

# Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies

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**Abstract** A sedimentary record from lake Stora Viðarvatn in northeast Iceland records environmental changes over the past 2000 years. Downcore data include chironomid (Diptera: Chironomidae) assemblage data and total organic carbon, nitrogen, and biogenic silica content. Sample scores from detrended correspondence analysis (DCA) of chironomid

assemblage data are well correlated with measured temperatures at Stykkishólmur over the 170 year instrumental record, indicating that chironomid assemblages at Stora Viðarvatn have responded sensitively to past temperature changes. DCA scores appear to be useful for quantitatively inferring past temperatures at this site. In contrast, a quantitative chironomid-temperature transfer function developed for northwestern Iceland does a relatively poor job of reconstructing temperature shifts, possibly due to the lake's large size and depth relative to the calibration sites or to the limited resolution of the subfossil taxonomy. The pre-instrumental climate history inferred from chironomids and other paleolimnological proxies is supported by prior inferences from historical documents, glacier reconstructions, and paleoceanographic studies. Much of the first millennium AD was relatively warm, with temperatures comparable to warm decades of the twentieth century. Temperatures during parts of the tenth and eleventh centuries AD may have been comparably warm. Biogenic silica concentrations declined, carbon:nitrogen ratios increased, and some chironomid taxa disappeared from the lake between the thirteenth and nineteenth centuries, recording the decline of temperatures into the Little Ice Age, increasing soil erosion, and declining lake productivity. All the proxy reconstructions indicate that the most severe Little Ice Age conditions occurred during the eighteenth and nineteenth centuries, a period historically associated with maximum sea-ice and glacier extent around Iceland.

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## Introduction

Instrumental temperature records provide a useful but limited perspective on current climate change, given that for most parts of the globe they do not extend back further than the late nineteenth century. At high latitudes, the instrumental record is especially limited (e.g. Overpeck et al. 1997; ACIA 2004). Recent data compilations for the past millennium have provided useful perspectives on the significance of present-day climate changes (e.g. Overpeck et al. 1997; Jones et al. 1998; Mann et al. 1999; Moberg et al. 2005; Osborn and Briffa 2006), but these studies intrinsically reduce the apparent spatiotemporal variability of past climate. A large and spatially resolved database of temporally detailed, well-dated climate reconstructions for recent millennia is needed in order to answer questions about the causes of natural climate change, climate sensitivity, and spatial patterns of the climate response to past forcings.

A number of paleoclimate proxies have demonstrated utility for reconstructing late Holocene temperature changes with both climatic and temporal precision (for example, tree-ring width and density and varve thickness in lake sediments; e.g. Hughen et al. 2000; Briffa et al. 2001; Jones and Mann 2004). Other promising proxies have not been thoroughly tested in the context of the Holocene, and as such it is unknown how reliably they record low-amplitude or short-lived climate changes. The study presented here tests the utility of a biological proxy—subfossil chironomid assemblages (Diptera: Chironomidae, or non-biting midges)—for reconstructing low-amplitude Holocene temperature changes.

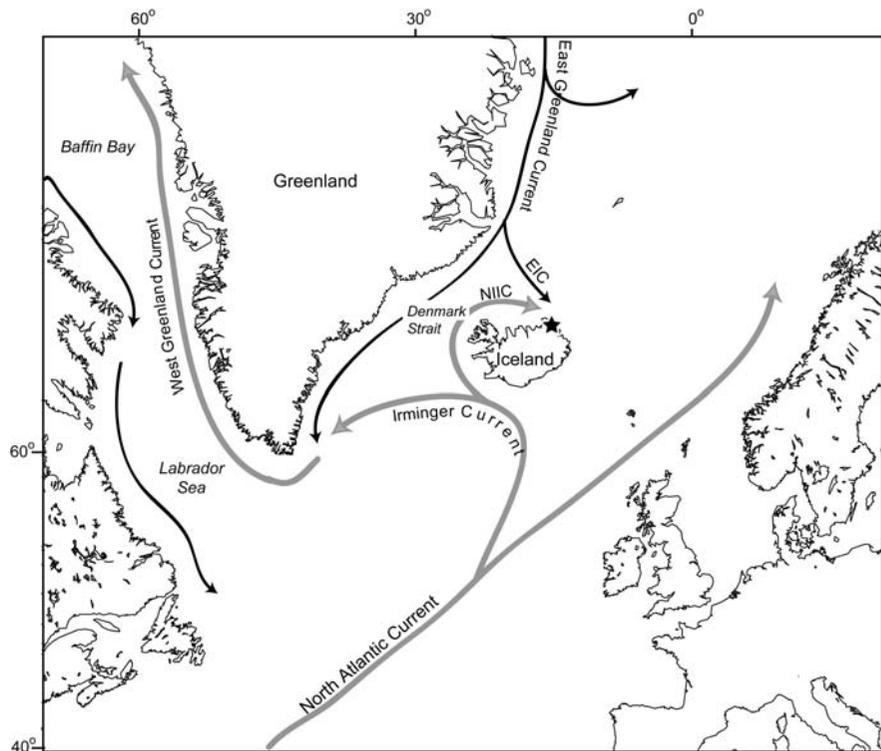
The sensitivity of chironomid species distributions (and thus subfossil chironomid assemblages) to temperature has been inferred based upon statistical relationships between temperature and species distributions in modern training sets (e.g. Walker et al. 1997, 2003; Lotter et al. 1999; Brooks and Birks 2001; Larocque et al. 2001; Barley et al. 2006; Francis et al. 2006; Langdon et al. 2008). Multi-proxy downcore studies have supported this inference, although with caveats regarding the influence of other factors including oxygen availability, lake

ontogeny and catchment soil development (e.g. Velle et al. 2005; Antonsson et al. 2006; Anderson et al. 2008; Brodersen et al. 2008). These caveats may be especially important for Holocene reconstructions, which are challenged by lower “signal-to-noise” ratios than studies reconstructing, for example, late-glacial temperature fluctuations (e.g. Velle et al. 2005; Brooks 2006; Walker and Cwynar 2006).

Few studies have assessed the sensitivity of chironomids based on comparisons with meteorological time series, primarily due to the dearth of long instrumental climate records and the relatively low temporal resolution of most chironomid studies. In a pioneering study, Larocque and Hall (2003) compared chironomid-inferred temperatures from lake sediments with twentieth-century instrumental temperature time series in northern Sweden and found strong coherence between the two, confirming the sensitivity and rapid response of chironomid assemblages to low-amplitude temperature changes in that region. More recently, Larocque et al. (2008) found good correspondence between instrumental temperature changes and temperatures reconstructed from chironomids in varved sediments of a Swiss lake. Total phosphorus and precipitation also appeared to affect chironomid assemblages and resulting temperature inferences at the Swiss site. Holmes (2008) concluded that the pattern and amplitude of chironomid-inferred temperature changes at two Icelandic lakes in the nineteenth and twentieth centuries compared well with meteorological data, although absolute temperatures were generally underestimated.

Like Holmes (2008), our study exploits Iceland’s unusually long meteorological record, which provides more than 170 years of overlap with downcore data, to test whether chironomids are sensitive and reliable indicators of temperature changes on Iceland. We then use chironomid assemblages alongside complementary paleoenvironmental proxies to reconstruct climatic and environmental changes in northeast Iceland over the past 2000 years. Northern Iceland (Fig. 1) is an ideal terrestrial site to record oceanographic changes of global importance, including those associated with changes in the convective strength of the thermohaline circulation (e.g. Curry and Mauritzen 2005); thus records from Iceland may contribute to understanding the role of the thermohaline circulation in regional and global climate change, e.g. cooling during the Little Ice Age (e.g. Broecker 2000).

**Fig. 1** The North Atlantic region, showing major ocean surface currents around Iceland and location of the study site Stora Viðarvatn (*black star*). EIC, East Iceland Current; NIIC, North Iceland Irminger Current



### Study site

Stora Viðarvatn (maximum depth  $Z_{\max} = 48.0$  m, surface area  $SA = 2.4$  km<sup>2</sup>) is situated at 151 m asl between the towns of Raufarhöfn and Þórshöfn on the Melrakkaslétta peninsula in northeast Iceland (66°14.232' N, 15°50.083' W; Figs. 1 and 2), 4.5 km from the bay of Þistilfjörður. Lake bathymetry is shown in Fig. 2.

Stora Viðarvatn had a surface water temperature of 9.8°C, conductivity of 60  $\mu\text{s cm}^{-1}$ , and Secchi depth of 7.7 m in July 2003 (Axford et al. 2007). The lake was not thermally stratified at this time, presumably due to mixing by strong winds. The lake is surrounded by open heath vegetation with scattered shrub birch and willow. Catchment soils are andosols with volcanic and eolian parent materials (e.g. Arnalds 2004). Mean August temperature at Raufarhöfn (23 km north of Stora Viðarvatn; Fig. 2) was 8.0°C, and mean annual temperature (MAT) was 2.0°C, for the time period 1961–1990 (Veðurstofa Íslands, <http://www.vedur.is>). August temperature over the past decade (1996–2006) averaged 9.6°C.

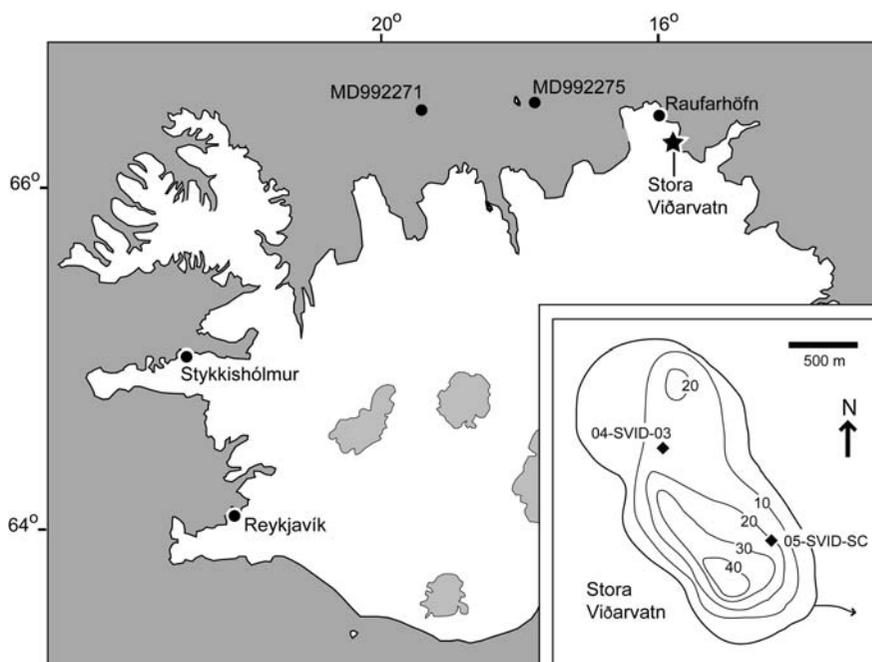
Temperatures have been recorded at Raufarhöfn since AD 1931 (Veðurstofa Íslands). Temperatures have been recorded at Stykkishólmur in western Iceland (Fig. 2) since AD 1845, and earlier data from Reykjavík have been used to extend the Stykkishólmur time series back to 1823 AD (Jónsson 1989). Although the long-term trends at the two sites are similar, Raufarhöfn is colder overall than Stykkishólmur, reflecting this northeasterly site's proximity to colder surface ocean waters derived from the polar East Greenland Current.

### Materials and methods

#### Coring and geochronology

In summer 2005, an 85-cm-long surface core (05-SVID-SC) was obtained from 20.6 m water depth in Stora Viðarvatn (Fig. 2) using a percussion-driven Universal coring device from Aquatic Research Instruments (Hope, Idaho, USA). The surface core, which captured the watery uppermost sediments intact, was subsectioned vertically into 0.5 cm slices

**Fig. 2** Map of Iceland, showing location of Stora Viðarvatn (black star) and other sites mentioned in the text (black circles). Gray areas on the island are modern ice caps. Inset bathymetric map of Stora Viðarvatn shows locations of the two coring sites (bathymetric contours in meters)



(for the upper 10 cm) and 1 cm slices (for the remainder) in the field.

The age model for the core is based on  $^{210}\text{Pb}$  (for the uppermost sediments) and AMS  $^{14}\text{C}$  analyses. Radiocarbon results were calibrated using Calib v 5.0.2 (<http://calib.qub.ac.uk/calib/>; Stuiver et al. 2005), and are reported throughout this paper as years AD. Alpha spectroscopy was used to determine  $^{210}\text{Pb}$  activity, and sediment  $^{210}\text{Pb}$  age was calculated by applying the constant-rate-of-supply (CRS) model to the unsupported  $^{210}\text{Pb}$  inventory (Appleby and Oldfield 1978).

Because this study specifically aimed to reconstruct paleoenvironmental changes of the past 2000 years, paleoenvironmental proxy data from the surface core (which extends back  $\sim 1300$  years) were spliced with  $\sim 700$  years of data from the late Holocene portion of a piston core that was recovered from the lake in 2004. This strategy is described further in the Results section below, and the chronology and stratigraphy of the piston core (04-SVID-03) are described by Axford et al. (2007).

#### Chironomid taxonomy, ordination, and temperature modeling

Paleolimnological studies have confirmed that chironomid distributions respond quickly to climate

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 2000; Cwynar and Spear 2001; Korhola et al. 2002; Brooks and Birks 2004; Heiri et al. 2004; Caseldine et al. 2006; Porinchi et al. 2007; Thomas et al. 2008). 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; Holmes 2008; Larocque et al. 2008). 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 (Hrafnadóttir 2005). Nevertheless, prior studies have demonstrated the utility of chironomids for reconstructing Holocene temperatures on Iceland (Caseldine et al. 2003, 2006; Holmes 2008).

For chironomid analysis, wet sediment samples were deflocculated in warm 5% KOH for 20 min, and rinsed on a 100  $\mu\text{m}$  sieve. Head capsules were

manually picked from a Bogorov sorting tray under a 40× power dissecting microscope, then permanently mounted on slides using Euparal (Walker 2001). All samples contained at least 45 identifiable whole head capsules, thus were assumed to contain representative count sums (e.g. Heiri and Lotter 2001; Quinlan and Smol 2001). Taxonomic identifications followed Brooks et al. (2007) and Langdon et al. (2008), with reference to Oliver and Roussel (1983), Wiederholm (1983), and Rieradevall and Brooks (2001).

Langdon et al. (2008) developed a chironomid-temperature transfer function based upon calibration data from surface sediments of 51 lakes in north-western and western Iceland. The model has been used to infer temperatures at two early Holocene sites in north-central Iceland (Caseldine et al. 2006) and for Holocene records from Stora Viðarvatn and two other north Iceland lakes (Axford et al. 2007). 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 1.1°C. Transfer-function-modeled paleotemperatures were calculated using the computer program C2 v 1.4.3 (Juggins 2003). All of the subfossil taxa found in the late Holocene records presented herein are represented in the training set. Detrended correspondence analysis (DCA) was conducted on downcore taxonomic data (untransformed percentage data) using the statistical software package R v 2.5.1. Rare taxa (with maximum abundance <2%) were excluded from the DCA. Linear regressions of instrumental temperatures versus DCA scores were also modeled in R.

### Complementary proxies

The organic carbon content of lake sediments is a function of aquatic and catchment productivity, influx of inorganic sediment, and preservation. The ratio of C to N in lake sediments can be related to the proportion of terrestrial versus aquatic organic material in the sediments (Kaushal and Binford 1999; Meyers and Teranes 2001). Total C and N were analyzed in freeze-dried bulk sediments combusted to CO<sub>2</sub> and N<sub>2</sub> at 1000°C in an on-line elemental analyzer (PDZEuropa ANCA-GSL). CO<sub>2</sub> was separated on a Carbosieve G column before introduction to a continuous flow isotope ratio mass spectrometer for measurement of  $\delta^{13}\text{C}$ .

Biogenic silica (BSi) in lake sediments primarily comprises diatoms (Conley 1988), and therefore provides a proxy for aquatic primary productivity, although as a percentage by sediment mass, BSi is also influenced by the influx of other materials and by preservation (e.g. Colman et al. 1995). Freeze-dried bulk-sediment samples were analyzed for BSi following the methods described by Mortlock and Froelich (1989), except for the use of 10% Na<sub>2</sub>CO<sub>3</sub> solution for BSi extraction. A HACH DR/2000 spectrophotometer was used to measure BSi concentration, which was then converted to weight percent SiO<sub>2</sub> of dry sediments. Percent mineral matter was estimated as the residual of (%C/0.4) + %BSi.

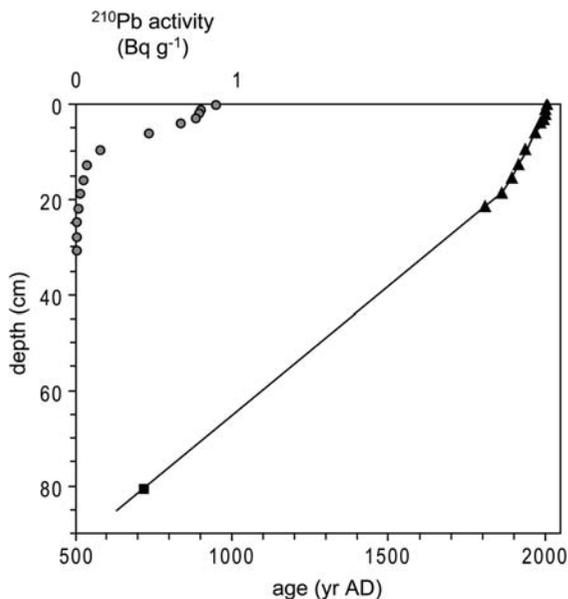
## Results<sup>1</sup>

### Chronology

The geochronology for the Stora Viðarvatn surface core (05-SVID-SC) includes a CRS model for the upper 22 cm of the core based upon <sup>210</sup>Pb data, and a linear interpolation between the base of the CRS model and one <sup>14</sup>C age on a terrestrial macrofossil (*Betula* leaf) recovered from 81 cm depth (Fig. 3). No other macrofossils were found for dating, and bulk sediments were not sampled for <sup>14</sup>C analyses because late Holocene lake sediments on Iceland have been shown to contain substantial reworked soil carbon, hundreds to thousands of years old (Geirsdóttir et al. this volume). Based upon this chronology, the core records the period from approximately 700 to 2005 AD, with an average wet sedimentation rate of 0.6 mm yr<sup>-1</sup>.

As mentioned in the Materials and Methods section above, this study splices data from the surface core with data from a longer piston core. Piston coring disturbed the uppermost sediments, such that the piston core is inappropriate for examining the last several centuries; sediments predating ~1600 AD in

<sup>1</sup> All of the geochronological and proxy data presented in this study are available online through the World Data Center for Paleoclimatology (<ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/europe/iceland/stora-vidarvatn2008.txt>).



**Fig. 3** Total  $^{210}\text{Pb}$  activity (circles),  $^{210}\text{Pb}$ -CRS ages (triangles) and  $^{14}\text{C}$  age (square) from the 85-cm-long Stora Viðarvatn surface core. The  $^{14}\text{C}$  age is lab no. CURL-8196, 0.48 mg graphite,  $\delta^{13}\text{C} = -28.3\text{‰}_{\text{PDB}}$ , fraction modern =  $0.8502 \pm 0.0014$ , age =  $1305 \pm 15$   $^{14}\text{C}$  year BP, calibrated age =  $715 \pm 53$  AD (midpoint  $\pm$  half the  $2\sigma$  range)

this core appear to be stratigraphically intact (Axford et al. 2007). Results from the piston core are presented for years 0–670 AD. The geochronology of the piston core, which is based primarily upon macrofossil  $^{14}\text{C}$  ages, is described in Axford et al. (2007) and includes two macrofossil  $^{14}\text{C}$  ages younger than 2000 years ( $390 \pm 70$  and  $1975 \pm 340$  cal year BP). Splicing of data from the two cores was based entirely upon the cores' independent geochronologies. There are no major jumps or breaks in the proxy data where the two records meet, providing independent support for this splicing strategy.

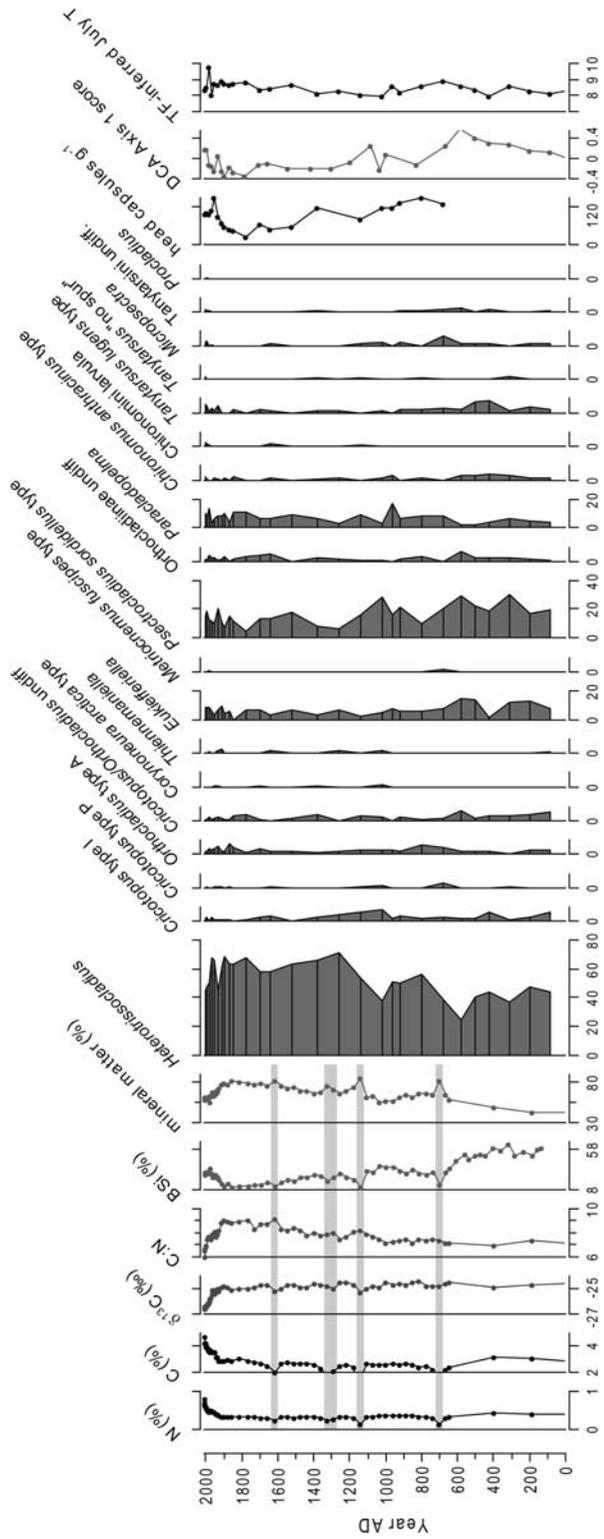
Because the cores were collected from different locations within the lake, with slightly different water depths (Fig. 2), subfossil chironomid assemblages might differ between the sites due to differences in resident faunal populations as well as taphonomic processes (e.g. Heiri et al. 2003). On the other hand, Holmes (2006) found that subfossil assemblages in surface sediments from lake Baulárvallavatn in western Iceland ( $Z_{\text{max}} = 45.6$  m,  $SA = 1.2$  km<sup>2</sup>) showed little variation around the lake despite sampling at a wide range of water depths. Substrate

was the most significant predictor of within-lake variability in “modern” (surface-sediment) subfossil assemblages in the Icelandic lakes studied by Holmes (2006). Proxy data from Stora Viðarvatn indicate that our two sampling sites have very similar substrates. There is some change in the chironomid assemblage at the break between the two records, e.g. a drop in the abundance of *Eukiefferiella*. On the other hand, more major changes including a decline in *Psectrocladius sordidellus* type and increase in *Heterotrissocladius* occur shortly above the break between records (i.e. within the surface core), suggesting that changes at or near the break between records are part of a faunal shift that occurred across the lake over a period of time. The lack of a major faunal break at the transition between the two records supports the conclusion that the two sites provide equivalent representations of the lake's overall chironomid assemblage.

### Chironomids

The most abundant chironomid taxa in the core are *Heterotrissocladius*, which composes up to 71% of the assemblage, and *P. sordidellus* type, with a maximum relative abundance of 31% (Fig. 4). Other important taxa include *Paracladopelma*, *Eukiefferiella fittkaui* type, *Cricotopus* type I, *Orthocladius* type A, and *Tanytarsus lugens* type. Minor taxa that are present throughout much of the record include *Micropsectra*, *Chironomus anthracinus* type, and undifferentiated *Cricotopus/Orthocladius*, Orthocla-diinae, and Tanytarsini. Other types (*Cricotopus* type P, *Corynoneura arctica* type, *Metricnemus fuscipes* type, and *Procladius*) are present in a few samples. Head capsule concentrations vary from 24 to 148 head capsules per gram in the surface core, with minimum abundances in the sixteenth through nineteenth centuries.

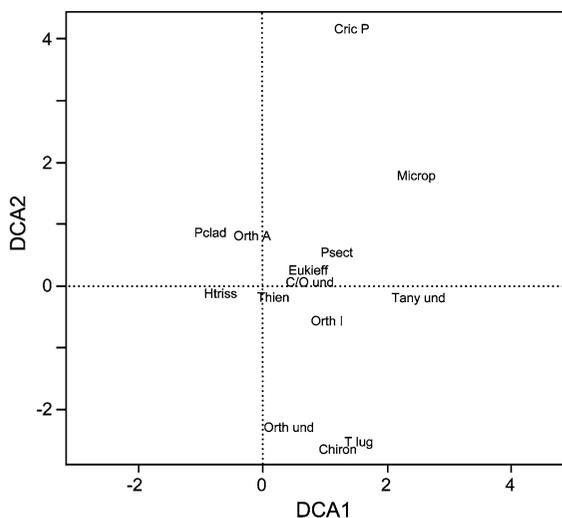
Chironomid assemblages at Stora Viðarvatn show shifts in relative abundance over the last 2000 years, although the same taxa occur throughout most of the record. Changes in the relative abundances of several important taxa show coherency through time, and correspondence with the complementary proxies described above. The cold indicator *Heterotrissocladius* was more abundant in the second millennium than the first, particularly after 1200 AD. Conversely, *P. sordidellus* type, an indicator of



**Fig. 4** Downcore data from Stora Vidarvatn. Qualitative paleoenvironmental proxies (nitrogen and carbon contents,  $\delta^{13}\text{C}$ , C:N, biogenic-silica content (BSi), and mineral-matter content), percentages of all identified chironomid taxa, chironomid head-capsule concentrations, Axis 1 scores from detrended correspondence analysis (DCA) of chironomid data, and July air temperatures inferred using the Langdon et al. (2008) transfer function. Horizontal gray bands indicate inferred, but unidentified, tephra layers

relative warmth in Icelandic records (Axford et al. 2007; Langdon et al. 2008), was generally more abundant in the first than second millennium AD. *C. anthracinus* type was also generally more abundant through the first millennium. *Micropsectra* disappeared just before 1200 AD, then reappeared in one sample at 1700 AD, and occurred throughout the twentieth century.

Transfer-function-modeled temperatures show little variation through the record (Fig. 4), except for one anomalously warm data point. Axis 1 of the detrended correspondence analysis (DCA) of the chironomid data explains 34% of the variance, and Axis 2 explains 11%. Only Axis 1 scores are discussed here. The DCA scores for Stora Viðarvatn reflect the changes in relative abundances of the two major chironomid types, *Heterotrissocladius* and *P. sordidellus* type, but are also influenced by variations in other taxa. Species with the highest positive loadings on Axis 1 are the Tanytarsini (including *Micropsectra* and *T. lugens* type), *Cricotopus* type P, *C. anthracinus* type, and *P. sordidellus* type (Fig. 5). Species with the highest negative



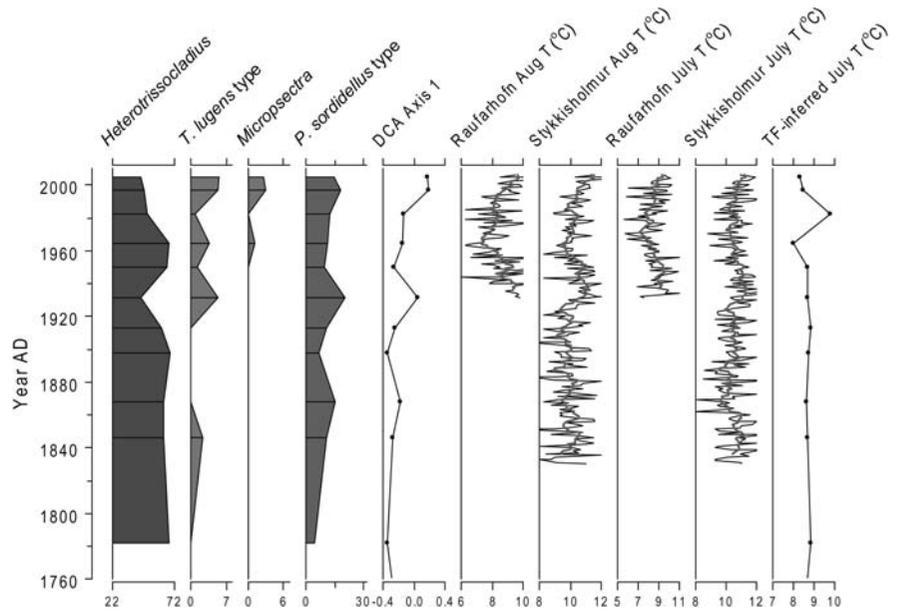
**Fig. 5** Biplot of species scores from detrended correspondence analysis (DCA). Rare taxa (with maximum abundance <2%) were excluded from the analysis. Taxonomic names are abbreviated as follows: Chiron, *Chironomus anthracinus* type; Cric P, *Cricotopus* type P; C/O und, *Cricotopus/Orthocladius* undifferentiated; Eukieff, *Eukiefferiella*; Htriss, *Heterotrissocladius*; Microp, *Micropsectra*; Orth A, *Orthocladius* type A; Orth I, *Cricotopus* type I; Orth und, Orthoclaadiinae undifferentiated; Pclad, *Paracladopelma*; Psect, *Psectrocladius sordidellus* type; T lug, *Tanytarsus lugens* type; Tany und, Tanytarsini undifferentiated; Thien, *Thienemanniella*

loadings on Axis 1 are *Paracladopelma* and *Heterotrissocladius*. DCA sample scores were relatively high until 700 AD, then (except for one sample with a high score at 1000 AD) declined to a minimum in the eighteenth century (Fig. 4). Scores for two samples near the surface of the core (younger than 1990 AD) are the highest of the past millennium.

#### Complementary proxies

The total percentages of C and N in Stora Viðarvatn bulk sediments are quite stable through most of the record (Fig. 4), except in the uppermost sediments and at discrete depths where low abundances of C, N, and BSi probably reflect the presence of tephra layers (e.g. at approximately 1100 AD). C and N contents both double in the uppermost (twentieth century) sediments. Although the percentages of these elements did not change markedly until the twentieth century, subtle trends in their relative abundances over time are revealed when the data are presented as the ratio of C to N. C:N increased from 7 to 9 through the second millennium AD, then declined abruptly after 1910 AD, with a second step down after 1980 AD. The isotopic composition of C in bulk sediments is quite stable through most of the record, except for changes in the twentieth century, and apparent excursions in  $\delta^{13}\text{C}$  at depths corresponding to presumed tephra layers (most likely these excursions reflect difficulties in measuring isotopic composition in sediment with low C content). Sediment  $\delta^{13}\text{C}$  declined abruptly from  $-25\text{‰}$  to nearly  $-27\text{‰}$  after 1950 AD. BSi was very abundant (up to 51%) in bulk sediments through much of the first millennium, then generally declined through the nineteenth century, except for a rise in values in the tenth century. BSi rose from 11% to as high as 35% in the twentieth century. Percent mineral matter rose gradually throughout the record, except for a slight decline around 1000 AD and an abrupt drop through the twentieth century. Apparent changes in sediment composition (e.g. C content) in the uppermost few centimeters of a core may result from oxidation of organic matter in underlying sediments. However, many of the recent changes in sediment composition at Stora Viðarvatn began as deep as  $\sim 14$  cm depth in the core, and as such probably represent changes in sedimentation rather than artifacts of ongoing oxidation.

**Fig. 6** Chironomid data compared with instrumental temperature data over the past two centuries. Percentages of selected chironomid taxa, chironomid detrended correspondence analysis (DCA) Axis 1 scores, and transfer function (TF)-inferred temperatures compared with measured summer temperatures at Raufarhöfn (23 km from Stora Viðarvatn) and Stykkishólmur (in western Iceland; see Fig. 2 for locations). Meteorological data are from Veðurstofa Íslands, <http://www.vedur.is>. Bold lines over temperature curves are 7-year running means



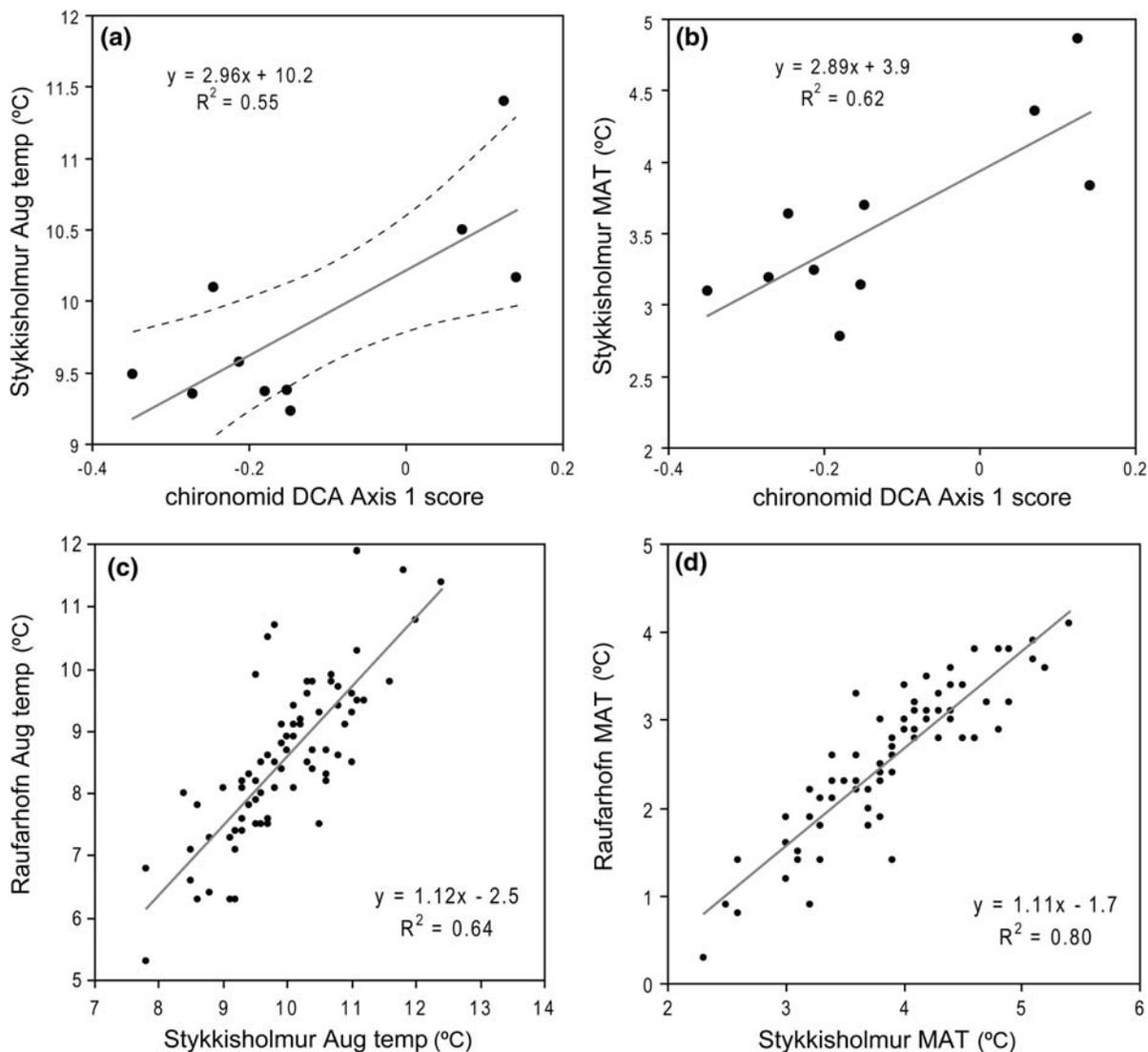
**Discussion**

Assessing chironomids as a paleo-temperature proxy

Comparison of chironomid DCA scores and percentage data with Stykkishólmur temperature data reveals coherence between temperature changes and shifts in the chironomid fauna over the instrumental period (Fig. 6). To quantitatively assess this coherence, we compared DCA scores over the instrumental period with the temperature data. We conducted bivariate regressions of temperature for all months, seasons (e.g. June–July–August temperature), and mean annual temperature (MAT) versus DCA scores. Each chironomid sample comprised either a 0.5 cm (for the upper 10 cm of the core) or 1 cm slice of the core, and as such represents a window of time that varies with sedimentation rate; regressions used the mean of a corresponding “time slice” of instrumental data to compare with each downcore data point (time slices ranged from 3 to 19 years; mean = 7.7 years). Although the chironomid life cycle is generally assumed to be sensitive primarily to summer temperatures, the strongest correlation ( $r^2 = 0.62$ ,  $P = 0.007$ ; Fig. 7) was for a linear regression of MATs versus DCA scores. This may reflect the impacts of cold winter and spring temperatures on

spring lake-ice thickness and melt-out date, which in turn affects growing season length and the timing of adult emergence. The second strongest correlation was for August temperatures ( $r^2 = 0.55$ ,  $P = 0.01$ ; Fig. 7).

The correlation between DCA scores and instrumental temperatures suggests a quantitative relationship with paleotemperatures. As a means of constraining the amplitude of temperature changes represented by the paleodata, we use the linear regression between DCA scores and August temperatures ( $AugT_{Stykk} = (2.96 * DCA) + 10.2$ ) to estimate past temperature changes. This regression has a Durbin-Watson statistic  $d = 2.03$ , indicating that autocorrelation does not significantly influence the regression. We choose to reconstruct August temperatures, rather than MATs, in recognition of widespread empirical evidence for dependence of chironomid distributions on summer air and water temperatures (e.g. Walker et al. 1991; Lotter et al. 1997). In order to reconstruct local temperatures at Stora Viðarvatn so that paleotemperatures can be compared with other proxies from this site, we also need to account for the temperature gradient between Stykkishólmur and Raufarhöfn (recall that the aforementioned regression is for the longer temperature time series from Stykkishólmur). August temperature data from the two sites are linearly related, with temperatures at Raufarhöfn



**Fig. 7** Linear regressions of instrumental temperature measurements at Stykkishólmur versus chironomid detrended correspondence analysis (DCA) Axis 1 scores from downcore samples (meteorological data are means for the series of years corresponding with the time-slice represented by each downcore sample) for **a** mean August temperatures (with 95%

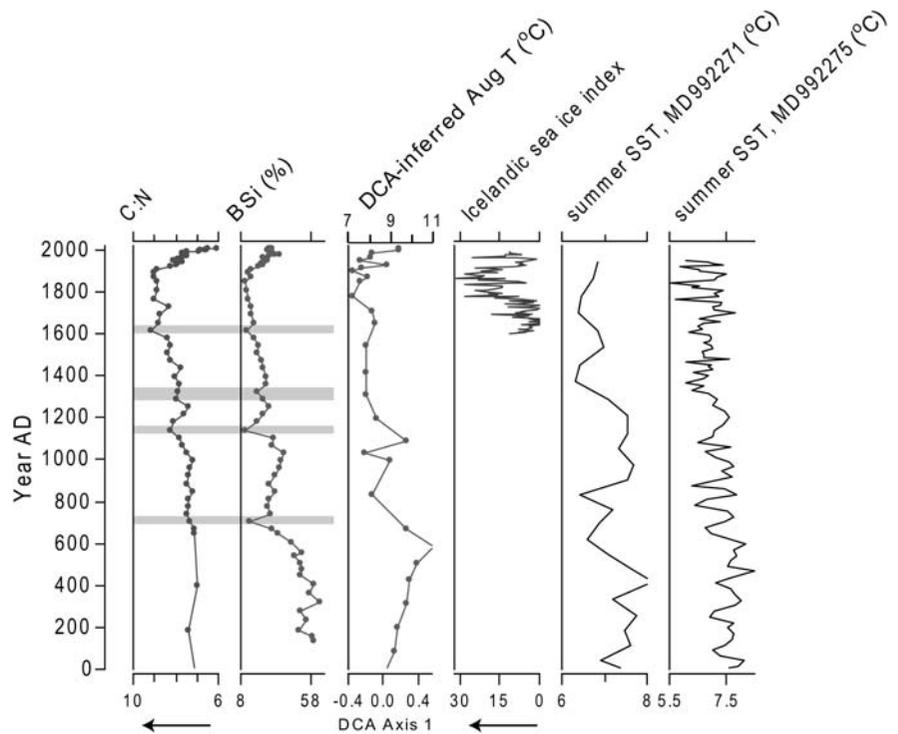
confidence interval shown as dotted lines), and **b** mean annual temperatures. Linear regressions of instrumental temperatures at Raufarhöfn versus Stykkishólmur for years AD 1931–2006 (data from Veðurstofa Íslands, <http://www.vedur.is>) for **c** mean August, and **d** mean annual temperatures

generally lower (Fig. 7;  $\text{Aug}T_{\text{Rauf}} = (1.12 * \text{Aug}T_{\text{Stykk}}) - 2.5$ ;  $r^2 = 0.64$ ,  $P < 0.001$ ; we note that MATs at the two sites are more strongly correlated than August temperatures, with  $r^2 = 0.80$ ,  $P < 0.001$ ).

By applying the two regressions to the DCA scores we can estimate past August temperatures for the pre-instrumental period (Fig. 8). This method provides a constraint on the magnitude of LIA cooling. Inferred

August temperatures during the coldest part of the record (between approximately 1800 and 1900 AD) were on average 1.5°C lower than in 2005 and 0.5°C lower than the mean inferred temperature for the period from 1000 to 2000 AD. The 95% confidence interval of the temperature-versus-DCA regression (Fig. 7) provides a minimum estimate of the error associated with reconstructing temperatures based upon this regression. The magnitude of this error

**Fig. 8** Paleoclimate proxies from Stora Viðarvatn (C:N, biogenic silica (BSi), chironomid detrended correspondence analysis (DCA) Axis 1 scores, and August temperatures inferred from DCA scores; horizontal gray bands indicate inferred tephra layers) compared with an historical index of sea-ice severity off Iceland (Ogilvie and Jonsdóttir 1996; Ogilvie and Jonsdóttir unpublished data) and diatom-inferred sea-surface temperatures reconstructed from two marine sediment cores on the North Iceland shelf (Jiang et al. 2005, 2007; see Fig. 2 for core locations). Note reversed axes for C:N and sea-ice index



(roughly  $\pm 0.5^{\circ}\text{C}$  within the range of the calibration data set; Fig. 7) compares favorably with RMSEP errors associated with weighted-averaging models developed based upon spatial calibrations (e.g. Langdon et al. 2008), although we note that this is a minimum estimate of uncertainty that does not incorporate error in the Raufarhöfn-versus-Stykkishólmur temperature regression.

This method for inferring paleotemperatures requires calibration using meteorological data in order to confirm that temperature is the dominant environmental gradient reflected in DCA loadings. Furthermore, it is essential that the calibration period adequately represents the range of taxonomic variability found within the pre-instrumental record (i.e. if taxa are present in the paleorecord that are not well-represented in the instrumental period, DCA scores for the pre-instrumental period may not be meaningful in terms of temperature). The warmest paleotemperatures reconstructed at Stora Viðarvatn exceed the range of our calibration data; thus the absolute values of these reconstructions, which are extrapolated beyond the range of the calibration data, should be interpreted cautiously.

Whereas DCA scores show strong coherence with instrumental temperature data, transfer-function modeled July temperatures show little similarity to measured July temperatures over the instrumental period (Fig. 6). This is somewhat surprising given the success of the transfer function in modeling Holocene paleotemperatures in prior studies on Iceland (Caseldine et al. 2006; Axford et al. 2007). On the other hand, a number of factors may cause difficulties using the transfer function for this record: One, shifts in chironomid assemblages throughout this record are subtle, involving changes in the relative abundances of taxa rather than appearance and disappearance of taxa. Two, Stora Viðarvatn is deeper than most of the lakes in the modern training set, and depth is acknowledged to be an important factor controlling chironomid assemblages in Icelandic lakes (Langdon et al. 2008). The range of aquatic habitats within Stora Viðarvatn and their sensitivity to changing climate may not be analogous to the calibration sites.

Some taxa appear to exhibit different temperature preferences at Stora Viðarvatn than in the calibration set. In particular, *T. lugens* type and *Micropsectra*, which are most abundant at colder sites in the training

set, become more abundant with warming temperatures through the twentieth century. This is problematic for temperature modeling based upon the training set. The problem could be a result of habitat differences within the lakes, or the low resolution of the subfossil taxonomy (if the training set and subfossil data contain different species with undifferentiated morphotypes). Indeed, the subfossil taxonomy of *T. lugens* type on Iceland is known to be problematic (Langdon et al. 2008). This subfossil designation may include individuals of *Tanytarsus gracilentus*, which is the most common *Tanytarsus* species in Iceland today (Hrafnisdóttir 2005), and may account for the counter-intuitively high abundances of *T. lugens* type in surface sediments of some of the warmer lakes in the training set (Langdon et al. 2008). Similarly, three different *Micropsectra* species are known to live in Iceland (Hrafnisdóttir 2005), but *Micropsectra* are lumped together in the subfossil taxonomy (Langdon et al. 2008). Future work will aim to determine whether multiple subfossil morphotypes can be distinguished on Iceland within *Micropsectra* and *T. lugens* type, and whether these morphotypes have different temperature optima.

There is ongoing debate about whether observed correlations between chironomid distributions and temperatures are due mainly to direct or indirect effects of temperature on chironomids (e.g. Walker and Cwynar 2006). For example, it has been proposed that oxygen conditions are a primary control on profundal fauna, and that temperature influences profundal chironomids mostly indirectly through its effects on lake-water oxygen concentrations (Brodersen et al. 2004, 2008). This uncertainty is not unique to chironomid studies, but is a potential complication in most paleotemperature inferences from proxy data. Fortunately this is not problematic for paleotemperature inferences *if* relationships between temperature, intermediary environmental conditions, and chironomid assemblages are consistent through space and time. The fact that chironomid DCA scores from Stora Viðarvatn show strong covariance with measured temperatures over the instrumental period, whereas transfer function-inferred temperatures do not, may suggest that chironomids at this site were responding to temperature indirectly through intermediary environmental processes that are unique to this site and thus not intrinsic to the calibration data

of the Langdon et al. (2008) training set. Future work should explore this possibility.

#### Interpreting complementary proxies

Carbon, nitrogen, and BSi in lake sediments reflect a range of interrelated factors including edaphic evolution of the surrounding watershed, influx of allochthonous organic and mineral materials, lake nutrient status and light availability, and lacustrine productivity (e.g. Last and Smol 2001; Smol 2008). In natural lake systems, most of these factors are in turn related directly or indirectly to climatic variables including lake ice-cover duration, air temperature, and precipitation. The importance of each of these parameters is site-specific and varies over time; thus multiple hypotheses explaining past changes in organic proxies are often warranted.

The pronounced changes in C:N and BSi that occurred at Stora Viðarvatn over the past two millennia are generally coherent with changes in climate inferred from chironomids (Figs. 4, 8). Lower BSi content (except at levels with inferred tephra layers) and higher C:N generally correspond with cooler periods. We hypothesize that these changes in lake sedimentation record a combination of (a) changes in primary productivity driven by changes in ice-cover duration and summer temperature (relatively direct impacts of temperature on lake sedimentation), and (b) changes in the influx of allochthonous (terrestrial) materials to the lake corresponding with changes in soil stability and erosion. Colder climate may have led to decreased vegetation cover and increased periglacial activity that favored soil erosion and a greater influx of terrestrial soil materials into the lake (changing the proportion of C:N deposition, increasing the deposition of clastic mineral material, and diluting BSi). In addition, later spring melt-out dates and lower summer temperatures may have limited the primary productivity of the lake (thus decreasing deposition of BSi) despite any increase in the influx of soil-derived nutrients. Although changes in precipitation may also have contributed to changes in sedimentation over time—through effects on vegetation, soil denudation, and transport of sediments and nutrients to the lake—our data do not provide an independent proxy for precipitation so we can not evaluate the importance of this effect.

Changes in C:N, which were closely coupled with changes in the relative proportions of BSi versus mineral matter, support the hypothesis that the influx of terrestrially derived sediment changed over time. On the other hand, the small amplitude of changes in C:N may indicate that changes in terrestrially derived sediments were small relative to total sedimentation rate, and that changes in aquatic production explain a significant portion of the changes in sediment composition. We do not attempt to deconvolve the relative contributions of these factors in explaining the proxy record, but assume that both factors played a role.

#### Paleoclimatic and paleoenvironmental inferences from Stora Viðarvatn

Chironomid DCA scores and the relative abundances of several temperature-diagnostic taxa at Stora Viðarvatn (especially *Heterotrissocladius*, an indicator of relatively cool temperatures, and *P. sordidellus*, an indicator of relative warmth; e.g. Brooks et al. 2007; Langdon et al. 2008) indicate similar patterns of temperature change over the past 2000 years (Figs. 4, 8): Much of the first millennium AD was relatively warm, with temperatures comparable to warm decades of the twentieth century. Following a period of cooling in the eighth century, temperatures during parts of the tenth and eleventh centuries were comparably warm. Temperatures generally declined between the twelfth and nineteenth centuries, with the most severe conditions occurring during the eighteenth and nineteenth centuries. Changes in BSi over time support these paleoclimatic interpretations, either because of direct effects of temperature on primary production or other effects of temperature on lake sedimentation.

Several features of the past two millennia—namely, the climatic changes associated with the so-called Little Ice Age and Medieval Warm Period, and the environmental impacts of Norse settlement of Iceland—have received particular attention in the literature and are discussed in more detail below.

#### *Little Ice Age*

The “onset” of the Little Ice Age (LIA) is a problematic target. Ogilvie and Jónsson (2001,

p. 15) say that the LIA “does not start, it creeps upon us.” Many records from Iceland and the surrounding region note climatic cooling after the twelfth or thirteenth century (Eiríksson et al. 2000; Andrews et al. 2001; Jiang et al. 2002, 2005, 2007; Castañeda et al. 2004; Knudsen et al. 2004). This cooling is often viewed as representing the end of the Medieval Warm Period, and has been implicated as a cause of the demise of Norse settlements on Greenland (e.g. Barlow et al. 1997). On the North Iceland shelf, biological and isotopic proxies in marine sediments indicate cooling of surface and bottom waters starting between 1200 and 1350 AD, with many records showing intensified cooling after 1550 or 1600 AD (Eiríksson et al. 2000; Andrews et al. 2001; Jiang et al. 2002, 2005, 2007; Castañeda et al. 2004; Knudsen et al. 2004). These shifts in temperatures are generally attributed to changes in the relative contributions of polar versus Atlantic waters to the waters over the shelf (e.g. Jiang et al. 2007). Data from Stora Viðarvatn record a similar pattern of cooling on land, as would be expected given the influence of sea-surface conditions on the climate of northeastern Iceland.

The peak of the LIA—the period of coldest conditions—is more straightforward to define. Iceland’s rich historical record provides information about temperatures, sea-ice conditions, and glacier fluctuations as far back as medieval times, and generally indicates that the most severe climatic conditions of the historical period occurred in the eighteenth and nineteenth centuries (e.g. Ogilvie and Jónsson 2001; McKinzey et al. 2005), thus agreeing with our inferences from Stora Viðarvatn (Fig. 8). Many of Iceland’s mountain glaciers and ice-cap outlet glaciers, reconstructed using historical records and tephra- and lichen-dated moraines, achieved historical maxima during the late eighteenth and nineteenth centuries (e.g. Gudmundsson 1997; Evans et al. 1999; Kirkbride and Dugmore 2001; Sigurðsson 2005; Bradwell et al. 2006; Black 2008). However, spatiotemporal variability among sites, discrepancies between geochronological methods, and possible confounding effects of precipitation, glacier dynamics and hypsometry, and human land-use practices make it difficult to discern from glacier and other proxy records precisely when the coldest conditions occurred (e.g. McKinzey et al. 2004, 2005).

### *Medieval Warm Period*

The idea of a widespread and spatially coherent “Medieval Warm Period” (MWP) has come under scrutiny in recent years, as more numerous and highly resolved paleoclimate records have become available (e.g. Bradley et al. 2003; D’Arrigo et al. 2006; Jansen et al. 2007). However, it remains a viable hypothesis that a period of relative warmth in northwestern Europe and the northern North Atlantic region helped facilitate Norse expansion across the North Atlantic from the ninth to thirteenth centuries, including settlement of Iceland and Greenland. The corollary to this hypothesis is that subsequent cooling contributed to the demise of the Norse settlements on Greenland.

Our data hint at warm temperatures in the tenth and eleventh centuries (Fig. 8), with one data point suggesting temperatures slightly warmer than present (for perspective, unlike most high-latitude northern locales, present-day temperatures on Iceland do not show much recent warming, consistent with Iceland’s position in the North Atlantic Ocean). However, temperatures were higher overall and more consistently high through much of the first millennium AD, until a cooling phase in the eighth century (Fig. 8). A number of other paleoceanographic and paleolimnological records from the region show a similar pattern of relative warmth in the first millennium AD, and only modest or equivocal warming centered on the tenth and eleventh centuries (e.g. Eiríksson et al. 2000; Jiang et al. 2005, 2007). The historical perception of a significant medieval climate anomaly in Iceland may be primarily a reflection of the human perspective: Iceland was settled ca. 870 AD, during a period of relative warmth that was followed by many centuries of progressively colder and less hospitable climate. Had the Norse settled Iceland 1000 years earlier, the MWP might be viewed only as a brief period of climatic amelioration, a respite from a shift to colder temperatures that began in the eighth century.

### *Impacts of Norse settlement*

Some Icelandic lake-sediment records show abrupt paleoenvironmental shifts immediately following Landnám (the Norse settlement of Iceland ca. 870 AD) that have been attributed to anthropogenic

disturbance, especially clearing of forests (e.g. Hallsdóttir 1987). Other records show gradual or time-transgressive paleoenvironmental changes around the time of Landnám that are less clearly attributable to direct impacts of Norse activities (e.g. Lawson et al. 2007). Aside from the deposition of tephra layers, the largest shifts in sedimentation at Stora Viðarvatn appear to have occurred in the twelfth through thirteenth centuries, the sixteenth through nineteenth centuries, and in the twentieth century—all periods of climatic change inferred from chironomids at Stora Viðarvatn and corroborated by historical, glacial geologic, and paleo-oceanographic records from the region (as discussed above). Mineral matter abundance and C:N ratio in Stora Viðarvatn sediments (arguably indicators of soil erosion) increased in the twelfth century, increased further in the late sixteenth century (a period of accelerated soil degradation also documented by Ólafsdóttir and Guðmundsson (2002) (also reference Geirsdóttir et al. this volume)), and maintained a maximum through the eighteenth and nineteenth centuries (Fig. 8), the coldest period in the record. Increases in allochthonous sediment input at Stora Viðarvatn generally track inferred cooling, supporting prior studies documenting or hypothesizing a correlation between climatic deterioration and soil erosion on Iceland (e.g. Jennings et al. 2001; Ólafsdóttir et al. 2001; Ólafsdóttir and Guðmundsson 2002). Although we find no obvious evidence for impacts of human activities at Stora Viðarvatn, we do not rule out the possibility that settlement impacted sedimentation at this site. Proxies we have not yet examined (e.g. algal assemblages or pollen) might show shifts closer to the time of Landnám; and human activities may have compounded the impacts of deteriorating climate on the landscape, thus contributing to the sedimentation changes observed at Stora Viðarvatn.

Landnám and the onset of LIA cooling on Iceland were separated by only a few centuries. In records with chronologies that cannot confidently distinguish these two events, it may be incorrectly assumed that environmental shifts were contemporaneous with Landnám when they were in fact responses to the onset of LIA cooling, or vice versa. Unfortunately the paleoenvironmental signatures of climatic deterioration—e.g. exacerbated landscape instability and expansion of herbaceous plants at the expense of trees and shrubs—are similar to those assumed to

have resulted from early Norse land use. Therefore, careful assessment of the timing of events is necessary in order to make inferences about the causal mechanisms (anthropogenic versus climatic) of paleoenvironmental changes (e.g. Ólafsdóttir et al. 2001; Geirsdóttir et al. this volume). This requires the development of well-dated, highly resolved records of paleoclimate and environmental change.

## Conclusions

Shifts in chironomid assemblages at Stora Viðarvatn correlate with measured summer temperature changes over the 170 year instrumental record, indicating that chironomid assemblages at this site respond sensitively and rapidly to temperature changes. Although a chironomid-temperature transfer function performs poorly for this record, DCA scores provide useful and potentially quantitative indicators of paleotemperatures. The temperature history inferred for Stora Viðarvatn over the past 2000 years based upon chironomids is consistent with other proxies from the lake, as well as Icelandic historical records and inferences from marine sediments and glacial geology. On average, the first millennium AD was warmer than the second. Following a period of cooling in the eighth century, there were brief periods of relative warmth in the tenth and eleventh centuries. Temperatures declined between the twelfth and nineteenth centuries in several steps, with the most severe conditions occurring during the eighteenth and nineteenth centuries. Cold periods at Stora Viðarvatn were characterized by some combination of intensified soil erosion and decreased lake productivity, along with changes in chironomid assemblages.

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