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Characteristics of recessional moraines at a temperate glacier in SE Iceland: Insights into patterns, rates and drivers of glacier retreat

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ABSTRACT

Icelandic glaciers are sensitive to climate variability on short-term timescales owing to their North Atlantic maritime setting, and have been undergoing ice-marginal retreat since the mid-1990s. Recent patterns, rates and drivers of ice-frontal retreat at Skálafellsjökull, SE Iceland, are examined using small-scale recessional moraines as a geomorphological proxy. These small-scale recessional moraines exhibit distinctive sawtooth planform geometries, and are constructed by a range of genetic processes associated with minor ice-margin re-advance, including (i) combined push/squeeze mechanisms, (ii) bulldozing of pre-existing proglacial material, and (iii) submarginal freeze-on. Remote-sensing investigations and lichenometric dating highlight sequences of annually-formed recessional moraines on the northern and central parts of the foreland. Conversely, moraines are forming on a sub-annual timescale at the southeastern Skálafellsjökull margin. Using annual moraine spacing as a proxy for annual ice-margin retreat rates (IMRRs), we demonstrate that prominent periods of glacier retreat at Skálafellsjökull are coincident with those at other Icelandic outlet glaciers, as well as those identified at Greenlandic outlet glaciers. Analysis of IMRRs and climate data suggests summer air temperature, sea surface temperature and the North Atlantic Oscillation have an influence on IMRRs at Skálafellsjökull, with the glacier appearing to be most sensitive to summer air temperature. On the basis of further climate data analyses, we hypothesise that sea surface temperature may drive air temperature changes in the North Atlantic region, which in turn forces IMRRs. The increase in sea surface temperature over recent decades may link to atmospheric-driven variations in North Atlantic subpolar gyre dynamics.

1. Introduction

Iceland lies in a climatically important location in the North Atlantic, situated at the boundary between polar and mid-latitude atmospheric circulation cells and oceanic currents (Guðmundsson, 1997; Bradwell et al., 2006; Geirsdóttir et al., 2009). As a consequence of this maritime setting, the temperate glaciers of Iceland are particularly sensitive to climatic fluctuations on an annual to decadal scale, and have exhibited rapid rates of ice-marginal retreat and mass loss during the past decade (e.g. Jóhannesson, 1986; Sigurðsson and Jónsson, 1995; Aðalgeirsdóttir et al., 2006; Sigurðsson et al., 2007; Björnsson and Pálsson, 2008; Björnsson et al., 2013; Bradwell et al., 2013; Mernild et al., 2014; Phillips et al., 2014; Hannesdóttir et al., 2015a,b). Icelandic glacier termini variations during the observational period (since ~1930s) have previously been argued to be associated with fluctuations of summer air temperature (e.g. Boulton, 1986; Sigurðsson and Jónsson, 1995; Jóhannesson and Sigurðsson, 1998; Bradwell, 2004a; Sigurðsson et al., 2007; Bradwell et al., 2013). However, there has been limited consideration of other climate variables (e.g. sea surface temperature and the North Atlantic Oscillation) and the complex interactions between them (e.g. Kirkbride, 2002; Mernild et al., 2014). This restricts current understanding of contemporary Icelandic glacier change and its wider significance. Thus, a thorough assessment of the patterns, rates and drivers of ice-frontal retreat currently evident in Iceland is of key importance.

Small-scale, annual ice-marginal fluctuations are manifest in the form of annual moraines in front of many active temperate glaciers in Iceland and elsewhere (Thórarinsson, 1967; Price, 1970; Worsley, 1974; Sharp, 1984; Boulton, 1986; Matthews et al., 1995; Evans and Twigg, 2002; Bradwell, 2004a; Schomacker et al., 2012; Bradwell et al., 2013; Reinardy et al., 2013; Hiemstra et al., 2015).

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According to previous studies, annual moraines are formed by short-lived seasonal re-advances of the ice-front during a period of overall retreat (e.g. Andersen and Sollid, 1971; Boulton, 1986; Krüger, 1995). Provided recession during the summer (ablation season) is greater than advance during the winter (accumulation season) over consecutive years, a long sequence of inset, consecutively younger annual moraines may be formed (Boulton, 1986; Krüger, 1995; Bennett, 2001; Lukas, 2012). Consequently, annual moraines potentially record a seasonal signature of glacier response to climate variations, and have been subject to renewed interest over recent years (e.g. Bradwell, 2004a; Beedle et al., 2009; Lukas, 2012; Bradwell et al., 2013; Reinardy et al., 2013).

Given the potential of annual moraines as a terrestrial climate archive, detailed examination of the characteristics of annual moraines on the forelands of Icelandic glaciers could yield valuable insights into the nature of, and controls on, recent ice-marginal retreat. In this study, we apply small-scale recessional moraines on the foreland of Skálafellsjökull, SE Iceland, as a geomorphological proxy to examine patterns, rates and drivers of ice-marginal retreat since the 1930s. These recessional moraines have previously been argued to form on an annual basis in response to seasonally-driven processes (cf. Sharp, 1984, Evans and Orton, 2015), and this concept is re-examined in this paper. We integrate multiple methods at a range of spatial and temporal scales in order to examine the characteristics of the recessional moraines, wherefrom the significance of patterns and rates of recent ice-marginal retreat at Skálafellsjökull are assessed.

2. Study site

Skálafellsjökull is a non-surging piedmont outlet lobe draining the southeastern margin of the Vatnajökull ice-cap, flowing for ~24 km (Table 1) from the Breiðabunga plateau and descending steeply onto a low elevation (20–60 m a.s.l.) foreland (Hannesdóttir et al., 2014, 2015a,b; Evans and Orton, 2015). At its northern margin, the piedmont lobe is topographically confined by the Hafrafellsháls mountain spur, which reaches a maximum elevation of ~1008 m a.s.l. (Evans and Orton, 2015). In the southern part of the foreland, the present-day glacier terminates near an area of heavily abraded, basalt bedrock outcrops on Hjallar. Two proglacial lakes front the contemporary Skálafellsjökull ice-margin, the largest being situated at the central sector of the margin (Fig. 1). The development of ice-marginal lakes is a characteristic feature of the retreating southern Vatnajökull outlet glaciers (e.g. Howarth and Price 1969; Price and Howarth 1970; Evans et al., 1999a; Evans and Twigg 2002; Björnsson et al., 2001; Nick et al., 2007; Schomacker, 2010). Recent mapping of the surficial geology and glacial geomorphology (Evans and Orton, 2015) has demonstrated that the glacier foreland is characterised by the three diagnostic depositional domains of the active temperate landsystem: marginal morainic, subglacial and glaciofluvial/glaciolacustrine (cf. Krüger, 1994; Evans and Twigg, 2002; Evans, 2003, and references therein).

Much debate remains regarding the veracity of the Skálafellsjökull Little Ice Age (LIA) maximum and its subsequent retreat pattern, with the application of different lichenometric dating techniques having resulted in contrasting age assignments (cf. Evans et al., 1999a; McKinzey et al., 2004, 2005; Evans and Orton, 2015). However, documentary and photographic evidence indicate Skálafellsjökull formerly coalesced with the neighbouring Heinabergsjökull on the coastal plain of Hornafjördur, and they remained confluent until sometime between 1929 and 1945 (Danish General Staff, 1904; Wadell, 1920; Roberts et al., 1933; Thórarinsson, 1943; Pálsson, 1945; Hannesdóttir et al., 2014). By the time of the US Army Map Service aerial photograph survey in 1945, the glaciers had separated. Ice-front measurements conducted at the glacier since the 1930s indicate Skálafellsjökull has undergone similar fluctuations to other Vatnajökull outlet glaciers (Fig. 2). The ice-front retreated during the period 1932–1957, with particularly rapid ice-marginal retreat occurring between 1937 and 1942 (~41 m a^{-1}). Since the 1970s, measurements have been sporadic, limiting understanding of the behaviour of this outlet glacier. Thus, the sequences of recessional (annual) moraines previously identified on the Skálafellsjökull foreland (Sharp, 1984; Evans and Orton, 2015) offer the opportunity to gain important insights into ice-frontal fluctuations.

3. Methods

3.1. Geomorphological mapping

Geomorphological mapping was undertaken through a combination of remote-sensing and field-based approaches, providing a framework for exploring the characteristics of the recessional moraines at Skálafellsjökull. The remote-sensing data included high-resolution scans of 2006 colour aerial photographs (0.41 m Ground Sampled Distance (GSD)), multispectral (8-band) WorldView-2 satellite imagery captured in June 2012 (2.0 m GSD) and associated panchromatic images (0.5 m GSD), along with a Digital Elevation Model (DEM) generated from Unmanned Aerial Vehicle (UAV) -captured imagery (spatial resolution: 0.09 m). This approach of integrating multiple remote-sensing datasets, augmented by field mapping, has been applied in a variety of contemporary and ancient glacial landscapes (e.g. Bennett et al., 2010; Boston, 2012; Bradwell et al., 2013; Reinardy et al., 2013; Brynjólfsson et al., 2014; Darvill et al., 2014; Evans et al., 2014, 2015; Jónsson et al., 2014; Pearce et al., 2014; Schomacker et al., 2014). Further details on the image processing, mapping techniques and map production are presented elsewhere (Chandler et al., 2015).

3.2. Chronological techniques

A chronological framework for the recessional moraines was established using two approaches: (i) examination and cross-correlation of imagery spanning the period 1945–2012; and (ii) lichenometric surveys of a sub-sample of moraines. Lichenometric dating conducted in this study employed the largest lichen (LL) and size-frequency (SF) approaches, following the strategy previously applied to annual moraines elsewhere in SE Iceland (cf. Bradwell, 2001, 2004a,b; Bradwell et al., 2013). This sampling approach involves measuring the longest axis of >200 thalli of lichen *Rhizocarpon* Section *Rhizocarpon* in fixed area quadrats on the ice-proximal slopes of moraines (cf. Bradwell, 2001, for further details). The longest axes were measured to the nearest millimetre using a ruler, with thalli less than 5 mm in diameter omitted from the surveys. Although callipers may have smaller *instrumental*

Table 1
Characteristics of Skálafellsjökull in 2010. Source: Hannesdóttir et al. (2015a,b).

Volume (km^3)	Area (km^2)	Length (km)	Mean thickness (m)	Ice divide (m a.s.l.)	Surface slope (°)	AAR (%)	Snowline range 2007–2011 (m)
33.3	100.6	24.4	331	1490	3.1	0.68	910–1020