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Holocene glacier and climate variations in Vestfirðir, Iceland, from the modeling of Drangajökull ice cap

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ABSTRACT

Drangajökull is a maritime ice cap located in northwest (Vestfirðir) Iceland. Drangajökull's evolution is therefore closely linked to atmospheric and ocean variability. In order to better constrain the Holocene climate and glacier history of Vestfirðir we model the past evolution of Drangajökull ice cap. Simulations from 10 ka to present are forced by general circulation model output, ice-core-based temperature reconstructions, and sea-surface temperature reconstructions. Based on these 10-thousand year simulations, Drangajökull did not persist through the Holocene. We estimate that air temperatures were 2.5–3.0 °C higher during the Holocene Thermal Maximum than the local 1960–1990 average. Simulations support Drangajökull's late Holocene inception between 2 and 1 ka, though intermittent ice likely occupied cirques as early as 2.6 ka. Drangajökull is primarily a Little Ice Age ice cap: it expanded between 1300 and 1750 CE, with the most rapid growth occurring between 1600 and 1750 CE. The maximum Holocene extent of Drangajökull occurred between 1700 and 1925 CE, despite the lowest late Holocene temperatures, occurring between 1650 and 1720 CE. Between 1700 and 1925 CE temperatures were likely 0.6–0.8 °C lower than the 1950–2015 reference temperature. The modern equilibrium line altitude (ELA) is bracketed by topographic thresholds: a 1 °C temperature increase from the modern ELA would eliminate the ice cap's accumulation area, while a reduction of 0.5 °C would lead to the rapid expansion of the ice cap across Vestfirðir. The proximity of Drangajökull to topographic thresholds may explain its late inception and rapid expansion during the Little Ice Age.

1. Introduction

Anthropogenic warming is a serious environmental issue, causing the global contraction of glaciers and sea ice (IPCC, 2014). In a paleoclimate context, recent global warming has reversed the nearly monotonic, natural cooling since the Holocene Thermal Maximum in the mid-to early- Holocene (e.g., Wanner et al., 2008). In response to this natural cooling, Icelandic glaciers have expanded since the mid-Holocene, reaching their maxima during the Little Ice Age (LIA; e.g., Geirsdóttir et al., 2009). Near synchronous Holocene glacier changes in Iceland imply uniform driving mechanisms, as is expected considering the close proximity of Icelandic glaciers to one another (Fig. 1; e.g., Björnsson et al., 2013). However, Iceland is also located near the Polar Front where Atlantic-sourced waters meet cold, Arctic currents. Past variability in ocean currents may have led to spatial changes in climate across Iceland, especially between the peninsulas of northwest Iceland (Vestfirðir) and central Iceland (Fig. 1).

Vestfirðir lacks quantitative Holocene temperature estimates despite the presence of the maritime ice cap, Drangajökull. The warm Irminger Current dominates surface waters to the west of Vestfirðir. Winds affecting Drangajökull primarily come from the northeast (Bromwich et al., 2005) where cooler, polar waters dominate. Accordingly, air temperatures near Drangajökull co-vary

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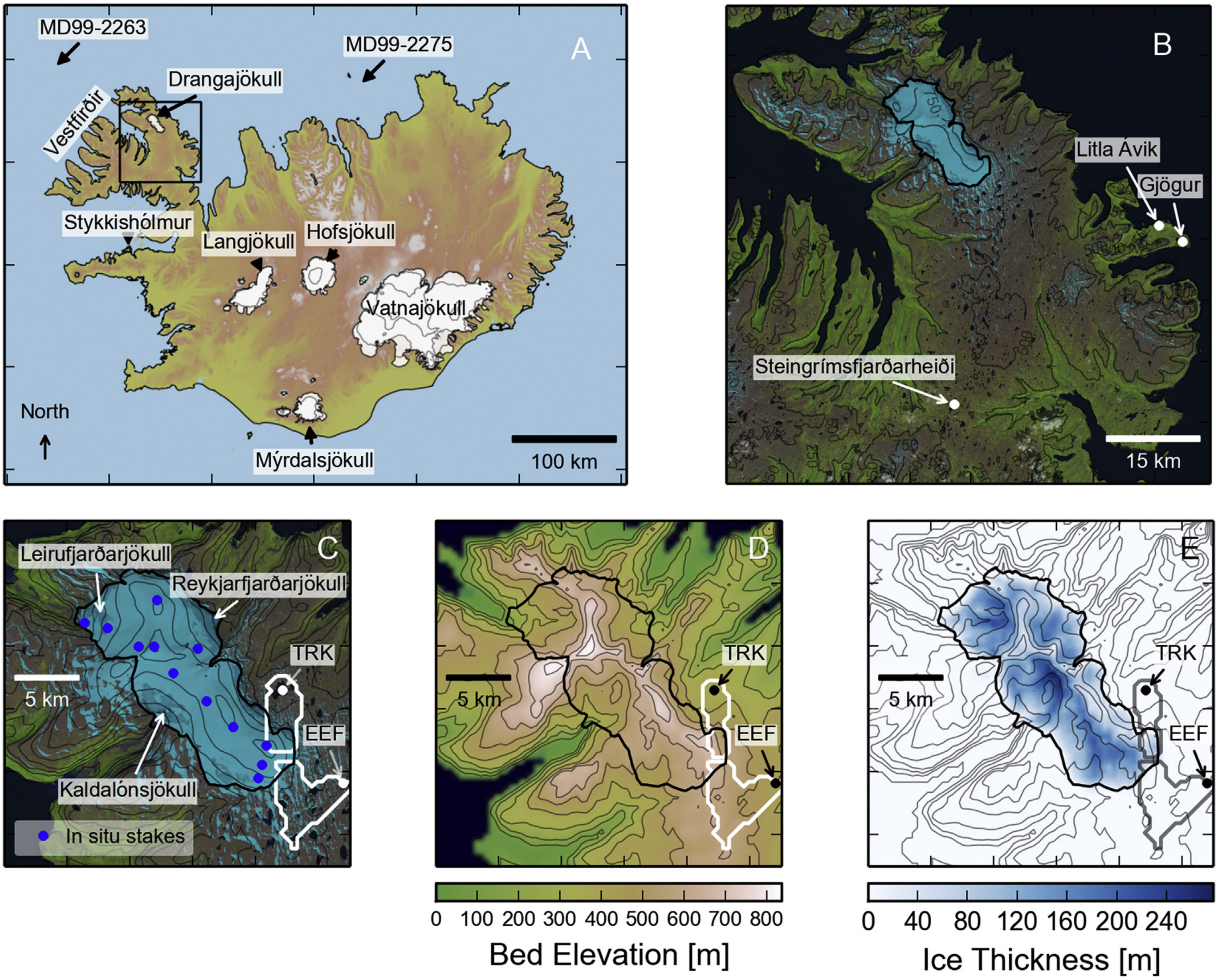

Fig. 1. Study area. A) Map of Iceland with the core site for the SST record. Extent of panel B shown with black box. B) Landsat 8 image (October 2016) showing meteorological station locations around Drangajökull. C) Same Landsat 8 image with ice-surface elevation contours. Labels on the glacier highlight the surging outlets. Lake catchment boundaries (white) for TRK and EEF based on 2011 ice surface elevations. D) Bed-elevation contours from (Magnússon et al., 2016a). Lake catchment boundaries (white) for TRK and EEF based on bed elevations. E) 2011 ice thickness (blue) with bed-elevation contours from (Magnússon et al., 2016a). Lake catchment boundaries (grey) for TRK and EEF based on bed elevations. For C-E the lowest contour is at 0 m a.s.l. with a contour interval of 100 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

with sea-surface temperatures (SSTs) to the northeast (Harning et al., 2016a). It follows that air temperatures at sea level near Drangajökull are 2 °C lower than along the south coast of Iceland where air is advected off of warmer seas (Einarsson, 1977, Fig. 1). Studying Drangajökull allows us to begin to test the effect of ocean currents on Icelandic paleoclimate. Our understanding of the glacier history of Vestfirðir has expanded recently from the analysis of moraines, lake sediments, and recently exposed dead vegetation (Brynjólfsson et al., 2015a; Harning et al., 2016a, 2016b; 2018a; Schomacker et al., 2016), but significant questions remain.

In this paper, we aim to determine: 1) the sensitivity of Drangajökull to climate; 2) the Holocene history of Drangajökull; and 3) the Holocene air temperature in Vestfirðir. To accomplish these objectives we develop a coupled mass-balance ice-flow model, which we tune using modern climate and glaciological data. To force the model we use air temperatures estimated from ice cores, sea-surface temperatures, and general circulation model (GCM) output. We evaluate our simulations using glacier extent data from Harning et al. (2016a, 2018a) and Schomacker et al. (2016). Below we introduce the state of knowledge related to Drangajökull and the specific questions we address, starting in the early Holocene and progressing towards the present.

Following retreat from the last glacial maximum, Drangajökull persisted at least until the early Holocene (Brynjólfsson et al., 2015b; Harning et al., 2016b; Schomacker et al., 2016). Cosmogenic radionuclide exposure dates suggest that ice was present in the valleys below modern Drangajökull at 10 ka (Brynjólfsson et al., 2015b). Subsequently, Drangajökull retreated to smaller than present dimensions by 9.2 ka based on sediment characteristics from lakes currently connected to the ice cap (Harning et al., 2016b). In contrast, Schomacker et al. (2016) suggested that Drangajökull persisted through the Holocene, based on sediment from distal lakes, due to increased winter precipitation (also see Harning et al., 2018b). Given the contradictions in the literature, the question remains: *did Drangajökull persist through the Holocene?*

Principato (2008) dated a moraine in the Kaldalónsjökull valley