retreat appears to be a high peak in the annual temperature anomaly. This unexpected relationship between falling temperatures and fast to rapid ice retreat is more likely a response to a marked decrease in both annual and, more importantly, winter precipitation (cf. Beedle et al. 2009), which dip to a 100 year low from 1965-70. Hence the 1960-73 phase of fast to rapid retreat may have been initiated by high temperatures but was intensified by reduced mass in the accumulation zone in the winter. The subsequent late 20th Century stabilization of 1973-94 appears to have been initiated by period of sustained below average summer temperatures. Finally, a rising trend in annual and summer temperatures from around 1985, with a sharp increase to a 100 year high from around 2004-present, clearly coincides with a sustained phase of moderate, into fast, and then rapid retreat.

Conclusion

Independent dating of the closely-spaced moraine sequence on the foreland of the Mávabyggðajökull and Esjufjallajökull ice flow units of Breiðamerkurjökull, using a range of historical archives and aerial imagery, has facilitated a comparative test of the accuracy of the size frequency (SF) and largest lichen (specifically average five largest; 5LL) approaches to lichenometric dating. The 5LL technique was the most accurate in the derivation of ages for undated moraines within the dated sequence and therefore there appear to be no advantages of using the SF technique as an exclusive replacement for the simpler 5LL method, despite previous proposals that the 5LL method suffers from a significant lack of statistical rigour. Moreover, relatively comparable growth rates and lag times for the two methods (0.71 mm yr^{-1} and 11 years for 5LL, compared to 0.64 mm yr^{-1} and 7 years for SF) lead us to reject previous conclusions that any one technique is demonstrably inferior to the other, at least for dating glacial landforms created over the last 130 years in SE Iceland. Rather it is, somewhat unsurprisingly, the density and the accuracy of the substrate dating control that improves the precision of regional lichen growth curves and consequently the performance level of the lichenometric dating procedures.

Comparisons of climate trends and recession rates indicate that air temperature anomalies, particularly those in summer, are the strongest driver of glacier retreat. Hence it appears that the Mávabyggðajökull and Esjufjallajökull flow units of Breiðamerkurjökull, like other SE Iceland outlet glaciers, have responded rapidly to summer temperature variations with one important exception, that of the 1960-73 phase of fast to rapid retreat. This may have been initiated by high temperatures but was intensified by significantly reduced mass in the accumulation zone in the winter. No clear relationship between NAO trends and glacier retreat were identified in this study, although a positive and/or rising trend in NAO is associated with the slowing of ice retreat overall, and the marked readvances of the mid-1950s, mid-1970s and mid-1990s are all coincident with positive and/or rising NAO 5yr moving averages. The NAO has had no apparent role in the recent rapid ice retreat, but instead summer and annual temperature trends clearly show that recent accelerated global warming is driving the marked recession from 1995-2015. Over the last 100 years of ice recession at west Breiðamerkurjökull, temperature has been the major driver of glacier terminus oscillations but it is clear that extreme decreases in winter precipitation have the potential to increase retreat rates significantly.

Acknowledgements

Scientific research permits allowing work at Breiðamerkurjökull were provided by Regina Hreinsdottir on behalf of the Vatnajökull National Park and by RANNIS (The Icelandic Centre for Research). Thanks to reviewers Martin Kirkbride and Rob Storrer and editor Tom Bradwell for helpful comments and discussion which helped improve an earlier draft of this paper.

References

AMS 1951. Kvísker/Veðurárdalsfjöll/Breiðamerkurjökull/Öræfajökull/Esjufjöll Sheets I/6019 - IV/6019, C 762, year of measurement 1945–1946, 1:50000. Washington DC, US Army Map service.

Andersen, J.L., Sollid, J.L. 1971. Glacial chronology and glacial geomorphology in the marginal zones of the glaciers Midtalsbreen and Nigardsbreen, South Norway. Norsk Geografisk Tidsskrift 25, 1–38.

Andrews, J.T., Webber, P.J. 1964. A lichenometric study of the northwestern margin of the Barnes Ice Cap: a geomorphological technique. Geographical Bulletin 22, 80-104.

Beedle, M.J., Menounos, B., Luckman, B.H., Wheate R. 2009. Annual push moraines as climate proxy. Geophysical Research Letters 36, L20501, doi:10.1029/2009GL039533

Benedict J.B. 1967. Recent glacial history of an Alpine area in the Colorado Front Range, USA. 1: Establishing a lichen growth curve. Journal of Glaciology 6, 817-832.

Beschel, R.E. 1973. Lichens as a measure of the age of recent moraines. Arctic and Alpine Research 5, 303–309.

Bickerton, R.W., Matthews, J.A. 1992. On the accuracy of lichenometric dates: an assessment based on the "Little Ice Age" moraine sequence of Nigardsbreen, southern Norway. The Holocene 2, 227-237.
Björnsson, F. 1993. Samtíningur um Jökulsá á Breiðamerkursandi og Jökulsárlón. Skaftfellingur 9, 8–25.
Björnsson, F. 1998. Samtíningur um jökla milli Fells og Staðarfjalls. Jökull 46, 49–61.
Björnsson, F. 1996. Þættir um Breiðamerkursand. Skaftfellingur 11, 105–125.
Björnsson, H. 1996. Scales and rates of glacial sediment removal: a 20 km long, 300 m deep trench created beneath Breiðamerkurjökull during the Litle Ice Age. Annals of Glaciology 22, 141–146.
Björnsson, H. 2009. Jöklar á Íslandi. Bókaútgáfan Opna, Reykjavík, 479 pp.
Björnsson, H., Pálsson, F., Guðmundsson, S. 2001. Jökulsárlón at Breidamerkursandur, Vatnajökull, Iceland: 20th century changes and future outlook. Jökull 50, 1–18.
Björnsson, H., Pálsson, F., Guðmundsson, S., Magnússon, E., Adalgeirsdóttir, G., Jóhannesson, T., Berthier, E., Sigurðsson, O., Thorsteinsson, T. 2013. Contribution of Icelandic ice caps to sea level rise: Trends and variability since the Little Ice Age. Geophysical Research Letters 40, 1546–1550.
Boulton, G.S. 1986. Push-moraines and glacier-contact fans in marine and terrestrial environments. Sedimentology 33, 677-698.
Bradwell T. 1998. Climate-induced twentieth-century glacier fluctuations in southeast Iceland. Frodskaparrit 46, 319-332.
Bradwell, T. 2001. A new lichenometric dating curve for southeast Iceland. Geografiska Annaler 83A, 91-101.
Bradwell, T. 2004a. Lichenometric dating in southeast Iceland: the size–frequency approach. Geografiska Annaler 86A, 31-41.
Bradwell, T. 2004b. Annual moraines and summer temperatures at Lambatungnajökull, Iceland. Arctic, Antarctic, and Alpine Research 36, 502-508.
Bradwell T. 2009. Lichenometric dating: a commentary, in the light of recent statistical studies. Geografiska Annaler 91A, 61-69.
Bradwell, T. 2018. Lichenometric dating of glacial landforms in southern Iceland. In: Evans D.J.A. (ed.), Glacial Landsystems of Southeast Iceland: Quaternary Applications – Field Guide. Quaternary Research Association, London, pp. 41-48.
Bradwell, T., Armstrong, R.A. 2007. Growth rates of Rhizocarpon geographicum lichens: a review with new data from Iceland. Journal of Quaternary Science 22, 311-320.
Bradwell, T., Dugmore, A.J. & Sugden, D.E. 2006. The Little Ice Age glacier maximum in Iceland and the North Atlantic Oscillation: evidence from Lambatungnajökull, southeast Iceland. Boreas 35, 61-80.
Bradwell, T., Sigurðsson, O. & Everest, J. 2013. Recent, very rapid retreat of a temperate glacier in SE Iceland. Boreas 42, 959-973.
Bull, W.B. 2018. Accurate surface exposure dating with lichens. Quaternary Research 90, 1-9.
Caseldine, C. 1991. Lichenometric dating, lichen population studies and Holocene glacial history in Tröllaskagi, Northern Iceland. In: Maizels J.K. & Caseldine C. (eds.), Environmental Change in Iceland: Past and Present. Kluwer, Dordrecht, pp. 219-233.
Caseldine, C., Baker, A. 1998. Frequency distributions of *Rhizocarpon geographicum s.l.*, modeling, and climate variation in Tröllaskagi, Northern Iceland. Arctic and Alpine Research 30, 175-183.
Chandler, B.M.P., Evans, D.J.A., Roberts, D.H. 2016a. Characteristics of recessional moraines at a temperate glacier in SE Iceland: Insights into patterns, rates and drivers of glacier retreat. Quaternary Science Reviews 135, 171-205.
Chandler, B.M.P., Evans, D.J.A., Roberts, D.H. 2016b. Recent retreat at a temperate Icelandic glacier in the context of the last ~80 years of climate change in the North Atlantic region. Arktos 2, article 24.
Chandler B.M.P., Evans D.J.A., Roberts D.H., Ewertowski M., Clayton A.I. 2016c. Glacial geomorphology of the Skálafellsjökull foreland, Iceland: A case study of 'annual' moraines. Journal of Maps 12, 905-916.
Chenet M., Roussel E., Jomelli V., Grancher D. 2010. Asynchronous Little Ice Age glacial maximum extent in southeast Iceland. Geomorphology 114, 253-260.
Cook-Talbot, J.D. 1991. Sorted circles, relative-age dating and palaeo-environmental reconstruction in an alpine periglacial environment, eastern Jotunheim, Norway: Lichenometric and weathering-based approaches. The Holocene 1, 128–141.
Crochet, P., Jóhannesson, T., Jónsson, T., Sigurðsson, O., Björnsson, H., Pálsson, F., Barstad, I. 2007. Estimating the

spatial distribution of precipitation in Iceland using a linear model of orographic precipitation. Journal of Hydrometeorology 8, 1285–1306.

Dabski, M. 2002. Dating of the Flàajökull moraine ridges SE Iceland: comparison of the glaciological, cartographic and lichenometrical data. Jökull 51, 17-24.

Dabski, M. 2007. Testing the size-frequency-based lichenometric dating curve on Fláajökull moraines (SE Iceland) and quantifying lichen population dynamics with respect to stone surface aspect. Jökull 57, 21-35.

Danish General Staff 1904. Öræfajökull, Sheet 87. Topographic map 1:50,000 scale. Geodetic Institute, Copenhagen.

Decaulne A. 2016. Lichenometry in Iceland, results and application. Géomorphologie 22, 77-91.

Durham University Iceland Expedition 1951. Breiðamerkurjökull map 1951. 1: 25000 scale map. Durham University.

Einarsson, M.A. 1984. Climate of Iceland. World Survey of Climatology 15, 673-697.

Evans, D. J.A. 2003. Ice-marginal terrestrial landsystems: Active temperate glacier margins. In: D.J.A. Evans (Ed.), Glacial landsystems. Arnold, London, pp. 12–43.

Evans, D. J. A. 2005. The glacier-marginal landsystems of Iceland. In: C. J. Caseldine, A. J. Russell, J. Harjardottir, & O. Knudsen (Eds.), Iceland: Modern processes and past environments. Elsevier, Amsterdam, pp. 93–126.

Evans, D. J. A. 2013. The glacial and periglacial research – Geomorphology and retreating glaciers. In: J. Shroder (Editor in Chief), R. Giardino, J. Harbor (Eds.), *Treatise on geomorphology*. Academic Press, San Diego, CA, vol. 8, *Glacial and Periglacial Geomorphology*, pp. 460–478.

Evans D.J.A., Chandler, B.M.P. 2018. Geology, physiography and glaciology of SE Iceland. In: Evans D.J.A. (ed.), Glacial Landsystems of Southeast Iceland: Quaternary Applications – Field Guide. Quaternary Research Association, London, pp. 1-19.

Evans, D. J. A., Hiemstra, J. F. 2005. Till deposition by glacier submarginal, incremental thickening. Earth Surface Processes and Landforms 30, 1633–1662.

Evans D.J.A., Orton C. 2015. Heinabergsjökull and Skalafellsjökull, Iceland: Active Temperate Piedmont Lobe and Outwash Head Glacial Landsystem. Journal of Maps 11, 415–431.

Evans, D.J.A., Twigg, D.R. 2000. Breiðamerkurjökull 1998. 1:30000 scale map. Universities of Glasgow and Loughborough.

Evans, D.J.A., Twigg, D.R. 2002. The active temperate glacial landsystem: a model based on Breiðamerkurjökull and Fjallsjökull, Iceland. Quaternary science reviews 21, 2143-2177.

Evans, D.J.A., Archer, S., Wilson, D.J.H. 1999. A comparison of the lichenometric and Schmidt hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. Quaternary Science Reviews 18, 13-41.

Evans, D. J. A., Butcher, C., Kirthisingha, A. V. 1994. Neoglaciation and an early “Little Ice Age” in western Norway: lichenometric evidence from the Sandane area. The Holocene 4*,* 278-289.

Evans D.J.A., Ewertowski M. & Orton C. 2016. Fláajökull (north lobe), Iceland: active temperate piedmont lobe glacial landsystem. Journal of Maps 12, 777–789.

Evans D.J.A., Ewertowski M. & Orton. C. 2017. Skaftafellsjökull, Iceland: glacial geomorphology recording glacier recession since the Little Ice Age. Journal of Maps 13, 358–368.

Evans, D. J. A., Shand, M., Petrie, G. 2009. Maps of the snout and proglacial landforms of Fjallsjökull, Iceland (1945, 1965, 1998). Scottish Geographical Journal 125, 304–320.

Gordon, J. E. & Sharp, M. 1983. Lichenometry in dating recent landforms and deposits, southeast Iceland. Boreas 12, 191-200.

Grove J.M. 1988. The Little Ice Age. Routledge, London 524pp.

Guðmundsson, H.J. 1998. Holocene glacier fluctuations of the Eiriksjökull ice cap, west central Iceland. Jökull 46, 17-28.

Guðmundsson, S. 2014. Reconstruction of late 19th century geometry of Kotárjökull and Breiðamerkurjökull in SE-Iceland and comparison with the present. Unpublished MSc thesis, University of Iceland.

Guðmundsson, S., Björnsson, H. 2017. Jöklabreytingar skoðaðar með gömlum ljósmyndum. Jökull 67, 51-64.

Guðmundsson, S., Björnsson, H., Pálsson, F. 2017. Changes of Breiðamerkurjökull glacier, SE-Iceland, from its late nineteenth century maximum to the present. Geografiska Annaler 99A, 338-352

Hamilton, S. J. 1995. Age determination of rock glaciers using lichenometry. Unpublished Ph.D. thesis, Queens University, Belfast.

Hannesdóttir H., Björnsson H., Pálsson F., Aðalgeirsdóttir G., Guðmundsson S. 2015. Area, volume and mass changes of southeast Vatnajökull ice cap, Iceland, from the Little Ice Age maximum in the late 19th century to 2010. The Cryosphere 9, 565–585.

Howarth, P. J., Welch, R. 1969a. Breiðamerkurjökull, South-east Iceland, August 1945. 1:30,000 scale map, University of Glasgow.

Howarth, P. J., Welch, R. 1969b. Breiðamerkurjökull, South-east Iceland, August 1965. 1:30,000 scale map, University of Glasgow.

Hurrell, J. & National Center for Atmospheric Research Staff 2016. The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based). Accessed at https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-indexstation-based on 29/01/17.

Innes, J.L. 1983. Size frequency distributions as a lichenometric technique: an assessment. Arctic and Alpine Research 15, 285-294.

Jaksch, K. 1970. Beobachtungen in den Gletschervorfeldern des Solheima und Sidujökull in sommer 1970. Jökull 20, 45-49.

Jaksch, K. 1975. Das Gletschervorfeld des Solheimajokull. Jökull 25, 34-38.

Jochimsen, M. 1973. Does the size of lichen thalli really constitute a valid measure for dating glacial deposits? *Arctic and Alpine Research* 5, 417-424.

Jóhannesson, T., Björnsson, H., Pálsson, F., Sigurðsson, O, Þorsteinsson, Þ. 2011. LiDAR mapping of the Snæfellsjökull ice cap, western Iceland. Jökull 61, 19–32.

Jóhannesson, T., Björnsson, H., Magnússon, E., Guðmundsson, S., Pálsson, F., Sigurðsson, O, Þorsteinsson, Þ., Berthier, E. 2013. Ice-volume changes, bias-estimation of mass-balance measurements and changes in subglacial lakes derived by LiDAR-mapping of the surface of Icelandic glaciers. Annals of Glaciology 54, 63–74.

Jomelli, V., Grancher, D., Naveau, P., Cooley, D. & Brunstein, D. 2007. Assessment study of lichenometric methods for dating surfaces. Geomorphology 86, 131-143.

Kirkbride, M.P. 2002. Icelandic climate and glacier fluctuations through the termination of the “Little Ice Age”. Polar Geography 26, 116-133.

Kirkbride, M.P. & Dugmore, A.J. 2001. Can lichenometry be used to date the “Little Ice Age” glacial maximum in Iceland? Climatic Change 48, 151-167.

Kirkbride, M.P., Dugmore, A.J. 2006. Responses of mountain ice caps in central Iceland to Holocene climate change. Quaternary Science Reviews 25, 1692-1707.

Krüger, J. 1995. Origin, chronology and climatological significance of annual-moraine ridges at Myrdalsjökull, Iceland. The Holocene 5, 420-427.

Locke, W.W., Andrews, J.T. & Webber, P.J. 1979. A manual for lichenometry. British Geomorphological Research Group, London.

Loso, M.G., Doak, D.F., Anderson, R.S. 2014. Lichenometric dating of Little Ice Age glacier moraines using explicit demographic models of lichen colonization, growth and survival. Geografiska Annaler 96A, 21-41.

Lukas, S. 2012. Processes of annual moraine formation at a temperate alpine valley glacier: insights into glacier dynamics and climatic controls. Boreas 41, 463–480.

Maizels, J.K., Dugmore, A.J. 1985. Lichenometric dating and tephrochronology of sandur deposits, Solheimajökull area, southern Iceland. Jökull 35, 69-77.

Marren, P. M. 2002. Glacier margin fluctuations, Skaftafellsjökull, Iceland: Implications for sandur evolution. Boreas 31, 75–81.

Matthews, J.A. 1974. Families of lichenometric dating curves from the Storbreen gletscherforveld, Jotunheimen, Norway. Norsk Geografisk Tidsskrift 28, 215-235.

Matthews, J.A. 1994. Lichenometric dating: a review with particular reference to “Little ice Age” moraines in southern Norway. In: Beck C. (Ed), Dating in Exposed and Surface Contexts, New Mexico University Press, Albuquerque, 185-212.

Matthews, J.A. 2005. ‘Little Ice Age’ glacier variations in Jotunheimen, southern Norway: a study in regionally controlled lichenometric dating of recessional moraines with implications for climate and lichen growth rates. The Holocene 15, 1-19.

Matthews, J.A., Briffa, K.R. 2005. The ‘Little Ice Age’: Re-evaluation of an evolving concept. Geografiska Annaler

87, 17-36.
Matthews, J.A., McCarroll, D., Shakesby, R.A., 1995. Contemporary terminal moraine ridge formation at a temperate glacier: Styggedalsbreen, Jotunheimen, southern Norway. Boreas 24, 129–139.
McCarthy, D.P. 2003. Estimating lichenometric ages by direct and indirect measurement of radial growth: a case study of Rhizocarpon agg. At the Illecillewaet Glacier, British Columbia. Arctic, Antarctic and Alpine Research 35, 203-213.
McKinzey, K. M., Orwin, J. F., Bradwell, T. 2004. Re-dating the moraines at Skalafellsjökull and Heinabergsjökull using different lichenometric methods: Implications for the timing of the Icelandic Little Ice Age maximum. Geografiska Annaler 86A, 319–335.
McKinzey, K. M., Orwin, J. F., Bradwell, T. 2005. A revised chronology of key Vatnajökull (Iceland) outlet glaciers during the Little Ice Age. Annals of Glaciology 42, 171–179.
Osborn G., McCarthy D., LaBrie A., Burke R. 2015. Lichenometry dating: science or pseudo-science? Quaternary Research 83, 1-12.
Price, R.J. 1969. Moraines, sandar, kames and eskers near Breiðamerkurjökull, Iceland. Transactions of the Institute of British Geographers 46, 17-43.
Price, R.J. 1982. Changes in the proglacial area of Breiðamerkurjökull, southeastern Iceland: 1890–1980. Jökull 32, 29–35.
Price, R.J., Howarth, P.J. 1970. The evolution of the drainage system (1904–1965) in front of Breiðamerkurjökull, Iceland. Jökull 20, 27–37.
Rosenwinkel S., Korup O., Landgraf A., Dzhumabaeva A. 2015. Limits to lichenometry. Quaternary Science Reviews 129, 229-238.
Sigurđsson, O., Jónsson, T. & Jóhannesson, T. 2007. Relation between glacier-termini variations and summer temperature in Iceland since 1930. Annals of Glaciology 46, 170-176.
Thompson, A. P. 1988. Historical development of the proglacial landforms of Svínafellsjökull and Skaftafellsjökull, southeast Iceland. Jökull 38, 17–31.
Thompson, A., Jones, A. 1986. Rates and causes of proglacial river terrace formation in southeast Iceland: an application of lichenometric dating techniques. Boreas 15, 231-246.
Þórarinsson, S. 1943. Vatnajökull: Scientific results of the Swedish–Icelandic investigations 1936–37–38. Chapter XI. Oscillations of the Icelandic glaciers in the last 250 years. Geografiska Annaler 25, 1–54.
Þórarinsson, S. 1956. On the variations of Svínafellsjökull, Skaftafellsjökull and Kvíárjökull in Öræfi. Jökull 6, 1–15.
Todtmann, E.M., 1960. Gletscherforschungen auf Island (Vatnajökull). Abhandlung aus dem Gebiet der Auslandskunde. Hamburg. Bd 65, Rh. C, Bd 19.

Figure captions

Figure 1: Location map of Breiðamerkurjökull and the identification of its three major ice flow units (from Guðmundsson 2014).

Figure 2: Variations since 1931 of the non-surge-type margins of the Vatnajökull South Region glaciers, using data from the Icelandic Glaciological Society.

Figure 3: Maps of sediment-landform assemblages and historical ice marginal positions for the Breiðamerkurjökull foreland, with ages derived from a variety of historical archives and aerial imagery; a) map of the whole foreland; b) enlarged area showing the foreland of the Esjufjallajökull ice flow unit and the locations of dated moraines used for lichenometry and the undated moraines LD 1-3.

Figure 4: Retreat patterns across the Breiðamerkurjökull foreland compiled from the sources identified in Table 2. Profiles across the foreland are numbered according to the ice flow unit whose margin was measured, where: A1-A11 are for Norðlingalægðarjökull; M12-M18 are for Esjufjallajökull; and V19-V24 are for Mávabyggðajökull. Colored lines are based on aerial photographs, satellite imagery and published glacier marginal observations. Broken lines are estimations based on other information such as historical

documentation and the grey lines are averages between the well controlled positions. Important trends are the impacts of the Jökulsárlón proglacial lake and its overdeepened profile on rapid calving and the relatively more steady recession of the Mávabyggðajökull and Esjufjallajökull ice flow units, following on from the slow retreat of the early 20th Century. The 1995 broken line marks the end of the mid-1970s – 1995 cooler period, during which ice-marginal retreat slowed considerably.

Figure 5: Graphs depicting the size-frequency distributions for the lichen populations on each independently dated moraine: a) histograms of frequency arranged in 3 mm bin classes; b) linear regression plots of the logarithm of the frequency against lichen axis.

Figure 6: Lichen growth curves or age-size plots derived from the lichen data for each independently dated moraine sample: a) size-frequency growth curve based on the largest lichens (upper graph) and size-frequency gradient curve (lower graph); b) age-size plot for the five largest lichens (5LL) in each moraine sample.

Figure 7: Graphs depicting the size-frequency distributions for the lichen populations on each of the three lichen dated (LD 1-3) moraines: a) histograms of frequency arranged in 3 mm bin classes; b) linear regression plots of the logarithm of the frequency against lichen axis.

Figure 8: Time series of annual temperature and summer temperature anomalies, annual and winter precipitation anomalies and NAO index compared with the relative retreat rates of the Mávabyggðajökull and Esjufjallajökull ice flow units. Periods during which readvances occurred are classified here as those of slow retreat.

Table 1: Details of lichenometric dating studies undertaken in SE Iceland compared with those of this study (after Evans et al. 1999 and Bradwell 2018).

Source	Method	Thallus axis	Survey area (m^2) or sample size	Calibration surface	Oldest surface	Growth rate (mm/yr)	Lag period (yrs)
Jaksch (1970)	LL	Long	Entire surface	Gravestones	~1870	0.73	15
Jaksch (1975)	LL	Long	Entire surface	Moraines	~1890	0.65	<15
Gordon and Sharp (1983) Breiðamerkurjökull	LL	Short	1500	Moraines	1894	0.675	5
Gordon and Sharp (1983) Skalafellsjökull	LL	Short	150	Moraines	1887	0.769	15
Gordon and Sharp (1983)	LL	Long	150	Moraines	1887	0.987	15
Maizels and Dugmore (1985)	LL, 5LL, 25LL	Long	200	Moraines	1890	0.85	20-25
Thompson and Jones (1986)	5LL	Short	Entire surface	Moraines	1870	0.585-0.725	??
Guðmundsson (1998)	5LL	Short	Entire surface	Used Gordon & Sharp (1983) and Thompson & Jones (1986)	1889	0.67	19
Evans *et al.* (1999) South coast	5LL	Long	Entire surface	Moraines, lake shorelines, bridges, gravestones	1887	0.56	>5
Evans *et al.* (1999) South coast forelands	5LL	Long	Entire surface	Moraines, lake shorelines, bridges, gravestones	1887	0.8	6.5
Bradwell (1998)	LL, 20LL	Long	Entire surface	Moraines	1881	0.6	??
Bradwell (2001)	LL, SF	Long	30-50	Flood deposit, lava flow, rockfall, moraines, striated rock	1727 1783 1789 1930 1957	0.545	??
Bradwell (2004a)	LL, SF	Long	30-50	Used Bradwell (2001)	1727	0.43-0.47	
Bradwell (2004b)	LL, SF	Long	30-50	Used Bradwell (2001)	1903	0.47	
McKinzey et al. (2004)	LL, 5LL, SF	Long	30	Used Evans (1999) and Bradwell (2001, 2004a)	1727, 1887	0.34-0.80	
McKinzey et al. (2005)	LL, 5LL, SF	Long	30	Used Evans (1999) and Bradwell (2001, 2004a)	1727, 1887	0.34-0.80	

Bradwell et al. (2006)	LL, SF	Long	30-50	Used Bradwell (2001)	1727	0.34-0.47	
Dabski (2002)	LL, 5LL	Long	6000	Used Gordon & Sharp (1983), Evans *et al*., (1999) and Bradwell (2001)	1727, 1887	0.34-0.80	
Dabski (2007)	SF	Long	6000	Used Bradwell (2001)	1727	0.34-0.47	
Orwin et al. (2008)	SF	Long	30	N/A	1727, 1887	0.34-0.80	N/A
Chenet et al. (2010)	LL, 5LL, SF	Long	50 thalli	Flood deposit, lava flow, rockfall, moraines, dams,	1727, 1996 1783 1789 1935 1968	0.4	
Dabski (2010)	5LL	Long	417 thalli	Used Evans et al. (1999)	1887	0.50-0.80	
Bradwell et al. (2013)	LL, SF	Long	30-50	Used Bradwell (2001) and Bradwell & Armstrong (2007)	1890-91	0.47	
This study (size-frequency)	SF	Long	100	Moraines	1904	0.64	7
This study (largest five)	5LL	Long	Entire surface	Moraines	1904	0.71	11

Table 2: Uncertainties for ice-marginal positons and moraine ages derived from historical archives

Terminus position/moraine	Uncertainty (error) in location	Uncertainty (error) in absolute age	Details
1890 (LIA end moraine)	± 10 m	1890 ± 10 yrs	Advance to limit 1870-1880s & stability for 10 yrs (also 150-300 m outside DGS 1904 survey)
1904 terminus	± 10 m	1904 ± 3 yrs	DGS survey
1930 terminus	± 20 m	1930 ± 5 yrs	Björnsson (1996, 1998)
1945 terminus	± 5 m	1945 ± 1 yr	1945 aerial photographs
1951 terminus	± 10 m	1951 ± 2 yrs	1955 aerial photographs & IGS observations
1960 terminus	± 5 m	1960 ± 1 yr	1960 aerial photographs
1964 terminus	± 5 m	1964 ± 1 yr	1964 aerial photographs
1970 terminus	± 15 m	1970 ± 3 yrs	Personal communication from Flosi Björnsson of Kvisker
1973 terminus	± 60 m	1973 ± 3 yrs	1973 Landsat 1 image.
1982 terminus	± 5 m	1982 ± 1 yr	1982 aerial photographs
1994 terminus	± 5 m	1994 ± 1 yr	1994 aerial photographs
1998 terminus	± 5 m	1998 ± 1 yr	1998 aerial photographs
2004	± 2 m	2004 ± 1 yr	2004 aerial photographs
2010	± 2 m	2010 ± 1 yr	LiDAR DEM
2018	± 15 m	2018 ± 1 yr	2018 Landsat 8 image

Table 3: The recession rates of the main flow units of Breiðamerkurjökull between 1890 and 2010, with the sum totals of recession and average recession for each unit for the whole period highlighted in grey (from Guðmundsson 2014).

Period	Norðlingalægðarjökull		Esjufjallajökull		Máfabyggðajökull	
	Retreat (m)	ma^{-1}	Retreat (m)	ma^{-1}	Retreat (m)	ma^{-1}
1890–1904	109	8	198	7	134	14
1904–1930	365	15	–	–	–	–
1930–1945	626	45	–	–	–	–
1904–1945	–	–	1493	37	972	24
1945–1951	265	53	439	88	293	59
1951–1965	1143	88	807	62	966	74
1965–1973	210	30	598	85	449	64
1973–1980	352	59	551	92	446	74
1980–1990	104	12	266	30	92	10
1990–1994	237	79	72	24	145	48
1994–1998	346	115	153	51	106	35
1998–2004	618	124	406	81	189	38
2004–2010	843	169	391	78	272	54
1890–2010	5216	66	5270	58	4127	45

Table 4: Mean and standard deviation of the five largest lichen on each moraine.

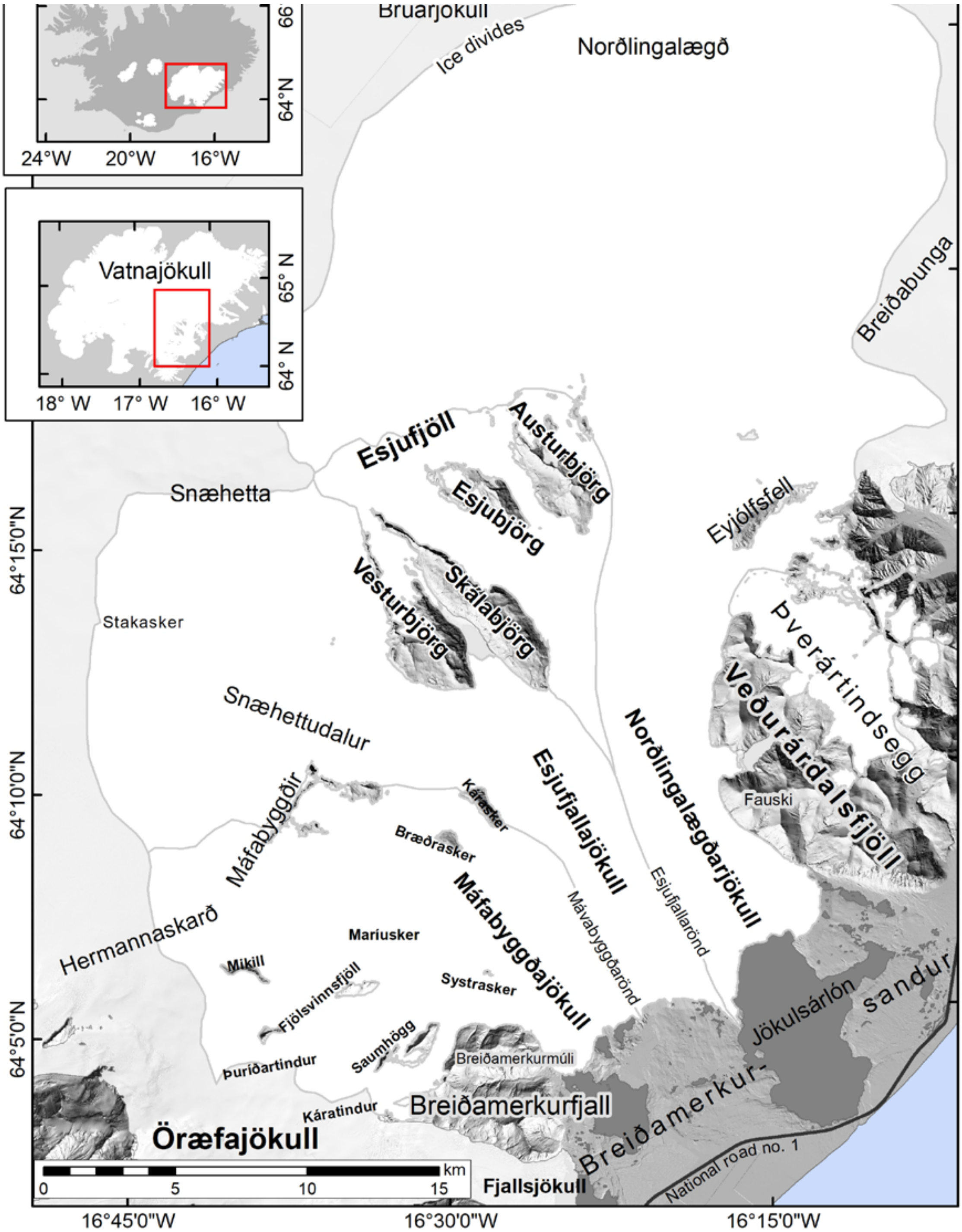
Moraine	Mean of five largest lichen	Standard deviation
1904	71.8	1.79
LD 1	57.6	0.89
1930	56.4	3.36
LD 2	41.4	3.78
1951	37.4	2.30
LD 3	37.4	3.29
1960	37.2	2.28
1964	26.2	2.17
1970	24.2	2.68
1973	23.0	1.58
1982	18.8	2.77

Table 5: A comparison of the calculated ages for the three lichenometrically dated moraines using the three alternative lichenometric techniques. The age range of the three moraines is indicated in brackets based upon their positions between the independently dated ice-margins (see Figure 3)

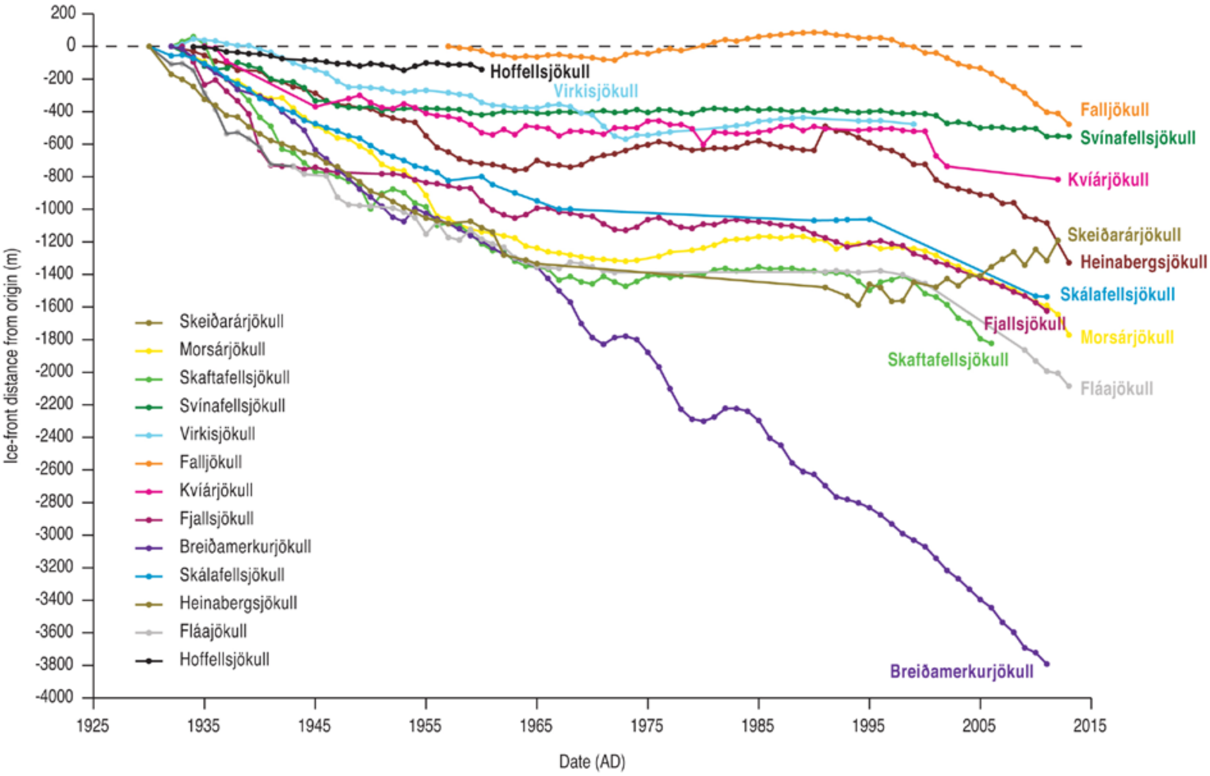
Lichenometric technique	**Lichenometrically calculated ages for moraines LD 1-3**		
	Moraine LD 1 (1904-1930)	**Moraine LD 2 (1945-1951)**	**Moraine LD 3 (1951-1955)**
Size-frequency gradient (SF)	87 yrs = 1929	90 yrs = 1926	58 yrs = 1958
Size-frequency largest lichen (LL)	91 yrs = 1925	74 yrs = 1942	59 yrs = 1957
Mean of largest 5 lichen (5LL)	90 yrs = 1926	68 yrs = 1948	62 yrs = 1954

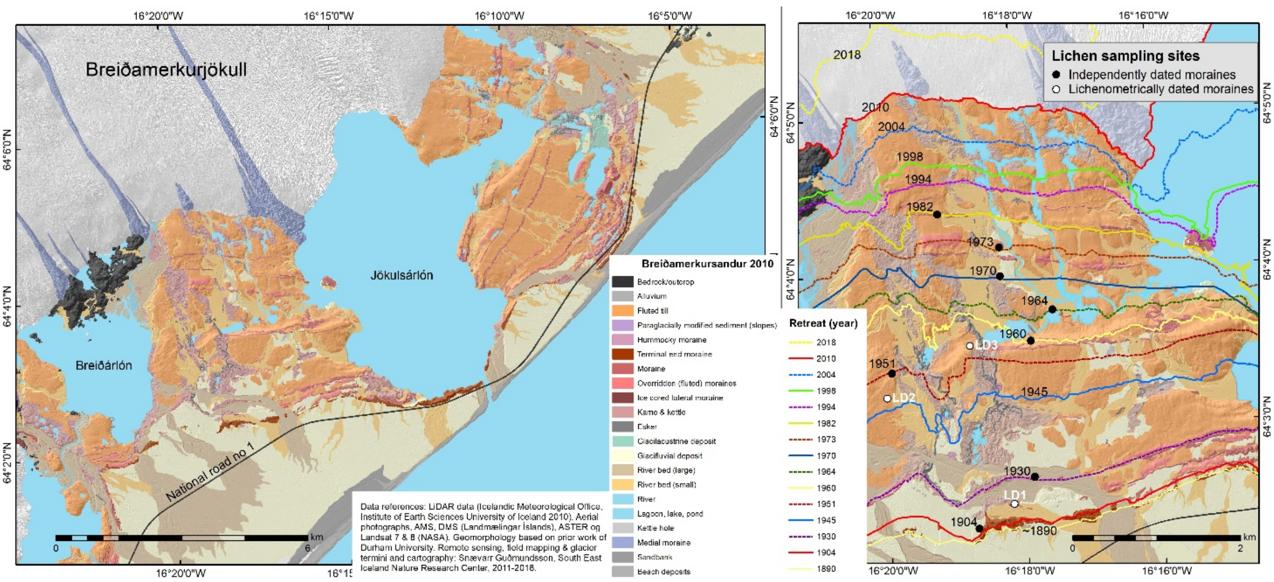
Table 6: The recession rates of the Mávabyggðajökull and Esjufjallajökull ice flow units of Breiðamerkurjökull, recalculated based upon the dates presented in this paper.

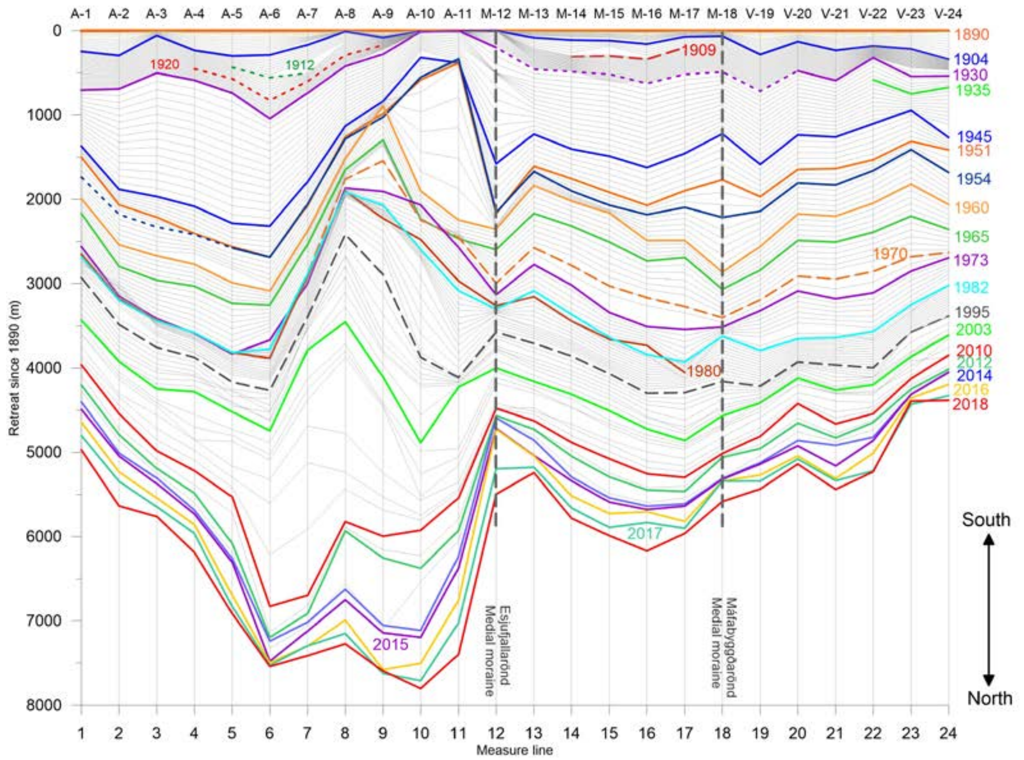
Period & (yrs)	Recession (m)	Recession rate ($m\ yr^{-1}$)
1890-1904 (14)	198	7
1904-1926 (22)	233	11
1926-1930 (4)	321	80
1930-1945 (15)	968	65
1945-1948 (3)	104	35
1948-1951 (3)	295	98
1951-1954 (3)	125	42
1954-1955 (1)	133	133
1955-1960 (5)	63	13
1960-1964 (4)	337	84
1964-1970 (6)	420	70
1970-1973 (3)	412	137
1973-1982 (9)	274	30
1982-1994 (12)	431	36
1994-2004 (10)	626	63
2004-2010 (6)	601	100
2010-2015 (5)	510	102



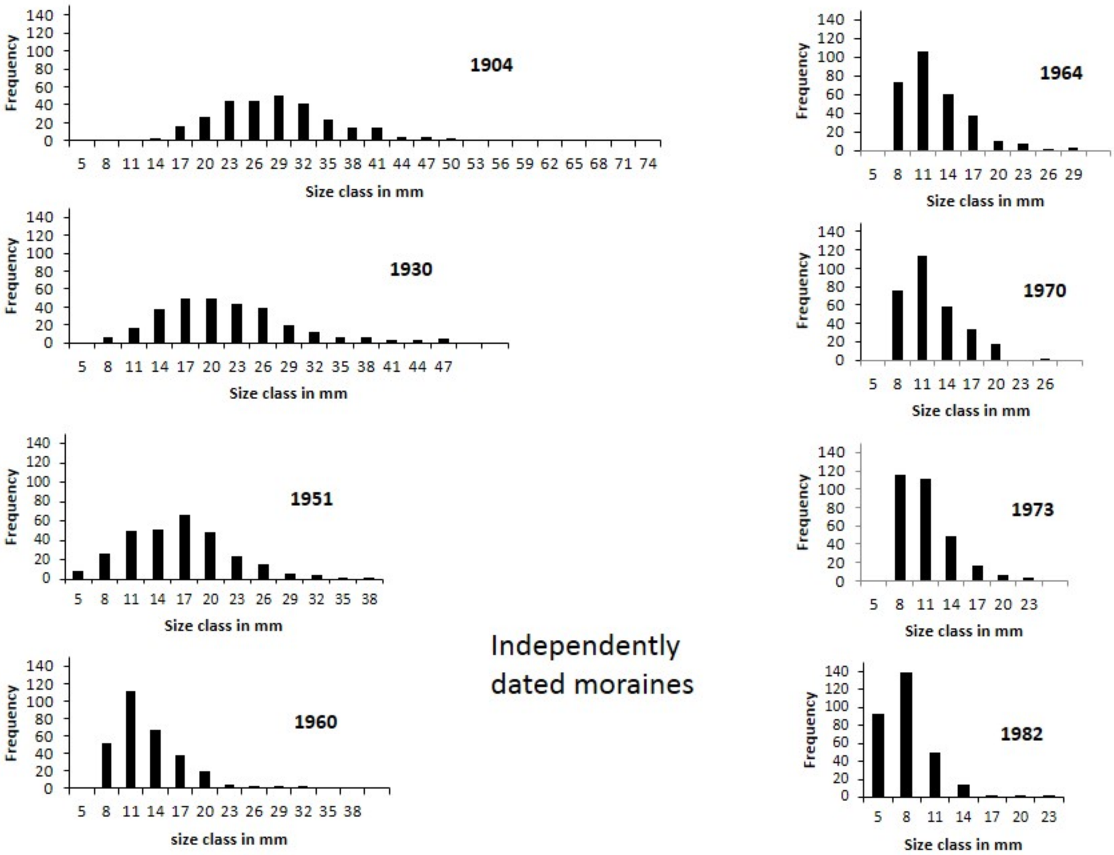
Brúarjökull
Ice divides
Norðlingalægð
Breiðabunga
Vatnajökull
24°W
20°W
16°W
64°N
66
18° W
17° W
16° W
64° N
65° N
Esjufjöll
Austurbjörg
Esjubjörg
Snæhetta
Eyjólfsfell
Vesturbjörg
Skálabjörg
Stakasker
Þverártindsegg
Veðurárdalsfjöll
Snæhettudalur
Esjufjallajökull
Norðlingalægðarjökull
Fauski
Máfabyggðir
Kárasker
Bræðrasker
Máfabyggðajökull
Mávabyggðarönd
Esjufjallarönd
Hermannaskarð
Maríusker
Mikill
Fjölsvinnsfjöll
Systrasker
Jökulsárlón
sandur
Saumhögg
Breiðamerkurmúli
Þuríðartindur
Káratindur
Breiðamerkurfjall
Breiðamerkur-
Öræfajökull
National road no. 1
Fjallsjökull
km
0
5
10
15
16°45'0"W
16°30'0"W
16°15'0"W
64°5'0"N
64°10'0"N
64°15'0"N
64°20'0"N
64°25'0"N

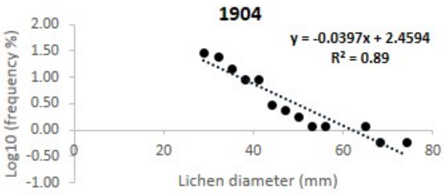

Ice-front distance from origin (m)
Date (AD)
Skeiðarárjökull
Morsárjökull
Skaftafellsjökull
Svínafellsjökull
Virkisjökull
Falljökull
Kvíárjökull
Fjallsjökull
Breiðamerkurjökull
Skálafellsjökull
Heinabergsjökull
Fláajökull
Hoffellsjökull

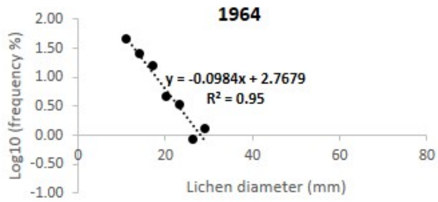

Breiðamerkurjökull
Jökulsárlón
Breiðárlón
National road no 1
Breiðamerkursandur 2010
Lichen sampling sites
Independently dated moraines
Lichenometrically dated moraines
Retreat (year)

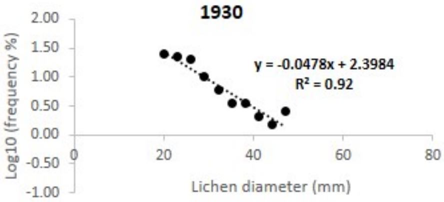


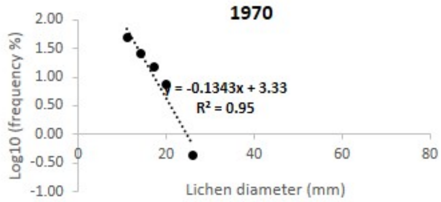
Courtesy of Snævarr Guðmundsson

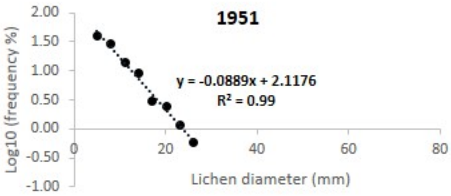

1904
1930
1951
1960
1964
1970
1973
1982
Frequency
Size class in mm
size class in mm
Independently dated moraines

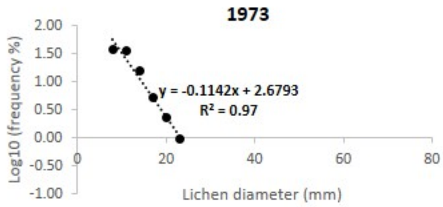

1904
y = -0.0397x + 2.4594
R² = 0.89
Log10 (frequency %)
Lichen diameter (mm)

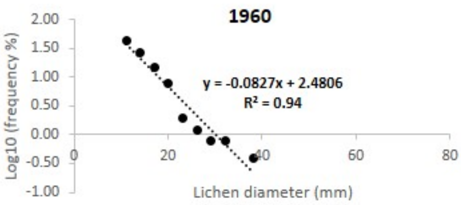

1964
y = -0.0984x + 2.7679
R² = 0.95
Log10 (frequency %)
Lichen diameter (mm)

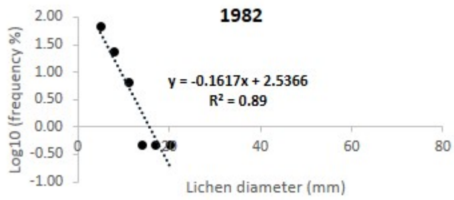

1930
y = -0.0478x + 2.3984
R² = 0.92
Log10 (frequency %)
Lichen diameter (mm)

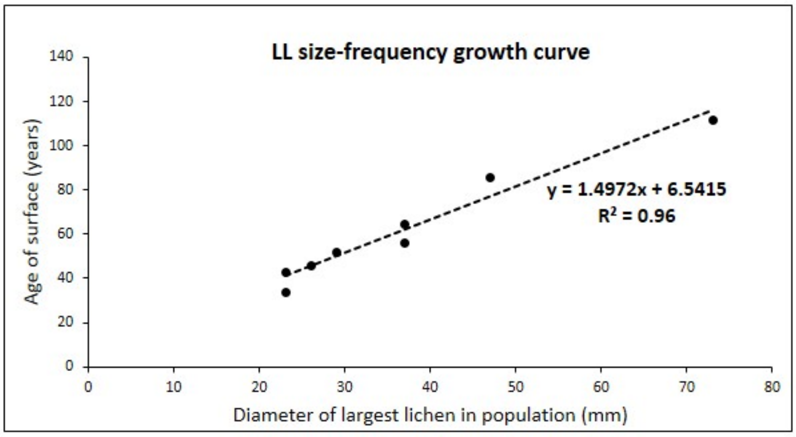

1970
y = -0.1343x + 3.33
R² = 0.95
Log10 (frequency %)
Lichen diameter (mm)

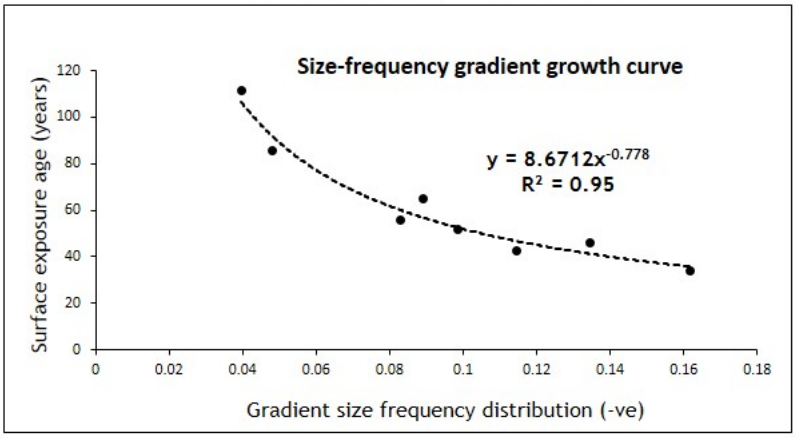

1951
y = -0.0889x + 2.1176
R² = 0.99
Log10 (frequency %)
Lichen diameter (mm)

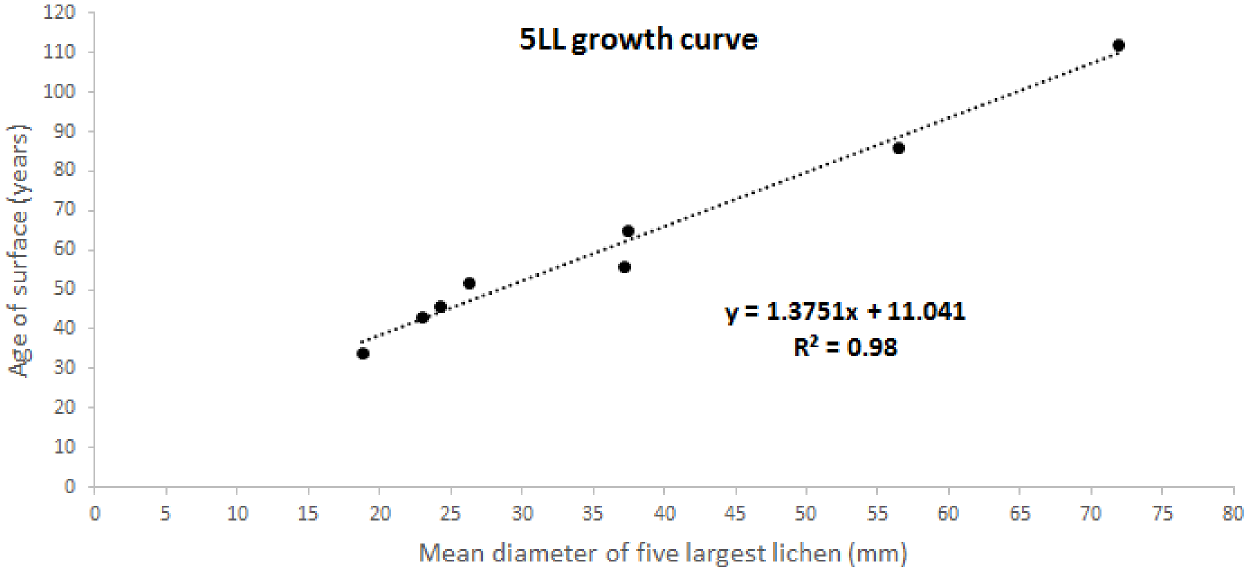

1973
y = -0.1142x + 2.6793
R² = 0.97
Log10 (frequency %)
Lichen diameter (mm)


1960
y = -0.0827x + 2.4806
R² = 0.94
Log10 (frequency %)
Lichen diameter (mm)

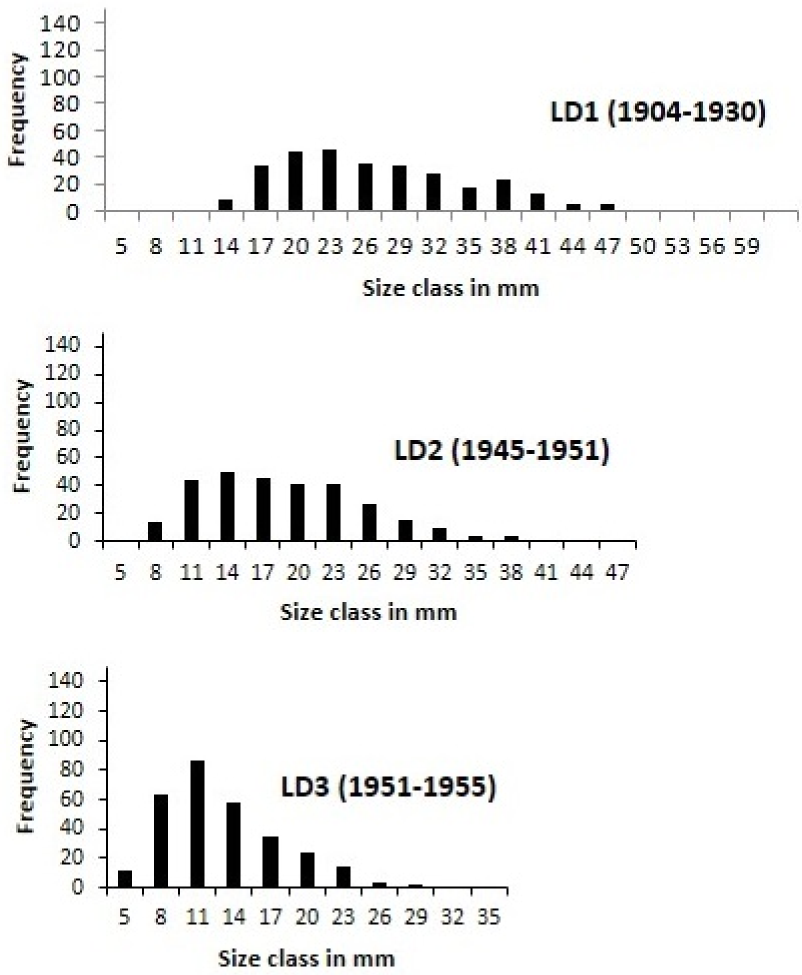

1982
y = -0.1617x + 2.5366
R² = 0.89
Log10 (frequency %)
Lichen diameter (mm)

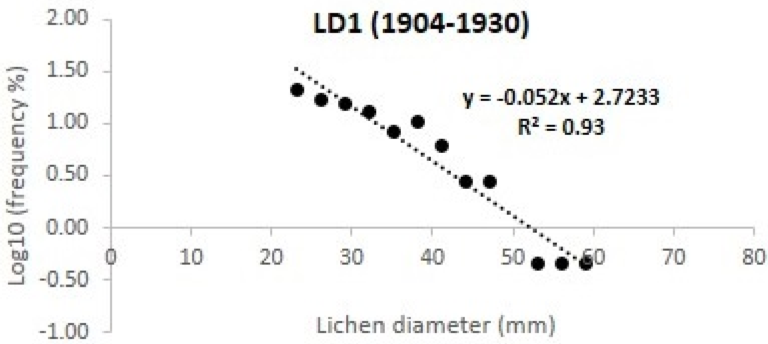

LL size-frequency growth curve
y = 1.4972x + 6.5415
R² = 0.96
Age of surface (years)
Diameter of largest lichen in population (mm)
0
20
40
60
80
100
120
140
0
10
20
30
40
50
60
70
80

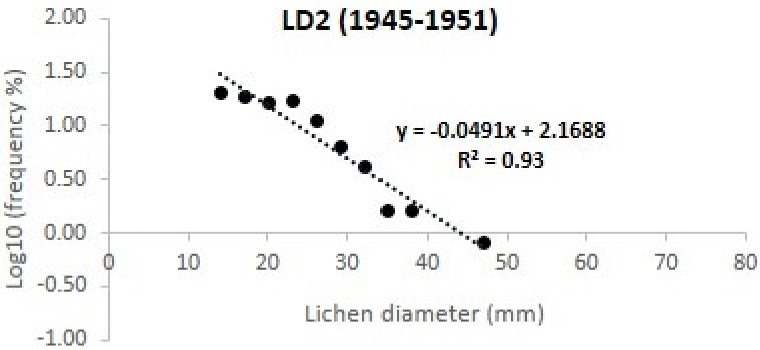

Size-frequency gradient growth curve
y = 8.6712x^-0.778
R² = 0.95
Surface exposure age (years)
Gradient size frequency distribution (-ve)
0
20
40
60
80
100
120
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18

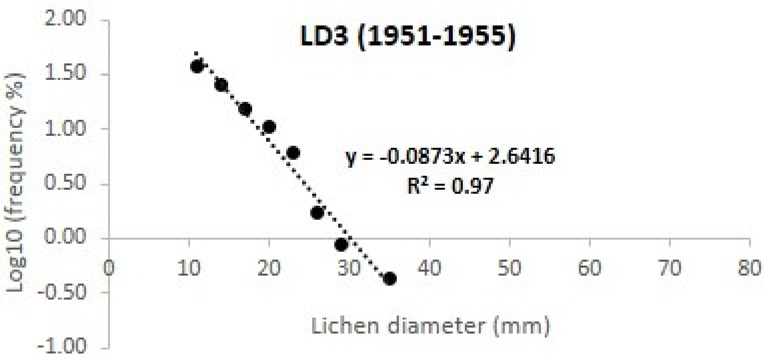

5LL growth curve
y = 1.3751x + 11.041
R² = 0.98
Age of surface (years)
Mean diameter of five largest lichen (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

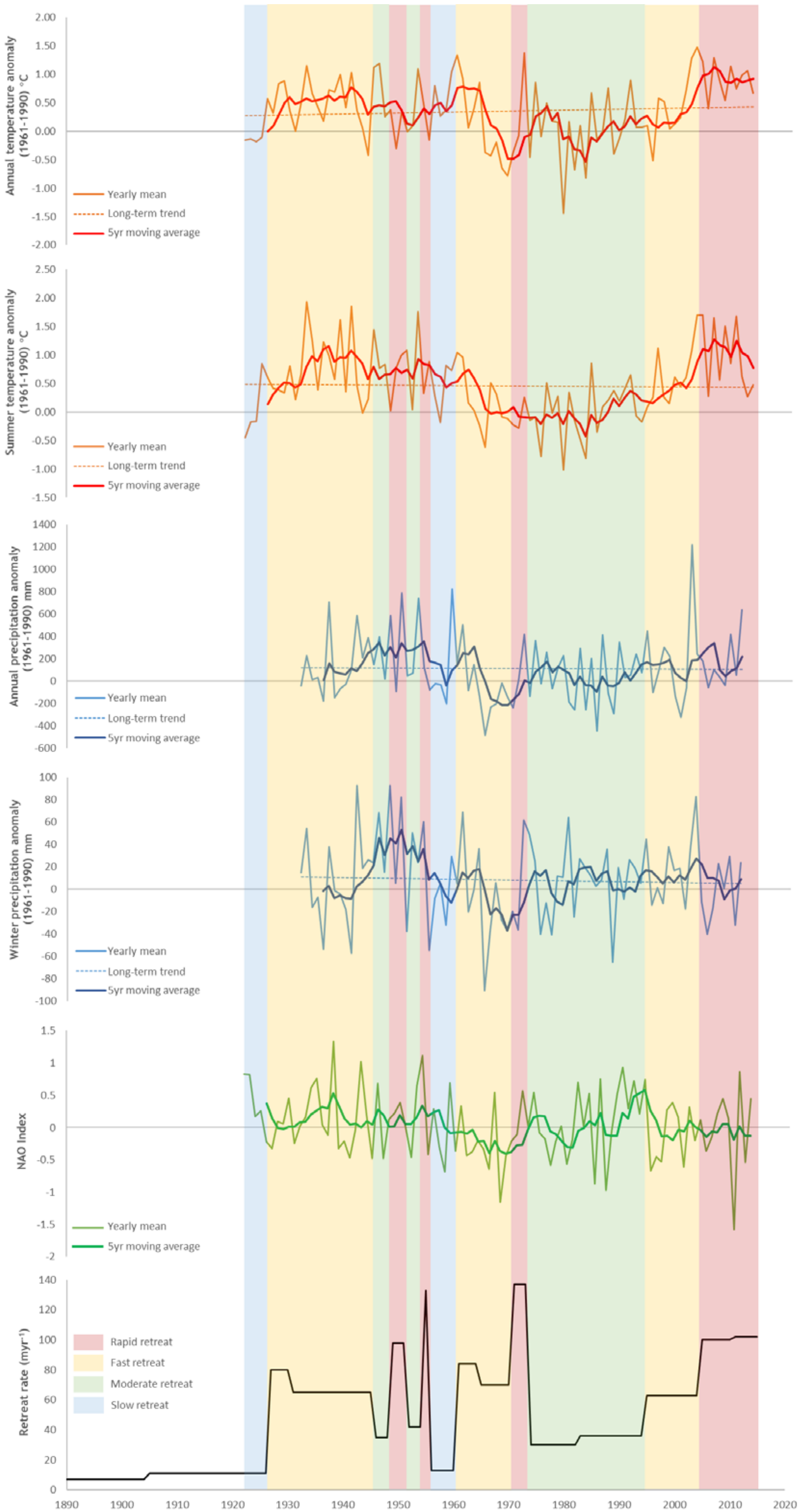
Lichen dated moraines




LD1 (1904-1930)
y = -0.052x + 2.7233
R² = 0.93
Log10 (frequency %)
Lichen diameter (mm)
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
0
10
20
30
40
50
60
70
80


LD2 (1945-1951)
y = -0.0491x + 2.1688
R² = 0.93
Log10 (frequency %)
Lichen diameter (mm)
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
0
10
20
30
40
50
60
70
80


LD3 (1951-1955)
y = -0.0873x + 2.6416
R² = 0.97
Log10 (frequency %)
Lichen diameter (mm)
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
0
10
20
30
40
50
60
70
80



Annual temperature anomaly (1961-1990) °C
Yearly mean
Long-term trend
5yr moving average
Summer temperature anomaly (1961-1990) °C
Yearly mean
Long-term trend
5yr moving average
Annual precipitation anomaly (1961-1990) mm
Yearly mean
Long-term trend
5yr moving average
Winter precipitation anomaly (1961-1990) mm
Yearly mean
Long-term trend
5yr moving average
NAO Index
Yearly mean
5yr moving average
Retreat rate (myr⁻¹)
Rapid retreat
Fast retreat
Moderate retreat
Slow retreat
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020