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# Holocene temperature history of northern Iceland inferred from subfossil midges

Yarrow Axford[a,*], Gifford H. Miller[a], Áslaug Geirsdóttir[b], Peter G. Langdon[c]

[a]Department of Geological Sciences, Institute of Arctic and Alpine Research, University of Colorado, UCB 450, Boulder, CO 80309, USA
[b]Department of Geosciences, Institute of Earth Sciences, University of Iceland, Askja, Sturlugata 7, Reykjavik 101, Iceland
[c]Department of Geography, University of Southampton, Highfield, Southampton SO17 1BJ, UK

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**Abstract**

The Holocene temperature history of Iceland is not well known, despite Iceland's climatically strategic location at the intersection of major surface currents in the high-latitude North Atlantic. Existing terrestrial records reveal spatially heterogeneous changes in Iceland's glacier extent, vegetation cover, and climate over the Holocene, but these records are temporally discontinuous and mostly qualitative. This paper presents the first quantitative estimates of temperatures throughout the entire Holocene on Iceland. Mean July temperatures are inferred based upon subfossil midge (Chironomidae) assemblages from three coastal lakes in northern Iceland. Midge data from each of the three lakes indicate broadly similar temperature trends, and suggest that the North Icelandic coast experienced relatively cool early Holocene summers and gradual warming throughout the Holocene until after 3 ka. This contrasts with many sites on Iceland and around the high-latitude Northern Hemisphere that experienced an early to mid-Holocene "thermal maximum" in response to enhanced summer insolation forcing. Our results suggest a heightened temperature gradient across Iceland in the early Holocene, with suppressed terrestrial temperatures along the northern coastal fringe, possibly as a result of sea surface conditions on the North Iceland shelf.


## 1. Introduction

A general picture of Holocene climate around the Northern Hemisphere is emerging, and with it recognition that the response of interglacial climate to changing radiative forcing has been neither linear nor spatially homogeneous (e.g., deMenocal et al., 2000; CAPE Project Members, 2001; Kaufman et al., 2004; Kaplan and Wolfe, 2006). Climate is clearly modulated by local- and regional-scale factors that complicate the response to radiative forcing. This presents a challenge for those aiming to predict local and even regional-scale climatic responses to anthropogenic greenhouse forcing. Because it is climate at these scales that matters to society—more so than global or hemispheric climatic averages—it should be a high priority for paleoclimate and modeling studies to understand the factors that modulate local climatic responses to radiative forcings.

Ocean circulation, which plays an important modulatory role in Earth's climate system, has undergone both millennial-scale and abrupt, decadal-scale changes during the Holocene (e.g., Bond et al., 2001; Mayewski et al., 2004; Alley and Ágústdóttir, 2005). Some of these changes probably originated with perturbations in the North Atlantic thermohaline circulation, which has been called the "Achilles heel" of the climate system (Broecker, 1997). Today there is concern that ongoing changes in the freshwater budget of the northern oceans could alter the thermohaline circulation, with potentially severe impacts on society (e.g., NRC (National Research Council Committee on Abrupt Climate Change), 2002; Bryden et al., 2005; Curry and Mauritzen, 2005). Thus the controls on, and impacts of, North Atlantic circulation are important to understand.

As the largest land mass in the central North Atlantic (Fig. 1), Iceland occupies a strategic position: The modern-day

*Corresponding author. Present address: Department of Geology, University at Buffalo, 876 Natural Sciences Complex, Buffalo, NY 14260, USA. Tel.: +1 716 380 5027; fax: +1 716 645 3999.
*E-mail addresses:* yaxford@buffalo.edu (Y. Axford), gmiller@colorado.edu (G.H. Miller), age@hi.is (A. Geirsdóttir), P.G.Langdon@soton.ac.uk (P.G. Langdon).

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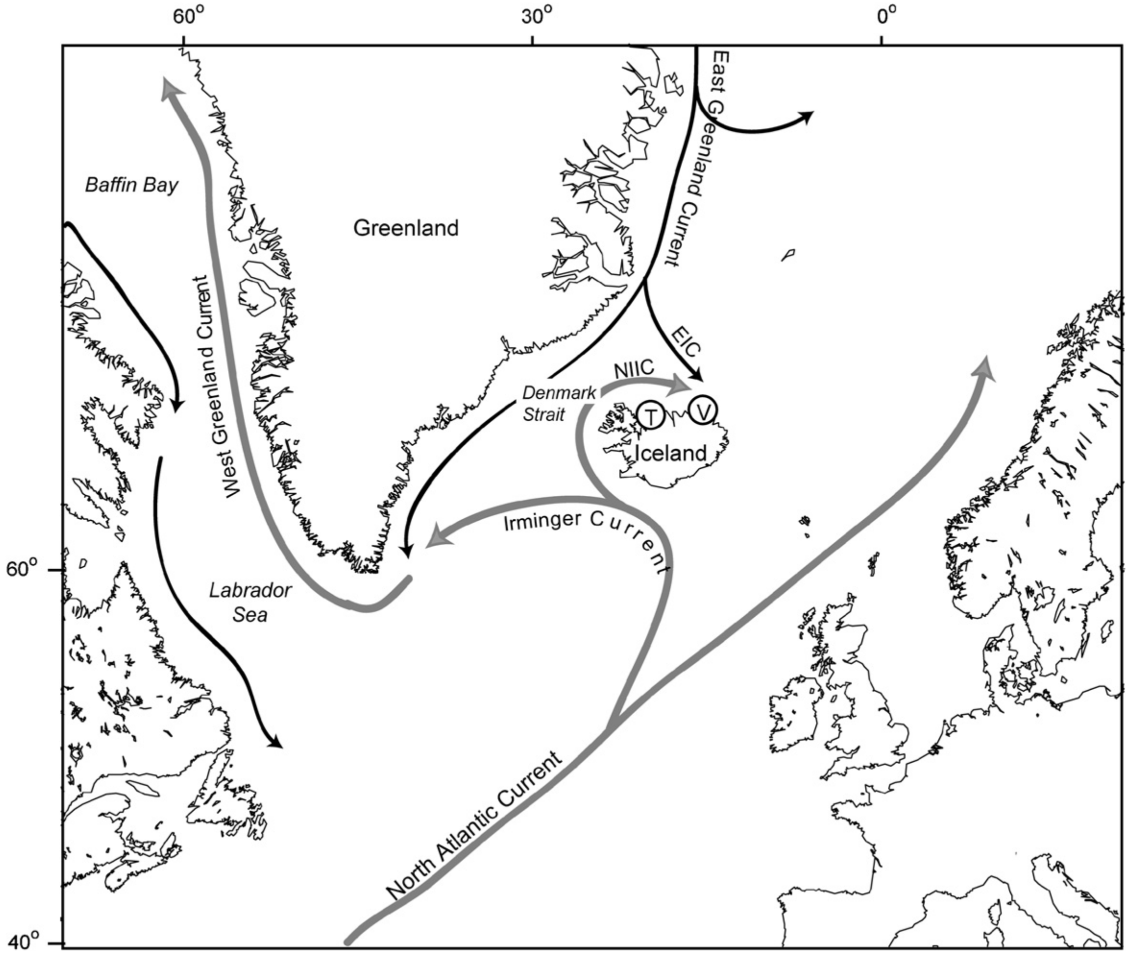


Fig. 1. The North Atlantic region, showing major ocean surface currents around Iceland, and locations of study sites Torfadalsvatn (T) and Stora and Litla Viðarvatn (V). EIC = East Iceland Current; NIIC = North Iceland Irminger Current.

Polar Front between cold, polar ocean surface currents and warm, Atlantic surface currents lies just north of Iceland, creating steep salinity and temperature gradients over the North Iceland shelf and a steep climate gradient across the island. Today Iceland's southern coast is warmed by the Atlantic Irminger Current (IC), which imports heat from the south. The cooler climate of northern Iceland reflects the competing influences of the IC and the cold East Iceland Current (EIC) a branch of the polar East Greenland Current (EGC; Fig. 1; Valdimarsson and Malmberg, 1999). Both the IC and EGC are important players in the global thermohaline circulation (e.g., Curry and Mauritzen, 2005). Changes in the strength and character of the Irminger and East Greenland currents cause dramatic oceanographic changes off northern Iceland (e.g., Ólafsson, 1999; Andrews and Giraudeau, 2003). Thus, Iceland sits in an ideal position to have been influenced by oceanographic changes of global importance, including those associated with changes in the convective strength of the thermohaline circulation.

Marine sediment core studies over the last decade have documented complex paleoceanographic changes off northern Iceland through the Lateglacial and Holocene (e.g., Eiríksson et al., 2000; Andrews et al., 2001; Jiang et al., 2002; Andrews and Giraudeau, 2003; Andersen et al., 2004; Castañeda et al., 2004; Giraudeau et al., 2004; Moros et al., 2004, 2006; Andresen and Björck, 2005; Smith et al., 2005; Ran et al., 2006; Solignac et al., 2006; Bendle and Rosell-Melé, 2007). But the overall pattern of these changes—and whether oceanographic changes were accompanied by simultaneous temperature changes on land, where temperatures are a function of marine conditions, regional wind patterns (Ólafsson, 1999), and solar forcing—remains unclear. A growing number of glacial geologic, pollen, chironomid, and other lake sediment records (e.g., Hallsdóttir, 1991, 1995; Gudmundsson, 1997; Rundgren, 1997, 1999; Stötter et al., 1999; Kirkbride and Dugmore, 2001, 2006; Wastl et al., 2001; Caseldine et al., 2003, 2006; Hallsdóttir and Caseldine, 2005; Wastl and Stötter, 2005; Hannesdóttir, 2006; Holmes, 2006) provide a general picture of terrestrial climate over the Holocene, but the terrestrial record from Iceland remains discontinuous and mostly qualitative.

This study uses subfossil chironomids (Diptera: Chironomidae, or non-biting midges) to reconstruct Holocene paleotemperatures at three lakes in northern Iceland, with the aim of providing a continuous, quantitative record of temperatures to help answer questions about spatial heterogeneity of Holocene climate across Iceland (e.g., Caseldine et al., 2006). In the past decade, paleolimnological studies have confirmed that chironomid distributions respond quickly to climatic change, and that chironomid assemblages can be used to accurately reconstruct both abrupt and low-amplitude temperature changes (e.g., Walker et al., 1991; Cwynar and Levesque, 1995; Brooks and Birks, 2000a, b; Cwynar and Spear, 2001; Korhola et al., 2002; Brooks and Birks, 2004; Heiri et al., 2004; Caseldine et al., 2006; Porinchu et al., 2007). Chironomid assemblages have been used successfully to reconstruct instrumentally measured temperature changes even when the measured temperature changes were of comparable magnitude to the estimated predictive error of chironomid-temperature transfer functions (Larocque and Hall, 2003). Iceland, which was entirely or almost entirely ice-covered during the last glaciation (e.g., Ingólfsson and Norðdahl, 1994; Norðdahl and Pétursson, 2005), and is ecologically isolated by the surrounding North Atlantic ocean, has a relatively impoverished chironomid fauna compared with mainland Europe or North America (Hrafnsdóttir, 2005); nevertheless, prior studies have demonstrated the utility of midges for reconstructing Holocene temperatures on Iceland (Caseldine et al., 2003, 2006; Holmes, 2006).

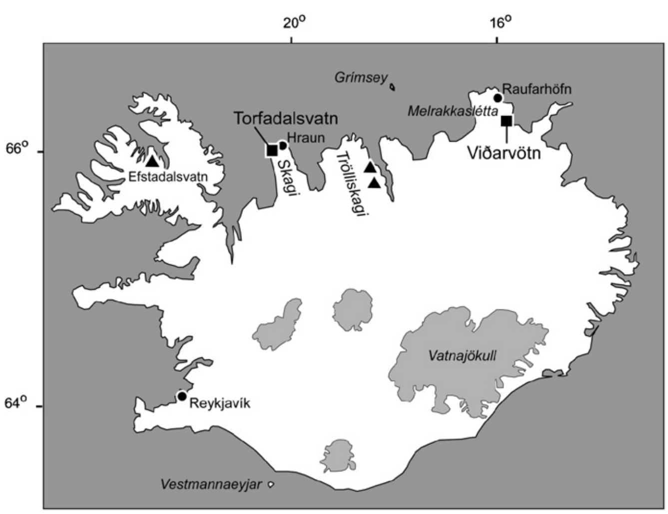


Fig. 2. Map of Iceland, showing locations of study sites (black squares) and other localities mentioned in the text. Circles are towns and settlements. Black triangles indicate locations of previously published chironomid-based temperature reconstructions (the two sites on the Trölliskagi peninsula are Hámundarstaðahals and Vatnamýri, studied by Caseldine et al., 2006; Efstadalsvatn was studied by Caseldine et al., 2003).

## 2. Study sites

Torfadalsvatn (maximum depth $Z_{max} = 5.8$ m, surface area SA $= 0.4\,km^2$) is located at 52 m a.s.l. on the Skagi peninsula in north-central Iceland (66°3.567′N, 20°22.815′W; Figs. 1–3). Mean July temperature at the nearby weather station at Hraun (Fig. 2) was 8.2 °C for the time period 1961–1990 (Veðurstofa Íslands, the Icelandic Meteorological Office, http://www.vedur.is). Lake-water properties measured in July 2003 are presented in Table 1. Lateglacial and early Holocene tephrostratigraphic and palynological studies previously conducted at Torfadalsvatn (e.g., Björck et al., 1992; Rundgren, 1995, 1997, 1999) have demonstrated that the site was deglaciated before the deposition of the ~12 ka Vedde tephra (Mangerud et al., 1984; Birks et al., 1996; ka = thousands of calibrated years before present), and that the lake contains a unique continuous record of the Younger Dryas on Iceland, as well as Holocene sediments.

Stora Viðarvatn ($Z_{max} = 48.0$ m, SA $= 2.4\,km^2$) is situated at 151 m a.s.l. between the towns of Raufarhöfn and Þórshöfn on the Melrakkaslétta peninsula in northeast Iceland (66°14.232′N, 15°50.083′W; Figs. 1–3; Table 1). This site is at or near the Preboreal (~11 ka) extent of the Icelandic ice sheet, and within the ice sheet's Younger Dryas limits (Norðdahl and Pétursson, 2005), so contains a younger record than does Torfadalsvatn. Mean July temperature at Raufarhöfn (Fig. 2) was 8.0 °C for the time period 1961–1990 (Veðurstofa Íslands, http://www.vedur.is).

Litla Viðarvatn (66°14.459′N, 15°48.457′W; 142 m a.s.l.; $Z_{max} = 2.5$ m, SA $= 0.2\,km^2$) sits only 0.7 km from Stora Viðarvatn, so the two lakes are subject to the same local climate, but Litla Viðarvatn is much smaller and shallower than Stora Viðarvatn (Fig. 3). Therefore, if the two lakes tell the same climatic story, we can say with some confidence that the chironomid records document climatic changes, rather than the effects of lake shallowing or other basin-specific edaphic or geomorphological changes. To our knowledge, this is the first study of Holocene lake sediments from the Melrakkaslétta. Northeastern Iceland is the part of Iceland most distal to North Atlantic waters today; thus this area may be especially sensitive to changes in ocean circulation.

Table 1
Lakewater Properties, North Iceland, Summer 2003

| Lake name | Max. depth (m) | Surface temp. (°C) | Temp. at 30 m depth (°C) | Conductivity (μs/cm) | Secchi depth (m) |
|---|---|---|---|---|---|
| Torfadalsvatn | 5.8 | 14.4 | N/A | 150 | 4.5 |
| Stora Viðarvatn | 48.0 | 9.8 | 7.8 | 60 | 7.7 |
| Litla Viðarvatn | 2.5 | 10.6 | N/A | 76 | Bottom |

Torfadalsvatn measurements taken on 24 June 2003; Viðarvötn measurements taken on 7 July 2003.

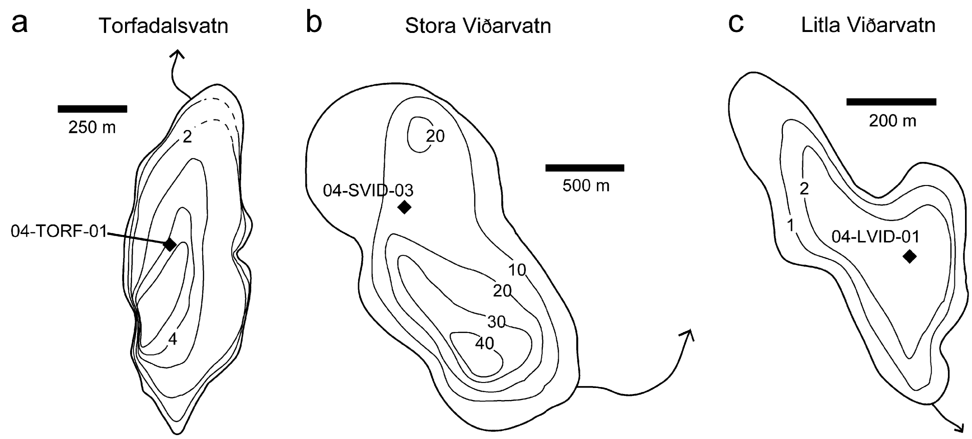


Fig. 3. Bathymetric maps of the three lake study sites. Coring sites are indicated by black diamonds, and outlet streams are shown as arrows. North is toward the top of the page for all maps, and depth contours are labeled in meters.

Table 2
Radiocarbon Ages from North Iceland Lakes

| Lab number[a] | Core name | Depth (cm) | Material | $\delta^{13}C$ | Fraction modern | $^{14}C$ age ($^{14}C$ yr BP) | Calibrated age (cal yr BP)[b] |
|---|---|---|---|---|---|---|---|
| AA60639 | 04-TORF-01 | 27.5 | Plant macro | −13.1 | 0.9553±0.0047 | 367±39 | 404±81 |
| NSRL-14520 | 04-TORF-01 | 120 | Plant macro | −26.5 | 0.8158±0.0018 | 1635±20 | 1539±19 |
| NSRL-14765 | 04-TORF-01 | 180 | Humic[c] | −19.3 | 0.7311±0.0014 | 2515±20 | 2618±101 |
| NSRL-14517 | 04-TORF-01 | 227.5 | Humic[c] | −17.4 | 0.6320±0.0010 | 3685±15 | 4031±49 |
| NSRL-14519 | 04-TORF-01 | 337.5 | *Betula* leaf | −4.7 | 0.4349±0.0010 | 6690±20 | 7551±31 |
| NSRL-14766 | 04-TORF-01 | 369 | Humic[c] | −18.5 | 0.3469±0.0006 | 8505+-16 | 9513±14 |
| NSRL-14518 | 04-TORF-01 | 432 | Humic[c] | −15.9 | 0.3221±0.0008 | 9100±25 | 10240±9 |
| AA60636 | 04-SVID-03 | 36.5 | Plant macro | −28.0 | 0.9585±0.0041 | 341±34 | 389±70 |
| NOSAMS-54832 | 04-SVID-03 | 177.5 | Plant macro | −19.7 | 0.7797±0.0123 | 2000±130 | 1975±342 |
| AA60637 | 04-SVID-03 | 346 | Plant macro | −29.6 | 0.6355±0.0030 | 3642±38 | 3978±87 |
| NOSAMS-54402 | 04-SVID-03 | 477.5 | Plant macro | −26.2 | 0.4867±0.0029 | 5780±50 | 6572±68 |
| NSRL-14521 | 04-SVID-03 | 584.5 | Plant macro | −23.6 | 0.3701±0.0014 | 7985±35 | 8883±105 |
| AA60638 | 04-SVID-03 | 731.5 | Plant macro | −25.2 | 0.3230±0.0040 | 9079±99 | 10277±126 |
| NSRL-14522 | 04-LVID-01 | 29.5 | Plant macro | −12.4 | 0.8139±0.0019 | 1655±20 | 1548±20 |
| AA60635 | 04-LVID-01 | 68 | Plant macro | −28.1 | 0.7808±0.0035 | 1988±36 | 1941±48 |
| NSRL-14523 | 04-LVID-01 | 180.5 | Plant macro | −26.7 | 0.6682±0.0013 | 3240±20 | 3443±33 |
| AA60634 | 04-LVID-01 | 304 | Plant macro | −27.6 | 0.4902±0.0026 | 5728±42 | 6533±84 |
| NSRL-14524 | 04-LVID-01 | 434.5 | Plant macro | −12.5 | 0.3674±0.0010 | 8045±25 | 8912±102 |

[a]Samples labeled AA were submitted to the Arizona Accelerator Mass Spectrometry Laboratory; samples labeled NSRL to the University of Colorado INSTAAR Laboratory for AMS Radiocarbon Preparation and Research; samples labeled NOSAMS to the National Ocean Sciences AMS facility at the Woods Hole Oceanographic Institution.
[b]Each calibrated age is the midpoint ±1/2 the 1$\sigma$ range calculated using CALIB 5.0.2 (Stuiver et al., 2005).
[c]Analysis of humic acids extracted from bulk sediment.

## 3. Materials and methods

### 3.1. Sediment cores and chronology

Percussion piston cores 5.4, 8.0 and 6.2 m long, respectively, were recovered from Torfadalsvatn, Stora Viðarvatn and Litla Viðarvatn in February 2004. All three cores are composed of faintly laminated lacustrine gyttja with numerous macroscopically visible layers of silt- and sand-sized tephra grains. The basal sediments of all three cores are inorganic finely laminated silts containing multiple tephra layers.

Age models for these cores are based on AMS $^{14}C$ ages (Table 2; Fig. 4) of *Betula* leaf fragments, unidentified plant macrofossils, and humic acids extracted from bulk sediments. All ages were calibrated using Calib v 5.0.2 (http://calib.qub.ac.uk/calib/; Stuiver et al., 2005), and are reported throughout this paper in thousands of calibrated years before present (ka). Humic acid ages on early- and middle-Holocene bulk sediments are statistically indistinguishable from macrofossil $^{14}C$ ages and tephrostratigraphic ages at Efstadalsvatn (in northwest Iceland; Axford, unpublished data) and Torfadalsvatn (Fig. 4); thus humic acid ages appear to accurately constrain the

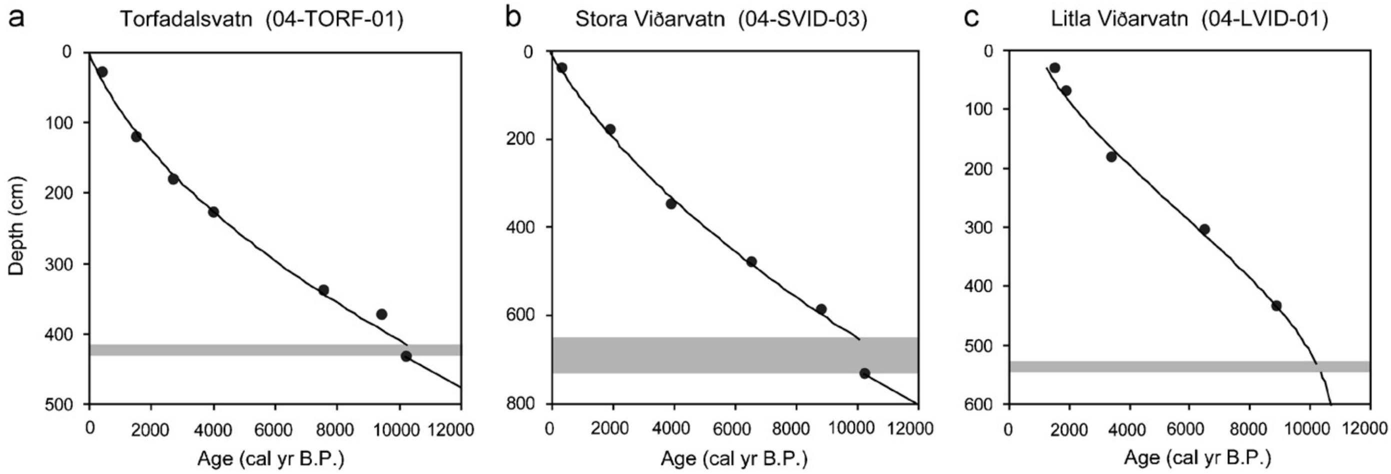


Fig. 4. Age models for the three sediment cores. Circles are $^{14}C$ ages (described in Table 2) and gray horizontal bars illustrate the depth and thickness of the 10.2 ka Saksunarvatn tephra.

ages of sediments from these lake systems during the early and middle Holocene. Preliminary results from other sites in Iceland suggest that humic acid ages may not be reliable for the late Holocene, when soils are better developed and more vigorous soil erosion may have delivered ancient soil carbon to the lakes, and/or may be problematic due to contamination of lakewater by geothermal waters (Sveinbjörnsdóttir et al., 1998; Geirsdóttir et al., 2006; Miller, unpublished data).

All three cores include the 10.18 ka (Mangerud et al., 1986; Birks et al., 1996; Andrews et al., 2002) Saksunarvatn tephra (identified based upon glass shard geochemistry and visible properties; G.E. Jóhannsdóttir, unpublished data), which is underlain and overlain by laminated lake sediments, and thus provides a minimum age for the onset of lacustrine sedimentation at all three lakes. The known age of the Saksunarvatn tephra is statistically indistinguishable from immediately underlying $^{14}C$ ages in both Stora Viðarvatn and Torfadalsvatn (Fig. 4), thus this tephra provides independent support of the $^{14}C$ chronology. Each of the cores contains between 12 and 15 additional macroscopically visible tephra layers, but these tephras have not yet been geochemically fingerprinted so are not used for geochronology in this study.

Sediment cores from Torfadalsvatn and Stora Viðarvatn appear to successfully capture near-modern surface sediments (as inferred from the zero *y*-intercept of their $^{14}C$ age models), and thus represent the entire Holocene. The core from Litla Viðarvatn apparently does not contain sediments from the last millennium (Fig. 4), either because the soft recent sediments were destroyed by the piston corer or because they are not preserved in the lake basin.

### 3.2. Midge taxonomy

Wet sediment samples for midge analysis were deflocculated in warm 5% KOH for 20 min, and rinsed on a 100-μm sieve. Head capsules were manually picked from a Bogorov sorting tray under a 40 × power dissecting microscope, then permanently mounted on slides using Euparal. All samples, except the bottom-most sample from the Torfadalsvatn core, contained at least 50 identifiable whole head capsules (the deepest Torfadalsvatn sample contained 9 *Oliveridia* and 1.5 *Metriocnemus fuscipes*-type head capsules). Taxonomic identifications followed Brooks et al. (2007), with reference to Oliver and Roussel (1983), Wiederholm (1983), and Rieradevall and Brooks (2001).

### 3.3. Temperature inferences

We estimated mean July air temperatures using a transfer function developed for northwestern and western Iceland (Langdon et al., in press). The temperature model is based upon calibration data from surface sediments of 51 lakes in northwest Iceland, and has been tested at two early Holocene sites in north-central Iceland (Caseldine et al., 2006). The two-component weighted-averaging partial least squares (WA-PLS) model has an $r^2_{\text{jack}}$ of 0.66 and a root mean squared error of prediction (RMSEP) of 1.10 °C. Paleotemperatures were modeled using the computer program C2 v 1.4.3 (Juggins, 2003). All but one of the taxa found downcore are represented in the training set. *Oliveridia* was not found at any of the calibration sites included in the transfer function (Langdon et al., in press), so this taxon was removed from downcore count sums and calibration data before modeling paleotemperatures. We note, however, that *Oliveridia* is known to occur in very cold, ultraoligotrophic lakes (e.g., Sæther, 1976; Brooks and Birks, 2004; Hrafnsdóttir, 2005; Francis et al., 2006), and thus where it is present *Oliveridia* provides a qualitative indicator of very cold conditions. It is likely that reconstructed temperatures would be lower for subfossil assemblages containing *Oliveridia* when included in temperature modeling. We did not obtain temperature inferences for the two deepest samples in Torfadalsvatn because each of these samples contained only two taxa (including *Oliveridia* for the bottom-most sample), and such low diversity is likely to yield spurious results.

The statistical software package R v 2.2.1 was used to calculate the squared-chord distance between each downcore assemblage and its closest analog in the calibration data. Except for the two deepest samples in Torfadalsvatn, all fossil samples (with *Oliveridia* omitted from count sums) were compared with the 51 calibration sites reported by Langdon et al. (in press).

Detrended correspondence analysis (DCA) was conducted on downcore taxonomic data independently for each of the three lakes. All taxa (including *Oliveridia*) were included, as were all samples except the bottommost sample from Torfadalsvatn, which yielded only 10.5 head capsules. DCA was performed using R v 2.2.1, with rare taxa down-weighted.

### 3.4. Qualitative proxies

Qualitative environmental proxies that are relatively fast to measure can be obtained at greater temporal resolution than the time-intensive chironomid data, and thus provide valuable supplementary information about changing paleoenvironments. Magnetic susceptibility provides a qualitative indication of sediment magnetic mineral content, and is useful for identifying the presence of tephra layers and changes in sediment organic content. Magnetic susceptibility was measured at 0.5-cm increments at the University of Minnesota Limnological Research Center using a Geotek Multi-Sensor Core Logger equipped with a Bartington point sensor. The organic carbon content of lake sediments is a function of aquatic and terrestrial productivity, and allochthonous sediment influx. Total carbon percent (%TC) was measured at the Earth Science Institute of the University of Iceland. Freeze-dried samples were run on a CM5200 Autosampler/Furnace (combusted to 950 °C) and measured on a CM5014 $CO_2$ Coulometer v 3.0 with a detection limit of 0.05 weight-percent. The samples are presumed to contain negligible $CaCO_3$, an assumption supported by comparisons with TC measurements on HCl-fumed samples. Biogenic silica ($BiSiO_2$) in lake sediments primarily comprises diatoms (Conley, 1988), and therefore provides a proxy for aquatic primary productivity, although $\%BiSiO_2$ is also determined by the influx of other materials. $BiSiO_2$ analysis at the University of Illinois followed Mortlock and Froelich (1989), except for the use of 10% $Na_2CO_3$ solution for $BiSiO_2$ extraction. A Spectronic Genesys 5 spectrophotometer was used to measure $BiSiO_2$ concentration, which was then converted to weight percent $SiO_2$ of dry sediments. Analytical precision of $BiSiO_2$ measurements was ~3%.

## 4. Results

Downcore changes in chironomid assemblages, organic carbon, and other parameters are shown in Figs. 5–7. The basal sediments of all three lakes are inorganic, finely laminated, and devoid of head capsules. In each of the cores, the oldest head capsules appear before 10 ka. Each lake contains a unique assemblage of midges and records significant faunal changes through the Holocene, as described below.

### 4.1. Torfadalsvatn

At Torfadalsvatn (Fig. 5), the pioneering assemblage was composed almost entirely of *Oliveridia*, a cold stenotherm that has been reported to dominate assemblages in modern ultraoligotrophic arctic lakes, including highly oligotrophic lakes in Iceland and a glacier-fed lake on Svalbard (Sæther, 1976; Brooks and Birks, 2004; Hrafnsdóttir, 2005). *Metriocnemus*, a primarily madicolous midge (dwelling for example in mosses, wet soils, and along stream margins in the highlands of Iceland today; Hrafnsdóttir, 2005) was the other major component of the assemblage. Together, these two taxa indicate very low lacustrine productivity.

The pioneering assemblage was replaced by an assemblage dominated by *Tanytarsus lugens*-type, which declined between 12 and 8.5 ka as a more diverse fauna developed. *Corynoneura arctica*-type reached peak abundance ~9.5 ka, and declined to very low abundances after 7 ka. *Psectrocladius sordidellus*-type appeared ~10.5 ka, shortly before the deposition of the Saksunarvatn tephra, and made up a significant part of the assemblage throughout the Holocene. Several relatively thermophilous taxa, including *Arctopelopia*-type, *Tanytarsus gracilentus*-type, and *Cricotopus* type P were absent in the early Holocene, appearing only after 7 ka or later. Organic carbon increased abruptly ~7.5 ka, and inferred temperatures rose gradually after that time.

The highest inferred temperatures occurred ~5 ka (with warmth generally sustained until ~1 ka), and the lowest inferred temperature was at ~0.5 ka, probably reflecting cold temperatures of the Little Ice Age. Squared-chord distances (SCDs) are lowest for the middle and late Holocene, indicating close modern analogs for the fossil assemblages, in contrast with relatively poor modern analogs for Lateglacial (pre-Saksunarvatn) assemblages.

### 4.2. Stora Viðarvatn

The early assemblage at Stora Viðarvatn (Fig. 6) was dominated by *Oliveridia*, which persisted until ~7.5 ka but is excluded from temperature inferences because its occurrence is not well constrained by the training set. *Pseudodiamesa*, *Cricotopus* type I, and *C. arctica*-type—cold indicators—were also present in the oldest samples, with *Pseudodiamesa* absent after ~8 ka. After 7 ka, *Heterotrissocladius* and *P. sordidellus*-type (a relatively thermophilous species) dominated the assemblage, and the proportion of *T. lugens*-type was generally low. *P. sordidellus*-type and *Paracladopelma* were most abundant in the middle Holocene, ~5–3.5 ka. *Chironomus* and *Orthocladius* type A were most abundant in the late

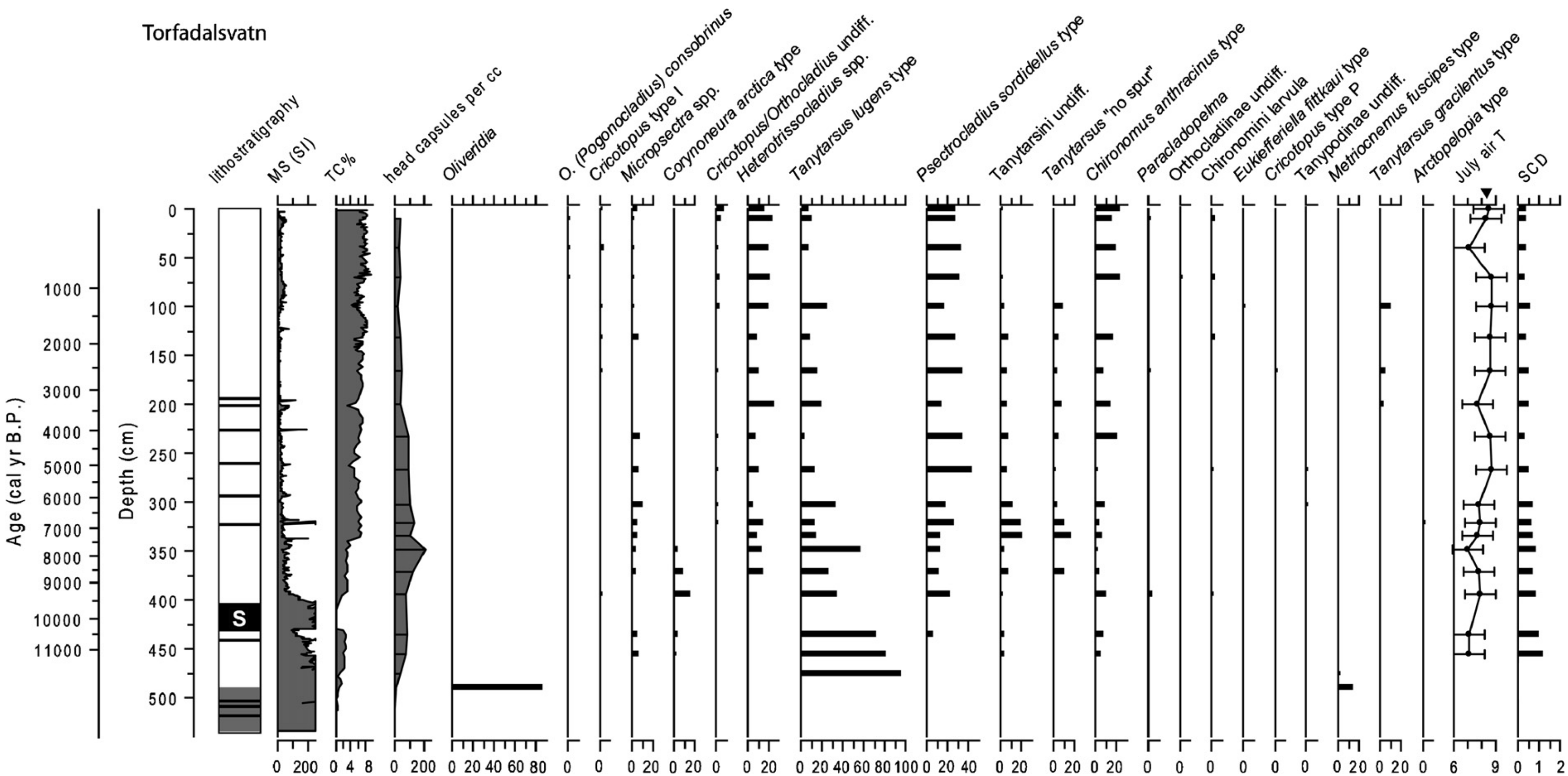


Fig. 5. Summary diagram of downcore data from Torfadalsvatn, including lithostratigraphy, MS, TC, head capsule concentrations, chironomid species percentages, chironomid-inferred temperatures, and squared-chord distances (SCDs) from closest modern analog. Black bands in lithostratigraphy are visible tephra layers (S = Saksunarvatn); the gray zone at the base of the core is stratified inorganic sediment; and the remainder (white) is organic gyttja. High MS values are truncated. Chironomid taxa are expressed as % of total identifiable head capsules. Error bars on the temperature plot are the model RMSEP (1.1 °C). The black triangle above the temperature plot indicates present-day mean July temperature (from the weather station at Hraun; see text).

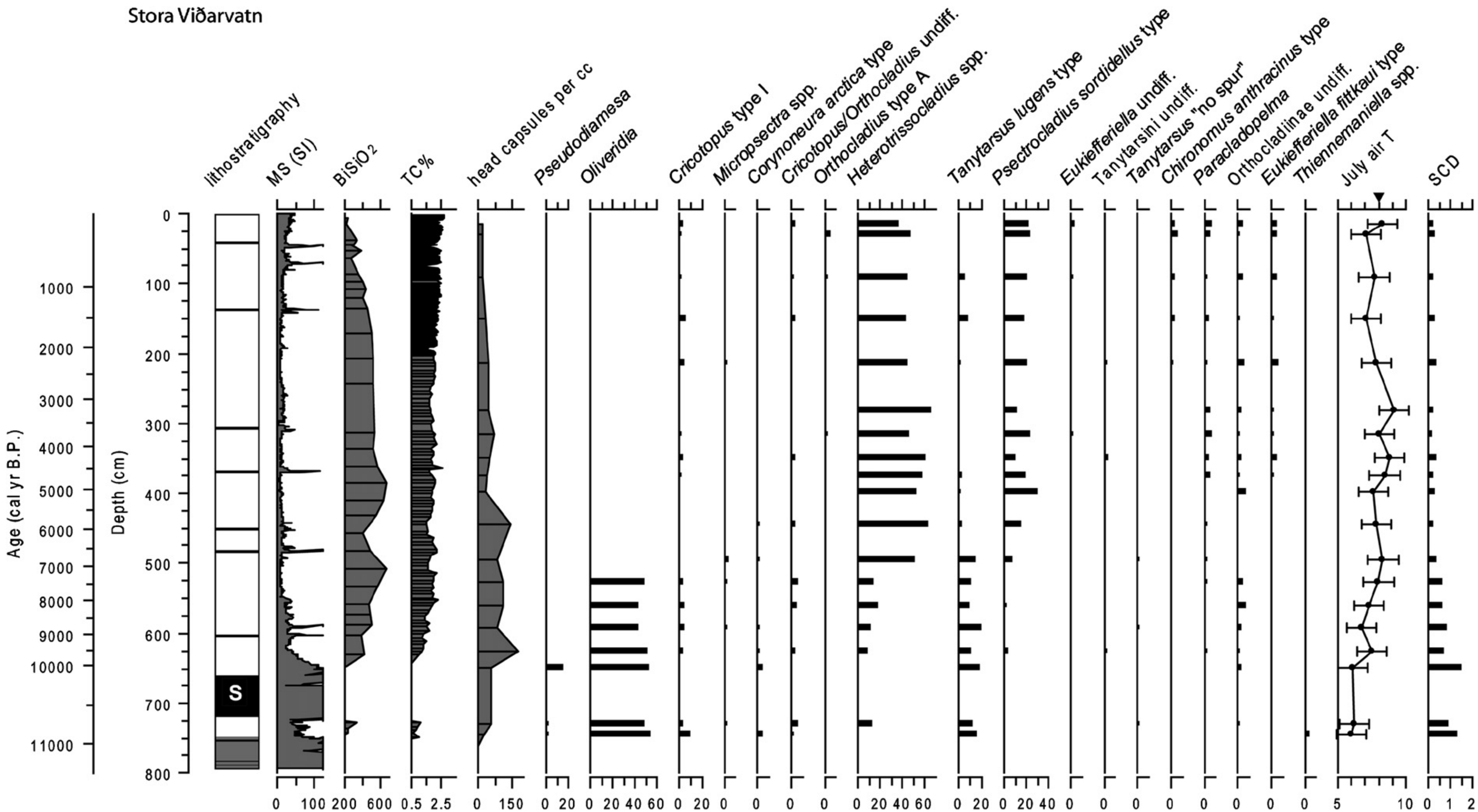


Fig. 6. Summary diagram of downcore data from Stora Viðarvatn, including lithostratigraphy, MS, $BiSiO_2$, TC, head capsule concentrations, chironomid species percentages, chironomid-inferred temperatures, and squared-chord distances (SCDs) from closest modern analog. Black bands in lithostratigraphy are visible tephra layers (S = Saksunarvatn); the gray zone at the base of the core is stratified inorganic sediment; and the remainder (white) is stratified organic sediment. High MS values are truncated. Chironomid taxa are expressed as % of total identifiable head capsules. Error bars on the temperature plot are the model RMSEP (1.1 °C). The black triangle above the temperature plot indicates present-day mean July temperature (from the weather station at Raufarhöfn; see text).

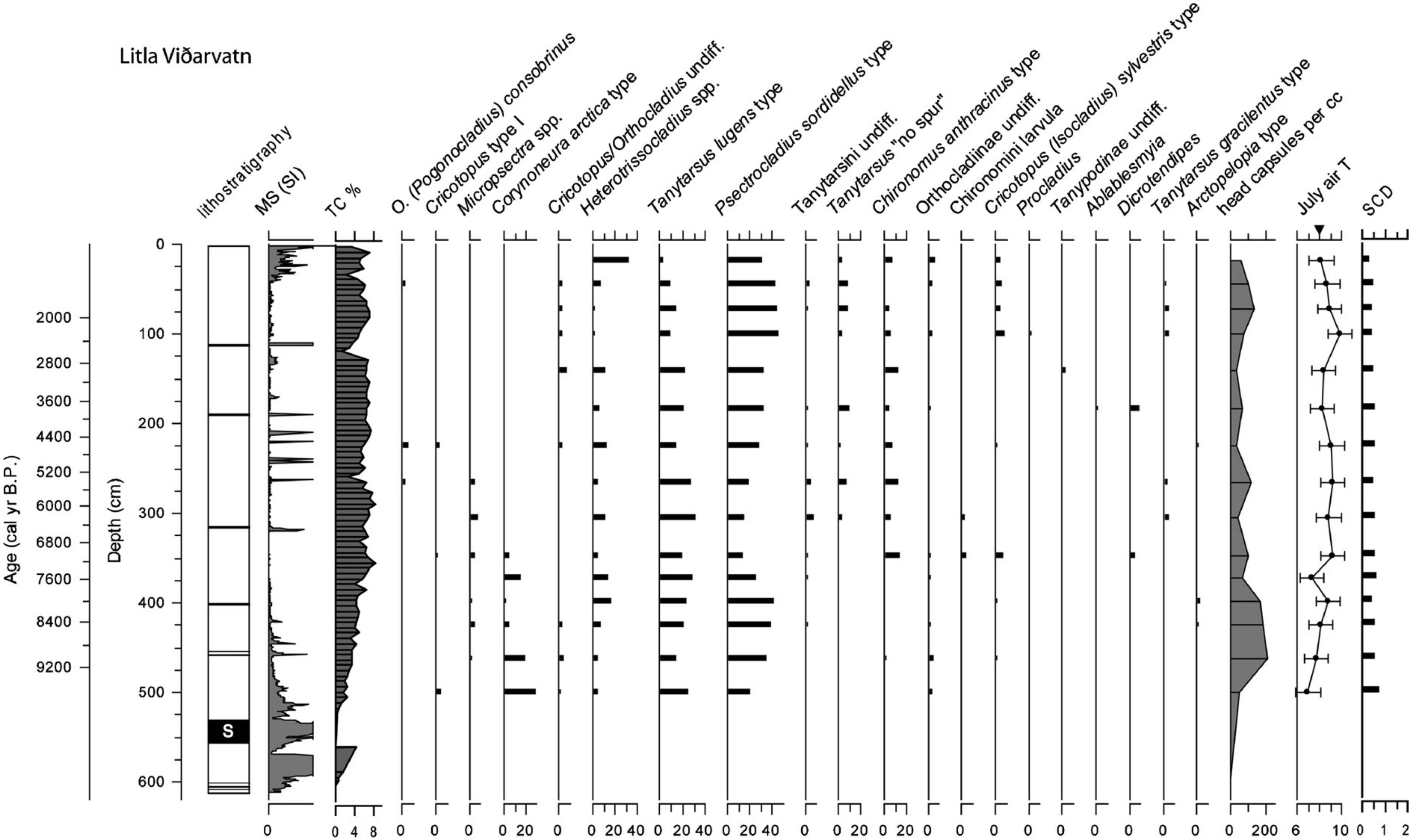


Fig. 7. Summary diagram of downcore data from Litla Viðarvatn, including lithostratigraphy, MS, TC, head capsule concentrations, chironomid species percentages, chironomid-inferred temperatures, and squared-chord distances (SCDs) from closest modern analog. Black bands in lithostratigraphy are visible tephra layers (S = Saksunarvatn), and the remainder (white) is organic gyttja. High MS values are truncated. Chironomid taxa are expressed as % of total identifiable head capsules. Error bars on the temperature plot are the model RMSEP (1.1 °C). The black triangle above the temperature plot indicates present-day mean July temperature (from the weather station at Raufarhöfn; see text).

Holocene, after ~4 ka. $BiSiO_2$ peaked ~5 ka, whereas %TC rose throughout the Holocene until ~2 ka.

Inferred temperatures at Stora Viðarvatn generally rose throughout the early and middle Holocene, with peak inferred warmth at 3.5 ka, followed by declining temperatures culminating in the Little Ice Age. The uppermost sample has a higher inferred temperature. Given the abundance of the cold stenotherm *Oliveridia* throughout the early Holocene, it is likely that inferred temperatures for the early Holocene would be even lower if *Oliveridia* was included in the temperature model. Like at Torfadalsvatn, SCDs are lowest (i.e., fossil assemblages have better analogs in the calibration data) in the middle and late Holocene.

### 4.3. Litla Viðarvatn

*T. lugens*-type and *P. sordidellus*-type were the most abundant taxa at Litla Viðarvatn throughout the Holocene (Fig. 7). *C. arctica*-type was abundant during the early Holocene, but disappeared after 7 ka. Cold indicators *Cricotopus* type I and *Micropsectra* were also most abundant in the early Holocene. *Chironomus* became relatively more important, and the thermophilous taxa *Dicrotendipes* and *Paratanytarsus* appeared, after ~7 ka. *Cricotopus sylvestris*-type *and T. gracilentus*-type became more abundant, and *Dicrotendipes* disappeared, ~2.5 ka. In general thermophiles, including Tanypodinae, *Dicrotendipes*, and *Paratanytarsus*, were most abundant between 7 and 2.5 ka. Peak inferred temperatures also occurred during this interval, with steady cooling inferred after 2.5 ka. Throughout the record, all samples have good analogs in the calibration data (i.e., low SCDs). Percent TC rose until ~7 ka, and did not show much change after that, except when tephra deposition diluted organic sedimentation.

### 4.4. "Consensus" temperature reconstructions

Because faunal changes at any single lake may be caused by lake-specific ontogenetic changes that are more-or-less independent of climate, it is important to consider the possibility that faunal changes observed in the sedimentary record were driven by lake-specific factors rather than regional temperature change (Velle et al., 2005; Brooks, 2006; Walker and Cwynar, 2006). In order to address this problem, this study compares records from three different lakes representing a range of lake depth, trophic status, and watershed properties. A summary of the inferred temperature histories from all three lakes reveals that inferred-temperature trends are similar between lakes, albeit with some differences, particularly in the late Holocene (Fig. 8).

"Consensus reconstructions," which combine data from several sites, summarize regional millennial-scale trends, and treat higher-frequency changes at individual sites as "noise" (e.g., Rosenberg et al., 2004; Velle et al., 2005). We generate a regional consensus reconstruction using a LOWESS smooth fit through the temperature estimates from all three lakes (expressed as deviations from the modern mean July temperature for each site; Fig. 9). LOWESS regression, commonly used in paleoecology, is a locally weighted least squares regression useful for identifying major trends in noisy time series. According to the consensus reconstruction, temperatures rose through the early and middle Holocene, with peak temperatures between 5 and 2.5 ka, followed by cooling that may have culminated in the Little Ice Age. The total range of July temperature variation through the Holocene in northern Iceland was at least 2 °C; this value is a minimum constraint because of the coarse temporal resolution of our analyses, with an average sampling interval of ~600 yr. The magnitude of warming over the Lateglacial to Holocene transition in particular is presumably underestimated

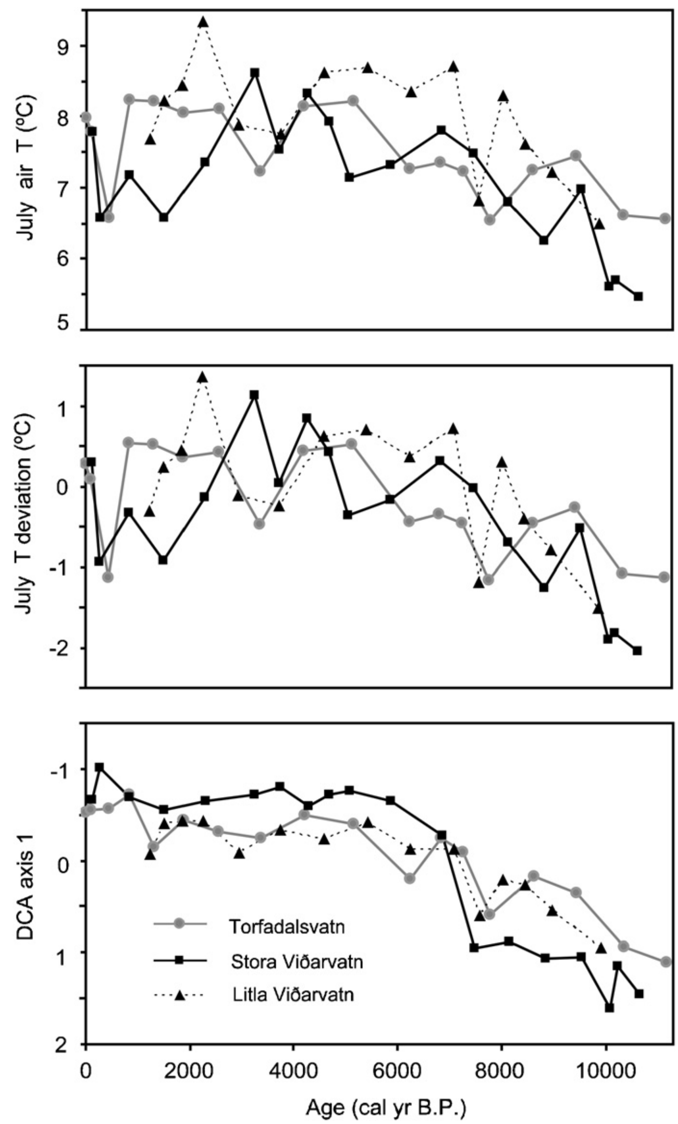


Fig. 8. Temperature inferences from the three study sites, expressed as: (a) July air temperature; (b) deviation from modern mean July temperature for each site; and (c) DCA axis 1 scores (in standard deviation units) for DCA analyses performed separately on taxonomic data from each lake.

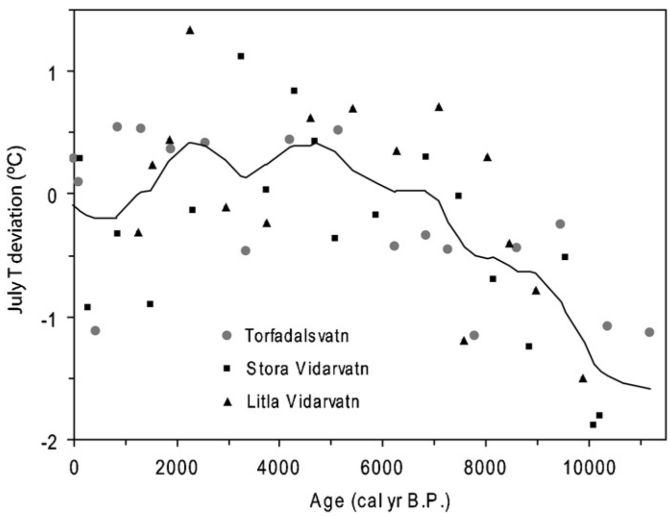


Fig. 9. Consensus temperature reconstruction. A single LOWESS smooth (span = 0.20) is fitted through combined temperature data from all three lakes.

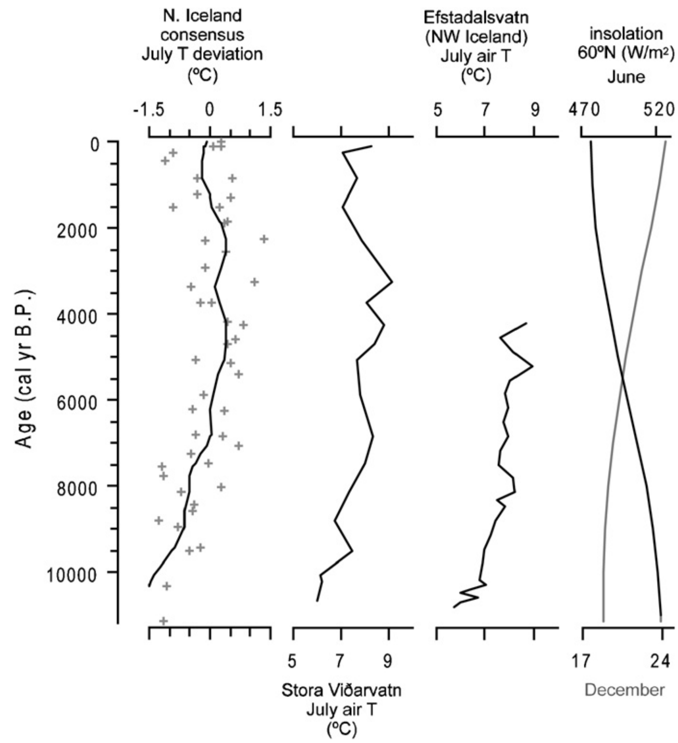


Fig. 10. Comparison of consensus temperature reconstruction for northern Iceland and chironomid-inferred temperatures from Stora Viðarvatn with chironomid-inferred temperatures from Efstadalsvatn (taxonomic data published by Caseldine et al., 2003; temperature inferences here use the Iceland training set of Langdon et al., in press; Holmes, 2006) and summer and winter insolation at 60°N (Berger and Loutre, 1991).

because we have excluded the cold stenotherm *Oliveridia* (abundant in Lateglacial and earliest Holocene sediments from Stora Viðarvatn and to a lesser extent Torfadalsvatn) from temperature reconstructions.

## 5. Discussion

The consensus temperature reconstruction (Fig. 9) and each of the individual lake records (Fig. 8) all indicate a general trend of gradual warming throughout the early and middle Holocene in northern Iceland, with peak warmth occurring at or after 5 ka. Inferred July air temperatures at all three sites were lower than present through the early Holocene. Midge data from the coastal lake Efstadalsvatn (Fig. 1) in northwestern Iceland (the longest midge record previously available for Iceland) indicate a similar pattern of gradual warming through the Holocene (Fig. 10; Caseldine et al., 2003; Holmes, 2006). Thus, data from four coastal lakes across northern Iceland record cooler-than-present temperatures in the early Holocene, despite enhanced insolation forcing (Fig. 10; Berger and Loutre, 1991) and widespread warmth around the Northern Hemisphere at this time (e.g., Kaufman et al., 2004). This surprising result will be further addressed in the last section of this Discussion.

Our chironomid data indicate that Neoglacial cooling began after ~3 ka in northeast Iceland. Nearly all terrestrial and marine records from north Iceland indicate that climate deteriorated in the last 2 to 3 ka. Polar waters exerted a greater influence on the North Iceland shelf and the Denmark Strait region, and hydrographic conditions were generally less stable (Andrews et al., 2001; Jiang et al., 2002; Andrews and Giraudeau, 2003; Andersen et al., 2004; Giraudeau et al., 2004; Moros et al., 2004; Ran et al., 2006). On land, Neoglacial cooling either began or intensified at many sites in the region around this time (e.g., Kaplan et al., 2002; Wastl and Stötter, 2005; although many records from Iceland indicate that Neoglacial cooling began in the mid-Holocene after 5 or 6 ka (e.g., Kirkbride and Dugmore, 2001, 2006; Wastl et al., 2001).

### 5.1. *Are chironomids recording temperature?*

As post-glacial landscapes have evolved over the Holocene, at some sites local factors such as changes in lake depth or trophic status have exerted stronger pressures on lake fauna than relatively low-amplitude Holocene temperature changes (e.g., Velle et al., 2005; Antonsson et al., 2006; Brodersen and Quinlan, 2006; Brooks, 2006; Walker and Cwynar, 2006). It is, therefore, important to consider whether faunal changes at our study sites might be primarily recording environmental changes other than temperature.

There are no obvious long-term trends in species trophic preference at any of our three study sites, and the relative abundance of profundal taxa at all three lakes remains quite steady throughout the Holocene. Furthermore, the three lakes show broadly similar inferred-temperature trends over time (Fig. 8), despite the fact that Stora Viðarvatn is a large, deep lake, which must have a very different ontogenetic history than the two shallower sites. The three lakes also show similar trends in their independently derived DCA scores (Fig. 8), despite the presence of unique assemblages in each lake. This indicates that major faunal shifts at the three lakes are occurring synchronously, and thus provides further evidence that midges are responding to regional climate rather than lake-specific environmental changes.

Another concern is whether the relatively thermophilous taxa (e.g., *Dicrotendipes* and *Paratanytarsus*) were absent from these sites in the early Holocene due to delayed postglacial colonization caused by Iceland's geographic isolation. If this was the case, then the absence of thermophilous taxa would artificially depress early Holocene temperature estimates. However, the presence of these thermophilous taxa, including *Dicrotendipes* and *Paratanytarsus,* in shallow lakes on the Tröllaskagi (located less than 120 km from each of the current study sites; Fig. 2) before 9.5 ka (Caseldine et al., 2006; Holmes, 2006) makes this scenario unlikely.

### 5.2. Spatial variability in early Holocene temperatures

Subdued early Holocene summer temperatures along the northern coast of Iceland stand in stark contrast with evidence that early Holocene summers were warmer than present in other parts of Iceland and in many parts of the Northern Hemisphere (e.g., Eiríksson et al., 2000; Wastl et al., 2001; Andersen et al., 2004; Castañeda et al., 2004; Kaufman et al., 2004; Smith et al., 2005; Hannesdóttir, 2006; Kaplan and Wolfe, 2006; Ran et al., 2006). Although the paleoceanographic history of Iceland's shelves is complex, there is a general consensus that advection of Atlantic water onto the west and North Iceland shelves was at a maximum during the early Holocene (Eiríksson et al., 2000; Andersen et al., 2004; Castañeda et al., 2004; Smith et al., 2005; Ran et al., 2006). Glacial deposits on Trolliskagi and in central Iceland record Neoglacial advances only after 5 or 6 ka (Gudmundsson, 1997; Stötter et al., 1999; Kirkbride and Dugmore, 2001, 2006; Wastl and Stötter, 2005). Palynological data indicate that early Holocene summers were warm enough to support birch woodlands and to allow birch treeline to reach higher elevations in parts of Iceland (Hallsdóttir, 1995; Wastl et al., 2001; Hallsdóttir and Caseldine, 2005). Ongoing paleolimnological studies of large lakes in southern and western Iceland also indicate peak aquatic productivity and reduced ice cap extent during the early to middle Holocene (Black et al., 2004; Hannesdóttir, 2006). Early Holocene chironomid records from two shallow lakes on the Tröllaskagi, ~100 km east of Torfadalsvatn and farther inland from the open ocean, indicate that temperatures rose ~4 °C between 10.5 and 7.5 ka (Caseldine et al., 2006). The Tröllaskagi records used the same chironomid-temperature transfer function as the present study, but the magnitude of inferred warming on Tröllaskagi over the recorded time period is at least twice that inferred for the current study sites. On the other hand, the warming trend itself is not inconsistent with our results, and the current study most likely underestimates the magnitude of deglacial warming because our temperature inferences do not reflect the prevalence of the cold stenotherm *Oliveridia* in Lateglacial/early Holocene sediments from two of our three study sites.

Cool early Holocene temperatures along the northern fringe of Iceland imply strong local modulation of insolation forcing, and an enhanced north–south temperature gradient across Iceland, with southern, western, and interior Iceland responding more directly to enhanced summer insolation. Sea ice conditions are one possible explanation: In historical times, when anomalous sea ice has formed along the north coast (e.g. during the Little Ice Age and the "Ice Years" of the late 1960s), coastal weather stations in northern and eastern Iceland have shown disproportionate cooling compared with the rest of Iceland (Ogilvie and Jónsson, 2001; Hanna et al., 2004). This has the effect of increasing the north–south temperature difference (between Grímsey and Vestmannaeyjar; Fig. 2) in late winter and early spring by as much as 8 °C versus ice-free years. Cold anomalies are apparently enhanced by greater vertical atmospheric stability during winters with sea ice (Ogilvie and Jónsson, 2001).

But is it possible that sea ice formed off North Iceland in the early Holocene, despite enhanced summer insolation forcing and strong northward advection of Atlantic waters? Atlantic waters flowing over the North Iceland shelf can be overlain by cold, fresh, low-density surface waters of the EIC (fed by the EGC). Strong salinity differences between the EIC and underlying Atlantic waters cause reduced convection and enhanced sea ice formation on the North Iceland shelf today (e.g., Hopkins, 1991). There is evidence that greater stratification over the North Iceland shelf has accompanied enhanced inflow of Irminger/Atlantic Intermediate water during parts of the Holocene (e.g., Giraudeau et al., 2004). Dinoflagellate assemblages indicate fresher surface waters off northern Iceland and East Greenland in the early Holocene (Solignac et al., 2006). A fresher or more vigorous EGC (both possible outcomes of enhanced freshwater flux into the Arctic and North Atlantic oceans from melting ice sheets in the early Holocene) and/or saltier Irminger waters would all favor stratification on the North Iceland shelf, and therefore formation of sea ice. Sea ice in turn would depress temperatures in northern Iceland (Ólafsson, 1999; Hanna et al., 2004) and enhance the north–south temperature gradient across Iceland. This scenario offers one plausible explanation for the observed spatial heterogeneity of early Holocene temperatures on Iceland, but there is clearly much left to be learned about Holocene climate variability in this important region.

## 6. Conclusions

Subfossil midge records from three coastal lakes in northern Iceland record relatively cool summer temperatures in the early Holocene, and gradual warming throughout the Holocene until 3.5 ka or later. Cooling at these sites in the last millennia of the Holocene was coincident with regional climatic deterioration and changes in oceanographic conditions on the North Iceland shelf. On the other hand, subdued early Holocene temperatures along the northern coastal fringe of Iceland stand in contrast to warmer-than-present temperatures inferred for other parts of Iceland in the early to middle Holocene, and suggest a strong north–south temperature gradient across Iceland at this time. Under present-day conditions, an enhanced north–south temperature gradient develops when sea ice forms off the north coast; one possible explanation for the pattern of early Holocene temperatures is that sea ice was more common off northern Iceland in the early Holocene, despite enhanced insolation forcing, due to greater freshwater influx and/or stratification over the North Iceland shelf.

Because of the coarse temporal resolution of midge analyses for this study, we are limited to reconstructing sub-millennial-scale temperature trends, and have therefore certainly underestimated the frequency, and probably also the maximum amplitude, of Holocene temperature variability in Iceland. Future work at the study sites will aim to reconstruct higher-frequency variability (e.g., Caseldine et al., 2006). Iceland should be an ideal setting for evaluating the terrestrial impacts of quasi-periodic millennial-scale North Atlantic Ocean variability (e.g., Bond et al., 2001) and abrupt perturbations in North Atlantic sea surface conditions (e.g., Alley and Ágústdóttir, 2005; Lund et al., 2006) during the Holocene.

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