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Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland

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A B S T R A C T

Two high-sediment-accumulation-rate Icelandic lakes, the glacial lake Hvítárvatn and the non-glacial lake Haukadalsvatn, contain numerous tephra layers of known age, which together with high-resolution paleomagnetic secular variations allow synchronization with a well-dated marine core from the shelf north of Iceland. A composite standardized climate record from the two lakes provides a single time series that efficiently integrates multi-proxy data that reflect the evolution of summer temperatures through the Holocene. The first-order trends in biogenic silica (BSi), $\delta^{13}C$, and C:N rise relatively abruptly following deglaciation, reaching maximum values shortly after 8 ka following a complex minimum between 8.7 and 8.0 ka. The Holocene Thermal Maximum (HTM) in the lakes is marked by all proxies, with a sharp transition out of the 8 ka cold event into peak summer warmth by 7.9 ka, and continuing warm with some fluctuations until 5.5 ka. Decreasing summer insolation after the HTM is reflected by incremental cooling, initially ~5.5 ka, with subsequent cold perturbations recorded by all proxies 4.3 to 4.0 ka and 3.1 to 2.8 ka. The strongest disturbance occurred after 2 ka with initial summer cooling occurring between 1.4 and 1.0 ka, followed by a more severe drop in summer temperatures after 0.7 ka culminating between 0.5 and 0.2 ka. Following each late Holocene cold departure, BSi re-equilibrated at a lower value independent of the sediment accumulation rate. Some of the abrupt shifts may be related to Icelandic volcanism influencing catchment stability, but the lack of a full recovery to pre-existing values after the perturbation suggests increased periglacial activity, decreased vegetation cover, and glacier growth in the highlands of Iceland. The similarity in timing, direction and magnitude of our multi-proxy records from glacial and non-glacial lakes, and from the adjacent marine shelf, suggests that our composite record reflects large-scale shifts in ocean/atmosphere circulation throughout the northern North Atlantic.

1. Introduction

On millennial timescales, the climate of the Holocene in the Northern Hemisphere was strongly influenced by the steadily decreasing summer insolation, whereas on decadal to centennial timescales Holocene climate was variable, fluctuating between warmer and colder, and more humid and more arid states (e.g. Wanner et al., 2011). Complex changes in atmospheric and ocean surface currents are documented for the northernmost North Atlantic through the Holocene (e.g. Bond et al., 2001; Mayewski et al., 2004; Alley and Ágústsdóttir, 2005; Wanner et al., 2008, 2011). For example, several studies of North Atlantic terrestrial and marine archives describe a delayed response to early Holocene peak summer insolation suggesting that meltwater from the lingering Laurentide Ice Sheet influenced thermohaline circulation (e.g. Kaufman et al., 2004; Kaplan and Wolfe, 2006; Geirsdóttir et al., 2009a). Cold summer anomalies since 8 ka that are superimposed on the decreasing Northern Hemisphere summer insolation are related to some combination of reduced solar irradiance, explosive volcanism, and changes in the internal modes of variability in the ocean-atmosphere system during the Holocene (Crowley, 2000; Denton and Broecker, 2008; Wanner et al., 2011). However, no consensus has been reached on the timing, duration, or dominant controlling mechanism for these short term and sometimes abrupt changes.

A prime target for Holocene paleoclimate studies is to test whether changes on decade-to-century scales are regionally coherent. This effort requires continuous records at high resolution

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that are well dated. Recent high-resolution Holocene paleoclimate studies from Iceland and the North Atlantic (Massé et al., 2008; Geirsdóttir et al., 2009b; Ólafsdóttir et al., 2010; Sicre et al., 2011) are limited by uncertainties associated with the various methods of age determination. Large offsets between radiocarbon ages from terrestrial sites, tephra ages and marine sites have been detected due to variable reservoir ages for marine carbon and reworked terrestrial carbon input into lacustrine systems (Wolfe et al., 2004). Diagnostic Icelandic tephra provide discrete timelines that can aid in the correlation of paleoclimate records from marine and terrestrial archives, but there are few widely distributed and well dated tephra layers common to most archives around the North Atlantic. Age models for marine and lake sediment cores can be improved using paleomagnetic secular variations (PSV) combined with tephra chronology.

This paper has two goals. Firstly, we present a new 10 ka high-resolution paleoclimate record from a non-glacial, low-elevation lake, Haukadalsvatn (HAK), in West Iceland, where the last 10 ka is contained in 18 m of sediment (Fig. 1). The 10 ka record builds on an initial study of the last 2 ka (Geirsdóttir et al., 2009b), using the same proxies to extend the proxy record back to 10 ka at near-decadal resolution. PSV synchronization with a well-dated marine core from the shelf north of Iceland (Stoner et al., 2007; Ólafsdóttir et al., 2013), coupled with tephrochronology provide temporal resolution at century or better resolution, allowing a well dated multi-proxy reconstruction of relative changes in summer temperatures over the past 10 ka. Secondly, in Section 4.5, we summarize the PSV and varve-dated record from the glacial lake Hvítarvatn (HVT), located in the central highlands of Iceland, with similar sedimentation rates and at similar resolution (Larsen et al., 2011, 2012). Multiple physical, biological, and chemical proxies derived from the sediment in each core are composited to derive continuous, annual to multi-decadal multi-proxy records of Holocene environmental change and ice-cap activity in Iceland (summarized in Section 5). Despite very different dominant catchment processes, the two lacustrine records show remarkably similar climate evolution, with a delayed Holocene Thermal Maximum (HTM), and a marked transition into Neoglaciation ~5.5 ka, when a first-order summer cooling trend is established. General cooling through the Late Holocene is punctuated by abrupt changes in background state about 4.2, and 3.0 ka, with the strongest cooling beginning ~1.5 ka, culminating in the Little Ice Age, the coldest multicentennial cool interval since 8 ka. Given Iceland's sensitive geographic location in the northern North Atlantic, we suggest that the combined records from these two lakes serves as a template for Holocene climate evolution and abrupt climate change around the northern North Atlantic and Nordic Seas regions.

2. Geological setting

Haukadalsvatn (3.3 km^2, elevation 32 m asl, max depth 42 m) is a coastal lake located in the narrow, steep-sided valley of Haukadalur in western Iceland with an ice-free catchment of 172 km^2 lying mostly above 500 m asl (Geirsdóttir et al., 2009b). The site can be influenced by both the North Atlantic Drift, which delivers warm, saline Atlantic water to the coast of Iceland in the Irminger Current, and the cold, low-salinity water of the East Greenland Current, which flows from the north along the shelf and slope of East Greenland (Fig. 1). Any changes in these opposing ocean surface currents are imprinted on the terrestrial environments in Iceland and sedimentation in HAK. The site is also sensitive to the North Atlantic Oscillation (NAO), the dominant extra tropical atmospheric forcing in the Atlantic sector (e.g. Hurrell, 1995). At present, HAK is neutral (pH 7.7) and well mixed, probably due to a high level of wind stress (Langdon et al., 2008; Geirsdóttir et al., 2009b). The surrounding bedrock is mainly easily erodible Tertiary basalt, and the region lies outside the active volcanic zones of Iceland (Jóhannesson, 1997). The valley of Haukadalur was submerged during deglaciation (marine limit 70 m asl) and the earliest lake sediment fill is of marine origin. The basin became isolated

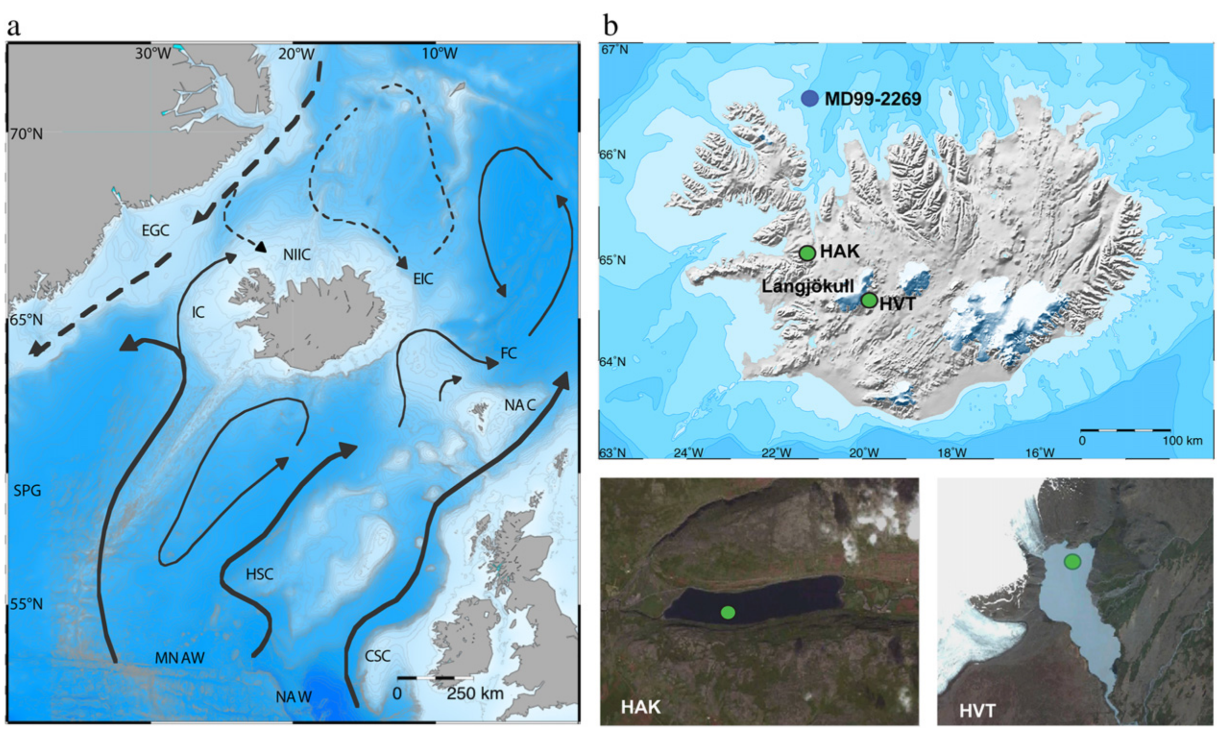

Fig. 1. (a) Map of Iceland in the North Atlantic showing generalized ocean circulation. (b) Location map of study sites in Iceland. The location of sediment cores from. Haukadalsvatn (HAK) and Hvítárvatn (HVT) and the marine shelf core MD99-2269 that is used as a reference curve (Stoner et al., 2007) are shown by the dots.