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Episodic expansion of Drangajökull, Vestfirðir, Iceland, over the last 3 ka culminating in its maximum dimension during the Little Ice Age

David J. Harning [a, b, *], Áslaug Geirsdóttir [a], Gifford H. Miller [b, a], Leif Anderson [a]

[a] Faculty of Earth Sciences, University of Iceland, Reykjavík, Iceland
[b] INSTAAR and Department of Geological Sciences, University of Colorado Boulder, Boulder, CO, USA

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ABSTRACT

Non-linear climate change is often linked to rapid changes in ocean circulation, especially around the North Atlantic. As the Polar Front fluctuated its latitudinal position during the Holocene, Iceland's climate was influenced by both the warm Atlantic currents and cool, sea ice-bearing Arctic currents. Drangajökull is Iceland's fifth largest ice cap. Climate proxies in lake sediment cores, dead vegetation emerging from beneath the ice cap, and moraine segments identified in a new DEM constrain the episodic expansion of the ice cap over the past 3 ka. Collectively, our data show that Drangajökull was advancing at ~320 BCE, 180 CE, 560 CE, 950 CE and 1400 CE and in a state of recession at ~450 CE, 1250 CE and after 1850 CE. The Late Holocene maximum extent of Drangajökull occurred during the Little Ice Age (LIA), occupying 262 km^2, almost twice its area in 2011 CE and ~20% larger than recent estimates of its LIA dimensions. Biological proxies from the sediment fill in a high- and low-elevation lake suggest limited vegetation and soil cover at high elevations proximal to the ice cap, whereas thick soil cover persisted until ~750 CE at lower elevations near the coast. As Drangajökull expanded into the catchment of the high-elevation lake beginning at ~950 CE, aquatic productivity diminished, following a trend of regional cooling supported by proxy records elsewhere in Iceland. Correlations between episodes of Drangajökull's advance and the documented occurrence of drift ice on the North Icelandic Shelf suggest export and local production of sea ice influenced the evolution of NW Iceland's Late Holocene climate.

1. Introduction

Persistent and rapid anthropogenic warming is one of the most pressing global environmental issues. In the Arctic, this abrupt warming is manifested in glacier, sea ice, snow cover and permafrost contraction (IPCC AR5, 2013). However, recent warming follows a trend of natural cooling since the mid-Holocene driven by the monotonic decrease in Northern Hemisphere summer insolation (Berger and Loutre, 1991). In Iceland, a general decline in summer temperatures beginning ~5.5 ka was punctuated by stepwise cooling (Geirsdóttir et al., 2013) which culminated in the Little Ice Age (LIA, 1250–1850 CE), the coldest multi-centennial climate anomaly of the Holocene (Grove, 1988; Miller et al., 2012). Some combination of reduced solar irradiance (Shindell et al., 2001), sustained volcanism (Zhong et al., 2010; Miller et al., 2012), expanded sea ice (Miller et al., 2012; Sicre et al., 2013) and changes in the internal modes of variability in the ocean-atmosphere system (Trouet et al., 2009; Olsen et al., 2012) are called upon to explain these transitions (Wanner et al., 2011), yet there is no clear consensus on which forcings were most responsible for or the spatial continuity and duration of these events.

Glacier and lacustrine climate records from across Iceland reveal a Late Holocene history punctuated by increased glacial extent (Stötter et al., 1999; Larsen et al., 2011), enhanced terrestrial erosion, and decreased summer temperature (Axford et al., 2009; Geirsdóttir et al., 2009, 2013; Holmes et al., 2016) with the most extensive glacial coverage occurring during the peak LIA, between 1700 and 1900 CE (Bradwell et al., 2006; Larsen et al., 2011, 2015). The similarities in timing and direction of changes imply uniform driving mechanisms, likely from ocean and atmospheric variability of the North Atlantic (Geirsdóttir et al., 2013). Although terrestrial glacial and paleoclimate records are dispersed across Iceland, the northwest (Vestfirðir) lacks Late Holocene climate records despite the presence of Drangajökull, a small ice cap situated within 10 km of the North Atlantic. Between 1950 and 2010, summer (JJA

* Corresponding author. Faculty of Earth Sciences, University of Iceland, Reykjavík, Iceland.
E-mail address: David.Harning@colorado.edu (D.J. Harning).

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average) air temperature at Drangajökull is strongly correlated to JJA averaged SSTs off the northeastern coast of Iceland, implying a dependency of local air temperatures on SSTs from this region (Fig. 1). Considering glacier mass balance is mainly controlled by summer temperature, and to a lesser degree precipitation (Oerlemans, 2005; Björnsson and Pálsson, 2008), constraining Drangajökull's evolution may improve our understanding of the role of ocean and atmospheric circulation in explaining rapid climate change.

Numerous marine records from the North Icelandic Shelf document variable Late Holocene sea surface temperatures (Bendle and Rosell-Melé, 2007; Sicre et al., 2011; Jiang et al., 2015) and the import of drift ice (Moros et al., 2006; Massé et al., 2008; Andrews et al., 2009; Cabedo-Sanz et al., 2016). Evidence suggests that marine conditions, particularly sea ice, exert a strong influence on near-shore environments of Iceland (Dickson et al., 1988; Stötter et al., 1999; Andrews et al., 2001; Hanna et al., 2006). The high albedo of sea ice reflects much of the incoming solar radiation in summer and insulates the ambient atmosphere from the relatively warm oceans during winter. Sea ice also limits the exchange of gases and moisture between the ocean and atmosphere (de Vernal et al., 2013). Due to its coastal setting, Drangajökull's mass balance is likely to have been strongly influenced by these ocean surface conditions.

In this paper, we provide a 3 ka multi-proxy record of Drangajökull's expansion and contraction. Historical accounts (Eythorsson, 1935; Grove, 1988) and previous mapping of ice-proximal surficial geology (Principato, 2008; Brynjólfsson et al., 2014, 2015) help to constrain the LIA areal extent of Drangajökull. However, previous maps of the glacier's LIA extent are largely limited to the three main outlet glaciers, which frequently surge and are not closely linked to climate change. Focusing on the non-surging margins, we better constrain Drangajökull's LIA margins and reconstruct its expansion over the last 3 ka by: 1) mapping LIA terminal moraines; 2) analyzing the sedimentary records of lakes proximal to the ice cap, which in some cases will define when Drangajökull was expanding; and 3) dating dead vegetation emerging from beneath the receding ice margin. By comparing our records with marine evidence from the North Icelandic Shelf, we test the dependence of Vestfirðir's past climate on local oceanic conditions.

2. Regional setting

Vestfirðir is located near the modern Polar Front: the warm and saline Irminger Current (IC) dominates the west coast, whereas, the cooler, lower-salinity North Iceland Irminger Current (NIIC) and East Icelandic Current (EIC) dominate surface waters to the north and east (Fig. 2A). Regional bedrock is primarily composed of Tertiary basalts interbedded with thin sedimentary units (Harðarson et al., 2008). Upland surfaces are characterized by discontinuous andosols and vitrosols, low in organic content and sparsely covered with vegetation (Arnolds, 2004).

The highland plateau in eastern Vestfirðir hosts Iceland's fifth largest ice cap, Drangajökull (~142 km^2 area in 2011; Jóhannesson et al., 2013, Fig. 2B). Drangajökull is a polythermal ice cap, with surging outlet glaciers draining most of the east, north and west catchments. Based on our evidence of dead vegetation emerging from beneath the receding margin, the southern half of the ice cap, which mantles a high elevation, low relief landscape, is at least in part cold based. The ice cap's maximum elevation rises to 915 m asl with a 2000–2015 ice cap average equilibrium line altitude (ELA) at ~660 m asl, which is several hundred meters lower than Iceland's other ice caps (Björnsson and Pálsson, 2008). Drangajökull's low ELA likely reflects its proximity to the relatively low SST of the adjacent ocean resulting in short, cool summers. Mean sea level summer (JJA) air temperatures and annual precipitation are 6.9 °C and 1100 mm at Hornbjargsviti (1949–1994), 27 km north of the ice cap (Fig. 2B). In contrast, average conditions 17 km west of the ice cap on the island of Æðey are 8.9 °C and 580 mm (1954–2011; Veðurstofa Íslands, http://www.vedur.is). These records show that warmer and drier conditions persist to the west of the ice cap compared to those to the north. Northeasterly prevailing winds imply that most moisture is delivered to the glacier from the NE and that snow is redistributed by wind to the western side (Eythorsson, 1935; Magnússon et al., 2016).

3. Material and methods

3.1. Remote imagery

Aerial imagery from 2005 (0.5 m resolution, Loftmyndir ehf., http://www.map.is) allowed identification of previously unrecognized moraines along Drangajökull's southern margin.

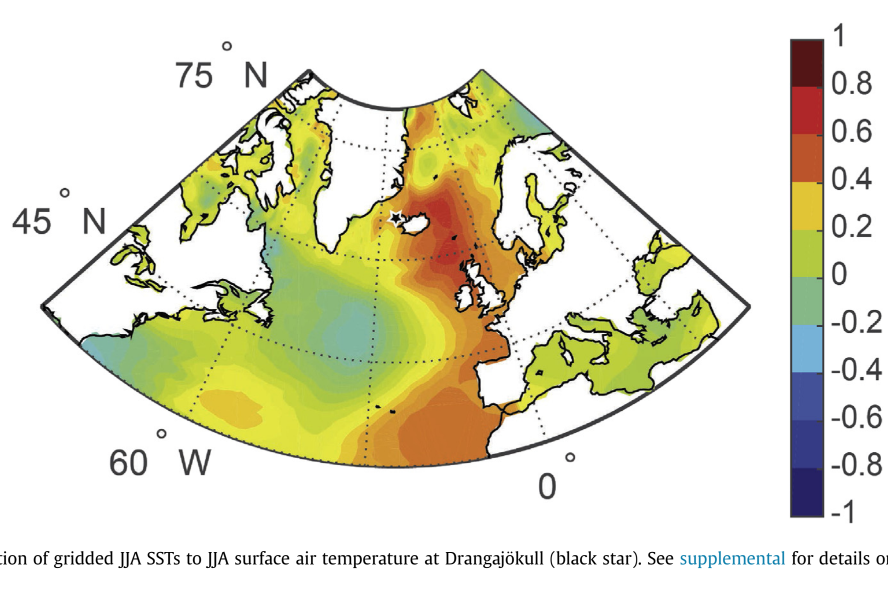

Fig. 1. Correlation of gridded JJA SSTs to JJA surface air temperature at Drangajökull (black star). See supplemental for details on methodology.