Quaternary Science Reviews 249 (2020) 106633

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Invited review

Holocene history of landscape instability in Iceland: Can we deconvolve the impacts of climate, volcanism and human activity?

Áslaug Geirsdóttir [a, *], David J. Harning [b, **], Gifford H. Miller [b, c], John T. Andrews [b], Yafang Zhong [d], Chris Caseldine [e]

[a] Faculty of Earth Sciences, University of Iceland, Reykjavík, Iceland
[b] Institute of Arctic and Alpine Research, University of Colorado Boulder, CO, USA
[c] Department of Geological Sciences, University of Colorado Boulder, CO, USA
[d] Space Science and Engineering Center, University of Wisconsin-Madison, WI, USA
[e] College of Life and Environmental Sciences, University of Exeter, UK

ARTICLE INFO

Article history:
Received 29 July 2020
Received in revised form
21 September 2020
Accepted 29 September 2020
Available online 12 October 2020

Keywords:
Iceland
Holocene climate
Lake sediments
Landscape instability
Vegetation cover
Volcanism
Settlement

ABSTRACT

Biogeochemical proxy records from Icelandic lake sediment track large-scale shifts in North Atlantic Holocene climate and highlight the impact that North Atlantic Ocean- and atmospheric circulation has on Iceland's climate and environment. Following Early Holocene warmth, centennial-scale climate change is superimposed on millennial-scale cooling, culminating in the transition to the Little Ice Age (~1300–1900 CE). Although the long-term cooling trend is presumably driven by variations in Earth's orbit and the concomitant decline in Northern Hemisphere (NH) summer insolation, the centennial-scale variability has been linked to the strength of the Atlantic Meridional Overturning Circulation (AMOC), volcanism coupled with sea ice/ocean related feedbacks, internal modes of atmospheric variability, and plausibly variations in solar irradiance. One manifestation of these regional climate changes on Iceland is the intensification of soil erosion, resulting in the degradation of ecosystems and landscape. In recent millennia, persistent and severe soil erosion has also been linked to human impact on the environment following the settlement ~870 CE, rapid population growth, introduction of livestock and the poorly consolidated nature of tephra dominated soils. Lake proxy composite records suggest that although event-dominated landscape instability and soil erosion from the Early to Middle Holocene were likely triggered by large volcanic eruptions, the landscape was capable of recovering. However, a threshold was reached ~5 ka BP, resulting in a state change whereby the Icelandic landscape could no longer fully recover from cold-events and/or tephra fall. Landscape sensitivity to climate further intensified at ~1.5 ka BP as identified by regime shift analysis. Hence, widespread and irreversible soil erosion began several centuries before the acknowledged settlement of Iceland, with a second acceleration ~1250 CE. A 2 ka fully coupled climate transient simulation using CESM1.1 shows a ~0.5 °C reduction in summer temperature around Iceland in the first millennium CE, consistent with increased landscape instability and soil erosion in Iceland. A second phase of persistent summer cooling in the model occurs after 1150 CE, with stronger cooling after 1450 CE, reaching a maximum shortly after 1850 CE, ~1 °C lower than at the start of the simulation. Our results suggest that natural variations in regional climate and volcanism are likely responsible for soil erosion prior to human impact, with intensification of these processes following settlement particularly during the cooling associated with the Little Ice Age. Given that the conclusions drawn in this review diverge from the standard paradigm of human-induced soil erosion history in Iceland, research should continue to focus on this complex question from multiple disciplines. In particular, a combination of emerging biogeochemical techniques (e.g. lipid biomarkers and ancient DNA) may be best poised to test and quantify the relative roles of natural environmental variables and human settlement in the history of soil erosion on Iceland.

* Corresponding author.
** Corresponding author.
E-mail addresses: age@hi.is (Á. Geirsdóttir), david.harning@colorado.edu (D.J. Harning).

https://doi.org/10.1016/j.quascirev.2020.106633

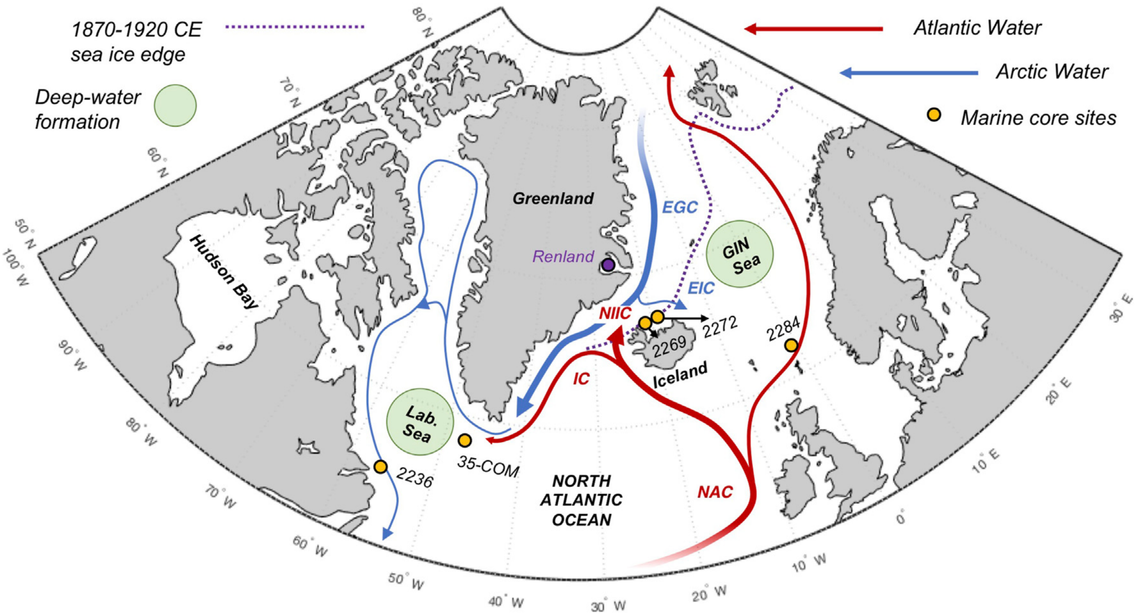


Fig. 1. Overview map of the Northern North Atlantic region. Stippled purple line delineates the instrumental (1870–1920 CE) sea ice edge position after Divine and Dick (2007). Green circles mark local regions of deep-water formation in the Labrador (Lab.) and GIN (Greenland, Iceland, and Norway) Seas. Warm Atlantic currents are marked in red: NAC = North Atlantic Current, IC = Irminger Current, NIIC = North Iceland Irminger Current. Cold Arctic currents are marked in blue: EGC = East Greenland Current, EIC = East Iceland Current. Marine sediment cores mentioned in the text are also marked and abbreviated (i.e. MD99-2269 = 2269 and RAPiD-35-COM = 35-COM).

1. Introduction

The largest variable on decadal to centennial timescales that impacts sub-Arctic and Arctic climate is the transport of heat and moisture from lower latitudes by the ocean-atmosphere system to the Polar regions (Wunsch, 1980). Northward flowing warm and saline surface waters release heat to the atmosphere, become denser and eventually sink, forming part of the Atlantic Meridional Overturning Circulation (AMOC, Buckley and Marshall, 2016). This system accounts for approximately one third of the heat flux to the Arctic and is known to vary in response to changes in the North Atlantic (NAO) and Arctic Oscillation (AO) and with important impacts on atmospheric patterns and weather in this part of the Northern Hemisphere (NH, Wunsch, 1980; Auger et al., 2019). The incursion of freshwater and sea ice can also impact the AMOC's efficiency, as observed during the Great Salinity Anomaly of the 1960s CE (Dickson et al., 1988; Mysak and Power, 1992; Serreze et al., 1992). Not only does Iceland lie within the North Atlantic region most strongly affected by the northward heat transport of AMOC (Fig. 1), but also within the periphery of the strongest contemporary warming (IPCC, 2013; Moffa-Sánchez and Hall, 2017). Hence, Iceland represents an important outpost to monitor the past climate variability of the sensitive North Atlantic region.

Recent high-resolution records of paleoceanography and sea ice around Iceland (Giraudeau et al., 2004; Moros et al., 2006; Solignac et al., 2006; Bendle and Rosell-Melé, 2007; Justwan et al., 2008; Sicre et al., 2008a, 2008b; Knudsen et al., 2004; Jiang et al., 2015; Moossen et al., 2015; Cabedo-Sanz et al., 2016; Kristjánsdóttir et al., 2017; Harning et al., 2020a), glacier history (Flowers et al., 2007, 2008; Larsen et al., 2011; Harning et al., 2016a, 2016b, 2018a; Anderson et al., 2018, 2019), and terrestrial climate proxy records from lake sediment (Axford et al., 2007, 2009; Geirsdóttir et al., 2009a, 2009b, 2013, 2019; Larsen et al., 2012; Blair et al., 2015; Eddudóttir et al., 2015, 2016, 2020; Harning et al., 2018a, 2020b) draw a complex yet comprehensive picture of regional climate during the Holocene (last 11.7 ka BP[1]). Collectively, they reflect the large-scale shifts detected in North Atlantic marine reconstructions and highlight the impact that North Atlantic Ocean- and atmospheric circulation has had on Iceland's climate throughout its pre-instrumental history. Although the primary NH summer insolation forcing has been monotonic, continuous Holocene reconstructions of relative summer temperature change in multiple Icelandic lakes show a non-linear response (e.g. Geirsdóttir et al., 2013, 2019). This centennial-scale variability has been linked to variations in solar irradiance, the strength of the AMOC, volcanism coupled with sea ice/ocean related feedbacks and internal modes of atmospheric variability (e.g. Wanner et al., 2011; Miller et al., 2012; Ólafsdóttir et al., 2013; Harning et al., 2018a). Prior work has focused on detailing various manifestations of these regional stepwise cooling events during the Holocene, such as the episodic expansion of the cryosphere and reduction in lake productivity and shrub cover (e.g. Geirsdóttir et al., 2013, 2019; Cabedo-Sanz et al., 2016; Eddudóttir et al., 2016). However, less explored throughout the Holocene is how the intensification of soil erosion is related to the impact of tephra fall and natural changes in climate (e.g. Larsen et al., 2011; Christensen, 2014; Eddudóttir et al., 2016).

Soil formation and soil erosion at higher latitudes depends on interaction of a number of forces, including climate, landscape, composition, organisms and time. In Iceland, explosive volcanic eruption with tephra production and aeolian and fluvial activities influence both soil formation ("thickening of soil") and soil erosion. The primary source of material is within the active volcanic zones of Iceland and the glaciofluvial sandur areas where tephra and fine-grained sediment accumulation takes place (e.g. Arnalds, 2000; Arnalds et al., 2001, 2010; Hallsdóttir, 1987, 1995). Due to the richness in volcanoclastic materials (mineral fragments and ash),

[1] All ages discussed are presented in calibrated ^{14}C kiloyears (ka) before present (BP), where present is equal to 1950 CE.

the soil is primarily classified as Andosol and by nature lacks cohesion. The lack of cohesion makes the soil more vulnerable to aeolian and fluvial erosional processes than most other soil types (e.g. Arnalds, 2013; Arnalds et al., 2016) and often results in remobilization and thickening of soil in one place and concurrent erosion in another (e.g. Gunnarsdóttir, 2018). Soil remobilization has through the years affected much of Iceland's ecosystem and has been a determining factor in soil formation and fertility (e.g. Gísladóttir, 2001). Although vascular vegetation cover plays an important role in preventing soil mobilization (Arnalds, 2013; Cutler et al., 2016), plants can be killed and efficiently removed following volcanic ash deposition as a result of suffocation, impaired photosynthesis, abrasion and/or acidification (e.g. Mack, 1981; Grattan and Pyatt, 1994; Grattan and Gilbertson, 2000).

In recent millennia, persistent and severe soil erosion has been linked to anthropogenic activities after the settlement of Iceland (~870 CE). The impacts of rapid population and livestock growth with sheep foraging seasonally at all elevations compromised the vegetation cover such that fine grained soil material became more easily accessible to wind, rain and fluvial, rill and gully erosional activity (e.g. Arnalds, 2000; Arnalds et al., 2001; Hallsdóttir, 1987, 1995). It is reasonable to assume that with human colonization came additional landscape modification to facilitate agricultural and pastoral enterprises, which also may have contributed to the observed landscape destabilization. However, temporal trends in landscape instability and erosion in Iceland are not well known due to a scarcity of well-dated, continuous records, and little is known about these processes before human settlement. Observations of severe soil erosion in recent centuries leave a lingering question regarding the role of human activities versus natural forcing such as climate and volcanism as the factors behind the extensive soil erosion still apparent across Iceland. Better characterization of the erosional and landscape instability trends in Iceland is thus needed to provide such long-term perspective to help understanding the causes and consequences of soil erosion.

Here, we briefly review the Holocene history of climate, vegetation (with a focus on *Betula*), volcanism and human impact on Iceland's landscape as interpreted from high resolution lake sediment records. By comparing the Holocene evolution of glacier expansions, vegetation and landscape instability with reconstructed and modeled summer temperatures, volcanism and the acknowledged arrival of settlers, we aim to deconvolve the climate impact on soil erosion versus anthropogenic activity. We take advantage of several normalized and composited high-resolution proxy records from seven Icelandic lakes that reflect relative diatom productivity and temperature variations (biogenic silica, BSi) and organic matter source and erosional activity (C/N and bulk $\delta^{13}C$) (Geirsdóttir et al., 2013, 2019). In order to statistically identify abrupt and persistent changes within our landscape stability proxy records, we performed an analysis that targets mean regime shifts in individual time series and look to a recent 2 ka fully coupled climate transient simulation using CESM1.1, with forcing data from Paleoclimate Modeling Intercomparison Project Phase 4 working group (PMIP4), including insolation, volcanic aerosols, land-cover, and greenhouse gas levels (Zhong et al., 2018). Finally, we review the most recent development regarding the use of novel biogeochemical toolsets and discuss how we can possibly make use of these emerging analytical techniques to better disentangle the past impacts of climate, volcanism and humans on the Icelandic landscape.

2. Materials and methods

2.1. Lakes that form the composite

The seven lakes that form the high-resolution composite proxy records lie along a transect spanning the temperature and precipitation gradient from south to northwest Iceland (Fig. 2). The lakes represent a range of catchment styles, including lowland/coastal lakes (Torfdalsvatn, TORF; Haukadalsvatn, HAK; Vestra-Gíslholtsvatn, VGHV; Skorarvatn, SKR), highland lakes (Hvítárvatn, HVT; Arnarvatn Stóra, ARN; Tröllkonuvatn, (TRK), and they span elevations between 30 and 540ma.s.l. (Table 1, see Supporting Information Text S1 for more details). The lakes vary in surface area (0.2–28.9 km^2) and lake depth (3–83 m) (Table 1, Fig. S1). In most years, the lakes are ice covered from November to April, although early winter thaws and/or late season ice cover may occur. All lakes occupy glacially scoured bedrock basins and contain a high-resolution Holocene record with sediment thickness ranging from 2.5 m (SKR) to > 20 m (HVT). Vestra Gíslholtsvatn (VGHV), Arnarvatn Stóra (ARN), Torfdalsvatn (TORF), Haukadalsvatn (HAK), and Skorarvatn (SKR) have not received glacial meltwater since Early Holocene and preserve organic-rich sediments deposited throughout the remainder of the Holocene. In contrast, Hvítárvatn (HVT) and Tröllkonuvatn (TRK) are glacial lakes that have received glacial meltwater when ice margins reoccupied lake catchments during the Middle to Late Holocene.

The vegetation around most of the lakes is characterized by shrub heath, with low-lying plants and mosses dominating the shallow soils (Fig. S1). The one exception is VGHV, the southernmost lake, which today is predominately surrounded by large planted hayfields. However, shrub heath grows near bedrock outcrops on elevated areas around VGHV, whereas fen/mires prefer locations where water can accumulate in lower elevation areas. Three of the lakes – VGHV, HVT, and ARN – lie within the current active volcanic zone of Iceland and therefore contain and preserve more frequent and thicker tephra layers compared to the other four lakes that all lie distal to the main volcanic zones (Fig. 1).

Based on historical accounts it is assumed that at least three lake catchments (VGHV, HAK, TORF) were influenced by early human settlement (~870 CE) and their livestock. The remaining four lake catchments (SKR, TRK, ARN and HVT) are located in more remote areas and would have been less accessible during the early decades following human settlement.

2.2. Selected paleoclimate records

Our primary goal when reconstructing Holocene climate evolution is to test whether changes on decade-to-century scales are regionally coherent (e.g., Geirsdóttir et al., 2013). This effort requires continuous records from different catchments where consideration is given to the large number of highly resolved climate proxies derived from each of the seven lake sediment records. Originally, Geirsdóttir et al. (2013) composited six different normalized climate proxies in high sedimentation-rate cores from two lakes: the glacial lake Hvítárvatn and the non-glacial, lowland lake Haukadalsvatn. Despite the different catchment-specific processes that characterized each lake's catchment, the composite proxy records show remarkably similar stepped changes toward colder states after the Middle Holocene. The common signal in

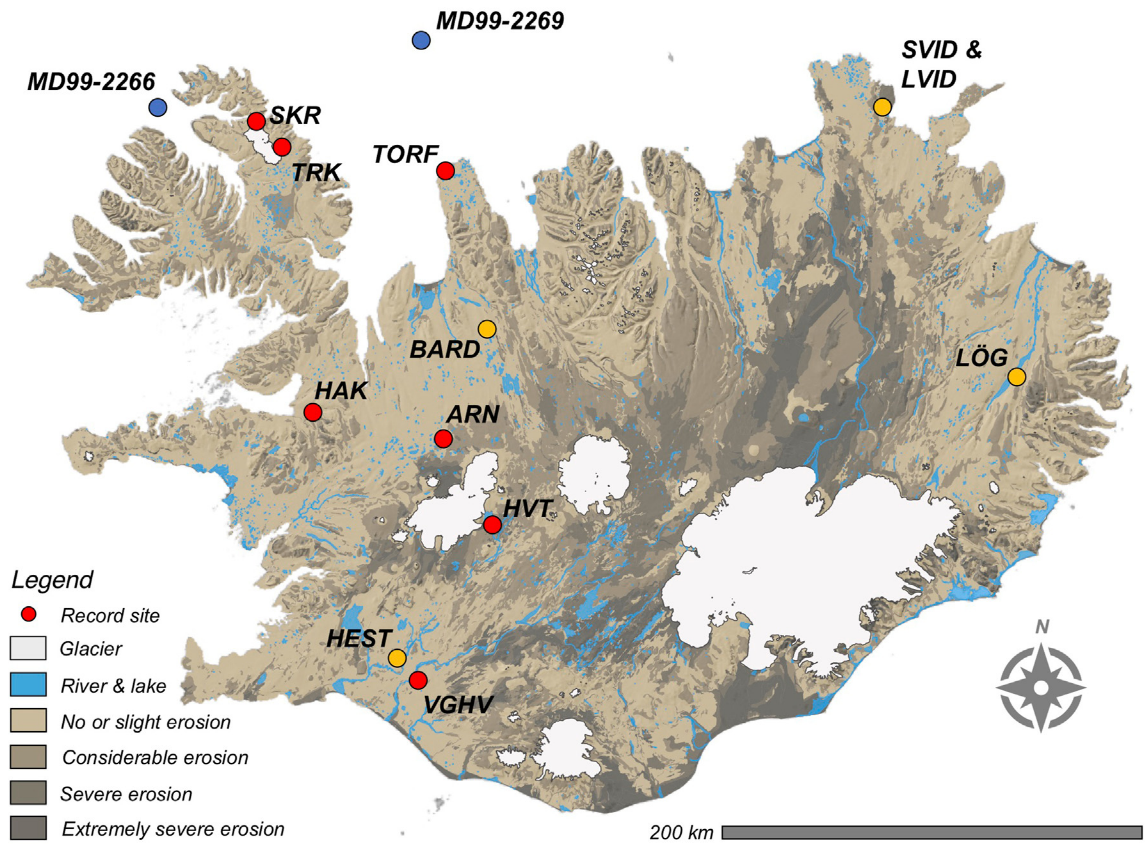


Fig. 2. Overview map of Iceland. The 7 lakes used in our proxy composite time series are marked in the red, and other important lake and marine sites mentioned in the text are marked in yellow and blue, respectively. The base map describes the severity of modern soil erosion of non-glaciated regions (after Arnalds et al., 2001).

Table 1
High-resolution and continuous Holocene paleoenvironmental lake sediment records from Iceland. MS = magnetic susceptibility, TOC = total organic carbon, BSi = biogenic silica, and IRD = ice-rafter debris. Lakes marked with an asterisk are included in our 7-lake proxy composites. See Fig. 2 for site locations.

Lake	Elevation	Lat (°)	Long (°)	Lake catchment area (km^2)	Lake area (km^2)	Max depth (m)	Basal age (cal ka BP)	Proxies	References
Skorarvatn (SKR) *	183	66.26	−22.32	1.2	0.2	25	10.3	MS, density, TOC, BSi, C/N, $\delta^{13}C$, alkenones, brGDGTs	Harning et al. (2016a, b, 2018a, b, 2020b)
Tröllkonuvatn (TRK) *	366	66.14	−22.05	9.4	1.3	16.4	9	MS, density, TOC, BSi, C/N, $\delta^{13}C$	Harning et al. (2016a, b, 2018a, b)
Torfdalsvatn (TORF) *	52	66.06	−20.38	2.76	0.4	5.8	12	MS, density, TOC, BSi, C/N, $\delta^{13}C$, $\delta^{15}N$, chironomids	Axford et al. (2007); Geirsdóttir et al. (2019)
Hvítárvatn (HVT) *	422	64.64	−19.84	820	28.9	83	10.3	Grain size, IRD, varve thickness, MS, density, TOC, BSi, C/N, $\delta^{13}C$, diatoms	Larsen et al. (2011, 2012, 2015)
Arnarvatn Stóra (ARN) *	540	64.96	−20.33	61	4	3	10.5	MS, density, TOC, BSi, C/N, $\delta^{13}C$	Gunnarson (2017); Geirsdóttir et al. (2019)
Haukadalsvatn (HAK) *	32	65.05	−21.63	172	3.3	42	10.3	MS, density, TOC, BSi, C/N, $\delta^{13}C$	Geirsdóttir et al. (2009b, 2013)
Vestra Gíslholtsvatn (VGHV) *	61	63.93	−20.52	4.2	1.57	15	>10.3	MS, density, TOC, BSi, C/N, $\delta^{13}C$, $\delta^{15}N$, pollen	Hallsdóttir and Caseldine (2005); Blair et al. (2015)
Barðalækjartjörn (BARD)	413	65.42	−19.87	n/a	0.1	0.9	10.3	MS, density, TOC, C/N, pollen, macrofossil	Eddudóttir et al. (2016)
Stóra Viðarvatn (SVID)	151	66.24	−15.84	n/a	2.4	48	>10.3	MS, TOC, BSi, C/N, chironomids	Axford et al. (2007, 2009)
Litla Viðarvatn (LVID)	142	66.24	−15.81	n/a	0.2	2.5	>10.3	MS, TOC, BSi, C/N, chironomids	Axford et al. (2007)
Lögurinn (LÖG)	20	65.25	−14.42	n/a	53	112	10.3	Grain size, varve thickness, MS, TOC, BSi, C/N, diatoms, chironomids	Striberger et al. (2011, 2012); Gudmundsdóttir et al. (2016)
Hestvatn	49.5	64.02	−20.71	n/a	6.8	60	>10.3	Pollen	This study

different catchments indicates that the climate proxies in the sediment records reliably reflect past climate change in Iceland. In 2019, Geirsdóttir et al. added five new Icelandic lake sediment records and tested whether the two-lake composite could be replicated in other lakes across Iceland. First, they generated a single multi-proxy composite record for each lake by applying the same methodology as in Geirsdóttir et al. (2013). Before calculating each regional mean record, all individual proxy records were standardized over the whole record/period. The Analyseries software (Paillard et al., 1996) was used to resample each proxy time series to the same 20-year increment, which reflects the minimum resolution within the dataset and permits a reliable comparison of the records with each other. The multi-proxy composites for each lake reduce proxy specific signals within each lake, while amplifying those signals that are recorded by most or all proxies. By isolating each individual lake composite record, the signal of catchment-specific processes within each lake record is preserved, which validates our comparison between different catchments to test for a regional, Iceland-wide signal (Geirsdóttir et al., 2019). Compared to the previous two-lake composite (Geirsdóttir et al., 2013), the seven-lake composite is nearly identical, which indicates that all lakes experienced similar climatic histories with relatively minor superimposed catchment-specific processes. Furthermore, the results from factor analyses show that communalities, a measure of shared information (Davis, 1986; Aabel, 2016), is high indicating that in addition to an all-proxy composite, a simple composite of BSi (relative spring/summer warmth; e.g., Geirsdóttir et al., 2009b) and C/N (cold or erosional activity) can disentangle the catchment responses (C/N) to climate change and the temperature forcing (BSi) (Fig. 3, S2 and S3; Geirsdóttir et al., 2019).

Here, we rely on the BSi and C/N composite records that were previously presented by Geirsdóttir et al. (2019), and we add a bulk $\delta^{13}C$ composite record derived from the same seven lakes (Figs. 2 and 3, Table 1). From each of these well-dated lake sediment records, in addition to the sediment record from Lake Lögurinn (LÖG, Fig. 2, Gudmundsdóttir et al., 2016), we have also compiled a composite tephra layer frequency (TLF) record (Fig. 3) to evaluate the impact of local tephra fall on the catchment environments. For the composite TLF record, we exclude other high-resolution lakes records that only account for marker tephra layers used for chronological constraint (Table 1, Axford et al., 2007; Eddudóttir et al., 2016). In terms of proxy interpretations, BSi is a proxy for algal (diatom) productivity (Conley and Schelske, 2001), and assuming little change in the overall sedimentation rate, BSi reflects qualitative changes of spring/summer lake temperature in Iceland (Geirsdóttir et al., 2009b), as seen elsewhere in the Arctic (McKay et al., 2008). In Iceland, modern end-member studies have shown that bulk C/N and $\delta^{13}C$ values provide information on organic matter provenance where terrestrial material generally exhibits higher C/N and more depleted $\delta^{13}C$ values (Fig. 4a, Wang and Wooller, 2006; Skrzypek et al., 2008; Langdon et al., 2010; Florian, 2016). The anti-correlation of our composite C/N and $\delta^{13}C$ records (Fig. 3), demonstrates that during the Holocene, the lakes received progressively more terrestrial organic matter (soil and plants), which we interpret to reflect increased soil erosion (Fig. 4b).

Along with our proxy composites, we aim to compare with a variety of other high-quality Holocene climate archives (Fig. 2). In this regard, we focus on sediments that have accumulated in marine troughs (particularly MD99-2269, Fig. 2) and glacially scoured terrestrial basins/lakes and capture continuous and high-resolution (decadal to centennial) records of past environmental change (e.g. Andrews et al., 2000; Geirsdóttir et al., 2009a, 2013, 2019). Although there are numerous records from terrestrial peat and soil records, these archives often miss the period directly following deglaciation due to the lag associated with the timing of peat and soil formation (e.g. Hallsdóttir, 1995), and stacked soil sequences can be discontinuous due to erosional processes (e.g. Dugmore et al., 2009). In terms of paleovegetation, peat records can also be complicated by over-representation of peat-specific taxa compared to lakes that capture an integration of the regional flora (Hallsdóttir, 1995). Although a wide variety of pollen records currently exist from Icelandic sedimentary archives (Table S1 and Fig. S4), only one has been published that features a continuous and well-dated lake record since local deglaciation (Barðalækjartjörn (BARD), Fig. 2, Eddudóttir et al., 2016). To supplement this north Iceland vegetation record, we present a previously unpublished and continuous pollen record from the lake Hestvatn (HST) in south Iceland (see Supporting Information Text S2). Given pollen's efficient wind dispersal (e.g. Birks and Birks, 2000), we interpret both records to reflect regional rather than local changes in vegetation. In this way, the pollen records also reflect average depictions of the Icelandic ecosystem and are therefore compatible with our proxy composites.

The bulk of the proxy records presented here derive from ecological assemblages and biogeochemical indicators that hold seasonal biases. For those that derive from photosynthetic organisms that require sunlight as their energy source for biological production, that season is generally spring and/or summer as the dark polar winter and sea/lake ice-cover hinders biosynthesis. Key examples include diatom-derived proxies, such as the sea ice biomarker IP_{25} (Belt, 2018) and biogenic silica (BSi, McKay et al., 2008), haptophyte-derived alkenones (Rodrigo-Gámiz et al., 2015; Longo et al., 2018), and birch treeline (Körner and Paulsen, 2004; Jónsson, 2005). Others such as glycerol dialkyl glycerol tetraethers (GDGTs) are biosynthesized by ammonia oxidizing marine Thaumarchaeota or heterotrophic bacteria that do not require sunlight or oxygen (Schouten et al., 2013). As a result, biosynthesis in darkness and under ice cover is possible. In the marine realm around Iceland, GDGTs correlate best with annual and winter subsurface temperatures (Rodrigo-Gámiz et al., 2015; Harning et al., 2019b), whereas recent work from the high latitudes (and altitudes) demonstrates a stronger relationship between lacustrine branched GDGTs (brGDGTs) and summer temperature (Shanahan et al., 2013; Peterse et al., 2014; Deng et al., 2016; Cao et al., 2020). The specific seasonality of biological proxies assessed in this review have been locally calibrated with surface sediment calibrations (Rodrigo-Gámiz et al., 2015; Harning et al., 2019b) and independent alkenone and BSi-derived proxies (brGDGTs, Harning et al., 2020b), as well as by comparison to overlapping instrumental records (BSi, Geirsdóttir et al., 2009b). As we cannot cover all the limits and assumptions of each proxy used in this review, we encourage the reader to explore the cited literature (and references therein) to inform their own understanding and interpretations (e.g. Axford et al., 2011).

Various chronological toolsets are available to constrain Iceland's marine and terrestrial sedimentary records. ^{14}C ages are one of the most common tools but can be hampered by variable and poorly constrained ^{14}C reservoir corrections (ΔR) in the marine realm (e.g. Eiríksson et al., 2004), and by the delivery of old terrestrial carbon to the lake sediments via aeolian and fluvial erosion as well as geothermal-derived CO_2 in groundwater (Sveinbjörnsdóttir et al., 1998; Ascough et al., 2007; Geirsdóttir et al., 2009b; Torres et al., 2020). If present, aquatic macrophytes offer the most reliable option for ^{14}C-based age control in Icelandic lakes, especially since the basaltic bedrock precludes hardwater effects. The abundance of compositionally distinct marker tephra layers (volcanic ash) from Icelandic eruptions offer an invaluable tool to correlate geologic records as they circumvent many potential ^{14}C-related issues (e.g. Thórarinsson, 1944; Larsen and Eiríksson, 2008). However, caution must be exercised as

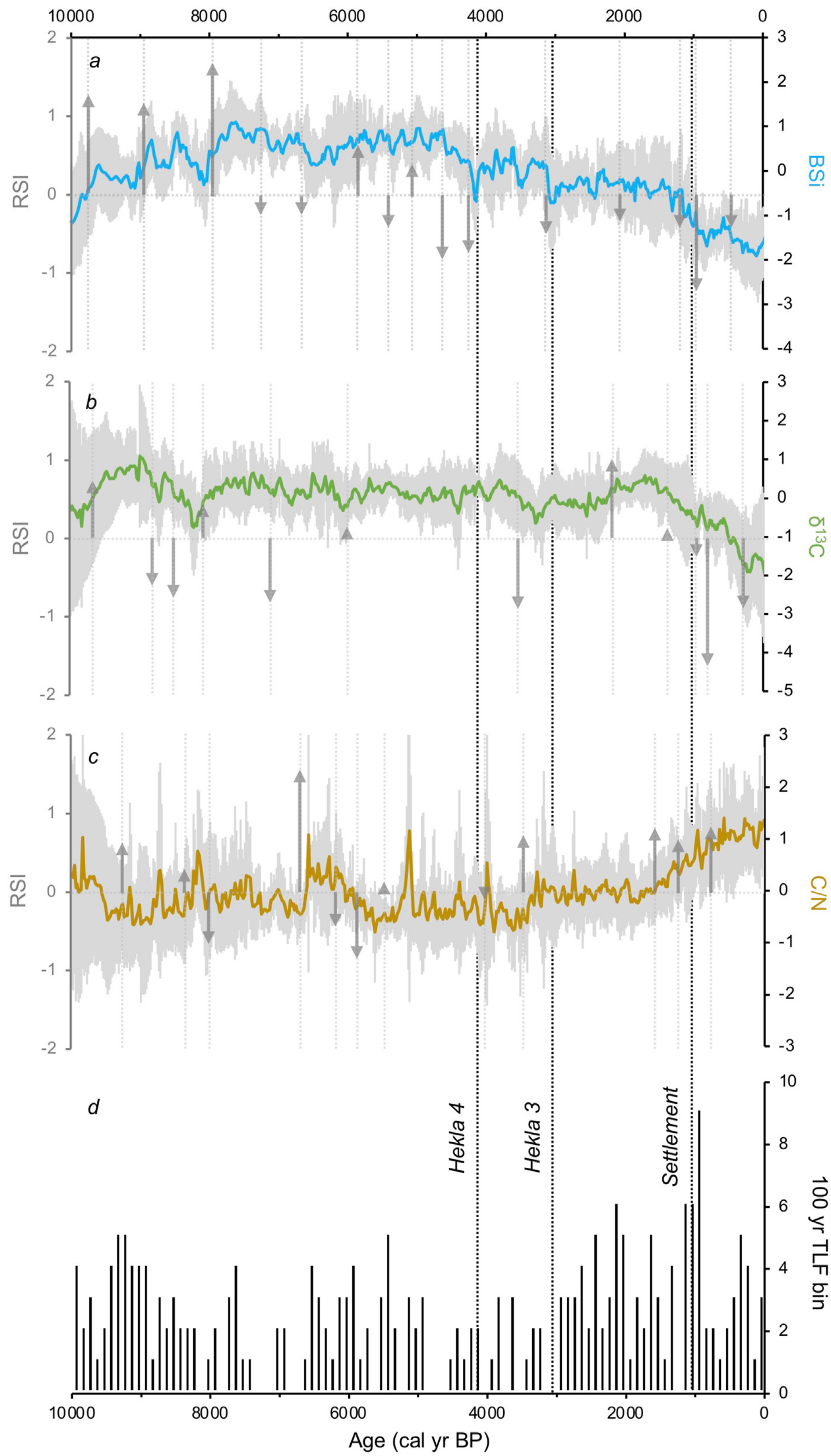


Fig. 3. Composite proxy time series derived from Icelandic lake sediment records. Composites of a) biogenic silica (BSi), b) bulk $\delta^{13}C$, c) elemental C/N, and d) tephra layer frequency (TLF) in 100-year bins. For climate proxies in panels a–c, we show the mean of normalized values (bold colored line) and standard deviation (light gray envelope). Also shown are the results of the regime shift analysis (vertical gray dashed lines), where higher regime shift indices (RSI) correspond to more significant regime shifts. Major marker tephra layers mentioned in the text are indicated with vertical black dotted lines. The Eldgjá eruption (940 CE) is not marked but occurred in the century following the eruptions that generated the Settlement Series tephra layer.

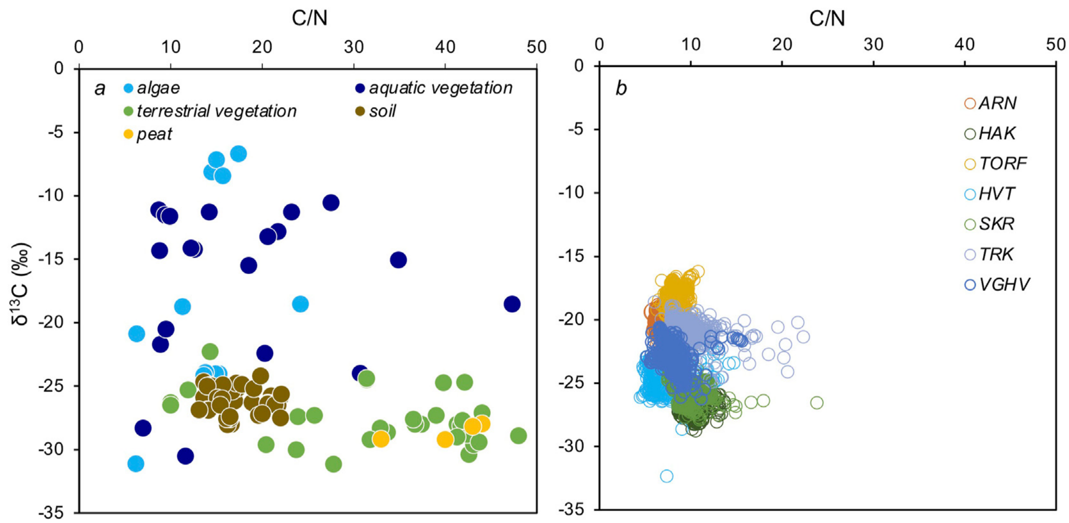


Fig. 4. Organic matter provenance biplots. a) End members synthesized from modern Icelandic vegetation datasets (Wang and Wooller, 2006; Skrzypek et al., 2008; Langdon et al., 2010; Florian, 2016). b) Values for the 7 lakes included in this review. Note: C/N axis terminated at a value of 50, but terrestrial vegetation from the modern end member studies range up to 205.

compositional similarities and sometimes poor supporting age constraint can complicate seemingly secure tephra correlations (e.g. Harning et al., 2018b, 2019a; Óladóttir et al., 2020). Paleomagnetic secular variation (PSV), based on the remanent magnetization of undisturbed lake sediment, has been used to securely date tephra layers as well as provide age models for high-resolution records by synchronizing to well-dated marine sediment core (MD99-2269, Fig. 2) from the North Iceland Shelf (Ólafsdóttir et al., 2013; Geirsdóttir et al., 2013; Harning et al., 2019a). In this way, PSV records can offer the potential for high-resolution regional synchronization between different archives, including land and sea, from which an assessment of leads and lags between primary insolation forcing and changes in ocean-atmosphere circulation can be derived (e.g. Ólafsdóttir et al., 2013). Third and finally, varve chronologies (annual sediment laminations), supported by marker tephra layer identifications, have been used where both clastic sedimentation and seasonality are high, such as for the lake Hvítárvatn (HVT), adjacent to Langjökull in the central highlands (Fig. 2, Larsen et al., 2011, 2015). All records assessed in this review feature age control with a minimum spacing of <2000 years.

2.3. Statistical analyses

In order to objectively determine persistent step shifts within our composite proxy time series and best compare with other local and regional paleoclimate records, we performed Sequential T-test Analysis of Regime Shifts (STARS) (Fig. 3, Rodionov, 2004, 2006). The algorithm was tuned to detect regime shifts on centennial timescales by setting the cutoff length to 60, and we report the timing of shifts identified at the 95% confidence level ($p \leq 0.05$). The regime shift index (RSI) reflects the relative significance of regime shifts where higher values are more significant. The timing of regime shifts is best interpreted as approximate (±100 years), as their timing and magnitude are affected by the chosen confidence level and cutoff length (e.g. Rodionov, 2006; Seddon et al., 2014).

2.4. CESM1.1 past2k simulation

An additional dataset for regional temperatures is from the CESM1.1 past2k simulation that has 1° resolution in the ocean and the sea ice and 2° resolution in the atmosphere (Zhong et al., 2018). The CESM1.1 is a state-of-the-art global climate model that has been widely used in numerical simulations of the Earth's past, present and future climate (Hurrell et al., 2013). The past2k simulation successfully reproduces major phenomena revealed by paleo proxies, e.g. Arctic-wide cooling from 1 CE to 1900 CE and the following sharp rise in temperature, the warm Medieval episode from 950 CE to 1250 CE, the Little Ice Age from 1300 CE to 1850 CE, and abrupt cooling in response to major explosive eruptions.

3. A brief review of Late Glacial and holocene climate, soil and vegetation evolution

3.1. Late Glacial (~22–11.7 ka BP)

During the last glacial maximum (LGM, ~28 to 22 ka BP), Iceland lay beneath the Icelandic Ice Sheet (IIS) that extended to the shelf break, reaching at least two km in thickness at the ice divide (Ólafsdóttir, 1975; Egloff and Johnson, 1979; Boulton et al., 1988; Norðdahl, 1991; Syvitski et al., 1999; Andrews et al., 2000; Geirsdóttir et al., 2002; Andrews and Helgadóttir, 2003; Hubbard et al., 2006; Licciardi et al., 2007; Spagnolo and Clark, 2009; Patton et al., 2017). A series of records from ^{14}C-dated marine shelf sediments indicate that lateral retreat of the marine-based ice sheet margins occurred between 18.6 and 15 ka BP followed by a catastrophic collapse of marine ice shelves between 15 and 14.7 ka BP under rapidly rising sea level and loss of grounding lines (Syvitski et al., 1999; Andrews et al., 2000; Jennings et al., 2000; Ingólfsson and Norðdahl, 2001; Geirsdóttir et al., 2002; Norðdahl and Ingólfsson, 2015) and likely exacerbated by the reinvigoration of deepwater convection and the AMOC forced under generally increasing NH summer insolation (Fig. 5a–c). Following the rapid disintegration of the marine-based components of the IIS (Ingólfsson and Norðdahl, 2001; Norðdahl and Ingólfsson, 2015; Patton et al., 2017), coastal regions emerged between 14.7 and 13.8 ka BP during the Bølling-Allerød warmth, offering new habitats for terrestrial and aquatic vegetation. However, local colonization of plants was likely stunted by the Younger Dryas, a millennial-scale cold interval (12.9–11.7 ka) characterized regionally by reduced AMOC strength (Fig. 5b–d, Broecker, 2006; Ritz et al., 2013;

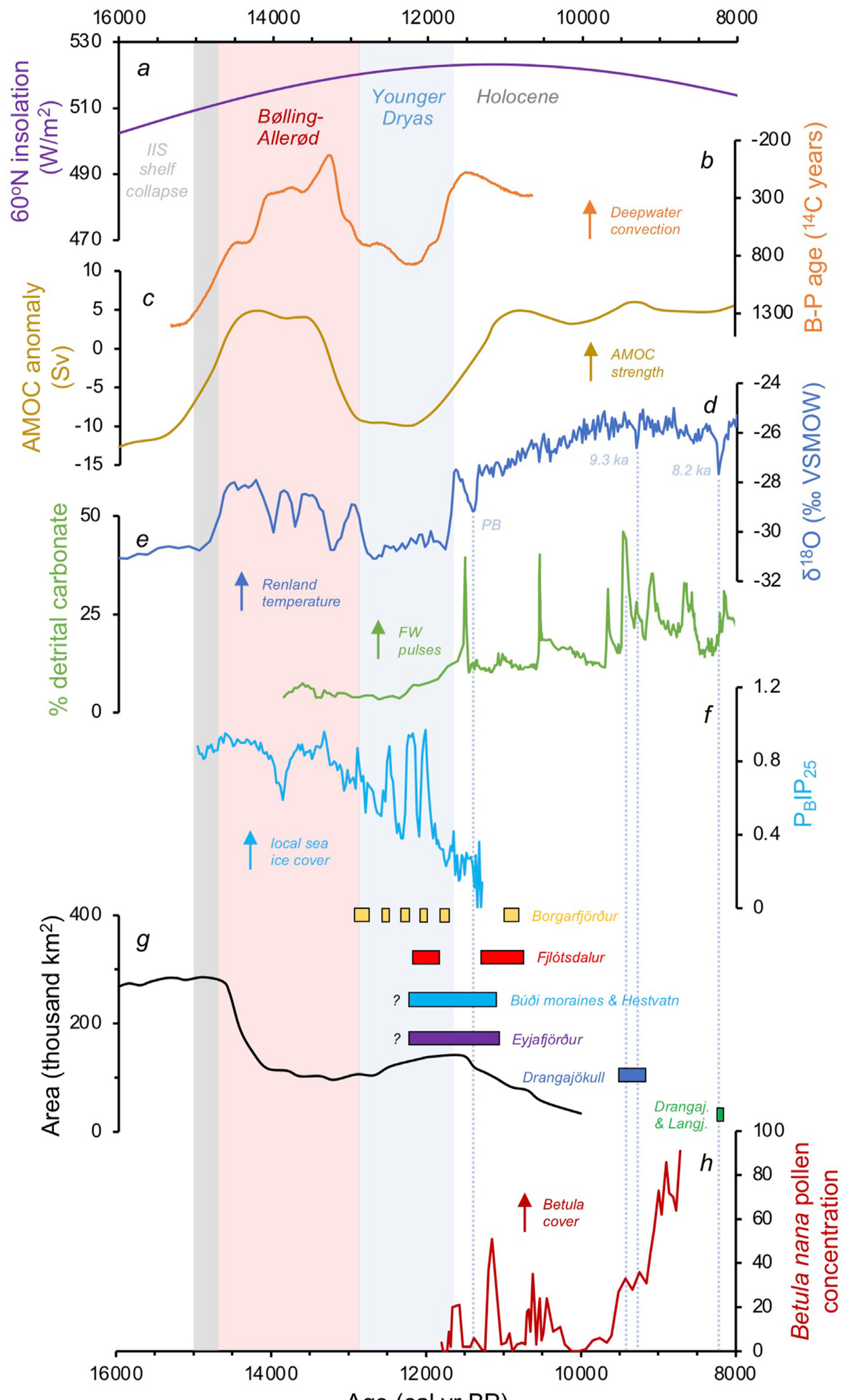


Fig. 5. Regional records of Icelandic deglaciation and forcing mechanisms. a) Northern Hemisphere (60°N) summer insolation (Berger and Loutre, 1991), b) changes in deepwater convection inferred from the offset of benthic-planktic (B–P) foraminifera ^{14}C ages in marine sediment core MD99-2284 (Muschitiello et al., 2019), c) AMOC anomaly reconstructed from the LOVECLIM model (Ritz et al., 2013), d) Renland Ice Cap $\delta^{18}O$ using the most recent Greenland Ice Core Chronology 2005 (GICC05, Vinther et al., 2008), e) detrital carbonate record for freshwater (FW) from Hudson Bay from marine sediment core MD99-2236, Labrador Sea (Jennings et al., 2015), f) P_BIP_{25} biomarker record for seasonal sea ice cover from marine sediment core MD99-2272, north of Iceland (Xiao et al., 2017), g) Late Glacial to Early Holocene glacier history in terms of modeled ice sheet area (Patton et al., 2017) and glacier advances (colored boxes) dated with ^{14}C at Borgarfjörður (Sigfúsdóttir et al., 2018, 2019), Fjlótsdalur (Norðdahl et al., 2019), the Búði moraines and Hestvatn (Geirsdóttir et al., 1997, 2000) and Eyjafjörður (Norðdahl and Pétursson, 2005), and dated with ^{36}Cl CRN and lake sediment records at Drangajökull (Brynjólfsson et al., 2015b; Harning et al., 2018a). No geomorphic evidence exists for the 8.2 ka BP advances of Drangajökull and Langjökull, but they have been simulated with numerical glacier models (Flowers et al., 2008; Anderson et al., 2018). See Fig. 2 for locations of glacier site locations. h) *Betula nana* pollen concentration from the lake Torfdalsvatn (Rundgren, 1995, 1998) using a revised ^{14}C-based age model (see Supporting Information Text S3). Timing of rapid Icelandic Ice Sheet (IIS) collapse marked with gray band (Norðdahl and Ingólfsson, 2015). Bølling-Allerød and Younger Dryas as inferred from Renland $\delta^{18}O$ record (Vinther et al., 2008) and marked with red and blue bands, respectively.

Muschitiello et al., 2019). On the North Iceland Shelf, marine proxy records from foraminifera assemblages illustrate that although Arctic Water dominated at this time, warm Atlantic Water also periodically reached the North Iceland Shelf (Eiríksson et al., 2000; Knudsen et al., 2004) that likely led to high-amplitude and rapid changes in surface waters as reflected in sea ice and open water biomarker records (Fig. 5f, Xiao et al., 2017). Glacial marine deposits and ice-rafted debris (IRD) in raised marine sediment sections in southwest and south Iceland also suggest outlet glaciers from the main IIS advanced into the sea at this time (Geirsdóttir and Eiríksson, 1994; Geirsdóttir et al., 1997, 2000; 2002, 2009; Knudsen et al., 2004). Recent geomorphic evidence and limiting ^{14}C ages further support large-scale readvances of the IIS in the west (Borgarfjörður) and east (Fljótsdalur) during the Younger Dryas (Fig. 5g) (Sigfúsdóttir et al., 2018, 2019; Norðdahl et al., 2019). Collectively, these records suggest that although some coastal regions were likely ice-free, the highly unstable climate variability associated with the Younger Dryas cold event may have limited the colonization of vascular plants, such as *Betula*, until ~12 ka BP (Fig. 5h, Rundgren, 1995; see revised chronology in Supporting Information Text S3).

3.2. Early Holocene (11.7–8.2 ka BP)

Following maximum NH summer insolation at ~11 ka BP, marine sediment proxy records from West and North Iceland Shelf (e.g. sites MD99-2256, MD99-2264 and MD99-2269, Fig. 2) reflect the dominance of warm Atlantic surface waters and restricted drift ice (Fig. 6b–g; Moros et al., 2006; Ólafsdóttir et al., 2010; Kristjánsdóttir et al., 2017; Harning et al., 2020a). The widespread presence of the G10ka Series tephra layers in Icelandic sedimentary records suggests that the IIS was in rapid retreat across the highlands of Iceland by ~10 ka BP (Stötter et al., 1999; Caseldine et al., 2003; Jóhannsdóttir, 2007; Geirsdóttir et al., 2009a; Harning et al., 2018), and the transition from glaciolacustrine to organic sediment in lake records show that Iceland became nearly ice-free by ~9 ka BP (Caseldine et al., 2003; Larsen et al., 2012; Striberger et al., 2012; Harning et al., 2016b, 2018b). Once *Betula* colonized the newly exposed landscape, molecular evidence from modern plants suggests that multiple colonization events followed (Anamthawat-Jónsson, 2011), with wind, sea ice, driftwood, and birds representing the most likely dispersal vectors (Rundgren and Ingólfsson, 1999; Alsos et al., 2016a). Despite general warmth, subsequent episodes of climate variability, such as the Preboreal cooling (Fig. 5), and the deposition of large amounts of tephra from the G10ka Series (e.g. Óladóttir et al., 2020) likely played a role in the postglacial development of Iceland's ecosystem (Rundgren, 1995). The deposition of the thick G10ka Series (>10 cm) disrupted the succession of plant evolution (Hallsdóttir, 1995; Rundgren, 1998; Eddudóttir et al., 2015) and only after a period of resultant landscape instability did *Juniperus* succeed in establishing itself (Hallsdóttir and Caseldine, 2005). As the soil continued to develop in the millennia following deglaciation, pollen and macrofossils records from north Iceland suggest that *Betula* woodland (dominated by *B. pubescens*) was established below 500 m asl by 9.2 ka BP in relatively dry areas (Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005; Wastl et al., 2001; Caseldine et al., 2006; Eddudóttir et al., 2015, 2016) whereas sedges dominated in damp habitats (Caseldine et al., 2006).

Increasing lake diatom productivity (BSi) and relative stable soils (low C/N) interpreted from our composite support generally warm summers until ~8.8 ka BP, before reversals in these proxies reflect a widespread climate deterioration (i.e. reduced lake productivity and increased soil erosion) that persisted until 7.9 ka BP (Geirsdóttir et al., 2009, 2013, 2019; Larsen et al., 2012; Harning et al., 2018a, 2020b). Similar to these environmental proxies, the succession of *Juniper* to *Betula* is also interrupted from ~8.8 to 8.0 ka BP in north Iceland, as recorded by pollen and macrofossils in lake sediments (e.g. Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005; Eddudóttir et al., 2015, 2018). This 8.8 to 7.9 ka BP time window includes the well-known 8.2 ka event (Barber et al., 1999; Alley and Ágústdóttir, 2005; Rohling and Pälike, 2005; Thornalley et al., 2009, 2010) as well as several additional freshwater pulses that all originated from the decaying Laurentide Ice Sheet (Figs. 1, 5e and 6) (Jennings et al., 2015) that drove local oceanographic cooling via a slowdown of the AMOC (e.g. Ólafsdóttir et al., 2010; Quillmann et al., 2012; Moossen et al., 2015). Atmospheric sulfate injection from volcanic eruptions may have also contributed to the prolonged nature of cooling observed in Iceland. The Greenland ice cores sulfate record suggests increased NH volcanic activity beginning at ~8.7 ka BP (Mayewski et al., 1997; Kobashi et al., 2017), which may have been compounded by the Thjórsá fissure eruption at ~8.6 ka BP (Fig. 7h) — the world's largest known Holocene lava flow (Thordarson et al., 2003; Geirsdóttir et al., 2012). A combination of empirical and modeling evidence suggests that periodic readvances of residual ice (or reformation) of Icelandic ice caps occurred ~9.3 and 8.2 ka BP (Flowers et al., 2008; Brynjólfsson et al., 2015a; Anderson et al., 2018; Harning et al., 2018a). Both of these rapid cooling punctuations are matched by regime shifts in the C/N record that indicate transient episodes of enhanced landscape instability and soil erosion superimposed over general warmth (Fig. 7c and d).

3.3. Middle Holocene (8.2–4.2 ka BP)

During the Holocene Thermal Maximum (HTM) ~8 to 6 ka cal BP (Figs. 6 and 7), a recent Holocene lake temperature reconstruction derived from lipid biomarkers quantifies summer warmth up to ~3.2 °C above modern in northwest Iceland (Fig. 7b, Harning et al., 2020b). These temperatures are independently supported by ice cap modeling simulations of Langjökull and Drangajökull tuned to local geologic constraints (3 °C above modern, Flowers et al., 2008; Anderson et al., 2018), and therefore, provide additional support for peak HTM warmth in Iceland. Although earlier work from chironomid-inferred temperature are available (Caseldine et al., 2006; Axford et al., 2007, 2009; Langdon et al., 2010) these records are hampered by a number of variables, such as carbon content of lake sediment (Langdon et al., 2008), soil erosion (Lawson et al., 2007), limited taxonomic resolution (Axford et al., 2009), and poor chronological constraint (Caseldine et al., 2006) that collectively make interpretations difficult. Further qualitative evidence of HTM summer warmth comes from contemporaneous peaks in lake diatom productivity reflected in our BSi composite (Fig. 7c) as well as benthic diatom assemblages from the lakes Hvítárvatn and Lögurinn (Black, 2008; Larsen et al., 2012; Striberger et al., 2012). This prevailing summer warmth was conducive to the development of soils and vegetation that generally prevented the mobilization of terrestrial material into lakes (Caseldine et al., 2006; Larsen et al., 2012; Geirsdóttir et al., 2013; Eddudóttir et al., 2015, 2016; Harning et al., 2018a; Tinganelli et al., 2018) as recorded by relatively low and stable C/N values in our composite (Fig. 7d).

Paleovegetation records from north (Barðalækjartjörn, BARD) and south (Hestvatn, HST) Iceland show that the stable soils of the HTM also coincided with the expansion of *Betula* woodlands (Fig. 7e–f), which are believed to have reached their maximum distribution and elevation (between 400 and 500 m asl) by 7.4 ka BP (Hallsdóttir, 1995; Wastl et al., 2001; Caseldine et al., 2006;

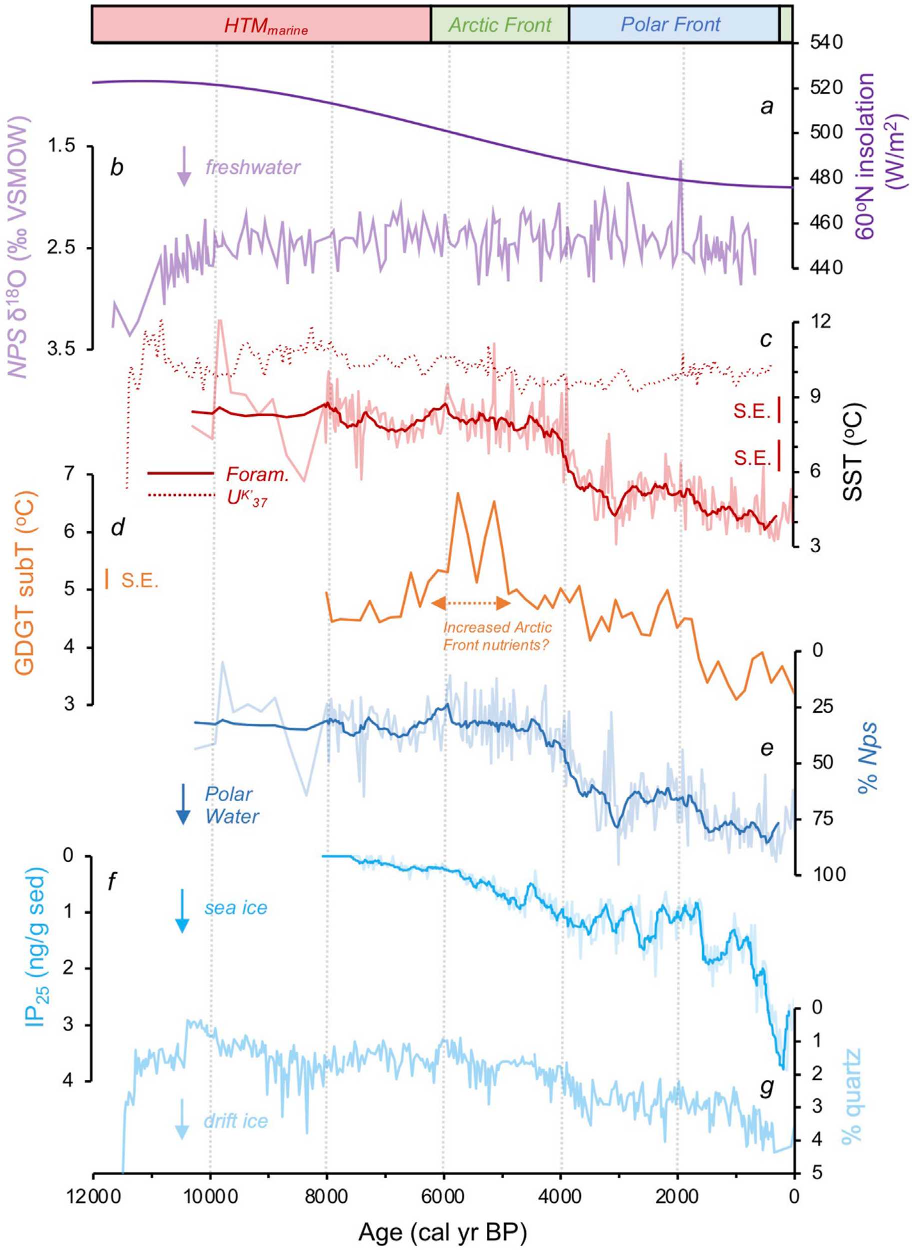


Fig. 6. Select Holocene paleoceanographic records from North Iceland Shelf marine sediment core MD99-2269. a) Northern Hemisphere (60°N) summer insolation (Berger and Loutre, 1991), b) $\delta^{18}O$ of planktic foraminifera *Nps* (Kristjánsdóttir et al., 2017), c) foraminifera assemblage and alkenone $U^{K'}_{37}$ derived SST (Kristjánsdóttir et al., 2017; Harning et al., 2020a), where standard error is 1.3 °C for and 1.0 °C, respectively, d) GDGT-derived subT (Harning et al., 2020a), with a standard error of 0.4 °C (Harning et al., 2019b), e) percent planktic foraminifera *Nps*, where higher values reflect colder Polar Water (Harning et al., 2020a), f) IP_{25}-inferred seasonal sea ice (Cabedo-Sanz et al., 2016), and g) percent quartz record for drift ice (Moros et al., 2006). All records are oriented down for cold. Constraint on the HTM_{marine} after Kristjánsdóttir et al. (2017) and on the presence of Arctic and Polar Fronts after Harning et al. (2020a).

Eddudóttir et al., 2016). Although not covering the Early Holocene period, a *Betula* pollen record from a site south of the glacier Hofsjökull at an altitude of about 600 m asl indicates that birch forests may have existed in the vicinity prior to human settlement (Hallsdóttir, 1995). Analysis of *Betula* pollen grain morphology also suggests the progressive introgression (hybridization) of two species, *B. nana* (dwarf birch) and *B. pubescens* (mountain birch), may have occurred during the HTM as reflected by the increased proportion of non-triporate grains (Fig. 7g, Eddudóttir et al., 2016), which may have been advantageous in Iceland's harsh sub-Arctic environment (Thórsson et al., 2007). Additional peat and lake sediment pollen records from Iceland suggest a similar process of introgression during the Holocene (Karlsdóttir et al., 2009, 2012, 2014), although these records lack the age control needed to assess spatio-temporal variability. When the *Betula* pollen records are compared with quantitative biomarker-based temperature estimates from Skorarvatn (SKR) in northwestern Iceland, notable similarities emerge, such as the synchronous expansion of *Betula* woodland and increasing MSAT at ~8 ka BP and subsequent reduction in woodland cover and MSAT at ~6.5 ka BP (Fig. 7). These similarities highlight the sensitivity of these taxa to heat (length and temperature of growing season) and local climate as described for other high latitude regions (e.g. Myers-Smith et al., 2011).

The environmental deterioration observed in the MSAT and

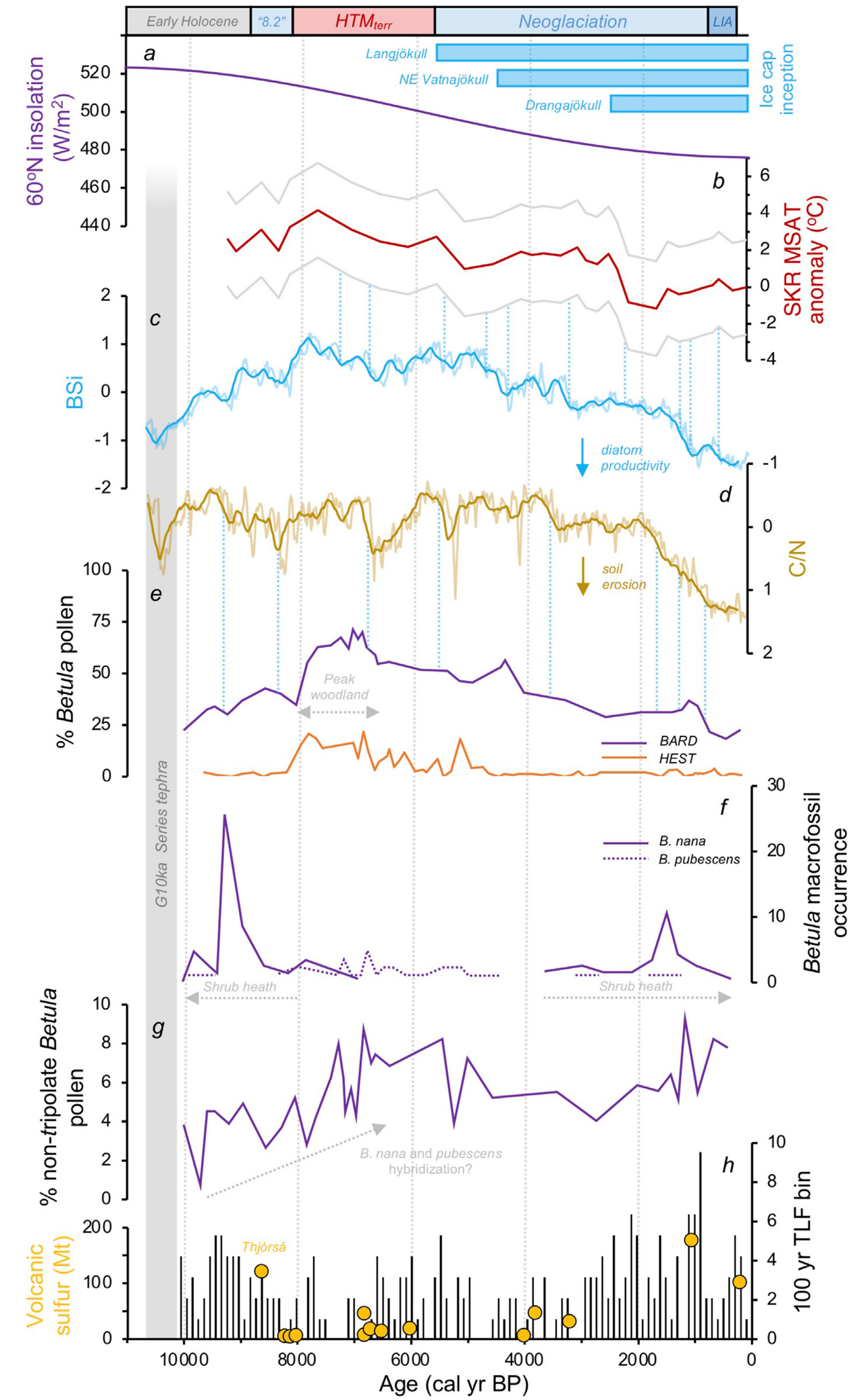


Fig. 7. Holocene evolution of glaciers, lakes and vegetation in Iceland. a) Northern Hemisphere (60ºN) summer insolation (Berger and Loutre, 1991) and the timing of topography-controlled ice cap inception inferred from lake sediments (Larsen et al., 2012; Striberger et al., 2012; Harning et al., 2016a, 2018a; Geirsdóttir et al., 2019), b) absolute MSAT derived from alkenones and brGDGTs from Skorarvatn lake sediment, where gray lines denote the temperature calibration uncertainty (Harning et al., 2020b), c) BSi composite for diatom productivity and qualitative summer temperature where bold line denotes 200-yr smoothing (Geirsdóttir et al., 2019), d) C/N composite for landscape stability where bold line denotes 200-yr smoothing (Geirsdóttir et al., 2019), e) percent *Betula* pollen from lake sediments (BARD and HEST, Eddudóttir et al., 2016; this study), f) *Betula* macrofossil occurrence from Barðalækjartjörn (BARD) (*B. nana and B. pubescens*) (Eddudóttir et al., 2016), g) percent non-tripolate *Betula* pollen from BARD lake sediment (Eddudóttir et al., 2016), and h) 8-lake tephra layer frequency (TLF) record in 100-year bins (black) and volcanic sulfur emissions (Mt) from Icelandic fissure eruptions (Thordarson et al., 2003). The blue dashed vertical lines in panels c and d reflect the regime shifts identified in each respective proxy time series that relate to cooler conditions (i.e. reduced productivity and increased soil erosion, see Fig. 3).

pollen records between 7 and 6 ka is also evident in our composite records (Fig. 7). Whereas as the *Betula* pollen decreases through the Middle Holocene (Fig. 7e), both the higher-resolution BSi and C/N composite records gradually return to their pre-disturbance states around ~6 ka (Fig. 7c–d). Although both decreasing *Betula* woodland and the lower resolution Skorarvatn MSAT record suggest slightly decreasing summer temperatures during this interval, the recovery seen in our composites records highlight the possibility of additional climate forcing(s) as modulators. Common global and regional mechanisms, such as total solar irradiance (e.g. Steinhilber et al., 2009) and oceanographic conditions on the North Iceland Shelf (Fig. 6) are relatively stable during this period, and therefore, unlikely to be contributing factors. However, multiple fissure eruptions from Katla and Veiðivötn-Bárðarbunga volcanic systems are known to have occurred in the centuries preceding this event (Fig. 7h, Thordarson et al., 2003) and our composite TLF record is relatively high at this time. The impacts of these repetitive fissure and/or explosive eruptions may have reduced vegetation cover from tephra fall and/or induced local cooling from sulfur emissions (e.g. Thordarson et al., 1996, 2001). In either or both cases, the local volcanic eruptions stand as a possible mechanism for the observed environmental deterioration.

During the HTM, flow speeds of the North Iceland Irminger Current were at their maximum, importing a considerable volume of warm water into the Nordic Seas (McCave and Andrews, 2019). Flow speeds decreased dramatically after 5.5 ka BP (McCave and Andrews, 2019), coincident with an increase in drift ice and sea ice biomarker data (Moros et al., 2006; Cabedo-Sanz et al., 2016) and decrease in SST and subsurface temperatures on the North Iceland Shelf (Harning et al., 2020a) (Fig. 6). Foraminifera assemblage data also suggest that the surface waters on the North Iceland Shelf were transitioning from Atlantic to Arctic/Polar Water in origin in response to the general reduction in NH summer insolation (Fig. 6, Harning et al., 2020a).

3.4. Late Holocene (4.2 ka BP to present)

Following the continued reduction of summer insolation across the NH and summer temperature in Iceland, local Neoglaciation (i.e. regrowth and/or expansion of the cryosphere) commenced at ~5 ka BP (e.g. Gudmundsson, 1997; Geirsdóttir et al., 2019), with widespread glacier and ice cap expansion occurring at ~4.5–4.0, 3.0, 2.3 and 1.5 ka BP (Fig. 7a–b and 8a, Stötter et al., 1999; Geirsdóttir et al., 2009a, 2019; Larsen et al., 2011; Striberger et al., 2012; Harning et al., 2016b, 2018a; Fernández-Fernández et al., 2019). This summertime cooling is further manifested in the recurrent regime shifts identified in our composite BSi and C/N records, which support stepwise reductions in lake diatom productivity and increases in landscape instability (Fig. 7c–d). In addition, pollen and macrofossil records suggest that *Betula* woodlands in Iceland were in steady decline (or already limited in the case of Hestvatn), becoming gradually replaced by dwarf shrub heath dominated by *Betula nana*, *Empetrum nigrum* and *Vaccinium*, as well as Cyperaceae grasses (Fig. 7e, Eddudóttir et al., 2015, 2016). The fact that lake productivity and soil stability never fully recovered to their prior states following stepwise shifts highlights the vulnerability and poor resilience of the Icelandic ecosystem to climate changes during the Late Holocene (e.g. Geirsdóttir et al., 2013). Although the gradual decline in summer insolation and summer temperature progressively lowered the glacier equilibrium line altitude (ELA, Anderson et al., 2019), the episodic advances of Icelandic glaciers and stepwise behavior of composite proxy records during the Late Holocene suggests that local to regional mechanisms and feedbacks modulated the primary insolation forcing. Variations in the strength of AMOC, weakening of the northward heat transport, and/or increasing influence of Polar waters (and concomitant advection of sea ice) influence all our locations and have been related to past cooling events (Trouet et al., 2009, 2012; Lehner et al., 2013; Cabedo-Sanz et al., 2016; Moreno-Chamarro et al., 2017; Zhong et al., 2018; Harning et al., 2019b).

The most pronounced changes in our composite records begin ~1.5 ka BP (i.e. 6th Century CE). From ~500 CE to 900 CE and again from ~1250 CE to 1920 CE, we observe steady decreasing lake productivity and relative summer temperatures (BSi, Fig. 8c) with a corresponding and persistent shift toward increased landscape destabilization and soil erosion (C/N, Fig. 8d). We presume that the depletion of stable soil cover was also related to the continued reduction of *Betula* woodland observed in a composite of 25 records from Iceland (Fig. 8e, Streeter et al., 2015), possibly as a positive feedback loop between the two processes. Quasi-persistent reductions in summertime temperatures after ~500 CE are further supported by enhanced glacial erosion from advancing glaciers, as reflected in Langjökull and Drangajökull proglacial lake sediment records (Fig. 8a, Larsen et al., 2011, 2013; Harning et al., 2016a, 2018a, 2020b) and moraines that document glacier advance/still-stands on Tröllaskagi in north Iceland (Stötter et al., 1999; Fernández-Fernández et al., 2019), as well as a ~0.5 °C reduction in summer temperature simulated in our CESM1.1 model simulation for the North Atlantic (Fig. 8b, Zhong et al., 2018). The timing of these intervals coincides with the well documented periods of climate change commonly known as the Dark Ages Cold Period (DACP), Medieval warmth and the Little Ice Age (LIA), which have previously been associated with changes in solar activity (Shindell et al., 2001; Steinhilber et al., 2009) and/or explosive volcanism (Fig. 8j, Gao et al., 2008; Zhong et al., 2010; Miller et al., 2012; Sigl et al., 2015; Büntgen et al., 2016; Slawinska and Robock, 2018).

The shift toward cooler conditions ~1.5 ka BP is consistent with historical accounts of crop failures, famines, and dry cold fogs in Europe and Asia in the 530s CE (e.g. Stothers and Rampino, 1983; Rampino et al., 1988; Büntgen et al., 2016). The episodes of cooling can also be linked to evidence from the North Iceland Shelf indicating dominance of cooler Polar Waters (Fig. 8f, Sicre et al., 2011; Wanamaker et al., 2012; Jiang et al., 2015; Reynolds et al., 2016; Harning et al., 2020a) and greater advection of sea ice (Fig. 8g, Moros et al., 2006; Massé et al., 2008; Andrews et al., 2009; Cabedo-Sanz et al., 2016; Harning et al., 2019) resulting from widespread changes in North Atlantic circulation (Fig. 8i, Moffa-Sanchez and Hall, 2017; Moffa-Sanchez et al., 2019). Although Medieval warmth (~900–1200 CE) is observed in regional CESM1.1 summer temperatures (Fig. 8b), higher SSTs in some Icelandic fjords (e.g. Moossen et al., 2015) and North Iceland Shelf records (e.g. Sicre et al., 2011) as well as recessions of both Langjökull and Drangajökull's margins (Fig. 8a, Larsen et al., 2011; Harning et al., 2016a), our composites do not indicate comparable warmth. Instead, the regime shifts identified in the overall declining BSi and increasing C/N composite records suggest that the Late Holocene cooling that culminated in the LIA occurred in steps, and that the background climate prevented these variables from returning to their pre-disturbance states. These observations are consistent with a second phase of persistent summer cooling in CESM1.1 after 1150 CE (Fig. 8b). The composite proxies suggest the coolest climate of last 10 ka occurred in the late 1800s CE when Langjökull (Flowers et al., 2007; Larsen et al., 2011, 2015), Drangajökull (Harning et al., 2016a; Anderson et al., 2018; Brynjólfsson et al., 2015b) and the southern outlets of Vatnajökull (Hannesdóttir et al., 2015) reached their maximum glacier extents. At this time CESM1.1 simulates summer temperatures ~1 °C lower than at the start of the experiment (Fig. 8b, Zhong et al., 2018).

In addition to natural climate changes and volcanism, the arrival of human settlers reflects another variable that left a lasting mark on the Icelandic environment. According to historical accounts written in Iceland in the 12th and 13th Centuries CE and archeological research, Iceland was settled ~870 CE (*Landnámabók*, i.e. The book of Settlement). In many cases, the timing of settlement is based on the occurrence of the Landnám tephra layer (a.k.a. Settlement or VÖ tephra layer) below archeological remains, which has been dated in a Greenland ice core to 871 ± 2 CE (Grönvold et al., 1995) and recently revised to 877 ± 1 CE (Schmid et al., 2017). Although at this time Iceland was described as having forests extending from the shoreline to the mountains (e.g. *Landnámabók,* i.e The book of Settlement; Smith, 1995, i.e The book of Settlement; Vésteinsson, 1998, 2000), contemporary descriptions of the state and extent of birch woodland at the time of settlement are not available. Several estimates based on historical records, pollen analyses, old place names and current distribution of woodlands (Hallsdóttir, 1995; Kristinsson, 1995) have been made regarding the vegetation cover at the time of settlement, and range from 8% (Ólafsdóttir, 2001) to almost 40% woodland cover (Bjarnason, 1974). To create pastures for farming, it is assumed that the settlers cut and burned some of the existing woodlands and used the wood as building material, fodder, and fuel (e.g. Smith, 1995 and references therein, Tanner et al., 2015). Presumably little action was taken to replenish the clear-cut woodlands, and with the introduction of domestic livestock, natural regeneration was inhibited (Arnalds, 1987). It is, however, noteworthy that the C/N composite record indicates a relatively stable condition between 870 and 940 CE. Thus, the Landnám tephra layer does not seem to have accelerated the rate of C/N in the composites, but the 940s CE increase in C/N does coincide with the Eldgjá eruption, which lasted from 934 to 941 CE (Thordarson et al., 2001). With the subsequent occupation and population expansion of humans and livestock in Iceland, birch woodlands continued to be reduced compromising the soil protection before reaching their postglacial minimum at the beginning of 1900s CE (~1% of total land area, Aradóttir and Eysteinsson, 2005).

4. Resolving the evolution of vegetation and soil erosion across Iceland

4.1. When did plants colonize Iceland following deglaciation?

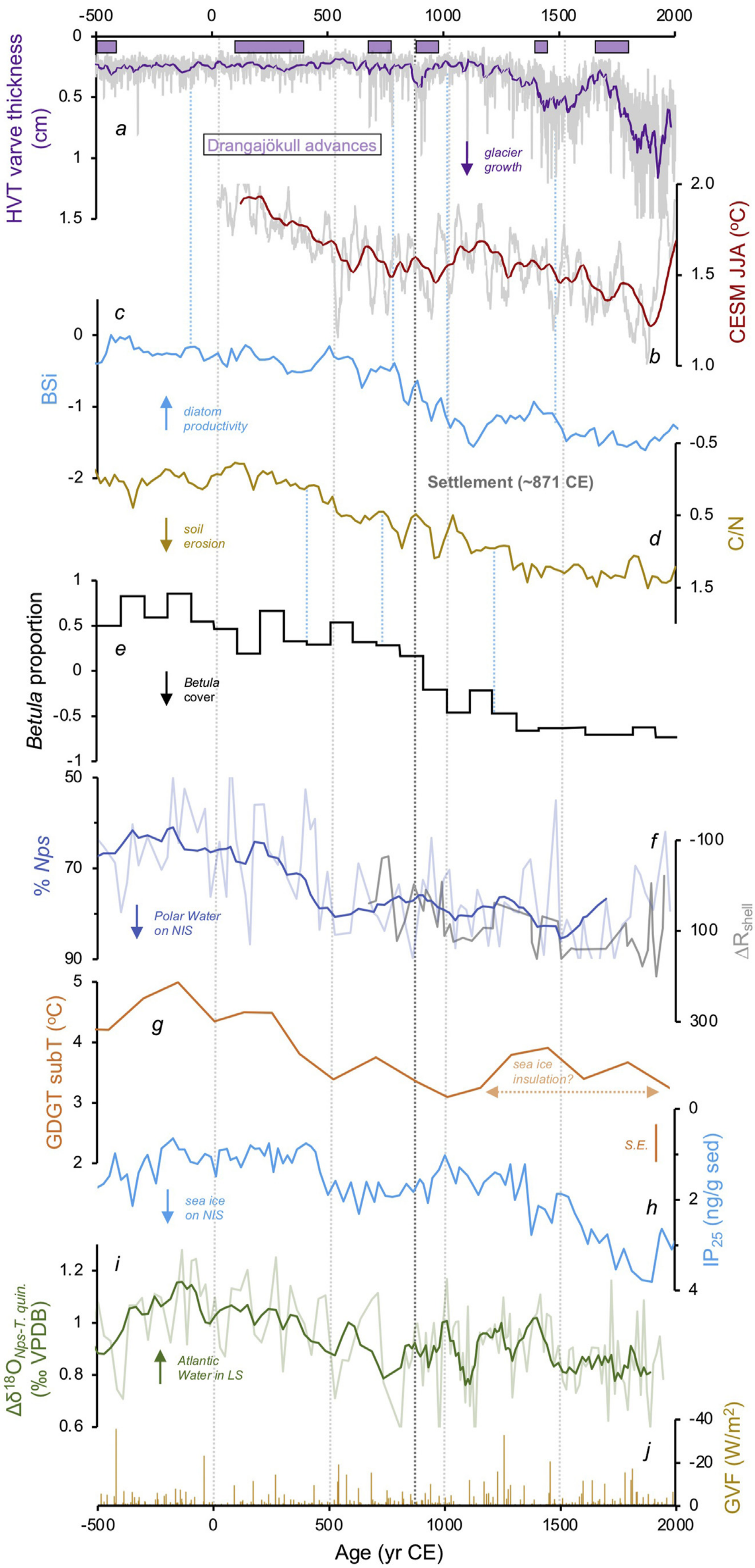
Securely constraining the timing of plant colonization on Iceland is important as it allows us to understand the role of shrub cover in both the development and stability of soils in the Early Holocene postglacial environment. However, as of yet, this information is lacking. The oldest dated Icelandic lake sediment comes from Torfdalsvatn (TORF, Fig. 2) and shows that a variety of pollen grains from grasses, herbs and woody taxa were present by ~12 ka BP, although of low concentrations (Björck et al., 1992; Rundgren, 1995, see Supporting Information Text S3) and can be obscured by long-distant transport from southern sources (Birks and Birks, 2000, 2015; Birks, 2003; Williams et al., 2004; Caseldine et al., 2006). Given that several other Early Holocene records from Iceland (>10 ka BP) also preserve overall low pollen concentrations, in addition to "exotic" tree pollen (i.e. *Pinus*, *Quercus, Corylus, Alnus,* and *Ulmus*) that have never been reported as macrofossils from Iceland (Caseldine et al., 2006; Eddudóttir et al., 2015), the first appearance of pollen does not necessarily reflect local colonization. Icelandic plant macrofossils records offer higher taxonomic resolution and a more local signal over pollen, allowing for more secure interpretations of past plant presence and absence (Fig. 7f, Eddudóttir et al., 2016). Although macrofossil add valuable information in paleoecological studies (Birks and Birks, 2000), their sample size is generally low and rarely captures the full range of vegetation (Anderson-Carpenter et al., 2011; Alsos et al., 2016b).

Recent analytical advances in sedimentary ancient DNA (*sed*aDNA) preserved in lake sediment provide new and improved paleoecological information (Pedersen et al., 2013; Parducci et al., 2017; Alsos et al., 2018). Updated plant reference libraries (Sønstebø et al., 2010; Willerslev et al., 2014) enable *sed*aDNA to provide more taxa than macrofossils (Alsos et al., 2016b) or pollen (Niemeyer et al., 2017; Alsos et al., 2018; Edwards et al., 2018). Moreover, the strong match between lake sediment DNA and catchment vegetation surveys suggests *sed*aDNA has a local origin (Niemeyer et al., 2017; Sjögren et al., 2017; Alsos et al., 2018; Edwards et al., 2018) compared to foreign pollen grains in Iceland whose sources are 1000s of km away. The preservation of *sed*aDNA fragments is also higher in cool, high-latitude settings where preservation is naturally improved relative to warmer, mid-latitude sites (Parducci et al., 2017). As such, recent records from elsewhere in the high-latitudes, such as Alaska, Arctic Canada, Svalbard and Norway, have used *sed*aDNA to successfully address similar research questions related to plant colonization and succession (Pedersen et al., 2016; Alsos et al., 2016b, 2020; Crump et al., 2019; Volstad et al., 2020). As the field continues to expand in terms of analytical efficiency and taxonomic resolution, the community will have a growing opportunity to test and apply this novel molecular approach in Icelandic lake sediments to better constrain the colonization and early evolution of plants on Iceland.

4.2. Does HTM warmth lead to more substantial woodland cover and stable landscape?

Quantitative temperature reconstructions derived from lake sediment proxies and glacier modeling simulations place peak HTM summer warmth at ~3–4 °C above modern in Iceland (Flowers et al., 2008; Anderson et al., 2018; Harning et al., 2020b). Our evaluation of high-resolution and well-dated pollen records from Barðalækjartjörn (BARD) (Eddudóttir et al., 2016) and Hestvatn (HST) suggest that *Betula* woodlands closely followed the trends in local summer temperature (Fig. 7) and were likely at their maximum distribution, both in extent and altitude, at this time. However, similar to the inherent limitations of pinpointing the timing of plant colonization in Iceland's postglacial landscape with pollen, it is also difficult to draw firm conclusions about the extent of *Betula* woodland due to pollen's efficient aeolian-dispersal. Kristinsson (1995) assumes that regions above 500–550 m asl were above tree-line, and that regions between 300 and 500 m asl often lacked woodland as well. It is also assumed *Betula* woodlands were not favored towards stormy coastlines (e.g. Reykjanes and Melrakkaslétta peninsulas) due to increased wind speeds and salt aerosols (e.g. Jónsson, 2002; Holtmeier, 2003), along steep slopes with loose material or periodically flooded areas along glacial rivers (Kristinsson, 1995), as well as in the harsh environments along Iceland's volcanic zones due to frequent volcanic eruptions and ash deposition. It is also uncertain whether *Betula*, which today is the only indigenous tree that forms woodland in Iceland, remained the sole woodland taxon throughout the Holocene. Pollen of rowan (*Sorbus aucuparia*) has been found in Icelandic sediments dating back 6 to 5 ka BP, but its presence is discontinuous and seldom reaches 1% (Hallsdóttir, 1995). The rare aspen (*Populus tremula*) is also a minor component of woodland remnants in Iceland today, but has not yet been found in pollen records (Hallsdóttir, 1995).

In this light, *sed*aDNA recovered from well-dated lake sediment records in Iceland offers improved opportunities to contribute to our understanding of the timing, range and composition of


HVT varve thickness (cm)
Drangajökull advances
glacier growth
CESM JJA (ºC)
BSi
diatom productivity
Settlement (~871 CE)
soil erosion
C/N
Betula proportion
Betula cover
% Nps
Polar Water on NIS
ΔR shell
GDGT subT (ºC)
sea ice insulation?
S.E.
sea ice on NIS
IP25 (ng/g sed)
Δδ18O Nps-T. quin. (‰ VPDB)
Atlantic Water in LS
GVF (W/m2)
Age (yr CE)

woodland cover in Iceland during the HTM and subsequent millennia. Recent analytical advances in the field of biogeochemistry, particularly lipid biomarkers, also provide improved toolsets to quantify the corresponding evolution of temperature that would, among other environmental variables, be responsible for changes in their distribution (e.g. Castañeda and Schouten, 2011; Schouten et al., 2013). However, before moving forward with these studies in Iceland, local calibrations are needed. A number of recent studies have demonstrated the importance of developing local calibrations to reduce uncertainty and capture the nuances of local environments in biomarker-derived temperature estimates, such as for GDGTs (e.g. Russell et al., 2018; Harning et al., 2019b; Feng et al., 2019) and alkenones (e.g. D'Andrea et al., 2016; Longo et al., 2016). Moreover, studies such as these will also reveal the impact that other environmental variables (e.g. pH, dissolved oxygen, nutrients, etc.) have on the lipid biomarker distributions that may confound temperature derivations.

4.3. Do prior cold events and periods of tephra deposition compromise vegetation cover and increase soil erosion?

Landscape destabilization is often triggered by local volcanism, although the persistence of landscape instability likely reflects the overarching state of summer climate. During the first 8 ka of our composite C/N record, we observe short-term pulse-like landscape instabilities, with more stable conditions in between (Fig. 3c). The first of these pulses occurred during the Early Holocene following deposition of the G10ka Series tephra when NH summer insolation was already at its peak. In those cases where lacustrine sediment has been found below the G10ka Series tephra, high autochthonous diatom productivity demonstrates that strong summer insolation allowed lake-based biota to become established immediately following catchment deglaciation and before the time of the G10ka tephra series deposition (e.g. Harning et al., 2016b, 2018a; Gunnarson, 2017). The composite thickness of multiple tephra layers within the G10ka tephra series had a drastic impact on vegetational succession in Iceland for several decades to centuries, with environmental instability sustained by sandstorms, soil erosion and mudflows (Hallsdóttir and Caseldine, 2005). However, like our C/N composite, pollen records from north Iceland imply that despite the ecosystem retrogression, the vegetation recovered to a state similar to before the tephra deposition within ~100 years (Rundgren, 1998; Hallsdóttir and Caseldine, 2005; Eddudóttir et al., 2015).

Similar to the timing of the G10ka tephra series deposition, several other episodes of landscape disturbance occurred during the warmer than present Early Holocene when soil had been developing for several millennia. The multiple short-term fluctuations between 9.3 and 8.2 ka BP indicated by the regime shift analyses of our BSi and C/N composites coincide with cooling episodes recognized in northern North Atlantic marine proxies and sea ice records (e.g. Ólafsdóttir et al., 2010; Quillmann et al., 2012; Moossen et al., 2015; Jennings et al., 2015). Studies indicate that the 8.2 ka cool event may have lowered MSAT from between 1 and 3 °C over a couple of centuries across large parts of the NH (Matero et al., 2017). In Iceland, Harning et al. (2020b) show similar relatively lower MSAT between 9.2 and 8.1 ka BP, ranging from ~2 °C above modern to 3.2 °C above modern after the event. The development of *Betula* woodland, which had been expanding in North Iceland, suffered a setback due to the transient episodes of cooling, particularly between ~8.8 and 8.0 ka BP, but recovered relatively quickly thereafter (Hallsdóttir, 1995; Hallsdóttir and Caseldine, 2005; Eddudóttir et al., 2015, 2018), similar to the recovery of soil stability as indicated in our C/N record (Fig. 7). The landscape disturbance observed around 6.7 ka BP in our C/N record started abruptly but tapers off during the following 500 years, thereby returning to the pre-disturbance states where organic matter is dominated by aquatic sources (Fig. 7). It is suggested here that the resulting landscape instability may relate to local cooling induced by multiple local fissure eruptions from Katla and Veiðivötn-Bárðarbunga volcanic systems that are known to have occurred in the centuries preceding this time of disruption.

The next major regime shift identified in the proxy composites starts at 5.5 ka BP with a shift toward less aquatic productivity related to increasingly cooler summers throughout the Late Holocene. Consistent with an insolation forcing, the brGDGT MSAT from northwest Iceland document a first-order cooling over this time interval (Fig. 7b). Although several abrupt shifts identified in the lake proxy composite may be related to local explosive volcanism with tephra deposition influencing catchment stability, the lack of a full recovery to pre-existing values after each perturbation suggests generally cooler summer temperatures of the Late Holocene led to decreased *Betula* woodland cover observed in pollen records (Fig. 7e). Furthermore, evidence indicates increased periglacial activity, and glacier growth in the highlands of Iceland at this time (e.g. Larsen et al., 2011, 2012; Striberger et al., 2012). This could also indicate that a certain threshold was reached around 5.5 ka BP, which resulted in a change in state for the Icelandic landscape compared to the HTM.

Principal component analyses conducted using high-resolution multi-proxy records before and after significant Holocene tephra fall events (Hekla T, 6.1 ka BP; Hekla 4, 4.2 ka BP; Katla N, 3.5 ka BP; and Hekla 3, 3.0 ka BP) were used to compare ecosystem responses between four of the seven lakes used in our composites (Christensen, 2013). In all cases, the tephra ushered in irreversible changes to the landscape starting at ~5.5 ka BP and intensified after Hekla 4 (~4.2 ka BP). The background climate state at the time of tephra fall influenced the length (decades to centuries) and magnitude of ecosystem perturbations, with more severe responses in the cooler Late Holocene (Christensen, 2013). Rhyolitic tephra layers (i.e. Hekla 4 and Hekla 3), which are normally thicker than basaltic tephra layers, are most disruptive to the landscape while basaltic tephra (i.e. Hekla T and Katla N) sometimes appear to improve lake and catchment productivity (Christensen, 2013). Furthermore, rhyolitic tephra deposition on relatively steep slopes and with thin soils during episodes of decreasing summer temperatures have the highest probability of producing sustained transitions into less ecologically productive states. Smaller lakes

Fig. 8. Late Holocene paleoenvironmental records from Iceland and the North Atlantic. a) glacier advance records from Langjökull (annual varve thickness, Larsen et al., 2011) and Drangajökull (threshold lake sediment records and dead vegetation, Harning et al., 2016a, 2018a), b) CESM JJA transient simulation temperatures over the North Atlantic where red line denotes 100-yr smoothing (Zhong et al., 2018), c) BSi composite for diatom productivity (Geirsdóttir et al., 2019), d) C/N composite for landscape stability (Geirsdóttir et al., 2019), e) *Betula* proportion composite from 25 lake and mire sites in 100-yr bins (Streeter et al., 2015), f) NIS Polar Water mass inferred from planktic foraminifera *Nps* (Harning et al., 2020a) and ^{14}C reservoir offset (ΔR_{shell}) from an absolutely-dated *Arctica islandica* shell record (gray, Wanamaker et al., 2012), g) GDGT subT record from MD99-2269 on the NIS (Harning et al., 2020a) using the local Icelandic calibration (S.E. ± 0.4 °C, Harning et al., 2019b), h) IP_{25} seasonal sea ice record from MD99-2269 (Cabedo-Sanz et al., 2016), i) difference in the δ^{18}O of *Nps* and *T. quinqueloba* from RAPiD-35-COM as an indicator of the relative presence of Atlantic waters in the Labrador Sea (LS, Moffa-Sánchez and Hall, 2017), j) radiative global volcanic forcing recorded in the polar ice sheets (GVF, Sigl et al., 2015). All records are oriented down for cold. The blue dashed vertical lines in panels c and d reflect the regime shifts identified in each respective proxy time series that relate to cooler conditions (i.e. reduced productivity and increased soil erosion, see Fig. 3). The Settlement tephra (i.e. acknowledged timing of human settlement) marked with vertical gray dashed line.

with greater background primary productivity and relatively thick, well-vegetated soils mantling low-relief catchments were more resilient and able to return to pre-eruption states within 100 years (Christensen, 2013).

For the Hekla 4 eruption, Eddudóttir et al. (2017) suggested that lowland areas with more substantial *Betula* woodland cover were more resilient to tephra fall compared to higher elevations sites that were already at the climatic/ecological limit for *Betula*. For the lowland lake, increased flux of minerogenic material is recorded following Hekla 4, in contrast to negligible changes in the pollen record (Eddudóttir et al., 2015, 2017). Geirsdóttir et al. (2019) discuss the potential regional climate and temperature changes induced by the Hekla 4 eruption pointing out that even though the great volume (~13.3 km^3) of fine to very fine ash emitted may have been capable of a significant impact on a local to regional scale lasting from weeks to 3 years, its impact on atmospheric properties and processes would have been negligible due to the low SO_2 content. Although it produced an almost equally voluminous tephra, the Hekla 3 tephra was notably coarser grained than Hekla 4 tephra (Stevenson et al., 2015) with perhaps less capability to impact the atmosphere on a regional scale. In any case, these studies collectively emphasise the impact of tephra fall on soil and vegetation archives and underscore the importance of vegetation cover in the event of heavy tephra fall.

For the Hekla 3 eruption, high-resolution proxy data from the lake Hvítárvatn in the highlands of Iceland (419 m asl) reflect an abrupt and prolonged (~100 year) perturbation in the wake of tephra deposition (Larsen et al., 2011). The most probable mechanism responsible for the sudden increase in terrestrial organic matter following the deposition of the tephra is vegetation damage due to abrasion and increased soil erosion within the catchment (Larsen et al., 2011; Christensen, 2013). However, unlike the Hekla 4 tephra disturbances, the composite does not show a discrete perturbation in C/N values, but instead a step shift in the background state of landscape instability lasting until ~1.5 ka BP (Fig. 7). At this time, robust woody vegetation cover that would have supported soil stability was becoming gradually reduced as a result of Late Holocene cooling (Fig. 7e, Eddudóttir et al., 2016, 2020), rendering the landscape more susceptible to perturbations in the regional climate, such as increased advection of Arctic/Waters and sea ice (Fig. 8). As the vegetation cover was reduced, the landscape also became less resilient to periods of increased Icelandic tephra deposition observed in our composite TLF record (Fig. 7h).

This reduced resilience to subsequent and continuing cooling may explain the turning point in the proxy composites at ~1.5 ka BP (~500 CE, Fig. 8d), i.e. from event-like soil erosion to irreversible and persistent soil erosion. Recent reconstructions over the past two millennia based on tree-ring chronologies (Büntgen et al., 2016) suggest an unprecedented, long-lasting and spatially synchronized cooling following a cluster of large volcanic eruptions in 536, 540 and 547 CE (Sigl et al., 2015), possibly sustained by ocean and sea-ice feedbacks, as well as solar minima (Steinhilber et al., 2009; Miller et al., 2012; McGregor et al., 2015). In addition, a parallel increase in the amount of cold Arctic/Polar Water and sea ice off North Iceland (Fig. 8f–h, Cabedo-Sanz et al., 2016; Harning et al., 2020a) suggests oceanographic cooling could be a leading, or at least complementary, factor. Similar explanations have been given for the subsequent Little Ice Age cooling, which started between 1200 and 1300 CE, culminating ca 1870 in Iceland and likely helped sustain the already severe soil erosion across Iceland.

Our evaluation of composite lake sediment proxies for soil erosion suggests that episodic soil erosional events that return to pre-disturbance states are concentrated during times of relative warmth whereas periods of soil erosion that cannot rebound to that pre-disturbance state occur during relatively cool periods of the Holocene. Expanding the number of studied lake sites throughout Iceland across the variable elevations and ecosystems that exist will undoubtedly contribute to better understanding this pattern of Holocene soil erosion that we observe. In this regard, there is also opportunity to apply certain analytical techniques that can refine organic matter source to lake sediment and more diagnostically trace contributions of soil input. Recent work from Iceland shows that brGDGT distributions derived from soil in the lake catchment differ from those biosynthesized in the lake (Harning et al., 2020b), similar to evidence from regions elsewhere around the globe (e.g. Naeher et al., 2014; Martin et al., 2019). Similar promise exists in studying the chain length distribution of *n*-alkane and *n*-alkanoic acids produced by vegetation (e.g. Ficken et al., 2000; Gao et al., 2011). However, before downcore application of these proxy toolsets, it is imperative to catalogue how both modern soil and plants are represented in these parameters (e.g. Wang and Wooller, 2006). Generating local catchment vegetation records from *sed*aDNA will also allow the community to better characterize the local impacts of tephra fall and climate change on ecosystem structure and better assess its resilience to these processes under different background climate states.

4.4. Is it possible to deconvolve the role of climate, volcanism and human activity in Late Holocene soil erosion?

Previous studies have inferred *a priori* that soil erosion was initiated by the settlement of Iceland, as a result of overgrazing and deforestation (e.g. Thórarinsson, 1944, 1961; Dugmore and Buckland, 1991; Dugmore and Erskine, 1994; Hallsdóttir, 1995), with climatic and volcanic forces also contributing at a secondary level (Thórarinsson, 1961; Gerrard, 1991). While not disagreeing that settlement resulted in long-lasting impacts to the Icelandic landscape (including soil erosion), modeling and empirical evidence suggests that vegetation cover, particularly that of woody vegetation that support soil stability, was already in steady decline at this time (e.g. Ólafsdóttir et al., 2001; Streeter et al., 2015). This progressive reduction in vegetation cover provides a mechanism by which significant pre-settlement soil erosion could occur, and decreasing summer temperatures, local oceanographic cooling and increased tephra layer deposition provide feasible forcings. As reviewed above, our composite records suggest event-dominated landscape instability and soil erosion from the Middle to Late Holocene likely related to large volcanic eruptions during orbitally-forced high NH summer temperatures (Fig. 7). However, a certain threshold was reached ~5 ka BP following reduced NH summer insolation resulting in a more vulnerable environment to explosive tephra producing volcanism, and again around ~500 CE, several centuries before the acknowledged settlement of Iceland, when the event dominated erosional activity change to increased and irreversible soil erosion (Fig. 8).

Although the majority of the earliest archeological sites are dated to the latter part of the 9th century and the 10th century, other sources suggest Iceland may have been inhabited earlier, at least seasonally (e.g. Einarsson, 2015; Einarsson, 2017, Einarsson, 2017). Early Icelandic sagas (*Íslendingabók,* i.e, The book of Icelanders) suggest that Papar (Irish Monks) may have been living in parts of southeastern Iceland (the island of Papey), although definitive archeological evidence is lacking (Eldjárn, 1989). Additional indications for an earlier period of settlement are turf walls found below the Landnám tephra within Reykjavík and on Vestmannaeyjar, islands off the south coast, where excavations revealed burnt peat and carbonized barley grains (e.g. Batt et al., 2015). As barley is not indigenous to Iceland, settlers must have brought it in.

The turf walls show that people resided in Iceland before the Landnám tephra was deposited. However, there are no secure dates that demonstrate whether settlement took place immediately or many decades before the eruption responsible for the deposition of the Landnám tephra layer (Vésteinsson and McGovern, 2012). Consequently, the actual timing of initial settlement remains uncertain, leaving the question open as to whether the changes we observe in the soil record at ~500 CE correspond to earlier human arrival or not. What is certain though is that some human settlements were established immediately after 870 AD, and most habitable land was occupied in the subsequent centuries.

Deconvolving the relative roles of climate, volcanism and human activity in soil erosion of the last two millennia remains a challenge but can be better addressed with new molecular approaches. In addition to proxies such as carbonized barley grains (Batt et al., 2015) and potentially coprophilous fungal spores (however, also produced by birds, Eddudóttir et al., 2015, 2020), diagnostic biomarkers exist that can record human activity and its effect on the local environment. Examples include fecal sterols of omnivores that differ from plant sterols due to microbially-mediated degradation pathways within the intestinal tracts of higher mammals (e.g. Bull et al., 2002; Tyagi et al., 2007), and bile acids that may be capable of distinguishing whether the fecal material originates from ruminants or human sources (deoxycholic vs lithocholic acid, Bull et al., 2002). Fire biomarkers, such as polycyclic aromatic hydrocarbons (PAHs) formed during the incomplete combustion of organic material (e.g. Simoneit, 2002; Lima et al., 2005), may also be able to complement fecal sterols and bile acids, especially given that their short atmospheric residence time (hours to days) means they record local burning events (Lammel et al., 2009; Denis et al., 2012). Recent research has highlighted that various combinations of these molecular proxies can effectively trace the timing of human arrival in lacustrine settings (e.g. D'Anjou et al., 2012; Musa Bandowe et al., 2014; Argiriadis et al., 2018; Vachula et al., 2019; Sear et al., 2020), and therefore, hold promise for application in Iceland as well. Once constrained, pairing these records with independent biomarker and DNA-based reconstructions of climate and vegetation change may provide the necessary tools to deconvolve the relative roles of climate, volcanism and human activity in soil erosion in Iceland during the last two millennia.

5. Conclusions

In this review, we discuss the impact of climate, vegetation, volcanism and human settlement on Iceland's Holocene landscape as interpreted from proxies preserved in high resolution and well-dated lake sediment records. Our synthesis suggests that landscapes that experienced episodes of soil erosion during times of relative warmth (Early to Middle Holocene) returned to pre-disturbance states, whereas periods of soil erosion that occurred during relatively cool periods of the Late Holocene did not rebound to their pre-disturbance state. Most of the soil erosion episodes that occurred during times of relative warmth are likely related to large fissure and/or explosive volcanic eruptions from Iceland. A threshold reached around 5.5 ka BP during rapidly declining NH summer insolation, resulted in a state change for the Icelandic landscape compared to the HTM, with reduced resilience to disturbances. As Late Holocene vegetation cover was progressively reduced by decreasing summer insolation, local oceanographic cooling, and increased tephra layer deposition, widespread and irreversible soil erosion appears to have begun before human settlement. With the subsequent occupation and population expansion of humans and livestock in Iceland, woodland clearance and grazing continued to compromise the soil protection that continues today.

Although considerable progress has been made in the development of high-resolution and well-dated lake sediment records in Iceland, this review brought forth several outstanding questions that cannot be addressed with classic toolsets. These realizations motivate us to not only continue working with more traditional qualitative proxies, but to also take advantage of emerging analytical techniques to quantify past rates of environmental change we detail here. Among these new toolsets are *sed*aDNA that can more accurately address past changes in local vegetation cover, and lipid biomarkers that can quantify paleotemperature as well as home in on past organic matter source changes related to soil erosion. Before downcore application in lake sediment records, we stress that local calibrations for the given proxy should be developed. The combination of these new paleoclimate approaches with training sets that inform how the proxies behave in the local Icelandic environment will better position the community to deconvolve the impacts of climate, volcanism and human settlement on the history and origins of local and persistent soil erosion.

Author contributions

Áslaug Geirsdóttir: Conceptualization, Visualization, Investigation, Interpretation, Writing - original draft, review and editing, Funding acquisition. David J. Harning: Investigation, Interpretation, Writing - original draft, review and editing. Gifford H. Miller: Conceptualization, Visualization, Interpretation, Funding acquisition, review and editing. John T. Andrews: Methodology, review and editing. Yafang Zhong: Methodology, review and editing. Chris Caseldine: Methodology, review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by a Visiting Fellowship to ÁG in spring 2019 at the Center for the Study of Origins (CSO), University of Colorado Boulder, where this paper was initiated, and by the Icelandic Centre for Research through grants awarded to ÁG and GHM (no. 130775051 and Grant of Excellence no. 141573052), and several grants awarded to ÁG from the University of Iceland Research Fund. This paper is a contribution to NSF OPP grant no.1836981, Integrating novel molecular techniques to disentangle the roles of climate, time, and human agency on the evolution of the Icelandic landscape.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106633.

References

Aabel, N.G., 2016. Software package. available at: http://www.gigawiz.com/. August 2018.
Alley, R.B., Ágústsdóttir, A.M., 2005. The 8k event: cause and consequences of a major Holocene abrupt climate change. Quat. Sci. Rev. 24, 1123–1149.
Alsos, I.G., Ehrich, D., Seidenkrantz, M.-S., Bennike, O., Kirchhefer, A.J., Geirsdóttir, Á., 2016a. The role of sea ice for vascular plant dispersal in the Arctic. Biol. Lett. 12, 20160264.
Alsos, I.G., Lammers, Y., Yoccoz, N.G., Jørgensen, T., Sjögren, P., Gielly, L.,

Edwards, M.E., 2018. Plant DNA metabarcoding of lake sediment: how does it represent the contemporary vegetation. PloS One 13, 1–23.
Alsos, I.G., Sjögren, P., Brown, A.G., Gielly, L., Merkel, M.K.F., Paus, A., Lammers, Y., Edwards, M.E., Alm, T., Leng, M., Goslar, T., Langdon, C.T., Bakke, J., van der Bilt, W.G.M., 2020. Last Glacial Maximum environmental conditions at Andøya, northern Norway; evidence for a northern ice-edge ecological "hotspot". Quat. Sci. Rev. 239, 106364.
Alsos, I.G., Sjögren, P., Edwards, M.E., Landvik, J.Y., Gielly, L., Forwick, M., Coissac, E., Brown, A.G., Jakobsen, L.V., Føreid, M.K., Pedersen, M.W., 2016b. Sedimentary ancient DNA from Lake Skartjørna, Svalbard: assessing the resilience of arctic flora to Holocene climate change. Holocene 26, 627–642.
Anamthawat-Jónsson, K., 2011. Hybridisation, introgression and phylogeography of Iceland birch. Current Topics in Phylogenetics and Phylogeography of Terrestrial and Aquatic Systems 117–144.
Anderson, L.S., Flowers, G.E., Jarosch, A.H., Aðalgeirsdóttir, G.Th, Geirsdóttir, Á., Miller, G.H., Harning, D.J., þorsteinsson, þ., Magnússon, E., Pálsson, F., 2018. Holocene glacier and climate variations in Vestfirðir, Iceland, from the modeling of Drangajökull ice cap. Quat. Sci. Rev. 190, 39–56.
Anderson, L.S., Geirsdóttir, Á., Flowers, G.E., Wickert, A.D., Aðalgeirsdóttir, G., Thorsteinsson, T., 2019. Controls on the lifespans of Icelandic ice caps. Earth Planet Sci. Lett. 527, 115780.
Anderson-Carpenter, L.L., McLachlan, J.S., Jackson, S.T., Kuch, M., Lumibao, C.Y., Poinar, H.N., 2011. Ancient DNA from lake sediments: bridging the gap between paleoecology and genetics. BMC Evol. Biol. 11, 1–15.
Andrews, J.T., Belt, S.T., Ólafsdóttir, S., Massé, G., Vare, L.L., 2009. Sea ice and marine climate variability for NW Iceland/Denmark Strait over the last 2000 cal. yr BP. Holocene 5, 775–784.
Andrews, J.T., Harðardóttir, J., Helgadóttir, G., Jennings, A.E., Geirsdóttir, Á., Sveinbjörnsdóttir, Á.E., Schoolfield, S., Kristjánsdóttir, G.B., Smith, L.M., Thors, K., Syvitski, J., 2000. The N and W Iceland Shelf: insights into Last Glacial Maximum ice extent and deglaciation based on acoustic stratigraphy and basal radiocarbon AMS dates. Quat. Sci. Rev. 19, 619–631.
Andrews, J.T., Helgadóttir, G., 2003. Late Quaternary ice extent and deglaciation of Hunafloaall, north Iceland: evidence from marine cores. Arctic. Antarctic and Alpine Research 35, 218–232.
Aradottir, A.L., Eysteinsson, Th, 2005. Restoration of birch woodlands in Iceland. In: Stanturf, J.A., Madsen, P. (Eds.), Restoration of Boreal and Temperate Forests. CRC Press, Boca Raton, pp. 195–209.
Argiriadis, E., Battistel, D., McWethy, D.B., Vecchiato, M., Kirchgeorg, T., Kehrwald, N.M., Whitlock, C., Wilmshurst, J.M., Barbante, C., 2018. Lake sediment fecal and biomass burning biomarkers provide direct evidence for prehistoric human-lit fires in New Zealand. Sci. Rep. 8, 2–10.
Arnalds, A., 1987. Ecosystem disturbance in Iceland. Arct. Alp. Res. 19, 508–513.
Arnalds, Ó., 2000. The Icelandic "rofabard" soil erosion features. Earth Surf. Process. Landforms 25, 17–28.
Arnalds, Ó., Gísladóttir, F.O., Sigurjónsson, H., 2001. Sandy deserts of Iceland: an overview. J. Arid Environ. 47, 359–371.
Arnalds, Ó., 2010. Dust sources and deposition of aeolian materials in Iceland. Icel. Agric. Sci. 23, 3–21.
Arnalds, O., 2013. The Influence of Volcanic Tephra (Ash) on Ecosystems. In: Sparks, D. (Ed.), Advances in Agronomy 121. Elsevier, Amsterdam, pp. 332–380.
Ascough, P.L., Cook, G.T., Church, M.J., Dugmore, A.J., McGovern, T.H., Dunbar, E., Einarsson, Á., Friðriksson, A., Gestsdóttir, H., 2007. Reservoir and radiocarbon: 14C dating problems in Mývatnssveit, northern Iceland. Radiocarbon 49, 947–961.
Auger, J.D., Mayewski, P.A., Maasch, K.A., Schuenemann, K.C., Carleton, A.M., Birkel, S.D., Saros, J.E., 2019. 2000 years of North Atlantic-arctic climate. Quat. Sci. Rev. 216, 1–17.
Axford, Y., Andresen, C.S., Andrews, J.T., Belt, S.T., Geirsdóttir, Á., Massé, G., Miller, G.H., Ólafsdóttir, S., Vare, L.L., 2011. Do paleoclimate proxies agree? A test comparing 19 late Holocene climate and sea-ice reconstructions from Icelandic marine and lake sediments. J. Quat. Sci. 26, 645–656.
Axford, Y., Geirsdóttir, Á., Miller, G.H., Langdon, P.G., 2009. Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. J. Paleolimnol. 41, 7–24.
Axford, Y., Miller, G.H., Geirsdóttir, Á., Langdon, P.G., 2007. Holocene temperature history of northern Iceland inferred from subfossil midges. Quat. Sci. Rev. 26, 3344–3358.
Barber, D.C., Dyke, A., Hillaire-Marcel, C., Jennings, A.E., Andrews, J.T., Kerwin, M.W., Bilodeau, G., McNeely, R., Southon, J., Morehead, M.D., Gagnon, J.M., 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. Nature 400, 344–348.
Batt, C., Schmid, M.M.E., Vésteinsson, O., 2015. Constructing chronologies in Viking Age Iceland: increasing dating resolution using Bayesian approaches. J. Archaeol. Sci. 62, 1–14.
Belt, S.T., 2018. Source-specific biomarkers as proxies for Arctic and Antarctic sea ice. Org. Geochem. 125, 277–298.
Bendle, J.A.P., Rosell-Melé, A., 2007. High-resolution alkenone sea surface temperature variability on the north Icelandic shelf: implications for Nordic Seas palaeoclimatic development during the Holocene. Holocene 17, 9–24.
Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quat. Sci. Rev. 10, 297–317.
Birks, H.H., 2003. The importance of plant macrofossils in the reconstruction of Lateglacial vegetation and climate: examples from Scotland, western Norway, and Minnesota,. USA. Quaternary Science Reviews 22, 453–473.
Birks, H.H., Birks, H.J.B., 2000. Future uses of pollen analysis must include plant macrofossils. J. Biogeogr. 27, 31–35.
Birks, H.J.B., Birks, H.H., 2015. How Have Studies of Ancient DNA from Sediments Contributed to the Reconstruction of Quaternary Floras? New Phytologist. https://doi.org/10.1111/nph.13657.
Bjarnason, H., 1974. Athugasemdir við sögu Íslendinga í sambandi við eyðingu skóglendis. Yearb. Icel. For. Soc. 30, 1974.
Björck, S., Ingólfsson, Ó., Haflidason, H., Hallsdóttir, M., Anderson, N.J., 1992. Lake Torfadalsvatn: a high resolution record of the North Atlantic ash zone I and the last glacial-interglacial environmental changes in Iceland. Boreas 21, 15–22.
Black, J., 2008. Holocene Climate Change in South Central Iceland: a Multiproxy Lacustrine Record from Glacial Lake Hvitarvatn. Ph.D. thesis. University of Colorado Boulder.
Blair, C.L., Geirsdóttir, Á., Miller, G.H., 2015. A high-resolution multi-proxy lake record of Holocene environmental change in southern Iceland. J. Quat. Sci. 30, 281–292.
Boulton, G.S., Jarvis, J., Thors, K., 1988. Dispersal of glacially derived sediment over part of the continental shelf of south Iceland and the geometry of the resultant sediment bodies. Mar. Geol. 83, 193–223.
Broecker, W.S., 2006. Was the younger Dryas triggered by a flood? Science 312, 1146–1148.
Brynjólfsson, S., Schomacker, A., Guðmundsdóttir, E.R., Ingólfsson, Ó., 2015b. A 300-year surge history of the Drangajökull ice cap, northwest Iceland, and its maximum during the 'Little Ice Age'. Holocene 25, 1076–1092.
Brynjólfsson, S., Schomacker, A., Ingólfsson, Ó., Keiding, J.K., 2015a. Cosmogenic 36Cl exposure ages reveal a 9.3 ka BP glacier advance and the Late Weichselian-Early Holocene glacial history of the Drangajökull region, northwest Iceland. Quat. Sci. Rev. 126, 140–157.
Buckley, M.W., Marshall, J., 2016. Observations, inferences, and mechanisms of the atlantic meridional overturning circulation: a review. J. Geophys. 54, 5–63.
Bull, I.D., Lockheart, M.J., Elhmmali, M.M., Roberts, D.J., Evershed, R.P., 2002. The origin of faeces by means of biomarker detection. Environ. Int. 27, 647–654.
Büntgen, U., Myglan, V.S., Ljungqvist, F.C., McCormick, M., Di Cosmo, N., Sigl, M., Jungclaus, J., Wagner, S., Krusic, P.J., Esper, J., Kaplan, J.O., de Vaan, M.A.C., Luterbacher, J., Wacker, L., Tegel, W., Kirdyanov, A.V., 2016. Cooling and societal change during the late antique little ice age from 536 to around 660 AD. Nat. Geosci. 9, 213–236.
Cabedo-Sanz, P., Belt, S.T., Jennings, A.E., Andrews, J.T., Geirsdóttir, Á., 2016. Variability in drift ice export from the Arctic Ocean to the North Icelandic Shelf over the last 8000 years: a multi-proxy evaluation. Quat. Sci. Rev. 146, 99–115.
Cao, J., Rao, Z., Shi, F., Jia, G., 2020. Ice formation on lake surfaces in winter causes warm-season bias of lacustrine brGDGT temperature estimates. Biogeosciences 17, 2521–2536.
Caseldine, C., Geirsdóttir, Á., Langdon, P., 2003. Efstadalsvatn – a multi-proxy study of Holocene lacustrine sequence from NW Iceland. J. Paleolimnol. 30, 55–73.
Caseldine, C., Langdon, P., Holmes, N., 2006. Early Holocene climate variability and the timing and extent of the Holocene thermal maximum (HTM) in northern Iceland. Quat. Sci. Rev. 25, 2314–2331.
Casteñeda, I.S., Schouten, S., 2011. A review of molecular organic proxies for examining modern and ancient lacustrine environments. Quat. Sci. Rev. 30, 2851–2891.
Christensen, C.L., 2013. Multi-proxy responses of Icelandic lakes to Holocene tephra perturbations. M.S. Thesis. University of Colorado Boulder.
Conley, D.J., Schelske, C.L., 2001. Biogenic silica, 2001. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments, ume 3. Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publishers, Dordecht, the Netherlands.
Crump, S.E., Miller, G.H., Power, M., Sepúlveda, J., Dildar, N., Coghlan, M., Bunce, M., 2019. Arctic shrub colonization lagged peak postglacial warmth: molecular evidence in lake sediment from Arctic Canada. Global Change Biol. 25, 4244–4256.
Cutler, N.A., Bailey, R.M., Hickson, K.T., Streeter, R.T., Dugmore, A.J., 2016. Vegetation structure influences the retention of airfall tephra in a sub-Arctic landscape. Prog. Phys. Geogr. 40, 661–675.
D'Andrea, W.J., Theroux, S., Bradley, R.S., Huang, X., 2016. Does phylogeny control UK37-temperature sensitivity? Implications for lacustrine alkenone paleothermometry. Geochem. Cosmochim. Acta 175, 168–180.
D'Anjou, R.M., Bradley, R.S., Balascio, N.L., Finkelstein, D.B., D'Anjou, R.M., Bradley, R.S., Balascio, N.L., Finkelstein, D.B., 2012. Climate impacts on human settlement and agricultural activities in northern Norway revealed through sediment biogeochemistry. Proc. Natl. Acad. Sci. Unit. States Am. 109, 20332–20337.
Davis, J.C., 1986. Statistics and Data Analysis in Geology. John Wiley & Sons, New-York, p. 646.
Deng, L., Jia, G., Jin, C., Li, S., 2016. Warm season bias of branched GDGT temperature estimates causes underestimation of altitudinal lapse rate. Org. Geochem. 96, 11–17.
Denis, E.H., Toney, J.L., Tarozo, R., Scott Anderson, R., Roach, L.D., Huang, Y., 2012. Polycyclic aromatic hydrocarbons (PAHs) in lake sediments record historic fire events: validation using HPLC-fluorescence detection. Org. Geochem. 45, 7–17.
Dickson, R.R., Meincke, J., Malmberg, S., Lee, A., 1988. The "Great salinity anomaly" in the northern North atlantic 1968–1982. Prog. Oceanogr. 20, 103–151.
Divine, D.V., Dick, C., 2007. March through August Ice Edge Positions in the Nordic Seas, 1750–2002. NSIDC: National Snow and Ice Data Center, Boulder, Colorado USA, Version 1.

Dugmore, A.J., Buckland, P.C., 1991. Tephrochronology and late Holocene soil erosion in south Iceland. In: Maizels, Judith K., Caseldine, Christopher (Eds.), Environmental Change in Iceland Past and Present. Dordrecht, the Netherlands: Kluwer, pp. 147–161.
Dugmore, A.J., Erskine, C.C., 1994. Local and regional patterns of soil erosion in southern Iceland. Munch. Geogr. Abhand. 2, 63–79.
Dugmore, A.J., Gísladóttir, G., Simpson, I.A., Newton, A., 2009. Conceptual models of 1200 years of Icelandic soil erosion reconstructed using tephrochronology. Journal of North Atlantic 2, 1–18.
Eddudóttir, S.D., Erlendsson, E., Gísladóttir, G., 2015. Life on the periphery is tough: vegetation in Northwest Iceland and its response to early-Holocene warmth and later climate fluctuations. Holocene 25, 1437–1453.
Eddudóttir, S.D., Erlendsson, E., Gísladóttir, G., 2017. Effects of the Hekla 4 tephra on vegetation in northwest Iceland. Veg. Hist. Archaeobotany 26, 389–402.
Eddudóttir, S.D., Erlendsson, E., Gísladóttir, G., 2018. An Icelandic terrestrial record of North Atlantic cooling c. 8800-8100 cal. yr BP. Quat. Sci. Rev. 197, 246–256.
Eddudóttir, S.D., Erlendsson, E., Gísladóttir, G., 2020. Landscape change in the Icelandic highland: a long-term record of the impacts of land use, climate and volcanism. Quat. Sci. Rev. 240, 106363.
Eddudóttir, S.D., Erlendsson, E., Tinganelli, L., Gísladóttir, G., 2016. Climate change and human impact in a sensitive ecosystem: the Holocene environment of the Northwest Icelandic highland margin. Boreas 45, 715–728.
Edwards, M.E., Alsos, I.G., Yoccoz, N., Coissac, E., Goslar, T., Gielly, L., Haile, J., Langdon, C.T., Tribsch, A., Binney, H.A., von Stedingk, H., Taberlet, P., 2018. Metabarcoding of modern soil DNA gives a highly local vegetation signal in Svalbard tundra. Holocene 28, 1–11.
Egloff, J., Johnson, G.L., 1979. Erosional and depositional structures of the southwest Iceland insular margin: thirteen geophysical profiles. In: Watkins, J.S., Montadert, L., Dickerson, P.W. (Eds.), Geological and Geophysical Investigations of Continental Margins. AAPG, Tulsa, Oklahoma, pp. 43–63.
Einarsson, B.F., 2015. Stöð. Rúst 16:1 Í Fjarðabyggð. Fornleifafræðistofan, p. 19.
Einarsson, B.F., 2017a. Stöð í Stöðvarfirði. Fornleifarannsóknir á skála frá 9. öld og fleiri rústum. Skýrsla II. Fornleifafræðistofan 69.
Einarsson, B.F., 2017b. Stöð í stöðvarfirði. Fornleifarannsóknir 2017. Leit tog rannsókn á húsum. Fornleifafræðastofan 83.
Eiríksson, J., Knudsen, K.L., Haflidason, H., Henriksen, P., 2000. Late-glacial and Holocene paleoceanography of the north Icelandic shelf. J. Quat. Sci. 15, 23–42.
Eiríksson, J., Larsen, G., Knudsen, K.L., Heinemeier, J., Símonarson, L.A., 2004. Marine reservoir age variability and water mass distribution in the Iceland Sea. Quat. Sci. Rev. 23, 2247–2268.
Eldjárn, K., 1989. Papey. Fornleifarannsóknir 1967-1981. Árbók hins Íslenska Fornleifafélags 1988, 35–188.
Feng, X., Zhao, C., D'Andrea, W.J., Liang, J., Zhou, A., Shen, J., 2019. Temperature fluctuations during the Common Era in subtropical southwestern China inferred from brGDGTs in a remote alpine lake. Earth Planet Sci. Lett. 510, 26–36.
Ficken, K.J., Li, B., Swain, D.L., Eglinton, G., 2000. An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. Org. Geochem. 31, 745–749.
Florian, C.R., 2016. Multi-proxy Reconstructions of Holocene Environmental Change and Catchment Biogeochemistry Using Algal Pigments and Stable Isotopes Preserved in Lake Sediment from Baffin Island and Iceland. PhD thesis. University of Colorado Boulder and University of Iceland.
Flowers, G.E., Björnsson, H., Geirsdóttir, Á., Miller, G.H., Black, J.L., Clarke, G.K.C., 2008. Holocene climate conditions and glacier variation in central Iceland from physical modelling and empirical evidence. Quat. Sci. Rev. 27, 797–813.
Flowers, G.E., Björnsson, H., Geirsdóttir, Á., Miller, G.H., Clarke, G.K.C., 2007. Glacier fluctuation and inferred climatology of Langjökull ice cap through the Little Ice Age. Quat. Sci. Rev. 22, 2337–2353.
Fernández-Fernández, J.M., Palacios, D., Andrés, N., Schimmelpfennig, I., Brynjólfsson, S., Sancho, L.G., Zamorano, J.J., Heiðmarsson, S., Sæmundsson, þ., ASTER Team, 2019. A multi-proxy approach to Late Holocene fluctuations of Tungnahryggsjökull glaciers in the Tröllaskagi peninsula (northern Iceland). Sci. Total Environ. 664, 499–517.
Gao, C., Robock, A., Ammann, C., 2008. Volcanic forcing of climate over the past 1500 years: an improved ice core-based index for climate models. J. Geophys. Res. 113, 1–15.
Gao, L., Hou, J., Toney, J., MacDonald, D., Huang, Y., 2011. Mathematical modeling of the aquatic macrophyte inputs of mid-chain n-alkyl lipids to lake sediments: implications for interpreting compound specific hydrogen isotopic records. Geochem. Cosmochim. Acta 75, 3781–3791.
Geirsdóttir, Á., Andrews, J.T., Ólafsdóttir, S., Helgadóttir, G., Harðardóttir, J., 2002. A 36 Ky record of iceberg rafting and sedimentation from north-west Iceland. Polar Res. 21, 291–298.
Geirsdóttir, Á., Eiríksson, J., 1994. Sedimentary facies and environmental history of the Late-glacial glaciomarine Fossvogur sediments in Reykjavík. Iceland. Boreas 23, 164–176.
Geirsdóttir, Á., Hardardóttir, J., Eiríksson, J., 1997. The depositional history of the Younger Dryas-Preboreal Búdi moraines in South-Central Iceland. Arct. Alp. Res. 29, 13–23.
Geirsdóttir, Á., Hardardóttir, J., Sveinbjörnsdóttir, Á.E., 2000. Glacial extent and catastrophic meltwater events during the deglaciation of Southern Iceland. Quat. Sci. Rev. 19, 1749–1761.
Geirsdóttir, Á., Miller, G.H., Andrews, J.T., Harning, D.J., Anderson, L.S., Larsen, D.J., Florian, C., Thordarson, T., 2019. The onset of Neoglaciation in Iceland and the 4.2 ka event. Clim. Past Discuss 15, 25–40.
Geirsdóttir, Á., Miller, G.H., Axford, Y., Ólafsdóttir, S., 2009a. Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. Quat. Sci. Rev. 28, 2107–2118.
Geirsdóttir, Á., Miller, G.H., Larsen, D.J., Ólafsdóttir, S., 2013. Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. Quat. Sci. Rev. 70, 48–62.
Geirsdóttir, Á., Miller, G.H., Larsen, D.J., Ólafsdóttir, S., Thordarson, Th, June 2012. 2012. Holocene climate extremes: the Little Ice Age and the 8.2 ka event as viewed from Iceland. AGU Chapman Conference on Volcanism and Atmosphere.
Geirsdóttir, A., Miller, G.H., Thordarson, T., Ólafsdóttir, S., 2009b. A 2000 year record of climate variations reconstructed from Haukadalsvatn, West Iceland. J. Paleolimnol. 41, 95–115.
Gerrard, J., 1991. An assessment of some of the factors involved in recent landscape change in Iceland. In: Maizels, Judith K., Caseldine, Christopher (Eds.), Environmental Change in Iceland Past and Present. Dordrecht, the Netherlands: Kluwer, pp. 237–253.
Giraudeau, J., Jennings, A.E., Andrews, J.T., 2004. Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Sea over the last 10000 cal years: a view from the North Iceland Shelf. Quat. Sci. Rev. 23, 2127–2139.
Gísladóttir, G., 2001. Ecological disturbance and soil erosion on grazing land in southwest Iceland. In: Conacher, A. (Ed.), Land Degradation. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 109–126.
Gudmundsson, H.J., 1997. A review of the Holocene environmental history of Iceland. Quat. Sci. Rev. 16, 81–92.
Grattan, J.P., Gilbertson, D.D., 2000. Prehistoric "Settlement Crisis", environmental changes in the British Isles and volcanic eruptions in Iceland: an exploration of plausible linkages. In: McCoy, F., Heiken, G. (Eds.), Volcanic Hazards and Disasters in Human Antiquity. Geological Society of America Special Paper, vol. 345, pp. 33–42.
Grattan, J.P., Pyatt, F.B., 1994. Acid damage to vegetation following the Laki fissure eruption in 1783 – an historical review. Sci. Total Environ. 151, 241–247.
Grönvold, K., Oskarsson, N., Johnsen, S.J., Clausen, H.B., Hammer, C.U., Bond, G., Bard, E., 1995. Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. Earth Planet Sci. Lett. 135, 149–155.
Gudmundsdóttir, E.R., Larsen, G., Björck, S., Ingólfsson, Ó., Striberger, J., 2016. A new high-resolution Holocene tephra stratigraphy in eastern Iceland: improving the Icelandic and North Atlantic tephrochronology. Quat. Sci. Rev. 150, 234–249.
Gunnarsdóttir, S., 2018. Holocene Environmental Changes in the Central Highlands of Iceland as Recorded in Soils. M.S. thesis. University of Iceland.
Gunnarson, S.R., 2017. Holocene Climate and Landscape Evolution in the West Central Highlands, Iceland. M.S. thesis. University of Iceland.
Hallsdóttir, M., 1987. Pollen analytical studies of human influence on vegetation in relation to the Landnám tephra layer in southwest Iceland. Lundqua Thesis 18, 45.
Hallsdóttir, M., 1995. On the pre-settlement history of Icelandic vegetation. Icel. Agric. Sci. 9, 17–29.
Hallsdóttir, M., Caseldine, C.J., 2005. The Holocene vegetation history of Iceland, state-of-the-art and future research. Dev. Quat. Sci. 5, 319–334.
Hannesdóttir, H., Björnsson, H., Pálsson, F., Aðalgeirsdóttir, G., Guðmundsson, S., 2015. Variations of southeast Vatnajökull ice cap (Iceland) 1650-1900 and reconstruction of the glacier surface geometry at the Little Ice Age maximum. Geografiska Annaler: series A. Phys. Geogr. 97, 237–264.
Harning, D.J., Andrews, J.T., Belt, S.T., Cabedo-Sanz, P., Geirsdóttir, Á., Dildar, N., Miller, G.H., Sepúlveda, J., 2019b. Sea ice control on winter subsurface temperatures of the North Iceland Shelf during the Little Ice Age: a TEX86 calibration case study. Paleoceanography and Paleoclimatology 34, 1006–1021.
Harning, D.J., Curtin, L., Geirsdóttir, Á., D'Andrea, W.J., Miller, G.H., Sepúlveda, J., 2020b. Lipid biomarkers quantify Holocene summer temperature and ice cap sensitivity in Icelandic lakes. Geophys. Res. Lett. 47 e2019GL085728.
Harning, D.J., Geirsdóttir, Á., Miller, G.H., 2018. Punctuated Holocene climate of Vestfirðir, Iceland, linked to internal/external variables and oceanographic conditions. Quat. Sci. Rev. 189, 31–42.
Harning, D.J., Geirsdóttir, Á., Miller, G.H., Anderson, L., 2016a. Episodic expansion of Drangajökull, Vestfirðir, Iceland, over the last 3 ka culminating in its maximum dimension during the Little Ice Age. Quat. Sci. Rev. 152, 118–131.
Harning, D.J., Geirsdóttir, Á., Miller, G.H., Zalzal, K., 2016b. Early Holocene deglaciation of Drangajökull, vestfirðir, Iceland. Quat. Sci. Rev. 153, 192–198.
Harning, D.J., Jennings, A.E., Köseoğlu, D., Belt, S.T., Geirsdóttir, Á., Sepúlveda, J., 2020a. Migration of the arctic and polar Fronts in the north atlantic during the Holocene. Clim. Past. https://doi.org/10.5194/cp-2020-119.
Harning, D.J., Thordarson, T., Geirsdóttir, Á., Zalzal, K., Miller, G.H., 2018. Provenance, stratigraphy and chronology of Holocene tephra from Vestfirðir, Iceland. Quat. Geochronol. 46, 59–79.
Harning, D.J., Thordarson, T., Geirsdóttir, Á., Ólafsdóttir, S., Miller, G.H., 2019a. Marker tephra in Haukadalsvatn lake sediment: a key to the Holocene tephra stratigraphy of northwest Iceland. Quat. Sci. Rev. 219, 154–170.
Holtmeier, F.K., 2003. Mountain Timberlines – Ecology, Patchiness, and Dynamics. Kluwer Academic Publishers, Dordrecht.
Hubbard, A., Sugden, D., Dugmore, A., Norðdahl, H., Pétursson, H., 2006. A modelling insight into the Icelandic Last Glacial Maximum ice sheet. Quat. Sci. Rev. 25, 2283–2296.
Hurrell, J.W., Holland, M.M., Gent, P.R., Ghan, S., Kay, J., Kushner, P.J., 2013. The community Earth system model: a framework for collaborative research. Bull. Am. Meteorol. Soc. 94, 1339–1360.

Ingólfsson, Ó., Norðdahl, H., 2001. High relative sea-level during the Bölling Interstadial in western Iceland: a reflection of ice sheet collapse and extremely rapid glacial unloading. Arctic. Antarctic and Alpine Research 33, 231–243.
Ipcc, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Jennings, A.E., Andrews, J.T., Pearce, C., Wilson, L., Ólafsdóttir, S., 2015. Detrital carbonate peaks on the Labrador shelf, a 13-7 ka template for freshwater forcing from the Hudson Strait outlet of the Laurentide Ice Sheet into the subpolar gyre. Quat. Sci. Rev. 107, 62–80.
Jennings, A., Syvitski, J., Gerson, L., Grönvold, K., Geirsdóttir, Á., Hardardóttir, J., Andrews, J., Hagen, S., 2000. Chronology and paleoenvironments during the late Weichselian deglaciation of the southwest Iceland shelf. Boreas 29, 167–183.
Jiang, H., Muscheler, R., Björck, S., Seidenkrantz, M.-S., Olsen, J., Sha, L., Sjolte, J., Eiríksson, J., Ran, L., Knudsen, K.-L., Knudsen, M.F., 2015. Solar forcing of Holocene summer sea-surface temperatures in the northern North Atlantic. Geology 43, 2–5.
Jóhannsdóttir, G.E., 2007. Mid-Holocene to Late Glacial Tephrochronology in West Iceland as Revealed in Three Lacustrine Environments. M.S. thesis. University of Iceland.
Jónsson, þ.H., 2002. The salt problem and research on salt tolerance of tree species in Iceland. In: Randrup, T.B., et al. (Eds.), Proc. Urban Forests and Trees, COST Action E12. European Commission, Director-General for Research. Luxembourg, Office for Official Publications of the European Communities, pp. 151–160.
Jónsson, þ.H., 2005. Útbreiðsla birkis á Íslandi. Skógræktarritið 2, 61–71.
Justwan, A., Koc, N., Jennings, A.E., 2008. Evolution of the Irminger and East Icelandic Current systems through the Holocene, revealed by diatom-based sea surface temperature reconstructions. Quat. Sci. Rev. 27, 1571–1582.
Karlsdóttir, L., Hallsdóttir, M., Thórsson, Æ.Th, Anamthawat-Jónsson, K., 2009. Evidence of hybridisation between Betula pubescens and B. Nana in Iceland during the early Holocene. Rev. Palaeobot. Palynol. 156, 350–357.
Karlsdóttir, L., Hallsdóttir, M., Thórsson, Æ.Th, Anamthawat-Jónsson, K., 2012. Early Holocene hybridisation between Betula pubescens and B. Nana in relation to birch vegetation in Southwest Iceland. Rev. Palaeobot. Palynol. 181, 1–10.
Karlsdóttir, L., Hallsdóttir, M., Eggertsson, Ó., Thórsson, Æ.Th, Anamthawat-Jónsson, K., 2014. Birch hybridization in thistilfjördur, north-east Iceland during the Holocene. Icel. Agric. Sci. 27, 95–109.
Knudsen, K.L., Jiang, H., Jansen, E., Eiríksson, J., Heinemeier, J., Seidenkrantz, M.S., 2004. Environmental changes off North Iceland during the deglaciation and the Holocene: foraminifera, diatoms and stable isotopes. Mar. Micropaleontol. 50, 273–305.
Kobashi, T., Menviel, L., Jeltsch-Thömmes, A., Vinther, B.M., Box, J.E., Muscheler, R., Nakaegawa, T., Pfister, P.L., Döring, M., Leuenberger, M., Wanner, H., Ohmura, A., 2017. Volcanic influence on centennial to millennial Holocene Greenland temperature change. Sci. Rep. 7, 1–10.
Korner, C., Paulsen, J., 2004. A world-wide study of high altitude treeline temperatures. J. Biogeogr. 31, 713–732.
Kristinsson, H., 1995. Post-settlement history of Icelandic forests. Icel. Agric. Sci. 9, 31–35.
Kristjánsdóttir, G.B., Moros, M., Andrews, J.T., Jennings, A.E., 2017. Holocene Mg/Ca, alkenones, and light stable isotope measurements on the outer North Iceland shelf (MD99-2269): a comparison with other multi-proxy data and sub-division of the Holocene. Holocene 26, 55–62.
Lammel, G., Sehili, A.M., Bond, T.C., Feichter, J., Grassl, H., 2009. Gas/particle partitioning and global distribution of polycyclic aromatic hydrocarbons - a modelling approach. Chemosphere 76, 98–106.
Langdon, P.G., Leng, M.J., Holmes, N., Caseldine, C.J., 2008. Environmental controls on modern chironomid faunas from NW Iceland and implications for reconstructing climate change. J. Paleolimnol. 40, 273–293.
Langdon, P.G., Leng, M.J., Holmes, N., Caseldine, C.J., 2010. Lacustrine evidence of early-Holocene environmental change in northern Iceland: a multiproxy palaeoecology and stable isotope study. Holocene 20, 205–214.
Larsen, D.J., Geirsdóttir, Á., Miller, G.H., 2015. Precise chronology of little ice age expansion and repetitive surges of Langjökull, central Iceland. Geology 43, 1–4.
Larsen, D.J., Miller, G.H., Geirsdóttir, Á., Thordarson, T., 2011. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. Quat. Sci. Rev. 30, 2715–2731.
Larsen, D.J., Miller, G.H., Geirsdóttir, Á., Ólafsdóttir, S., 2012. 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. Quat. Sci. Rev. 39, 14–25.
Larsen, D.J., Miller, G.H., Geirsdóttir, Á., 2013. Asynchronous little ice age glacier fluctuations in Iceland and European alps linked to shifts in subpolar North Atlantic circulation. Earth Planet Sci. Lett. 380, 52–59.
Larsen, G., Eiríksson, J., 2008. Holocene tephra archives and tephrochronology in Iceland – a brief overview. Jokull 58, 229–250.
Lawson, I., Gathorne-Hardy, F.J., Church, M.J., Newton, A.J., Edwards, K.J., Dugmore, A.J., Einarsson, Á., 2007. Environmental impacts of the Norse settlement: palaeoenvironmental data from Mývatnssveit, northern Iceland. Boreas 36, 1–19.
Lehner, F., Born, A., Raible, C.C., Stocker, T.F., 2013. Amplified inception of European Little Ice Age by sea ice-ocean-atmosphere feedbacks. J. Clim. 26, 7586–7602.
Licciardi, J.M., Kurz, M.D., Curtice, J.M., 2007. Glacial and volcanic history of Icelandic table mountains from cosmogenic 3He exposure ages. Quat. Sci. Rev. 26, 1529–1546.
Lima, A.L.C., Farrington, J.W., Reddy, C.M., 2005. Combustion-derived polycyclic aromatic hydrocarbons in the environment—a review. Environ. Forensics 6, 109–131.
Longo, W.M., Huang, Y., Yao, Y., Zhao, J., Gilbin, A.E., Wang, X., Zech, R., Haberzettl, T., Jardillier, L., Toney, J., Liu, Z., Krivonogov, S., Kolpakova, M., Chu, G., D'Andrea, W.J., Harada, N., Nagashima, K., Sato, M., Yonenobu, H., Yamada, K., Gotanda, K., Shinozuka, Y., 2018. Widespread occurrence of distinct alkenones from Group I haptophytes in freshwater lakes: implications for paleotemperature and paleoenvironmental reconstructions. Earth Planet Sci. Lett. 492, 239–250.
Longo, W.M., Theroux, S., Gilbin, A.E., Zheng, Y., Dillon, J.T., Huang, Y., 2016. Temperature calibration and phylogenetically distinct distributions for freshwater alkenones: evidence from northern Alaskan lakes. Geochem. Cosmochim. Acta 180, 177–196.
Mack, R.N., 1981. Initial effects of ashfall from Mount St Helens on vegetation in eastern Washington and adjacent Idaho. Nature 213, 537–539.
Martin, C., Ménot, G., Thouveny, N., Davtian, N., Andrieu-Ponel, V., Reille, M., Bard, E., 2019. Impact of human activities and vegetation changes on the tetraether sources in Lake St Front (Massif Central, France). Org. Geochem. 135, 38–52.
Massé, G., Rowland, S.J., Sicre, M.-A., Jacob, J., Jansen, E., Belt, S., 2008. Abrupt climate changes for Iceland during the last millennium: evidence from high resolution sea ice reconstructions. Earth Planet Sci. Lett. 269, 565–569.
Matero, I.S.O., Gregoire, L.J., Ivanovic, R.F., Tindall, J.C., Haywood, A.M., 2017. The 8.2 ka cooling event caused by Laurentide ice saddle collapse. Earth Planet Sci. Lett. 473, 205–214.
Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., Prentice, M., 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. J. Geophys. Res.: Oceans 102, 26345–26366.
McGregor, H.V., Evans, M.N., Goosse, H., Leduc, G., Martrat, B., Addison, J.A., Mortyn, P.G., Oppo, D.W., Seidenkrantz, M.-S., Sicre, M.-A., Phipps, S.J., Selvaraj, K., Thirumalai, K., Filipsson, H.L., Ersek, V., 2015. Robust global ocean cooling trend for the pre-industrial Common Era. Nat. Geosci. 8, 671–677.
McCave, I.N., Andrews, J.T., 2019. Distinguishing current effects in sediments delivered to the ocean by ice. II. Glacial to Holocene changes in North Atlantic high latitude upper ocean flows. Quat. Sci. Rev. 223 (105902), 21.
McKay, N.P., Kaufman, D.S., Michelutti, N., 2008. Biogenic silica concentration as a high-resolution, quantitative temperature proxy at Hallet Lake, south-central Alaska. Geophys. Res. Lett. 35, 4–9.
Miller, G.H., Geirsdóttir, Á., Zhong, Y., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., Björnsson, H., Thordarson, T., 2012. Abrupt onset of the Little Ice Age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophys. Res. Lett. 39, 1–5.
Moffa-Sánchez, P., Hall, I.R., 2017. North Atlantic variability and its links to European climate over the last 3000 years. Nat. Commun. 8, 1–9.
Moffa-Sánchez, P., Moreno-Chamarro, E., Reynolds, D.J., Ortega, P., Cunningham, L., Swingedouw, D., Amrhein, D.E., Halfar, J., Jonkers, L., Jungclaus, J.H., Perner, K., Wanamaker, A., Yeager, S., 2019. Variability in the northern North atlantic and arctic oceans across the last two millennia: a review. Paleoceanography and Paleoclimatology 34, 1399–1436.
Moossen, H., Bendle, J., Seki, O., Quillmann, U., Kawamura, K., 2015. North Atlantic Holocene climate evolution recorded by high-resolution terrestrial and marine biomarker records. Quat. Sci. Rev. 129, 111–127.
Moreno-Chamarro, E., Zanchettin, D., Lohmann, K., Luterbacher, J., Jungclaus, J.H., 2017. Winter amplification of the European Little Ice Age cooling by the subpolar gyre. Sci. Rep. 7, 1–8.
Moros, M., Andrews, J.T., Eberl, D.D., Jansen, E., 2006. Holocene history of drift ice in the northern North Atlantic: evidence for differential spatial and temporal modes. Paleoceanography 21, 1–10.
Musa Bandowe, B.A., Srinivasan, P., Seelge, M., Sirocko, F., Wilcke, W., Bandowe, B.A.M., Srinivasan, P., Seelge, M., Sirocko, F., Wilcke, W., 2014. A 2600-year record of past polycyclic aromatic hydrocarbons (PAHs) deposition at Holzmaar (Eifel, Germany). Palaeogeography, Palaeoclimatology,. Palaeoecology 401, 111–121.
Muschitiello, F., D'Andrea, W.J., Schmittner, A., Heaton, T.J., Balascio, N.L., deRoberts, N., Caffee, M.W., Woodruff, T.E., Welten, K.C., Skinner, L.C., Simon, M.H., Dokken, T.M., 2019. Deep-water circulation changes lead North Atlantic climate during deglaciation. Nat. Commun. 10, 1–10.
Myers-Smith, I.H., Forbes, B.C., Wilmking, M., Hallinger, M., Lantz, T., Blok, D., Tape, K.D., Macias-Fauria, M., Sass-Klaassen, U., Lévesque, E., Boudreau, S., Ropars, P., Hermanutz, L., Trant, A., Collier, L.S., Weijers, S., Rozema, J., Rayback, S.A., Schmidt, N.M., Schaepman-Strub, G., Wipf, S., Rixen, C., Ménard, C.B., Venn, S., Goetz, S., Andreu-Hayles, L., Elmendorf, S., Ravolainen, V., Welker, J., Grogan, P., Epstein, H.E., Hik, D.S., 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environ. Res. Lett. 6, 1–15.
Mysak, L.A., Power, S.B., 1992. Sea-ice anomalies in the western Arctic and Greenland-Iceland Sea and their relation to an interdecadal climate cycle. Climatological Bulletin 26, 147–176.
Niemeyer, B., Epp, L.S., Stoof-Leichsenring, K., Pestryakova, L.A., Herzschuh, U., 2017. A comparison of sedimentary DNA and pollen from lake sediments in recording

vegetation composition at the Siberian treeline. Molecular Ecology Resources 17, e46–e62.
Norðdahl, H., 1991. A review of the glaciation maximum concept and the deglaciation of Eyjafjordur, North Iceland. In: Maizels, J.K., Caseldine, C. (Eds.), Environmental Changes in Iceland: Past and Present. Kluwer Academic Publishers, Dordrecht, pp. 31–47.
Norðdahl, H., Ingólfsson, Ó., 2015. Collapse of the Icelandic ice sheet controlled by sea-level rise? Arktos 1, 1–18.
Norðdahl, H., Pétursson, H.G., 2005. Relative sea level changes in Iceland. New aspects of the Weichselian deglaciation of Iceland. In: Caseldine, C., Russel, A., Harðardóttir, J., Knudsen Ó (Eds.), Iceland - Modern Processes and Past Environments. Elsevier, Amsterdam, pp. 25–78.
Ólafsdóttir, K.B., Geirsdóttir, Á., Miller, G.H., Larsen, D.J., 2013. Evolution of NAO and AMO strength and cyclicity derived from a 3-ka varve-thickness record from Iceland. Quat. Sci. Rev. 69, 142–154.
Olafsdottir, R., Schlyter, P., Haraldsson, H.V., 2001. Simulating Icelandic vegetation cover during the Holocene. Implications for long term land degradation. Geografiska Annaler: Series A 83, 203–215.
Ólafsdóttir, S., Jennings, A.E., Geirsdóttir, Á., Andrews, J., Miller, G.H., 2010. Holocene variability of the North Atlantic Irminger current on the south- and northwest shelf of Iceland. Mar. Micropaleontol. 77, 101–118.
Óladóttir, B.A., Thordarson, T., Geirsdóttir, Á., Jóhannsdóttir, G.E., Mangerud, J., 2020. The Saksunarvatn Ash and the G10ka series tephra. Review and current state of knowledge. Quat. Geochronol. 56, 101041.
Olafsdottir, T., 1975. Jokulgardur á sjávarbotni út af Breidafirdi. (English summary: a moraine ridge on the Iceland shelf, west of Breidafjordur). Natturufraedingurinn 45, 31–36.
Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh program performs time-series analysis. Eos Trans. Am. Geophys. Union 77, 379.
Parducci, L., Bennett, K.D., Ficetola, G.F., Alsos, I.G., Suyama, Y., Wood, J.R., Pedersen, M.W., 2017. Ancient plant DNA in lake sediments. New Phytol. 214, 924–942.
Patton, H., Hubbard, A., Bradwell, T., Schomacker, A., 2017. The configuration, sensitivity and rapid retreat of the Late Weichselian Icelandic ice sheet. Earth Sci. Rev. 166, 223–245.
Pedersen, M.W., Ginolhac, A., Orlando, L., Olsen, J., Andersen, K., Holm, J., Funder, S., Willerslev, E., Kjær, K.H., 2013. A comparative study of ancient environmental DNA to pollen and macrofossils from lake sediments reveals taxonomic overlap and additional plant taxa. Quat. Sci. Rev. 75, 161–168.
Pedersen, M.W., Ruter, A., Schweger, C., Friebe, H., Staff, R.A., Kjeldsen, K.K., Mendoza, M.L.Z., Beaudoin, A.B., Zutter, C., Larsen, N.K., Potter, B.A., Nielsen, R., Rainville, R.A., Orlando, L., et al., 2016. Postglacial viability and colonization in North America's ice-free corridor. Nature 537, 1–15.
Peterse, F., Vonk, J.E., Holmes, R.M., Giosan, L., Zimov, N., Eglington, T.I., 2014. Branched glycerol dialkyl glycerol tetraethers in Arctic lake sediments: sources and implications for paleothermometry at high latitudes. J. Geophys. Res.: Biogeosciences 119, 1738–1754.
Quillmann, U., Marchitto, T.M., Jennings, A.E., Andrews, J.T., Friestad, B.F., 2012. Cooling and freshening at 8.2 ka on the NW Iceland Shelf recorded in paired δ18O and Mg/Ca measurements of the benthic foraminifer Cibicides lobatulus. Quat. Res. 78 (528), 539.
Rampino, M.R., Self, S., Stothers, R.B., 1988. Volcanic winters. Annu. Rev. Earth Planet Sci. 16, 73–99.
Reynolds, D.J., Scourse, J.D., Halloran, P.R., Nederbragt, A.J., Wanamaker, A.D., Butler, P.G., Richardson, C.A., Heinemeier, J., Eiriksson, J., Knudsen, K.L., Hall, I.R., 2016. Annually resolved North Atlantic marine climate over the last millennium. Nat. Commun. 7, 1–11.
Ritz, S.P., Stocker, T.F., Grimalt, J.O., Menviel, L., Timmermann, A., 2013. Estimated strength of the Atlantic overturning circulation during the last deglaciation. Nat. Geosci. 6, 208–212.
Rodionov, S.N., 2004. A sequential algorithm for testing climate regime shifts. Geophys. Res. Lett. 31, L09204.
Rodionov, S.N., 2006. Use of prewhitening in climate regime shift detection. Geophys. Res. Lett. 33, 1–4.
Rodrigo-Gámiz, M., Rampen, S.W., de Haas, H., Baas, M., Schouten, S., Sinninghe-Damsté, J.S., 2015. Constraints on the applicability of the organic temperature proxies UK37', TEX86 and LDI in the subpolar region around Iceland. Biogeosciences 12, 6573–6590.
Rohling, E.J., Pälike, H., 2005. Centennial-scale climate cooling with a sudden cold event around 8,200 years ago. Nature 434, 975–979.
Rundgren, M., 1995. Biostratigraphic evidence of the allerød-younger dryas-preboreal oscillation in northern Iceland. Quat. Res. 44, 405–416.
Rundgren, M., 1998. Early-Holocene vegetation of northern Iceland: pollen and plant macrofossil evidence from the Skagi peninsula. Holocene 5, 553–564.
Rundgren, M., Ingólfsson, Ó., 1999. Plant survival in Iceland during periods of glaciation? J. Biogeogr. 26, 387–396.
Schouten, S., Hopmans, E.C., Sinninghe Damsté, J.S., 2013. The organic geochemistry of glycerol dialkyl glycerol tetraether lipids: a review. Org. Geochem. 54, 19–61.
Schmid, M.M.E., Dugmore, A.J., Vésteinsson, O., Newton, A.J., 2017. Tephra isochrons and chronologies of colonisation. Quat. Geochronol. 40, 56–66.
Sear, D.A., Allen, M.S., Hassall, J.D., Maloney, A.E., Langdon, P.G., Morrison, A.E., Henderson, A.C.G., Mackay, H., Croudace, I.W., Clarke, C., Sachs, J.P., Macdonald, G., Chiverrell, R.C., Leng, M.J., Cisneros-Dozal, L.M., Fonville, T., 2020. Human settlement of East Polynesia earlier, incremental, and coincident with prolonged South Pacific drought. Proc. Natl. Acad. Sci. Unit. States Am. 201920975.
Seddon, A.W.R., Froyd, C.A., Witkowski, A., Willis, K.J., 2014. A quantitative framework for analysis of regime shifts in a Galápagos coastal lagoon. Ecology 95, 3046–3055.
Serreze, M.C., Maslanik, J.A., Barry, R.G., Demaria, T.L., 1992. Winter atmospheric circulation in the arctic basin and possible relationships to the great salinity anomaly in the northern North atlantic. Geophys. Res. Lett. 19, 293–296.
Shanahan, T.M., Hughen, K.A., Van Mooy, B.A.S., 2013. Temperature sensitivity of branched and isoprenoid GDGTs in Arctic lakes. Org. Geochem. 64, 119–128.
Shindell, D.T., Schmidt, G.A., Mann, M.E., Rind, D., Waple, A., 2001. Solar forcing of regional climate change during the Maunder Minimum. Science 294, 2159–2152.
Sigl, M., Winstrup, M., McConnell1, J.R., Welten, K.C., Plunkett, G., Ludlow, F., Büntgen, U., Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C., Maselli, O.J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D.R., Pilcher, J.R., Salzer, M., Schüpbach, S., Steffensen, J.P., Vinther, B.M., Woodruff, T.E., 2015. Timing and climatic forcing of volcanic eruptions for the past 2,500 years. Nature 523, 543–549. https://doi.org/10.1038/nature14565.
Sicre, M.-A., Hall, I.R., Mignot, J., Khodri, M., Ezat, U., Truong, M.-X., Eiríksson, J., Knudsen, K.-L., 2011. Sea surface temperature variability in the subpolar Atlantic over the last two millennia. Paleoceanography 26, 1–10.
Sicre, M.-A., Jacob, J., Ezat, U., Rousse, S., Kissel, K., Eiriksson, J., Knudsen, K.-L., Jansen, E., Turon, J.L., 2008b. Decadal variability of sea surface temperatures off North Iceland over the last 2000 yrs. Earth Planet Sci. Lett. 268, 137–142.
Sicre, M.-A., Yiou, P., Eiriksson, J., Ezat, U., Guimbaut, E., Dahhaoui, I., Knudsen, K.-L., Jansen, E., Turon, J.-L., 2008a. A 4500-year reconstuction of sea surface temperature variability at decadal time-scales off North Iceland. Quat. Sci. Rev. 27, 2041–2047.
Sigfúsdóttir, T., Benediktsson, Í.Ö., 2019. Refining the history of younger Dryas and early Holocene glacier oscillations in the Borgarfjörður region, western Iceland. Boreas 49, 296–314.
Sigfúsdóttir, T., Benediktsson, Í.Ö., Phillips, E., 2018. Active retreat of a Late Weichselian marine-terminating glacier: an example from Melasveit, western Iceland. Boreas 47, 813–836.
Simoneit, B.R.T., 2002. Biomass burning — a review of organic tracers for smoke from incomplete combustion. Appl. Geochem. 17, 129–162.
Sjögren, P., Edwards, M.E., Gielly, L., Langdon, C.T., Croudace, I.W., Merkel, M.K.F., Fonville, T., Alsos, I.G., 2017. Lake sedimentary DNA accurately records 20th Century introductions of exotic conifers in Scotland. New Phytol. 213, 929–941.
Skrzypek, G., Paul, D., Wojtun, B., 2008. Stable isotope composition of plants and peat from Arctic mire and geothermal area in Iceland. Polar Res. 29, 365–376.
Slawinska, J., Robock, A., 2018. Impact of volcanic eruptions on decadal to centennial fluctuations of Arctic sea ice extent during the last millennium and on initiation of the Little Ice Age. J. Clim. 31, 2145–2167.
Smith, K.P., 1994. Landnám: the settlement of Iceland in archaeological and historical perspective. World Archaeol. XXVI:3, 319–47.
Solignac, S., Giraudeau, J., de Vernal, A., 2006. Holocene sea surface conditions in the western North Atlantic: spatial and temporal heterogeneities. Paleoceanography 21, 1–6.
Sønstebø, J.H., Gielly, L., Brysting, A.K., Elven, R., Edwards, M., Haile, J., Willerslev, E., Coissac, E., Rioux, D., Sannier, J., Taberlet, P., Brochmann, C., 2010. Using next-generation sequencing for molecular reconstruction of past Arctic vegetation and climate. Molecular Ecology Resources 10, 1009–1018.
Spagnolo, M., Clark, C.D., 2009. A geomorphological overview of glacial landforms on the Icelandic continental shelf. J. Maps 5, 37–52.
Steinhilber, F., Beer, J., Fröhlich, C., 2009. Total solar irradiance during the Holocene. Geophys. Res. Lett. 36, 1–5.
Stevenson, J., Larsen, G., Thordarson, T., 2015. Physical volcanology of the prehistoric Hekla 3 and Hekla 4 eruptions, Iceland. EGU General Assembly, id.4207.
Stothers, R.B., Rampino, M.R., 1983. Historic volcanism, European dry fogs, and Greenland acid precipitation, 1500 B.C. to A.D. 1500. Science 222, 411–413.
Stötter, J., Wastl, M., Caseldine, C., Häberle, T., 1999. Holocene palaeoclimatic reconstruction in northern Iceland: approaches and results. Quat. Sci. Rev. 18, 457–474.
Streeter, R., Dugmore, A.J., Lawson, I.T., Erlendsson, E., Edwards, K.J., 2015. The onset of the palaeoanthropocene in Iceland: changes in complex natural systems. Holocene 25, 1662–1675.
Striberger, J., Bjorck, S., Benediktsson, Í.Ö., Snowball, I., Uvo, C.B., Ingólfsson, Ó., Kjær, K., 2011. Climatic control of the surge periodicity of an Icelandic outlet glacier. J. Quat. Sci. 26, 561–565.
Striberger, J., Björck, S., Holmgren, S., Hamerlík, L., 2012. The sediments of Lake Lögurinn – a unique proxy record of Holocene glacial meltwater variability in eastern Iceland. Quat. Sci. Rev. 38, 76–88.
Sveinbjörnsdóttir, Á.E., Heinemeier, J., Kristensen, P., Rud, N., Geirsdóttir, Á., Harðardóttir, J., 1998. 14C AMS dating of Icelandic lake sediments. Radiocarbon 40, 865–872.
Syvitski, J., Jennings, A.E., Andrews, J.T., 1999. High-resolution seismic evidence for multiple glaciation across the southwest Iceland shelf. Arctic Antarct. Alpine Res. 31, 50–57.
Tanner, L.H., Nivison, Morgan, Arnalds, Ó., Svavarsdóttir, K., 2015. Soil carbon accumulation and CO2 flux in experimental restoration plots, southern Iceland: comparing soil treatment strategies. Hindawi publishing corporation applied and environmental soil science volume 2015. Article ID 205846, 10.
Thórarinsson, S., 1944. Tefrokronoliska studier pa Island (Tephrochronological studies in Iceland). Geogr. Ann. 26, 1–217.

Thórarinsson, S., 1961. Uppblástur Á Islandi í Ljósi Öskulaga-Rannsókna. Ársrit Skógræktarfélag Íslands, Reykjavik, pp. 17–54.
Thordarson, T., Miller, D.J., Larsen, G., Self, S., Sigurdsson, H., 2001. New estimates of sulphur degassing and atmospheric mass-loading by the AD 934 Eldgjá eruption, Iceland. J. Volcanol. Geoth. Res. 108, 33–54.
Thordarson, T., Self, S., Miller, D.J., Larsen, G., Vilmundardóttir, E.G., 2003. Sulphur release from flood lava eruptions in the Veiðivötn, Grímsvötn and Katla volcanic systems, Iceland. In: Oppenheimer, C., Pyle, D.M., Barclay, J. (Eds.), Volcanic Degassing, vol. 213. Geological Society, London, pp. 103–121 (Special Publications).
Thordarson, T., Self, S., Óskarsson, N., Hulsebosch, T., 1996. Sulphur, chlorine, and fluorine degassing and atmospheric loading by the 1783-1784 AD Laki (Skaftár Fires) eruption in Iceland. Bull. Volcanol. 58, 205–225.
Thornalley, D.J.R., Elderfield, H., McCave, N., 2009. Holocene oscillations in temperature and salinity of the subpolar North Atlantic. Nature 457, 711–714.
Thornalley, D.J.R., McCave, N., Elderfield, H., 2010. Freshwater input and abrupt deglacial climate change in the North Atlantic. Paleoceanography and Paleoclimatology 25.
Thórsson, Æ.Th, Pálsson, S., Sigurgeirsson, A., Anamthawat-Jónsson, K., 2007. Morphological variation among Betula nana (diploid), B. pubescens (tetraploid) and their triploid hybrids in Iceland. Ann. Bot. 99, 1183–1193.
Tinganelli, L., Erlendsson, E., Eddudóttir, S.D., Gísladóttir, G., 2018. Impacts of climate, tephra, and land use upon Holocene landscape stability in Northwest Iceland. Geomorphology 322, 117–131.
Torres, M.A., Kemeny, P.C., Lamb, M.P., Cole, T.L., Fischer, W.W., 2020. Long-term storage and age-biased export of fluvial organic carbon: field evidence from west Iceland. Geochemistry, Geophysics. Geosystems 21 e2019GC008632.
Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic oscillation mode dominated the medieval climate anomaly. Science 324, 78–80.
Trouet, V., Scourse, J.D., Raible, C.C., 2012. North Atlantic storminess and atlantic meridional overturning circulation during the last millennium: reconciling contradictory proxy records of NAO variability. Global Planet. Change 84–85, 48–55.
Tyagi, P., Edwards, D.R., Coyne, M.S., 2007. Use of selected chemical markers in combination with a multiple regression model to assess the contribution of domesticated animal sources of fecal pollution in the environment. Chemosphere 69, 1617–1624.
Vachula, R.S., Huang, Y., Longo, W.M., Dee, S.G., Daniels, W.C., Russell, J.M., 2019. Evidence of Ice Age humans in eastern Beringia suggests early migration to North America. Quat. Sci. Rev. 205, 35–44.
Vésteinsson, O., 1998. Patterns of settlement in Iceland. A study in pre-history. Saga-Book of the Viking Society 25, 1–29.
Vésteinsson, O., 2000. The archaeology of Landnám Icelandic early settlement. In: Fitzhugh, W.W., Ward, E. (Eds.), Vikings: the North Atlantic Saga. Smithsonian Institution Press, Washington, DC, pp. 164–174.
Vésteinsson, O., McGovern, T., 2012. The peopling of Iceland. Norweg. Archaeol. Rev. 45, 206–218.
Volstad, L.H., Alsos, I.G., Farnsworth, W.R., Heintzman, P.D., Håkansson, L., Kjellman, S.E., Rouillard, A., Schomacker, A., Eidesen, P.B., 2020. A complete Holocene lake sediment ancient DNA record reveals long-standing high Arctic plant diversity hotspot in northern Svalbard. Quat. Sci. Rev. 234, 106207.
Wang, Y., Wooller, M., 2006. The stable isotopic (C and N) composition of modern plants and lichens from northern Iceland: with ecological and paleoenvironmental implications. Jokull 56, 27–38.
Wanner, H., Solomina, O., Grosjean, M., Ritz, S.P., Jetel, M., 2011. Structure and origin of Holocene cold events. Quat. Sci. Rev. 30, 3109–3123.
Wastl, M., Stötter, J., Caseldine, C., 2001. Reconstruction of Holocene variations of the upper limit of tree or shrub birch growth in northern Iceland based on evidence from Vesturárdalur-Skíðadalur, Tröllaskagi. Arctic Antarct. Alpine Res. 33, 191–203.
Willerslev, E., Davison, J., Moora, M., Zobel, M., Coissac, E., Edwards, M.E., Lorenzen, E.D., Vestergård, M., Gussarova, G., Haile, J., Craine, J., Gielly, L., Boessenkool, S., Epp, L.S., Pearman, P.B., Cheddadi, R., Murray, D., Bråthen, K.A., Yoccoz, N., Binney, H., Cruaud, C., Wincker, P., Goslar, T., Alsos, I.G., Bellemain, E., Brysting, A.K., Elven, R., Sønstebø, J.H., Murton, J., Sher, A., Rasmussen, M., Rønn, R., Mourier, T., Cooper, A., Austin, J., Möller, P., Froese, D., Zazula, G., Pompanon, F., Rioux, D., Niderkorn, V., Tikhonov, A., Savvinov, G., Roberts, R.G., MacPhee, R.D.E., Gilbert, M.T.P., Kjær, K., Orlando, L., Brochmann, C., Taberlet, P., 2014. Fifty thousand years of Arctic vegetation and megafaunal data. Science 506, 46–57.
Williams, J.W., Shuman, B.N., Webb, T., Bartlein, P.J., Leduc, P.L., 2004. Late-Quaternary vegetation dynamics in North America: scaling from taxa to biomes. Ecol. Monogr. 74, 309–334.
Wunsch, C., 1980. Meridional heat flux of the north Atlantic Ocean. Proc. Natl. Acad. Sci. Unit. States Am. 77, 5043–5047.
Xiao, X., Zhao, M., Knudsen, K.L., Sha, L., Eiríksson, J., Gudmundsdóttir, E., Jiang, H., Guo, Z., 2017. Deglacial and Holocene sea-ice variability north of Iceland and response to ocean circulation changes. Earth Planet Sci. Lett. 472, 14–24.
Zhong, Y., Jahn, A., Miller, G.H., Geirsdóttir, Á., 2018. Asymmetric cooling of the Atlantic and Pacific Arctic during the past two millennia: a dual observation-modeling study. Geophys. Res. Lett. 45, 12497–12505.
Zhong, Y., Miller, G.H., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Schneider, D.P., Geirsdóttir, Á., 2010. Centennial-scale climate change from decadally-paced explosive volcanism: a coupled sea ice-ocean mechanism. Clim. Dynam. 37, 2373–2387.