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Non-linear Holocene climate evolution in the North Atlantic: a high-resolution, multi-proxy record of glacier activity and environmental change from Hvítárvatn, central Iceland

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A B S T R A C T

Iceland is well situated to monitor North Atlantic Holocene climate variability. Terrestrial sites there offer the potential for well-dated, high-resolution, continuous records of environmental change and/or glacier activity. Laminated sediments from the proglacial lake Hvítárvatn provide a continuous record of environmental change and the development of the adjacent Langjökull ice cap for the past 10.2 ka. Replicate lake sediment cores, collected from multiple locations in the basin, are placed in a secure geochronology by splicing a varve chronology for the past 3 ka with a tephra-constrained, paleomagnetic secular variation derived chronology for older sediments. Multiple proxies, including sedimentation rate, bulk density, ice-rafted debris, sediment organic matter, biogenic silica, and diatom abundance, allow annual to multi-decadal resolution and reveal a dynamic Holocene terrestrial climate. Following regional deglaciation of the main Iceland Ice Sheet, summer temperatures were high enough that mountain ice caps had already melted, or were contributing insignificant sediment to the lake. Pronounced increases in sedimentation rate, sediment density, and the influx of terrestrial organic matter, between 8.7 and 7.9 ka suggest early Holocene warmth was interrupted by two distinct pulses of cold summers leading to widespread landscape destabilization and possibly glacier growth. The Holocene thermal maximum (HTM; 7.9 to 5.5 ka) was characterized by high within-lake productivity and ice-free conditions in the watershed. Neoglaciation is recorded as a non-linear transition toward cooler summers, landscape destabilization, and the inception and expansion of Langjökull beginning ca 5.5 ka, with notable increases in ice cap size and landscape instability at 4.2 and 3.0 ka. The past two millennia are characterized by the abrupt onset of sustained cold periods at ca 550 and 1250 AD, separated by an interval of relative warmth from ca 950 to 1150 AD. The greatest Holocene extent of Langjökull occurred in the nineteenth century and is coincident with peak landscape instability, followed by ice recession throughout the twentieth century.

1. Introduction

The primary control on Northern Hemisphere climate during the Holocene has been the monotonic decline in Northern Hemisphere summer insolation, related to the precession of the equinoxes (Berger and Loutre, 1991). However, despite this nearly linear forcing, strong evidence exists for widespread and regionally correlative perturbations in Holocene climate that have been both periodic and abrupt in nature, and that have underscored the sensitivity of the climate system to additional forcings and feedbacks (e.g. Mayewski et al., 2004 and references therein). The non-linear nature of these centennial-scale changes reflects the disproportionate response of the climate system to a relatively constant factor. Associated with many of the perturbations is the role of North Atlantic Ocean circulation in global heat distribution, including the strength of the thermohaline circulation and the position of North Atlantic Deep Water (NADW) formation (e.g. Denton and Broecker, 2008; Sicre et al., 2008). Because variations in these marine systems are often preserved in sedimentary archives, investigations conducted in the North Atlantic have been successful in documenting Holocene paleoceanographic changes (e.g. Eiríksson et al., 2000a; Oppo et al., 2003; Bendle and Rosell-Melé, 2007; Massé et al., 2008; Ólafsdóttir et al., 2010). What remains unclear is how these oceanographic changes have been manifested

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on land, or how nonlinearities in Holocene climate have been expressed in terrestrial environments.

Iceland (~103,000 km^2) is the largest landmass in the central North Atlantic and is positioned in a region with strong ocean and atmospheric thermal gradients (e.g. Knudsen and Eiríksson, 2002, Fig. 1a). Holocene climate in Iceland has been reconstructed from a variety of geologic records (e.g. Hallsdóttir, 1991, 1995; Gudmundsson, 1997; Rundgren, 1998; Stötter et al., 1999; Kirkbride and Dugmore, 2001, 2006; Wastl et al., 2001; Caseldine et al., 2003, 2006; Hallsdóttir and Caseldine, 2005; Wastl and Stötter, 2005; Hannesdóttir, 2006; Axford et al., 2007, 2009; Geirsdóttir et al., 2009a,b; Langdon et al., 2010) but remains coarsely resolved and largely incomplete or discontinuous. A recent review of Holocene glacier and climate fluctuations in Iceland highlights important issues that remain unresolved (Geirsdóttir et al., 2009b). What was the timing and character of early Holocene warmth in central Iceland, and was it sufficient to completely melt Iceland's ice caps? Did Iceland experience periodic or non-linear climate changes such as the 8.2 ka cold event? When was the onset of Neoglaciation and what was the evolution of large ice caps through the mid to late Holocene? The goal of this paper is to directly address these questions using multiple physical, biological, and chemical proxies contained in sediments from an ideally positioned proglacial lake in Iceland's central highlands.

Lake basins preserve a record of environmental change by continuously accumulating sediment and climate proxies produced within the lake and from their surrounding catchments. In glacier-dominated catchments, where sedimentation rates are high and sediment deposition is influenced by upstream ice erosion and meltwater transport, lacustrine archives can also reflect the evolution of glacier activity in response to changes in regional climate and can be inspected at high-resolution (e.g. Desloges, 1994; Dahl et al., 2003; Larsen et al., 2011). This study exploits well-dated glacially derived sediments from Hvítárvatn, a glacial lake adjacent to Langjökull, second largest of Iceland's ice caps, to provide a continuous, high-resolution (annual to multi-decadal), multi-proxy record of Holocene environmental change and ice cap activity in Iceland.

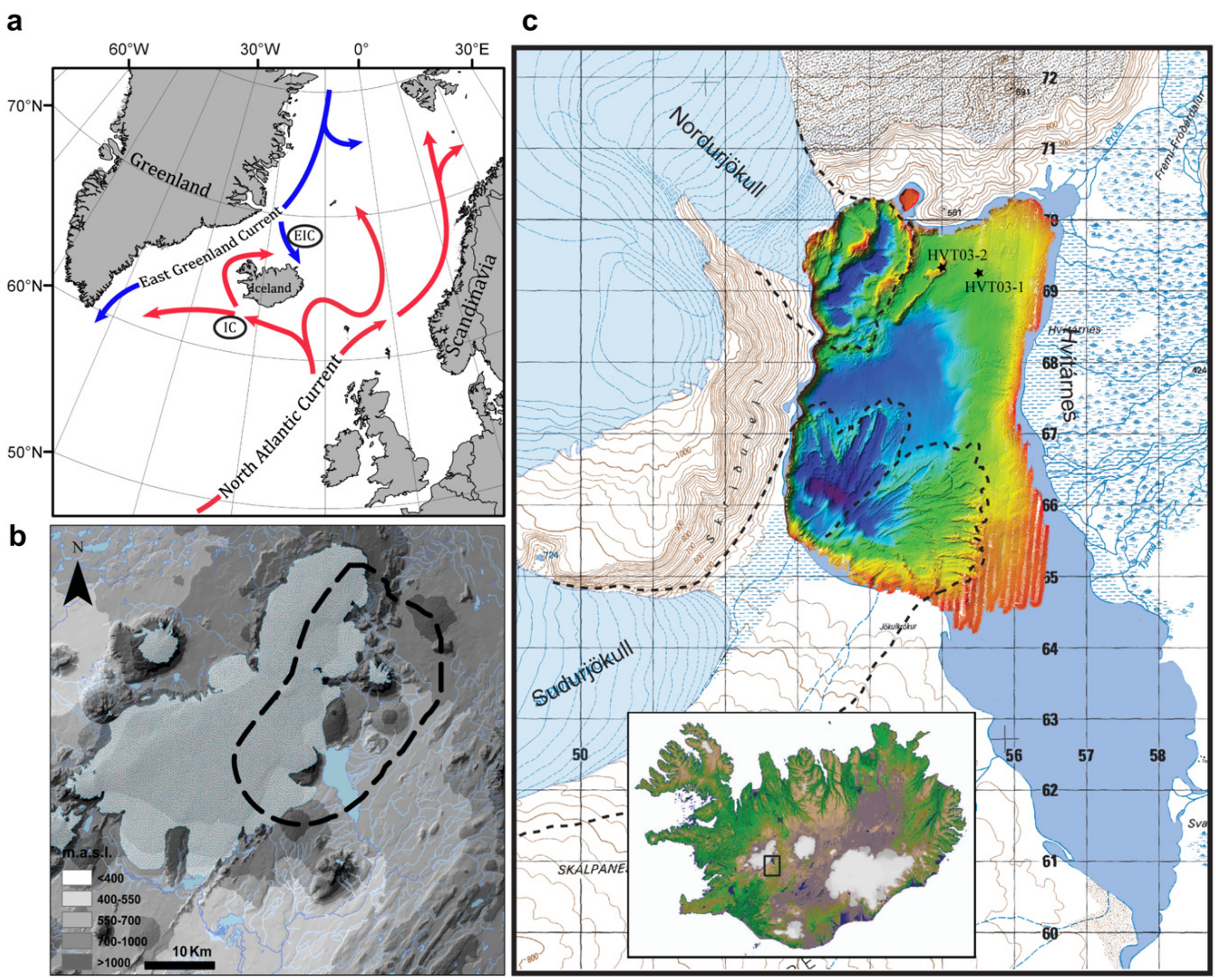

Fig. 1. (a) Map of Iceland in the North Atlantic showing generalized ocean current circulation. At present, Iceland is located near the boundary between contrasting water masses. The Irminger Current (IC), a branch of the warm and saline North Atlantic Current, bends around the south and west coasts, while the colder and fresher East Iceland Current (EIC) descends from the north with the East Greenland Current. (b) Location map and approximate catchment area (dashed line) of Hvítárvatn seen adjacent to the Langjökull ice cap. (c) Topographic map of field area (gridlines on map are 1 km^2) with inset map highlighting the position of the lake within Iceland. The current ice margins of the outlet glaciers Norðurjökull and Suðurjökull are shown along with their approximate LIA maximum limits (dashed lines). Bathymetric map illustrates water depth in the main basin (cooler colors reflect increasing depth) and the location of the two cores sites, HVT03-1 and HVT03-2. Image modified from Geirsdóttir et al. (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)