Recent retreat at a temperate Icelandic glacier in the context of the last ~80 years of climate change in the North Atlantic region

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Abstract

Over recent decades, glaciers outside of Greenland and Antarctica have displayed accelerating rates of mass loss and ice-frontal retreat, and this has been associated with unequivocal climatic and oceanic warming. Icelandic glaciers are particularly sensitive to climate variations on short-term timescales owing to their maritime setting, and have shown rapid rates of retreat and mass loss during the past decade. This study uses annual moraine spacing as a proxy for ice-frontal retreat in order to examine variability in glacier retreat at Skálafellsjökull, SE Iceland, over the last ~80 years. Two pronounced six-year periods (1936–1941 and 1951–1956) of ice-frontal retreat are recognised in the record for comparison with the most recent phase of retreat (2006–2011), and these three retreat phases are shown to be similar in style and magnitude. Analysis of climate data indicates that these periods of glacier retreat are associated with similar summer air temperature values, which is a key control on Icelandic terminus variations. This demonstrates that both the most recent phase of ice-frontal retreat at Skálafellsjökull and the recent warming of summer temperatures are not unusual in the context of the last ~80 years. These findings demonstrate the importance of placing observations of contemporary glacier change in a broader decadal- to centennial-scale context.

Keywords: ice-frontal retreat, annual moraines, glacier-climate interactions, Iceland

1. Introduction

Glaciers are now losing mass in response to unequivocal atmospheric and oceanic warming, according to the Intergovernmental Panel on Climate Change (IPCC, 2013). This mass loss has contributed to global mean sea-level rise, with mass loss from glaciers and ice-caps accounting for the majority of the recent cryospheric contribution (~56% between 1993 and 2010: IPCC, 2013). Recent studies of glacier mass balance and ice-frontal positions of glaciers outside of Greenland and Antarctica have demonstrated accelerating rates of mass loss and ice-frontal retreat since the 1970s (e.g. Kaser et al., 2006; Cogley, 2009; Zemp et al., 2009; Jacob et al., 2012; Marzeion et al., 2012; Gardner et al., 2013; Stokes et al., 2013; Carr et al., 2014). Icelandic glaciers, in particular, are highly sensitive climate indicators owing to their maritime setting, and are particularly sensitive to short-term (annual to decadal-scale) climatic fluctuations (Sigurðsson et al., 2007; Bradwell et al., 2013). Over the past decade, studies have demonstrated that Icelandic glaciers have undergone rapid rates of ice-frontal retreat and mass loss (e.g. Sigurðsson et al., 2007; Björnsson et al., 2013; Bradwell et al., 2013; Mernild et al., 2014; Hannesdóttir et al., 2015). Moreover, a recent study at Falljökull (Bradwell et al., 2013) has suggested that retreat at this outlet is unprecedented in the context of the last ~80 years. An assessment of ongoing ice-frontal retreat at other Icelandic outlets is therefore of key importance to placing the present period of atmospheric warming and associated glacier retreat in a broader centennial context.

Long, continuous records of ice-front fluctuations form an integral component of monitoring glacier change at regional and global scales, but such detailed records may be absent or incomplete in many localities. Annual moraines, which represent annual ice-frontal variations, offer a valuable geomorphological proxy for examining ice-frontal retreat where such records are unavailable (e.g. Bradwell, 2004; Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013). These features are a characteristic signature of active temperate glaciers in SE Iceland (e.g. Price, 1970; Evans and Twigg, 2002; Evans, 2003; Evans and Orton, 2015), and this region is an exemplar for demonstrating the potential of annual moraine records. Previous studies of annual moraines have primarily focused on process-form observations (e.g. Price, 1970; Sharp, 1984; Evans and Hiemstra, 2005; Reinardy et al., 2013; Hiemstra et al., 2015), the climatic significance of the moraines (e.g. Bradwell, 2004; Beedle et al., 2009; Bradwell et al., 2013), or a combination thereof (e.g. Boulton, 1986; Krüger, 1995; Lukas, 2012; Chandler et al., 2016a). However, there has so far been limited use of annual moraine records to undertake detailed comparisons of variations *between* phases of ice-frontal retreat within the same record (e.g. Bradwell et al., 2013), with the emphasis on drivers of the overall pattern.

In this study we apply annual moraine spacing as a proxy for annual ice-frontal retreat rates of Skálafellsjökull, a major non-surging temperate outlet glacier of the Vatnajökull ice-cap, SE Iceland (Figure 1), in order to examine variability both within the ice-front record and the associated climate records since the 1930s. Skálafellsjökull has lost ~15% of its mass since the end of the Little Ice Age (Hannesdóttir et al., 2015), but understanding of the behaviour of this glacier is partly limited by a paucity of ice-front measurement data since the 1970s. Annual moraines previously identified on the Skálafellsjökull foreland (Sharp, 1984; Chandler et al., 2016a, b; Evans and Orton, 2015) could therefore yield valuable insights into the pattern and rates of recent ice-front retreat at Skálafellsjökull. Our previous contribution on this topic (Chandler et al., 2016a) demonstrated that the *overall* pattern of ice-frontal retreat (moraine spacing) was driven predominantly by variations in summer air temperature. In the present contribution, we take this further by undertaking quantitative analysis to examine differences between the most recent phase of retreat recorded by the annual moraines (2006–2011) and two earlier pronounced phases with an equivalent timespan (1936–1941 and 1951–1956). Moreover, we undertake statistical analyses of climate anomalies associated with these three periods of ice-frontal retreat. The analyses demonstrate that both the most recent phase of ice-frontal retreat (2006–2011) and associated climate anomalies are not unusual in the context of the ~80-year period examined.

2. Previous research

2.1 Icelandic termini variations

Regular monitoring of Icelandic glacier termini variations commenced in the 1930s (e.g. Eyþórsson, 1931, 1935), and 41 outlet glaciers, at 55 locations, are currently being actively monitored by *Jöklarannsóknafélag Íslands* (the Icelandic Glaciological Society: http://spordakost.jorfi.is). This instrumental record reveals that the period 1930–1960 was characterised by rapid retreat of all monitored ice-fronts, with retreat occasionally interrupted by surge activity at surge-type glaciers (Eyþórsson, 1931, 1963; Sigurðsson, 1998; Sigurðsson and Jónsson, 1995; Sigurðsson et al., 2007). By 1960, all monitored ice-margins had retreated from their 1930 position, though 10–20% of glacier termini were advancing in any given year (Sigurðsson and Jónsson, 1995; Jóhannesson and Sigurðsson, 1998; Sigurðsson et al., 2007). During the 1940s and 1960s the rate of ice-frontal retreat slowed, with many non-surge-type glaciers advancing to varying degrees in the decades following the 1960s (Figure 2; Sigurðsson and Jónsson, 1995; Sigurðsson et al., 2007). During the 1990s many non-surge-type glaciers recommenced ice-marginal retreat, and by 2000 all monitored non-surge-type glaciers were retreating (Sigurðsson, 2005; Sigurðsson et al., 2007). Over the past decade many of the monitored glaciers have shown increasingly rapid rates of ice-marginal retreat (e.g. Bradwell et al., 2013).

Comparison of non-surge-type glacier termini variations since the 1930s with climate variations show ice-front fluctuations are in sympathy with air temperature variations, with warming and cooling trends coinciding with periods of ice-marginal retreat and advance, respectively (Figure 2; Sigurðsson and Jónsson, 1995; Jóhannesson and Sigurðsson, 1998; Sigurðsson et al., 2007). Relatively high air temperatures during the period 1931–1960, particularly during 1931 and 1940, are associated with a period of rapid ice-front retreat. The reversal of this retreat trend to a period of advance after ~1965 coincides with a period of climate cooling, and the number of non-surge-type advancing glaciers reached its maximum in 1975–1990 period following a summer air temperature minimum around 1980 (Jóhannesson and Sigurðsson, 1998; Sigurðsson et al., 2007). Icelandic glaciers returned to ice-marginal retreat during the 1990s, particularly after 1995, as temperatures began rising rapidly (Sigurðsson, 2005; Sigurðsson et al., 2007). Thus, the instrumental record appears to demonstrate that summer air temperature variations exert a dominate control on Icelandic glacier variations (Sigurðsson and Jónsson, 1995; Jóhannesson and Sigurðsson, 1998; Sigurðsson et al., 2007).

Despite the large body of data on Icelandic glacier termini variations and previous analyses of this (e.g. Sigurðsson et al., 2007), as well as a detailed examination of Icelandic climate (Hanna et al., 2004), to date there has been limited quantitative analysis of ice-frontal retreat rates *between* different periods of retreat and the associated climate variations (e.g. Bradwell et al., 2013). As such, there are unresolved research issues: (i) Are pronounced periods of Icelandic ice-frontal retreat in the last ~80 years comparable? (ii) Are current rates of ice-frontal retreat more rapid than in previous periods in the record? (iii) Are prominent periods of ice-frontal retreat, including the present period, associated with comparable climate anomalies? Our contribution explores these issues through inter-comparison and quantitative analysis of ice-frontal retreat periods at Skálafellsjökull, with the intention that this will stimulate a detailed assessment of ice-frontal retreat rates at a regional scale and highlight the importance of placing ice-frontal retreat in a long-term context.

2.2 Moraine spacing as a proxy for ice-frontal retreat

Although a comprehensive database of ice-front measurements exists for Icelandic glaciers, there are extended periods in the records of many outlets where measurements are sporadic/data is incomplete, with Skálafellsjökull being a notable example (see Figure 2). To circumvent these issues, the spacing between annual moraines can be applied as a geomorphological proxy for ice-frontal retreat rates (e.g. Bradwell, 2004; Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013). Small-scale, annual ice-marginal fluctuations manifest in the form of annual moraines in front of many active temperate glaciers in Iceland and elsewhere (e.g. Thórarinsson, 1967; Price, 1970; Worsley, 1974; Sharp, 1984; Boulton, 1986; Matthews et al., 1995; Evans and Twigg, 2002; Bradwell, 2004; Bradwell et al., 2013; Reinardy et al., 2013; Hiemstra et al., 2015). These features form as a result of short-lived seasonal re-advances during overall retreat (e.g. Andersen and Sollid, 1971; Boulton, 1986; Krüger, 1995). Despite an overall net negative mass balance over a number of consecutive years, much-reduced ablation in winter and early spring may result in a temporary switch to seasonally positive mass balance when the glacier snout advances (Lukas, 2012). Provided recession during the ablation season is greater than advance during the accumulation season over consecutive years, a long sequence of inset, consecutively younger annual moraines may be formed (Boulton, 1986; Bennett, 2001; Lukas, 2012). Since the spacing between successive annual moraines equates to the net ice-front recession in a single balance year, annual moraine sequences facilitate the examination of the relationship between annual ice-frontal retreat rates and climate variations (e.g. Bradwell, 2004; Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013). Consequently, annual moraines offer the opportunity to link ice-marginal moraines to specific climatic and glaciological conditions, and to increase understanding of glacier dynamics (Boulton, 1986; Krüger, 1995; Lukas, 2012; Reinardy et al., 2013). To date, analyses of the climatological drivers of moraine spacing (ice-frontal retreat) have utilised linear regression and focused on the overall record (Bradwell, 2004; Beedle et al., 2009; Lukas, 2012; Chandler et al., 2016a), but there is the opportunity build on this and apply annual moraine records to examine variations between different periods of retreat within the same record, along with concurrent variations in climate.

In our previous contribution on this topic, we have demonstrated that small-scale recessional (annual) moraines previously identified on the Skálafellsjökull foreland (Figure 3; Sharp, 1984; Evans and Orton, 2015; Chandler et al., 2016b) are constructed by a range of genetic processes associated with minor, annual ice-margin re-advance (Chandler et al., 2016a). We subsequently utilised the spacing between these moraines to examine the overall pattern of glacier retreat from the 1930s to present, and demonstrate that ice-frontal retreat is associated with elevated summer (ablation-season) temperatures (see also Bradwell, 2004; Bradwell et al., 2013). We take our previous work, and that conducted on annual moraines elsewhere, further by undertaking statistical analysis (Wilcoxon rank-sum tests) to examine the differences/similarities between key phases of retreat in our record and the associated climate variations.

3. Methods

Before detailed examination of the ice-front retreat record (moraine spacing) can be undertaken, it must be demonstrated that the moraines represent successive annual ice-frontal positions. This was achieved by describing, analysing and interpreting: (i) the distribution and geomorphology of the moraines; (ii) the chronology of the moraines; and (iii) moraine sedimentology (cf. Chandler et al., 2016a, b). On this basis, annual ice-frontal retreat rates have been calculated for the period covered by the moraine record (1936–1964, 1969–1974 and 2006–2011) using crest-to-crest (i.e. longitudinal) spacing (cf. Bradwell, 2004; Lukas, 2012). Moraine spacing was measured in *ArcMap* along a number of transects through the annual moraine sequences on the central and northern parts of the foreland, as no part of the foreland contains a 'complete' sequence covering the entire period. The sub-metre resolution of the imagery utilised in mapping ensures that the accuracy and precision of the mapped moraines is sufficient to calculate spacing to the nearest metre: (i) high-resolution scans of 2006 colour aerial photographs (0.41 m Ground Sampled Distance (GSD)); (ii) pansharpened multispectral (8-band) WorldView-2 satellite imagery captured in June 2012 (0.5 m GSD); and (iii) a Digital Elevation Model (DEM) generated from Unmanned Aerial Vehicle (UAV) -captured imagery (spatial resolution: 0.09 m). In order to assess the statistical significance of the differences between periods of pronounced glacier recession identified in the record of ice-frontal retreat, unpaired Wilcoxon rank-sum (or Mann Whitney U) tests have been applied (cf. Miles et al., 2013). We also conduct time-series analysis of climate data (ambient air temperatures and sea surface temperatures) for the entire period covered by the moraine record at Skálafellsjökull, and then compare the climate anomalies associated with the prominent periods we investigated.

4. Results

4.1 Ice-frontal retreat record

The record of ice-frontal retreat at Skálafellsjökull, calculated from the annual moraine record, indicates that the glacier underwent ice-frontal retreat in every year between 1936 and 1964 (average: 25.6 m a^{-1}). This is the longest sustained period of glacier recession during the ~80-year period examined (Figure 4). Gaps in the record of ice-frontal retreat at Skálafellsjökull (1965–1968) and (1975–2005) represent periods during which annual moraine production ceased. Ice-front measurements conducted by the Icelandic Glaciological Society also show net glacier recession in every year during the period 1932–1957, with a paucity of data during the 1960s (e.g. Sigurðsson, 1998). According to the moraine record, the most rapid rates of ice-front retreat during the earliest period of glacier recession occurred in the late 1930s and early 1940s, before a reduction in rates of ice-frontal retreat in the latter part of the 1940s (Figure 4). More pronounced glacier recession again occurred during the mid-1950s, before ice-frontal retreat slowed in the early 1960s. Aerial photographs captured by *Landmælingar Íslands* (National Land Survey of Iceland) suggest some sectors of the Skálafellsjökull ice-front subsequently underwent re-advance sometime during 1964–1969. Unfortunately, there is an absence of ice-front measurement data from Skálafellsjökull to corroborate this, with no measurements taken during the period 1969–1989. Nevertheless, this appears to be a common pattern across all Icelandic non-surge-type glaciers, with many of them advancing to varying degrees during the 1960s (cf. Sigurðsson et al., 2007). A short period of annual moraine formation occurred at Skálafellsjökull between 1969 and 1974, with ice-front retreat averaging 9.9 m a^{-1} over this time. Annual moraine formation ceased at the ice-margin following 1974 and did not subsequently recommence until during winter 2005/2006. Remote sensing observations and ice-front measurements show that, during the intervening period, the glacier was relatively stable (1975–1989) before advancing in the 1990s, though the available data is sporadic: only 3 ice-front measurements were taken during the 1990s (1992, 1993 and 1995). However, observations at other Icelandic non-surge-type glaciers do show similar terminus variations (e.g. Sigurðsson and Jónsson, 1995; Sigurðsson, 1998; Sigurðsson et al., 2007), indicating re-advance was common across Iceland at this time. Although the ice-frontal record used here only extends to 2012, continued ice-frontal retreat (and moraine production) was evident during fieldwork conducted at the glacier in 2014.

Based on the record of ice-frontal retreat, we identify two key 6-year periods (1936–1941 and 1951–1956) of ice-frontal retreat for comparison with the most recent phase of retreat (2006–2011). During the most recent period, the Skálafellsjökull ice-front retreated 134 m, with an average ice-front retreat rate of ~22 m a^{-1} (maximum retreat rate: 44 m a^{-1}). However, the two earlier periods identified exhibited more pronounced glacier recession. A total ice-front retreat distance of 200 m occurred between 1936 and 1941, at an average of ~33 m a^{-1} (maximum retreat rate: 41 m a^{-1}). Similarly, the period 1951–1956 displayed ice-frontal retreat totalling ~197 m, at an average of ~33 m a^{-1}. Moreover, the greatest ice-front recession in any given year occurs in 1953 (~50 m). Statistical analysis conducted to examine the difference between these periods (Table 1) indicates no statistically significant differences exist between the three periods of pronounced ice-front retreat. Thus, glacier recession during these 6-year periods was comparable both in style and magnitude. Recent ice-frontal retreat (2006–2011) at Skálafellsjökull is therefore not unusual in the context of the ~80-year period examined in this study.

4.2 Inter-annual variability in climate

In our previous analysis of the overall retreat record and climate drivers, we demonstrated that the Skálafellsjökull ice-margin appears to be most sensitive to summer ambient air temperature (AAT) variations (Chandler et al., 2016a), in accordance with previous comparisons (e.g. Bradwell, 2004; Sigurðsson et al., 2007). Additionally, we also showed that summer sea-surface temperatures (SSTs) may have an (indirect) influence on ice-front retreat at this outlet. Based on this, we present time-series analysis of summer AATs and SSTs since the 1930s in this section and then subsequently compare the anomalies associated with the prominent periods of ice-frontal retreat identified in the record.

For the purposes of analysing inter-annual variability in summer AAT, values have been used from Hólar í Hornafirði (64°17.995'N, 15°11.402'W; 16.0 m a.s.l.), the nearest long-term weather station to Skálafellsjökull. During the period 1930–2012, mean and median summer AAT values at this weather station were 9.44 °C (σ = 0.65 °C) and 9.33 °C, respectively. The maximum negative deviation of summer AAT (–1.09 °C) from the 1961–1990 average (9.03 °C) occurs in

1979 (Figure 5a): remote-sensing observations suggest the ice-margin was relatively stable at this time. Meanwhile, the maximum positive deviation in summer AAT during the period 1930–2012 was 1.87 °C, occurring in 1933, preceding the formation of the oldest moraine in our record. The period 2002–2006 exhibits the greatest positive AAT anomaly for any five-year period on record, with an average of 1.21 °C. Furthermore, during the period 2003–2012, five years exhibit temperature anomalies greater than 1.5 °C. The longest period of consecutive years with negative AAT anomalies occurs between 1968 and 1971, with an average of –0.25 °C. Despite these negative anomalies, annual moraine production (and ice-frontal retreat) did occur during this period (see Figure 4). Other periods with consecutive negative summer AAT anomalies occur between 1963 and 1965 (average: –0.34 °C), and between 1981 and 1983 (average: –0.55 °C), with the latter being associated with a period ice-front stability (see section 4.1).

Summer SST anomalies have been extracted from the Second Hadley Centre SST dataset (HadSST2: Rayner et al., 2006) in order to explore inter-annual variability in ocean surface conditions. SST anomalies were extracted from four grid cells covering latitudes 57.5–67.5°N and longitudes 7.5–17.5°W, with the values from the grid cells averaged to provide an indication of SST variations in proximity to SE Iceland. It should be noted that restricting the SST anomaly domain does not imply SE Iceland climate is only influenced by variability in this region of the North Atlantic. Indeed, Icelandic climate may be influenced by variability in far-travelled ocean currents (cf. Walter and Graf, 2002; Phillips and Thorpe, 2006). The period 1930–2012 exhibited a mean summer SST anomaly of 0.24 °C (σ = 0.48 °C) in the domain identified, with SST values ranging from –0.81 °C to 2.46 °C. Prominent phases of positive SST anomalies occurred during the periods 1932–1941 (average anomaly: 0.48 °C), 1958–1961 (average anomaly: 0.57 °C) and

2001–2012 (average: 0.66 °C) (Figure 5b). This latter period of elevated SST values coincides with a period of positive summer AAT anomalies, with AAT anomalies >1.5 °C displayed on five occasions during 2003–2012 (see above). The coincidence of periods of elevated summer AATs and SSTs is demonstrated by least squares regression analysis (Figure 6): the analysis indicates that ~55% of the variance in summer AATs can be explained at an annual timescale ($p < 0.0001$). Thus, highlighting the importance of atmosphere-ocean interactions even at such short-term timescales. Two of the prolonged periods of positive SST anomalies (1932–1941 and 2001–2012) also occur concurrently with periods of pronounced ice-frontal retreat at Skálafellsjökull (see section 4.1). Conversely, the longest sustained period of negative annual SST anomalies lasts for four years, between 1962 and 1965 (average: –0.19 °C): this is coincident with a period of negative summer AAT anomalies, identified above. Aside from this, there are two occasions in the record where negative SST anomalies persist for three years, in 1977–1979 (average: –0.46 °C) and 1992–1994 (average: –0.41 °C). These two periods are coincident with ice-front stability or re-advance, according to remote-sensing observations and ice-front measurement data (see section 4.1).

5. Significance

5.1 Comparison with other Icelandic outlets

The calculated ice-frontal retreat rates for Skálafellsjökull are comparable to retreat rates calculated from annual moraine spacing at other Icelandic outlet glaciers (Bradwell, 2004a; Bradwell et al., 2013). For the period 1936–1941, Lambatungnajökull underwent the same amount of glacier recession as Skálafellsjökull: the ice-front retreated 200 m, at an average of ~33 m a^{-1}

(Bradwell, 2004). Meanwhile, the Falljökull ice-front retreated a distance of 310 m during the period 1935–1945, at an average of ~28 m a^{-1} (Bradwell et al., 2013). Comparable ice-frontal retreat rates were displayed by Skálafellsjökull during the 1930s and 1940s, with the ice-front retreating 277 m between 1936 and 1945 (average: ~28 m a^{-1}). This demonstrates that the glaciers underwent similar change during the 20th Century, and is supported by ice-front measurements from all non-surge-type outlet glaciers in Iceland (cf. Sigurðsson et al., 2007). More recently, Falljökull underwent ~230 m of recession during the period 2005–2011 (average: ~33 m a^{-1}), representing a significant increase in the rate of frontal retreat (Bradwell et al., 2013). Falljökull has undergone ice-frontal retreat in every year since 1990, the longest series of net retreat on record at this glacier. Owing to this trend and the magnitude of ice-front retreat, it has been argued that this recent very rapid retreat at Falljökull is an exceptional and unusual event (Bradwell et al., 2013). This contrasts with Skálafellsjökull which has retreated by 134 m during the most recent phase of ice-frontal retreat (2006–2011), with earlier periods in the record exhibiting greater glacier recession (see above). The differences evident between Falljökull and Skálafellsjökull are likely to reflect site-specific conditions, with the more rapid ice-frontal retreat rates and recent change in dynamics at Falljökull (cf. Bradwell et al., 2013; Phillips et al., 2013, 2014) being a consequence of the smaller, steeper nature of the glacier, high mass turnover and the influence of an increasingly flooded overdeepening at the base of the icefall.

5.2 Climate during the pronounced retreat periods

Examination of the climate data shows that the most recent period of ice-frontal retreat (2006–2011) is associated with average summer AAT deviations of +1.07ºC from the 1961–1990 average at Hólar í Hornafirði, while the earlier periods of glacier recession are associated with anomalies of +1.03ºC (1936–1941) and +0.66ºC (1951–1956). The period 2002–2006, preceding the most recent phase of retreat, exhibits the greatest positive AAT anomalies in any five-year period on record, with an average of 1.21ºC. Additionally, during the period 2002–2011, five years exhibit temperature anomalies >1.5ºC (10-year average: +1.09ºC). Similarly, three years display summer AAT anomalies >1.5ºC between 1932 and 1941 (10-year average: +1.02ºC). Statistical analysis undertaken to examine these similarities indicates that no statistically significant differences exist between the summer AAT anomalies for these three periods (Table 2). Thus, the phases of pronounced glacier recession in 1936–1941 and 2006–2011 are associated with comparable summer AAT values.

Examination of SST anomalies shows greater differences exist in summer SST between the phases of glacier recession. The most recent period of ice-frontal retreat at Skálafellsjökull (2006–2011) coincides with SST anomalies of +0.75ºC, whereas the earlier periods are associated with somewhat lower averages of +0.40ºC (1936–1941) and 0.20ºC (1951–1956), respectively. Additionally, three out of six years between 1951 and 1956 exhibit negative summer SST anomalies. During the period 1932–1941, only one year displays a positive summer SST anomaly >1ºC (10-year average: +0.48ºC). By comparison, the ten-year period 2002–2011 experiences positive summer SST anomalies >1ºC on three occasions (10-year average: +0.72ºC). Thus, the most recent phase of ice-frontal retreat at Skálafellsjökull is associated with a phase of somewhat warmer summer SSTs. Nevertheless, Wilcoxon rank-sum tests performed on the data show no statistically significant differences exist between the summer SST anomalies for the three periods (Table 2). It should also be recognised that the influence of SST variations on Icelandic termini variations is still relatively unknown. Statistically significant relationships have been identified between ice-frontal retreat at Skálafellsjökull and summer SST variations (Chandler et al., 2016a), but the coefficient of determination is low (r^2 = 0.1623, p = 0.0010). Additionally, no such relationships have been previously identified at other Icelandic glaciers and this therefore requires further exploration.

In this study, we have shown that both recent ice-frontal retreat at Skálafellsjökull and warming summer air temperatures in SE Iceland are not unusual in the context of the ~80-year records examined. Our findings are important at a time when glaciers both in Iceland (e.g. Sigurðsson et al., 2007; Hannesdóttir et al., 2015) and elsewhere (e.g. Marzeion et al., 2012; Gardner et al., 2013; Stokes et al., 2013; Carr et al., 2014) have shown accelerating rates of mass loss and retreat. Moreover, contemporary glacier change has been associated with unequivocal warming (e.g. IPCC, 2013). This highlights the need for further and continued investigation of current glacier change, and the need for comparison with previous periods of ice-frontal retreat in order to provide a broader context for current glacier variations. Individual outlet glaciers have also been shown to exhibit variable behaviour at short-term timescales (e.g. Skálafellsjökull and Falljökull), reflecting site-specific conditions. Although internal mechanisms are important, this signal will nonetheless be overridden by longer-term external forcing mechanisms, as demonstrated by the coincidence of phases of ice-front retreat and advance at Icelandic outlet glaciers (cf. Sigurðsson et al., 2007). The approach employed in this study has the capability to provide decadal to centennial-scale records of ice-front retreat, complementing observations of contemporary change (sub-decadal to decadal-scale) and studies of the glacial geological record (millennial-scale).

5.3 Complexity in the moraine record

Although annual moraine spacing represents a valuable proxy for ice-frontal retreat, it should be recognised that there are a number of potential issues with utilising this approach and that there is complexity in recessional (annual) moraine records. The principal issue with using the Skálafellsjökull moraine record – and other moraine sequences – relates to establishing a robust moraine chronology. In this case, some uncertainty remains over the earliest moraines (pre-1945) in our record, as these formed before the first aerial photograph was captured (cf. Chandler et al., 2016a). As a result, lichenometric dating of these features was undertaken, but it is recognised that this technique is associated with a number of uncertainties (e.g. Jochimsen, 1973; Worsley, 1981; Osborn et al., 2015), bringing into question the validity of ages ascribed purely on the basis of lichenometric dating. Nevertheless, we have confidence in the dates of formation ascribed to these moraines given that remote-sensing data provide strong evidence for annual moraine formation both in this sequence and on other parts of the foreland (cf. Chandler et al., 2016a). Indeed, a number of previous studies have assumed that moraines formed on an annual basis if the number of ridges between two moraines of 'known' age is equal to the time elapsed between the formation of those reference moraines (e.g. Krüger, 1995; Bradwell, 2004; Beedle et al., 2009; Krüger et al., 2010; Lukas, 2012). Although sub-annual formation has been identified at the southeastern sector of the ice-front, we argue that this relates to specific conditions – the presence of a reverse bedrock slope, an aquiclude and highly saturated subglacial sediments – in this area of the foreland (see Chandler et al., 2016a, for further details).

Depositional and erosional censoring may also affect the integrity (preservation) of the moraine sequences; thus, reducing their representativeness of ice-frontal fluctuations (cf. Gibbons et al., 1984; Kirkbride and Brazier, 1998; Kirkbride and Winkler, 2012; Barr and Lovell, 2014). With respect to Skálafellsjökull, both self- and external censoring processes (*sensu* Kirkbride and Winkler, 2012) may have impacted the annual moraine sequences to varying degrees. Firstly, there is some evidence of localised glacier overriding and superimposition of moraines (obliterative overlap) (cf. Chandler et al., 2016a, b; Evans and Orton, 2015). Secondly, ice-cored moraines have previously been identified at Skálafellsjökull (cf. Sharp, 1984) and meltout of debris-covered ice in ice-cored moraines may have impacted the moraine record (e.g. Andersen and Sollid, 1971; Krüger and Kjær, 2000; Lukas et al., 2005; Lukas, 2012; Reinardy et al., 2013). Although ice-cored moraines were not identified during excavations through moraines in 2014, their presence cannot be ruled out altogether and isolated, large dead-ice bodies were found underlying other surficial deposits (Chandler, 2015). Finally, glaciofluvial processes are a notable feature of active glacial landsystems (cf. Evans and Twigg, 2002; Evans, 2003, Evans et al., 2015, and references therein), and the moraine sequences have, in places, been partially affected by glaciofluvial activity (cf. Evans and Orton, 2015; Chandler et al., 2016b). Although these processes introduce uncertainties, these were minimised by utilising multiple transects across the foreland (see section 3).

Aside from these issues, it is also recognised that there is complexity in the links between the moraine record and climate. The annual moraines at Skálafellsjökull – and elsewhere in Iceland – primarily reflect seasonally-driven submarginal processes active in a given year (cf. Chandler et al., 2016a, and references therein), and will therefore largely reflect short-term climate variability.

This rapid short-term behaviour at the ice-front (glacier *reaction* time) should be distinguished from the integrated longer-term behaviour of the whole glacier (glacier *response* time), which is usually of the order of decades in maritime glaciers (cf. Jóhannesson et al., 1989; Haeberli, 1995; Bahr et al., 1998; Benn and Evans, 2010; Cuffey and Paterson, 2010; Bradwell et al., 2013). Indeed, whilst the time lag between climate variation and the detection of change at the ice-front is small, it does not necessarily indicate that the ice-front has fully responded to the climate variation (cf. Sigurðsson et al., 2007; Benn and Evans, 2010). Thus, our analyses demonstrate that Skálafellsjökull is currently *reacting* in a similar manner to previous periods in the 1930s, 1940s and 1950s. Nevertheless, the links between the moraine record and climate are inherently complex, and the record will integrate underlying longer-term climate variations (glacier response) in addition to short-term variations (glacier reaction), with multiple periodicities reinforcing or modulating each other (cf. Kirkbride and Brazier, 1998; Kirkbride and Winkler, 2012).

6. Conclusions

Using the crest-to-crest spacing of annual moraines on the foreland of Skálafellsjökull, a temperate non-surging outlet glacier of the Vatnajökull ice-cap in SE Iceland, we calculate ice-frontal retreat rates since the 1930s. From the calculated record of ice-front retreat we recognise two pronounced periods of glacier recession for comparison with the most recent phase of retreat (2006–2011). We undertake quantitative analysis to examine variability between these three periods of retreat, and show that they are comparable both in style and magnitude. Analysis of climate data for SE Iceland also indicates that the three periods of ice-frontal retreat identified are associated with similar summer air temperature values, which has previously been shown to be a key control in terminus variations in Iceland. We therefore demonstrate that the coincidence of the most recent phase of ice-frontal retreat at Skálafellsjökull (2006–2011) and warming summer temperatures is not unusual in the context of the last ~80 years. This highlights the need to place observations of contemporary glacier change in a broader, longer-term (centennial) context. Moreover, the novel approach used in this study demonstrates the potential of annual moraine records for analysing ice-frontal variations where continuous records of glacier length change are absent or incomplete.

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Tables

Table 1. Comparison of three prominent periods of ice-frontal retreat at Skálafellsjökull, SE Iceland.

Period	Minimum retreat rate (m a^{-1})	Maximum retreat rate (m a^{-1})	Average retreat rate (m a^{-1})	Wilcoxon rank-sum test		
				1936–1941	1951–1956	2006–2011
1936–1941	30	41	33	-	NS*	NS
1951–1956	22	50	33	NS	-	NS
2006–2011	8	44	22	NS	NS	-

* NS: No statistically significant difference

Table 2. Comparison of the climate variations associated with the three prominent periods of ice-frontal retreat at Skálafellsjökull, SE Iceland. Temperature anomalies represent deviations from the respective 1961–1990 averages.

Period	Minimum anomaly (ºC)	Maximum anomaly (ºC)	Average anomaly (ºC)	Wilcoxon rank-sum test		
				1936–1941	1951–1956	2006–2011
Summer AAT anomalies:						
1936–1941	1.03	1.79	0.29	-	NS*	NS
1951–1956	0.66	1.69	-0.03	NS	-	NS
2006–2011	1.07	1.61	0.50	NS	NS	-
Summer SST anomalies:						
1936–1941	0.11	0.61	0.40	-	NS*	NS
1951–1956	-0.32	0.76	0.20	NS	-	NS
2006–2011	0.33	1.25	0.75	NS	NS	-

* NS: No statistically significant difference

Figure captions

Figure 1. Multispectral satellite image of the Skálafellsjökull, and neighbouring Heinabergsjökull, foreland. Imagery was captured by the WorldView-2 sensor (June 2012) and supplied by European Space Imaging. The boxes marked A and B show the locations of extracts from the geomorphological map of the foreland (Figure 3A) and hillshaded relief models derived from UAV-captured imagery (Figure 3C), respectively. Scale and orientation are given by the Eastings and Northings. Projection: WGS 1984/UTM Zone 28N (ESPG: 32628). Modified from Chandler et al. (2016b).

Figure 2. Ice-front variations at a selection of non-surge-type glaciers from across Iceland (A) and comparison with annual temperature (B) and precipitation (C) variations at Kirkjubæjarklaustur (South Iceland) since 1931. Meteorological data was supplied by *Veðurstofa Íslands* (the Icelandic Meteorological Office), whilst glacier termini variations were taken from the Icelandic Glaciological Society database (http://spordakost.jorfi.is).

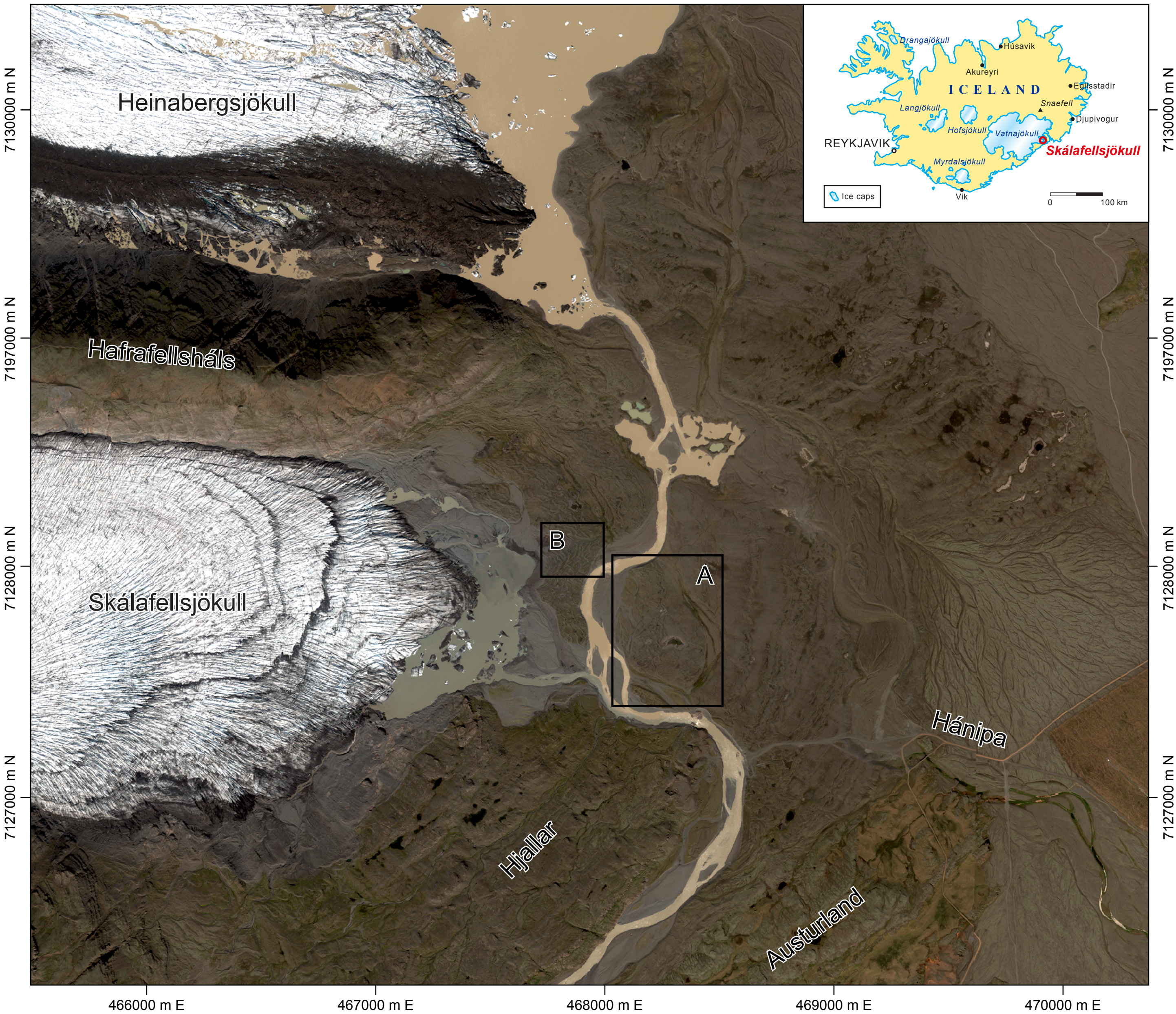
Figure 3. Examples of annual moraines on the Skálafellsjökull, showing the distinctive 'sawtooth' planform of these features. (A) Excerpt from mapping by Chandler et al. (2016b) of annual moraines on the central part of the foreland. For the location, see Figure 1. Scale and orientation are given by the Eastings and Northings. Projection: WGS 1984/UTM Zone 28N (ESPG: 32628). (B) Field photograph showing the characteristic geometry of the moraines (22.05.2014). (C) Digital Elevation Model (DEM) visualised as a hillshaded relief (illumination angle = 30°; azimuth

= 315°). The DEM was generated using UAV-captured imagery and structure-from-motion photogrammetry (see Chandler et al., 2016b, for further details).

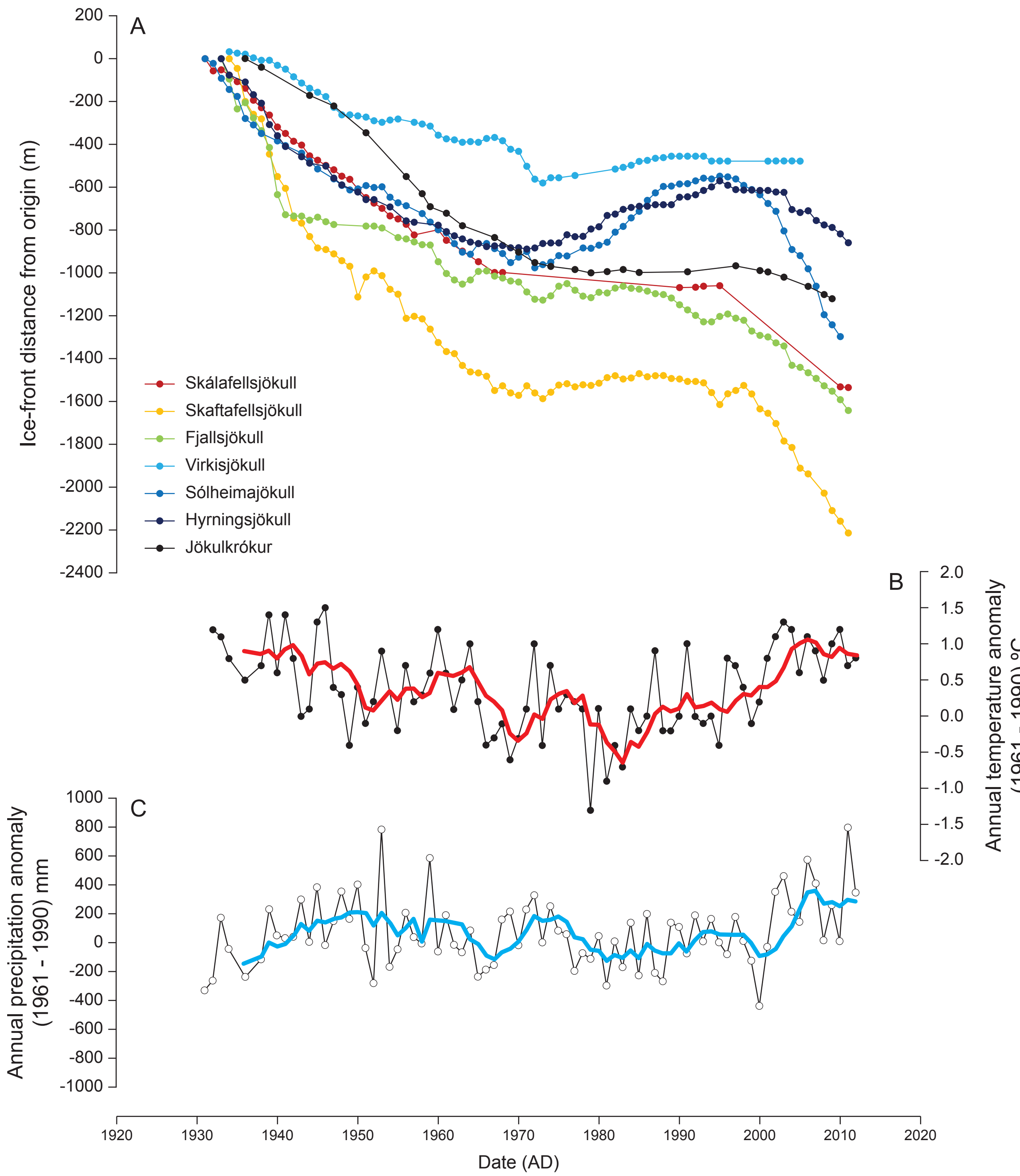
Figure 4. Annual ice-front retreat rates at Skálafellsjökull calculated from annual moraine crest-to-crest spacing (see Section 3). Shading in indicates the three periods of ice-frontal retreat (1936–1941; 1951–1956; and 2006–2011) examined in this study. Gaps in the record reflect periods where annual moraine production ceased at the ice-front.

Figure 5. Time-series plots for (A) summer ambient air temperature (AAT) and (B) summer sea surface temperature (SST), and comparison with the Skálafellsjökull ice-front retreat record. Summer season follows the convention of the Icelandic Meteorological Office (cf. Hanna et al., 2004). Solid lines in A and B show 5-year moving averages, with the climate variables reported as deviations from the respective 1961–1990 averages. Summer AAT data Hólar í Hornafirði (64°17.995'N, 15°11.402'W; 16.0 m a.s.l.), the nearest long-term weather station to Skálafellsjökull. SST values are based on the average between latitudes 57.5–67.5°N and longitudes 7.5–17.5°W, and were extracted from the HadSST2 dataset (Rayner et al., 2006). The three prominent periods of ice-front retreat examined in this study are also indicated.

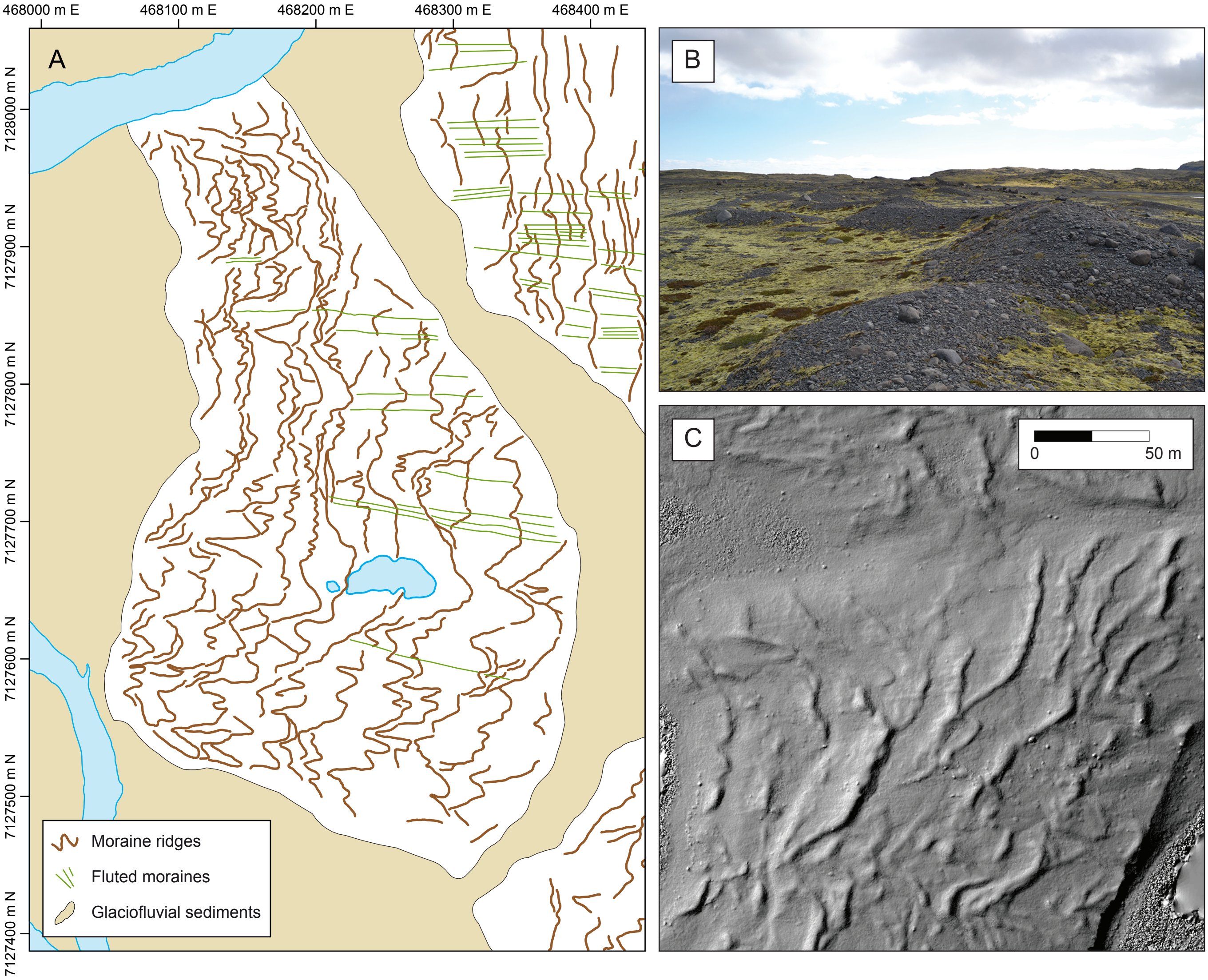
Figure 6. Covariance plot showing variations in the summer (1st June–30th September) signatures of ambient air temperature (AAT) and sea surface temperature (SST). Values for 1945 are excluded from the analysis of SST owing to a lack of SST data. The covariance analysis implies that SSTs have an influence on AATs, even at very short-term timescales.

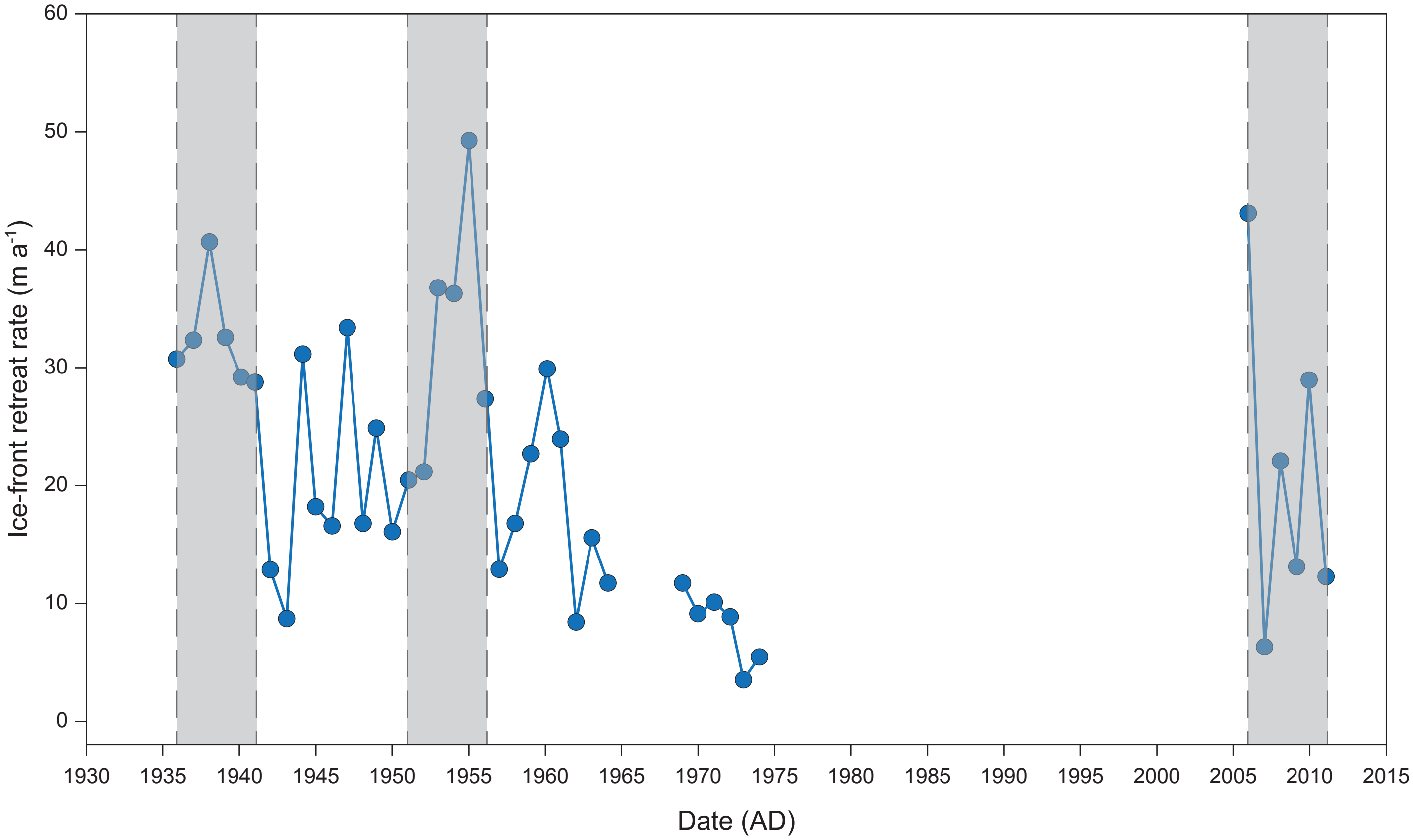


Heinabergsjökull
Hafrafellsháls
Skálafellsjökull
B
A
Hánipa
Hjallar
Austurland
Drangajökull
Húsavik
Akureyri
ICELAND
Egilsstadir
Snaefell
Langjökull
Hofsjökull
Vatnajökull
Djupivogur
REYKJAVIK
Skálafellsjökull
Myrdalsjökull
Ice caps
Vik
0
100 km
7130000 m N
7197000 m N
7128000 m N
7127000 m N
466000 m E
467000 m E
468000 m E
469000 m E
470000 m E

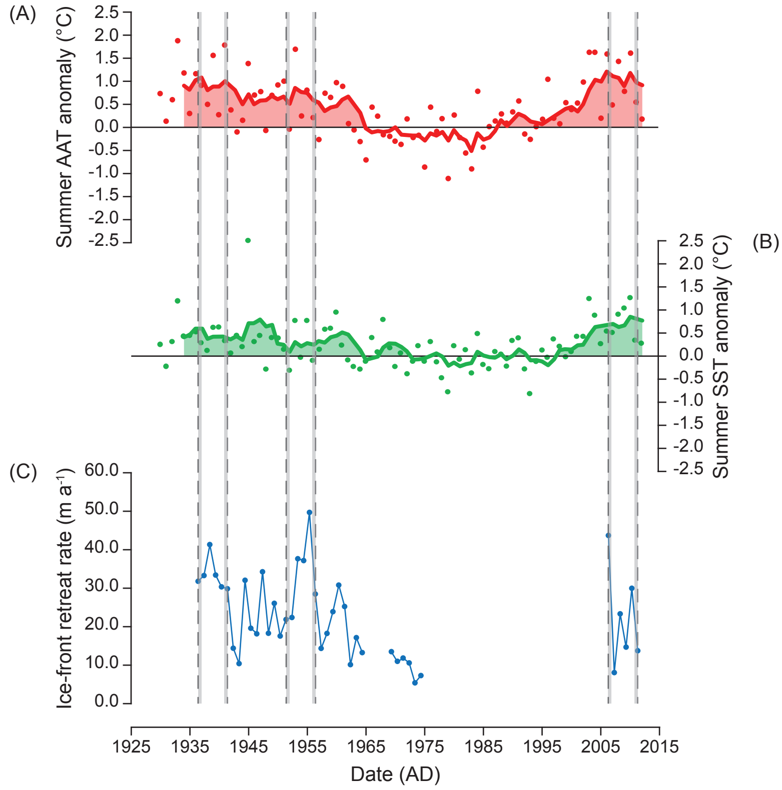


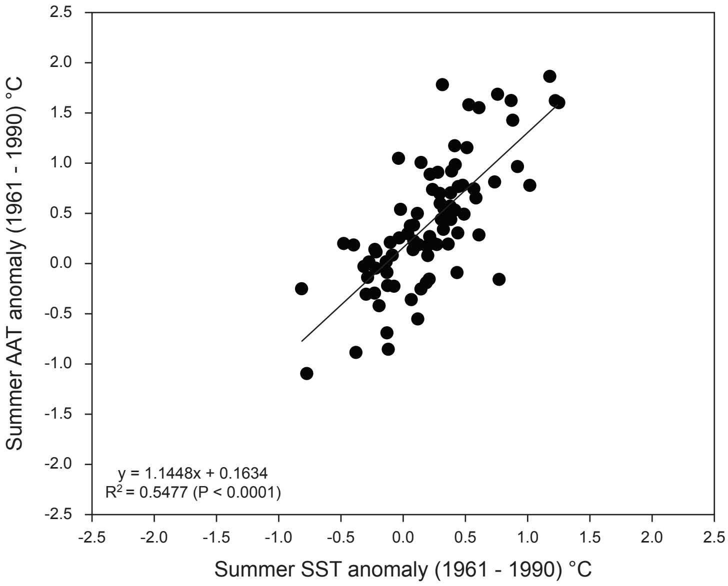
A
B
C
Ice-front distance from origin (m)
200
0
-200
-400
-600
-800
-1000
-1200
-1400
-1600
-1800
-2000
-2200
-2400
Skálafellsjökull
Skaftafellsjökull
Fjallsjökull
Virkisjökull
Sólheimajökull
Hyrningsjökull
Jökulkrókur
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Annual temperature anomaly (1961 - 1990) °C
Annual precipitation anomaly (1961 - 1990) mm
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
Date (AD)


468000 m E
468100 m E
468200 m E
468300 m E
468400 m E
7128000 m N
7127900 m N
7127800 m N
7127700 m N
7127600 m N
7127500 m N
7127400 m N
A
B
C
Moraine ridges
Fluted moraines
Glaciofluvial sediments
0
50 m



Ice-front retreat rate (m a-1)
0
10
20
30
40
50
60
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Date (AD)


(A)
Summer AAT anomaly (°C)
(B)
Summer SST anomaly (°C)
(C)
Ice-front retreat rate (m a-1)
Date (AD)


Summer AAT anomaly (1961 - 1990) °C
Summer SST anomaly (1961 - 1990) °C
y = 1.1448x + 0.1634
R2 = 0.5477 (P < 0.0001)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5