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Asynchronous Little Ice Age glacier fluctuations in Iceland and European Alps linked to shifts in subpolar North Atlantic circulation

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ABSTRACT

Records of past glacier fluctuations are an important source of paleoclimate data and provide context for future changes in global ice volume. In the North Atlantic region, glacier chronologies can be used to track the response of terrestrial environments to variations in marine conditions including circulation patterns and sea ice cover. However, the majority of glacier records are discontinuous and temporally restricted, owing in part to the extensive advance of Northern Hemisphere glaciers during the Little Ice Age (LIA), the most recent and severe climate anomaly of the Neoglacial period. Here, we combine an absolutely dated and continuous record of Langjökull ice marginal fluctuations with new reconstructions of sediment flux through the past 1.2 ka using varved sediments from Hvítárvatn, a proglacial lake in Iceland's central highlands. Large spatial and temporal variations in sediment flux related to changing ice cap dimensions are reconstructed from six sediment cores and seismic reflection profiles. Sediment data reveal two discrete phases of ice expansion occurring ca. 1400 to 1550 AD and ca. 1680 to 1890 AD. These advances are separated by a persistent interval of ice retreat, suggesting that a substantial period of warming interrupted LIA cold. The pattern of Icelandic glacier activity contrasts with that of European glaciers but shows strong similarities to reconstructed changes in North Atlantic oceanographic conditions, indicating differing regional responses to coupled ocean–atmosphere–sea ice variations. Our data suggest that subpolar North Atlantic circulation dynamics may have led to coherent asynchronous glacier fluctuations during the mid LIA and highlight the importance of circulation variability in triggering and transmitting multidecadal scale climate changes to nearby terrestrial environments.

1. Introduction

The cryosphere plays an important role in Earth's climate system (CCSP, 2009); particularly in the Arctic where climate changes are amplified (Serreze and Francis, 2006; Miller et al., 2010a) and where melting ice can have global impacts through albedo feedbacks and sea level rise (e.g. Meier et al., 2007). Because their dimensions can respond quickly to changes in mass balance, small ice caps and alpine glaciers are highly sensitive to climate change (Oerlemans, 2005) and geologic records of past glacial fluctuations are prime targets for terrestrial paleoclimate reconstructions (e.g. Dyurgerov and Meier, 2000). However, due to ice erosion processes and the destructive nature of successive glacier advances, continuous records are difficult to obtain and are often statistically biased toward periods of moraine emplacement.

Most glaciers in the Northern Hemisphere are currently retreating from advanced positions achieved during the Little Ice Age (LIA; ca. 1250 to 1900 AD; Miller et al., 2010b). The transition from earlier warmth during the Medieval Warm Period (MWP; ca. 1000 to 1250 AD; Lamb, 1965) and the onset of LIA cooling has been attributed to some combination of increased volcanism and/or decreased solar activity, and dynamic variability associated with changes in atmospheric and oceanic circulation, such as the Atlantic Meridional Overturning Circulation (AMOC) and the North Atlantic Oscillation (NAO) (e.g. Crowley, 2000; Mann et al., 2009). Recent evidence from proxy data and model experiments suggest that prolonged cooling following the MWP-LIA climatic shift was likely maintained by modes of internal variability and feedback effects, including dominantly negative NAO phases (Trouet et al., 2009), reduced AMOC strength (Lund et al., 2006; Wanamaker et al., 2012), and increased Arctic sea ice cover (Miller et al., 2012). The aim of this study is to investigate how observed changes in North Atlantic atmospheric and oceanic conditions were transmitted to nearby terrestrial environments by comparing high-resolution records of glacier history in Iceland and the European Alps over the past millennium.

Iceland is well suited for glacier-based paleoclimate reconstructions due to its large glacier inventory and its climatically sensitive location in the central North Atlantic, at the northern dipole of the

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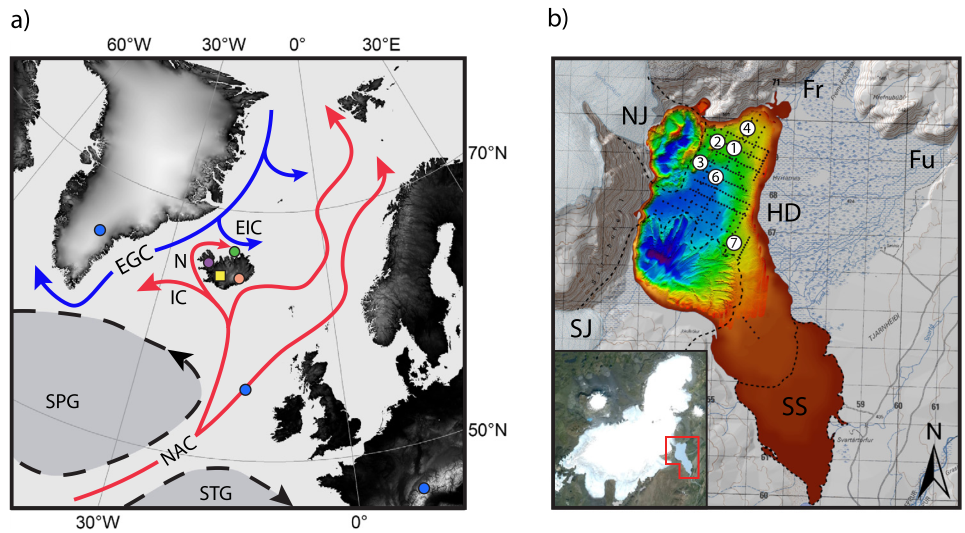

Fig. 1. (a) Map of North Atlantic with generalized surface ocean currents (after Orvik and Niiler, 2002), including the NAC = North Atlantic Current, SPG = Subpolar Gyre, IC = Irminger Current, N = North Icelandic Irminger Current, EGC = East Greenland Current, EIC = East Icelandic Current. Also shown are locations of proxy records mentioned in the text and presented in Fig. 4 (Greenland borehole temperatures at DYE3 site; Hvítárvatn, Iceland (square); Haukadalsvatn, northwestern Iceland; Vatnajökull ice cap, southeast Iceland; North Icelandic shelf marine core MD99-2275; Rockall Trough, eastern subpolar North Atlantic; Swiss Alps). (b) Topographic map of study site (gridlines are 1 km^2) with lake bathymetry illustrating water depth (cooler colors reflect increasing depth). Disturbed areas in front of outlet glaciers Norðurjökull (NJ) and Suðurjökull (SJ) were excluded from seismic survey. The shallow southern region of the lake (SS) contains little sediment fill and was also excluded from the seismic survey. The locations of the six core sites (white circles, from north to south: HVT03-4, HVT03-2, HVT03-1, HVT03-3, HVT09-6, HVT10-7) and 271 seismic point measurements are shown. Also shown are the meltwater streams Fróðá (Fr) and Fulakvisl (Fu) and the expansive Hvítárnes delta (HD). Inset satellite image highlights Langjökull ice cap and the position of Hvítárvatn along its eastern margin.

NAO and near the marine polar front and historic boundary of seasonal Arctic sea ice (Fig. 1a). Icelandic temperatures are heavily influenced by the relative strengths of opposing Arctic and Atlantic surface water masses (see summary in Knudsen et al., 2012). Warm and saline water of the Irminger Current (IC), a westward flowing branch of the North Atlantic Current (NAC), is transported to the southwest coast of Iceland where it divides and a portion continues northward around Iceland as the North Icelandic Irminger Current (NIIC). The character of the IC is related to coupled atmospheric and oceanic variability, with stronger IC flow attributed to a negative NAO (Myers et al., 2007; Miettinen et al., 2011) and contracted modes of subpolar gyre circulation (Hátún et al., 2005). Likewise, the extent of the NIIC varies according to the NAO. During negative NAO phases, the cold, fresh and potentially sea-ice bearing surface waters of the East Icelandic Current (EIC), a branch of the southward flowing East Greenland Current (EGC), are moved toward Iceland, while prevailing northerly winds can reduce the amount of warm Atlantic water carried around the island by the NIIC (Blindheim and Malmberg, 2005). Complex changes to these oceanographic systems during the onset and duration of the LIA have been observed in recent studies of North Atlantic marine sediment cores (e.g. Sicre et al., 2011; Knudsen et al., 2012; Andresen et al., 2013) but the expression of such changes on land is poorly documented.

Here, we develop a continuous record of glacier erosion related to changing dimensions of Langjökull ice cap using annually resolved sediment accumulation rates in proglacial lake Hvítárvatn. We demonstrate a novel combination of multiple sediment cores and a network of seismic reflection profiles to accurately constrain temporal and spatial variations in sediment flux. The pattern of sediment yield is used to assess the character of LIA cooling in Iceland and to place the pattern of glacier fluctuations here within the context of North Atlantic ocean–atmosphere–sea ice variability. We then focus a discussion on the timing of and mechanisms behind contrasting LIA glacier fluctuations in Iceland and the European Alps.

2. Geologic setting and glacial history

Langjökull (∼925 km^2) is an oblong temperate ice cap located in the central Icelandic highlands (Fig. 1a). Empirical data and model simulations reconstruct ice free conditions from 7.9 to 5.5 ka, during the Holocene Thermal Maximum (HTM), when insolation-driven summer temperatures in the highlands are estimated to be ∼3 °C above present (Flowers et al., 2008; Larsen et al., 2012). A continuous record of Langjökull fluctuations after 5.5 ka is preserved in the sediments of Hvítárvatn, positioned immediately adjacent to Langjökull's eastern margin (Fig. 1b).

Hvítárvatn (∼29 km^2; 422 m asl) lies within a partially glaciated 820 km^2 catchment where lake sedimentation rates are controlled by the production and delivery of glacially eroded clastic material (Larsen et al., 2011). Primary sediment sources are two outlet glaciers, Norðurjökull and Suðurjökull, and two meltwater streams, Fróðá and Fulakvisl, which drain the ice cap's northeastern sector. The varved nature of the sediment fill indicates that Langjökull has been continuously present and contributing to suspended sediment deposition since ∼5.5 ka (Larsen et al., 2012). Neoglacial ice cap activity can be reconstructed through changes in lake sedimentation (see Supplementary Information), which imply discrete ice advances at ca. 4.2, 2.9, 0.7, and 0.3 ka (Larsen et al., 2012). Langjökull's maximum aerial extent was achieved during the LIA and is defined by moraines and trimlines (Fig. 1b). During this interval, Norðurjökull and Suðurjökull advanced into Hvítárvatn, but have since receded and no longer terminate in the lake.

3. Methods

Sediment cores were retrieved from six locations along a transect spanning multiple depositional environments (i.e. varying water depths and proximity to inlets and outlet glacier limits) in Hvítárvatn's main basin (Fig. 1b; Supplementary Table S1). Initial core processing and description were performed as outlined in Larsen et al. (2011). A tephra-constrained composite varve chronology was established for Hvítárvatn sediments using three cores