Evidence for a warmer period during the 12th and 13th centuries AD from chironomid assemblages in Southampton Island, Nunavut, Canada

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ABSTRACT

This study presents the Late-Holocene evolution of a northern Southampton Island (Nunavut, Canada) lake, using fossil chironomids supported by sedimentological evidences (XRF, grain size and CNS). All proxies revealed a relatively stable environment during the last millennium with short-lived events driving changes in the entire lake ecosystem. The chironomid-based paleotemperatures revealed variations of significant amplitude coincident with changes in the sediment density and chemical composition of the core. Higher temperature intervals were generally correlated to lower sediment density with higher chironomid concentration and diversity. Higher temperatures were recorded from cal yr AD 1160 to AD 1360, which may correspond to the Medieval Warm Period. Between cal yr AD 1360 and AD 1700, lower temperatures were probably related to a Little Ice Age event. This study presents new information on the timing of known climatic events which will refine our knowledge of the paleoclimate and climatic models of the Foxe Basin region. It also provides a new framework for the evolution of such freshwater ecosystems under the "Anthropocene" and underlines the importance of including sedimentological proxies when interpreting chironomid remains as this combined approach provides an extended overview of the past hydrological and geochemical changes and their impacts on lake biota.

Introduction

Evidence of rapid climate change at northern latitudes has focussed research efforts on arctic environments. Due to possible feedback mechanisms, such as snow and sea ice extent (albedo), these regions are believed to be particularly sensitive to global warming (Everett and Fitzharris, 1998; IPCC, 2007). Many studies have already shown that some arctic areas have undergone major modifications of their annual thermal budget during the second half of the last century. They specifically showed an increase of surface air temperatures during summer, and a drastic reduction of winter sea ice cover thickness and summer extent (Johannessen et al., 1995, 1999; Dickson, 1999; Rothrock et al., 1999; Comiso, 2002). On the other hand, regions surrounding the Foxe Basin, the Hudson Bay, and the Hudson Strait are so far only slightly affected by such global warming effects (Serreze et al., 2000; ACIA, 2005). These contrasting scenarios revealed the necessity to extend our knowledge of past and present environmental conditions in order to be able to refine our ability to model past, present and future environmental changes in the Arctic.

The arctic landscape is covered by thousands of lakes and ponds, from which sediment archives can be retrieved and biological and chemical proxies can be used to reconstruct climate and environmental changes through time. Chironomids (Insecta: Diptera: Chironomidae) are considered to be valuable proxies to infer past environmental variables due to their relatively short response time to environmental forces. These non-biting midges spend most of their life time in the aquatic ecosystem (four larval stages), whereas in their winged-flying adult stage they are directly influenced by the ambient atmospheric conditions (Brodersen and Lindegaard, 1997). Based on the chironomid assemblages from the surface sediments of selected lakes distributed along an ecotonal transect, the development of statistical inference models provided an opportunity to use them specifically to infer water and air temperature (e.g. Walker et al., 1991; Olander et al., 1999; Larocque et al., 2001, 2006). These models were used to reconstruct the Late Glacial period (e.g. Brooks and Birks, 2000; Bedford et al., 2004) and the Holocene (e.g. Palmer et al., 2002; Heiri et al., 2003; Larocque and Hall, 2004), although the approach can also be limited when the fossil samples have no modern analogues, or when chironomids respond to environmental variables other than climate (e.g. Heinrichs et al., 2005; Velle et al., 2005).

To validate such biological analyses, quantitative reconstructions can be associated with sedimentological studies, such as grain size and geochemical analyses. A combination of these two proxies is still fairly

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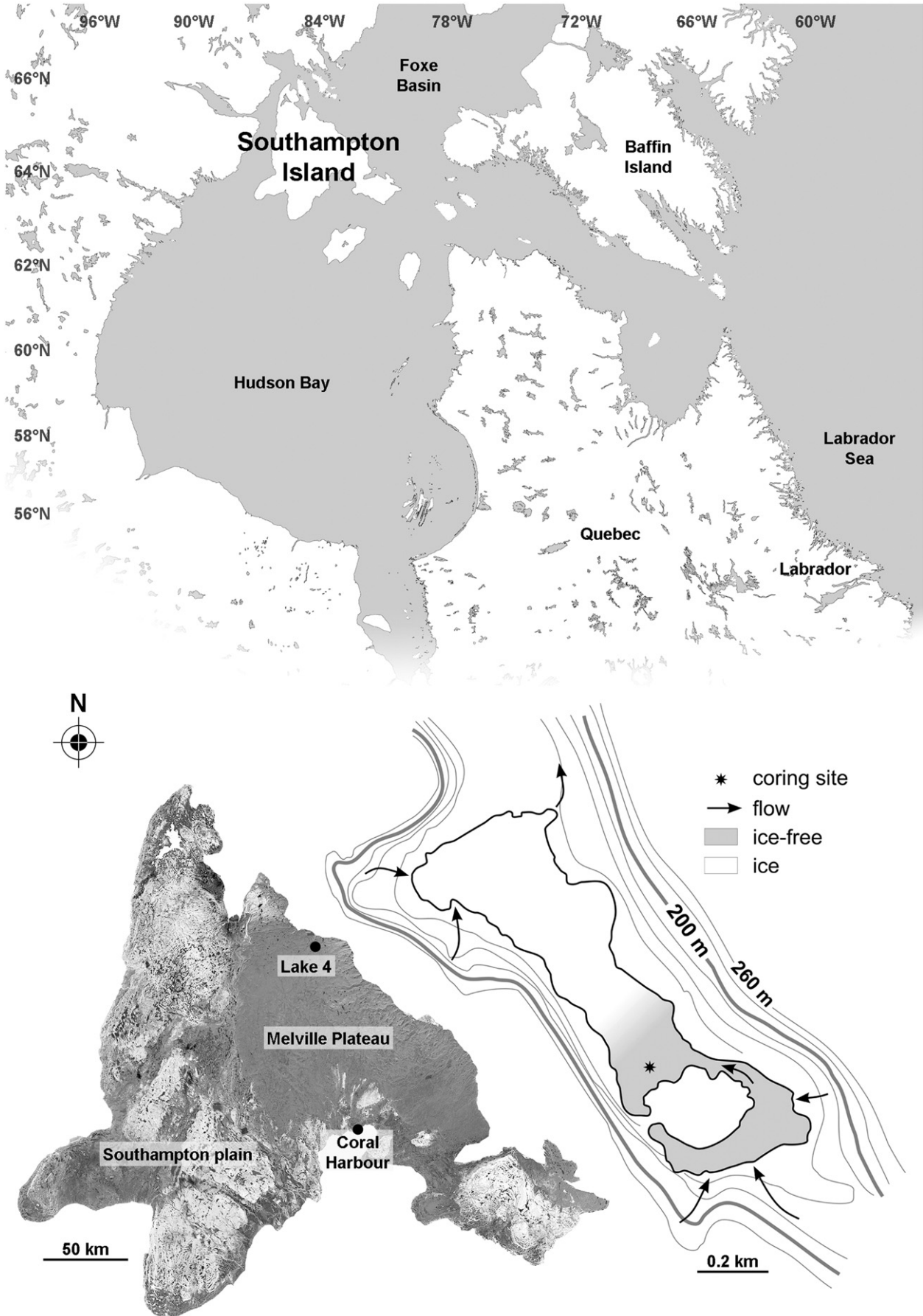*E-mail address:* Nicolas.Rolland@cen.ulaval.ca (N. Rolland).

Figure 1. Location and satellite image of Southampton Island with a diagram of lake 4 morphology and the coring site.

unique and provides an understanding of the environmental parameters (including climate) affecting the studied lake and the chironomid assemblages (Rolland et al., 2008). Hydrological conditions and organic input from the surrounding watershed which can be specifically correlated to changes observed in the biological communities are thus useful to understand the ecological factors at play (Ammann et al., 2000).

As part of concerted studies of the Foxe Basin and surrounding regions, a first paleoenvironmental study of the Southampton Island was initiated in 2004. This island occupies a transitional zone because of its central position between northern islands (Ellesmere and Baffin Islands) which already experience major climatic changes (Perren et al., 2003; Antoniades et al., 2005; Smol et al., 2005) and areas in northern Québec and Labrador which do not provide evidence for major significant environmental changes due to non-natural climate forces (Ponader et al., 2002; Saulnier-Talbot et al., 2003; Pienitz et al., 2004). New data on the postglacial and Holocene history of Southampton Island were already obtained using past inshore marine limit (Rouault, 2006), diatoms (Laperrière, 2006) and chironomids (Rolland et al., 2008). These latter two studies revealed stable climatic conditions for this island during the last 3000 yr. However, their results were obtained from a lake basin with low sedimentation accumulation and therefore did not provide high enough temporal resolution for reconstructing recent environmental changes in the region under investigation.

Here we present a higher resolution record from a lake located on northern Southampton Island. Using biological (chironomids) and sedimentological indicators, this study generates new insights into past natural climatic variations of this region over the last millennium.

Materials and methods

Study area

Southampton Island (Nunavut) is located in the northern part of Hudson Bay at the limit of Foxe Basin and at the apex of Hudson Strait (Fig. 1). Lake 4 (Tasiq Qikitalik, unofficial name; 65°05'70"N, 83°47'49"W) is situated 100 m a.s.l in the northeastern part of the island. This lake has a maximal length and width of 1.6 and 0.75 km, respectively, with a total area covering 0.66 km². The maximum measured depth was 36.5 m, but this might not represent the actual deepest point of the lake as ice still covered two-thirds of the total lake area at the time of sampling. A large island divides the lake into two physically different basins, the smallest one receiving the inflow of at least two rivers collecting water from a surrounding watershed of about 125.7 km². As water flows out of this basin, it is mainly constrained into a small channel with relatively high water flow that feeds the larger basin. This latter is relatively less turbulent, with a favourable core sampling area located close to the island. The lake is surrounded by low elevation hills (~300 m) composed of Precambrian rocks which are part of the Melville plateau and are composed of acid bedrock made of gneiss and granites and covered by typical arctic tundra vegetation such as Ericaceae (*Cassiope tetragona* (L.) D. Don), Rosaceae (*Dryas integrifolia* Vahl), *Sphagnum* and other peat mosses. Water physical and chemical properties of the lake during sampling are provided in Table 1.

Sediment sampling and analyses

In July 2004, a 34-cm long core (core 2G) was retrieved from the deepest reachable point inside the larger basin using a gravity corer (inner diameter = 6.8 cm) from Aquatic Research Instruments. The core was transported intact inside its sampling tube to our laboratory facilities, and kept refrigerated at 4 °C. Another core (core 1G), not described in this paper, but also retrieved at the same location in July 2004, was subsampled at 0.5 cm intervals in the field (Laperrière,

Table 1
Water physical and chemical properties of lake 4 during sampling in July 2004.

Variables	Depth (m)		
	0	5	15
Water temperature (°C)	3.64	3.55	3.73
pH (units)	6.34	5.54	5.49
Conductivity (mS cm⁻¹)	0.009	0.009	0.009
Dissolved oxygen (mg L⁻¹)	13.70	12.59	12.14

All measurements were done in July 2004 with a Hydrolab sensor and logger. 15 m was the maximum reachable depth of the analytic instrument.

2006). Core 2G was then half-sectioned lengthwise using a rotary tool and a fine iron wire.

A non-destructive geochemical analysis was achieved using an Itrax™ core scanner at the GIRAS laboratory, Institut National de la Recherche Scientifique, Eau-Terre-Environnement (INRS-ETE), in Québec city. This high-resolution tool, presented in Croudace et al. (2006) and St-Onge et al. (2007), used X-ray fluorescence (XRF) to determine the fluctuation in the species and amount of chemical elements along a half-sectioned core. This tool also provides a high-resolution X-ray profile of the core and a high-definition optical image of its surface. A step size of 100 μm was used for the radiographic profile. This profile is represented as a 2D positive image, with lower and higher X-ray attenuation represented by lighter and darker zones, respectively. For the XRF analysis, a molybdenum X-ray tube was used at a step size of 1000 μm and a 20 s exposure time.

The half-sectioned core used for the ITRAX™ analysis was then subsampled every 0.5 cm and all the subsamples were freeze-dried for 24 h. A grain size analysis was conducted every 1 cm using ~0.3 g of dry sediment that were previously treated in a hydrogen peroxide solution (30% v/v) and in a 1 M sodium hydroxide solution. These treatments were conducted to remove any organic residues and biogenic silicate that may corrupt the particle-size distribution as determined using a Fritch Analysette 22 laser particle sizer. Results were plotted as a two-dimensional contour plot (Beierle et al., 2002) with the boundaries of the particle-size distribution set following Last (2001). Organic matter content in every 1 cm subsample was then estimated on 0.5 g dry sediment subsamples by loss-on-ignition (LOI) at 550 °C during 5 h following Heiri et al. (2001). The total carbon and nitrogen contents (C/N ratio) were also performed using a LECO CHNS-932.

Chironomid analyses

Processing chironomid subfossils followed the most recent methodology: at least 50 chironomid head capsules per sample (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001) were counted in order to obtain a representative sample of the chironomid assemblages, and more than 1 g of dry sediment was retrieved every 1 cm in the uppermost 10 cm and at 1 or 2 cm intervals for the remainder of the core. The known amount of dry sediment used for each sample allowed for the calculation of head capsule concentration per gram for subsequent data analysis. These subsamples were first treated in a hot 10% KOH solution, and then head capsules were extracted using the kerosene flotation technique (Rolland and Larocque, 2006). Particles collected by the kerosene flotation were then placed in a Bogorov counting tray. Using a stereomicroscope (35–60×), all the chironomid head capsules were picked and mounted ventral side facing upwards on a microscope slide. Identification was done under a microscope at 400× magnification according to different taxonomic guides available at that time (Cranston, 1982; Oliver and Roussel, 1983; Wiederholm, 1983; Larocque and Rolland, 2006; Brooks et al., 2007). Dedicated keys were used to identify Tanytarsini taxa (Brooks et al., 1997; Brooks, unpublished) and Tanypodinae taxa (Rieradevall and Brooks, 2001). The Tanytarsini and Tanypodinae are now part of Brooks et al. (2007). Identification of *Zalutschia* sp. B followed Barley et al.

Table 2a

AMS radiocarbon dates from core 1G and 2G (humic-acids and macrofossils).

Laboratory number	Core ID	Depth (cm)	Material	^{14}C yr BP (± 1 SD)	δ^{13}C	cal yr BP 1σ (68.3%)	2σ (95.4%)
UCI-21591	1G	7.0–7.5	Humics	1995 ± 25	−26.0	1902–1987	1889–1994
UCI-21588	1G	11.0–11.5	Humics	2190 ± 25	−25.1	2150–2303	2130–2310
UCI-21590	1G	17.0–17.5	Humics	2280 ± 25	−26.6	2211–2344	2180–2348
Beta-218843	2G	13.0–14.0	Plant material	560 ± 40	−26.4	530–550	510–640
Beta-218844	2G	27.0–27.5	Plant material	1150 ± 40	−25.5	980–1070	960–1160

The age ranges are based on the INTCAL98 calibration using CALIB 5.0.1 (Stuiver et al., 2005). Laboratories were the Keck Carbon Cycle AMS Facility, Earth System Science Department, UC Irvine, USA and Beta Analytic in Miami, Florida, USA.

(2006). Fragments with more than half a head capsule were counted as one head capsule, whereas capsules that were half one head capsule were counted as half. All other fragments were disregarded.

Dating

The chronology of this sedimentary sequence (Table 2a) was based on two calibrated accelerator mass spectrometry (AMS) radiocarbon dates of terrestrial macrofossils (Ericaceae leaves) at 13–14 and 27–27.5 cm in core 2G. Samples were processed by Beta Analytic Laboratories in Miami, Florida, USA. The obtained carbon dates were calibrated to calendar years (cal yr BP, cal yr AD) using the program CALIB version 5.0.1 (Stuiver et al., 2005). To increase the age model precision, ^{210}Pb- and humic-acids-derived dates from core 1G were also used (Laperrière, 2006). The humic-acids were dated at the Keck Carbon Cycle AMS Facility, Earth Science Department, University of California Irvine, USA.

For the ^{210}Pb dating (Table 2b), seven samples of dry sediment from core 1G were processed by the National Water Research Institute, Canada Centre for Inland Waters, Burlington, Ontario, Canada (Report 05-03) The constant rate of supply (CRS) model was used to calculate these dates (Binford, 1990).

Statistical analyses

Standardization between the X-ray grey profile and the selected chemical element profiles was achieved using a negative exponential smooth method on each profile using SigmaPlot. A principal component analysis (PCA), with square root transformation, was run on these smoothed data in order to detect any trend in the chemical element profiles that may explain the resulting grey profile. The program CANOCO (ter Braak and Šmilauer, 2002) was used for the PCA.

The abundance per gram and relative abundance of selected chironomid taxa were plotted in two stratigraphic diagrams using the program C2 (Juggins, 2003). For each stratigraphic level, a Hill's N1 diversity index was calculated using Primer 6 (Clarke and Gorley, 2006). Zonation methods followed the recommendations of Birks and Gordon (1985) and Bennett (1996). Numerical zonation was carried out by optimal partitioning using sum of squares criteria (program ZONE (Version 1.2; Juggins, 1992)) and the number of statistically significant zone limits was determined with the broken-stick model (software BSTICK version 1.0, Bennett, 1996). The relative abundance of chironomid taxa was used to infer mean August air temperatures by a weighted averaging partial least squares (WAPLS) analysis with a leave-one-out cross validation method and a square root transformation. The calibration data set used for this reconstruction was derived from a modified model developed for northern Québec (Larocque et al., 2006) with ten more lakes added north of the previous transect. The correlation coefficient (r^2_{jack}) of this new model is 0.80, the root mean square error of prediction (RMSEP) is 1.26 °C, and the maximum bias is 2.14 °C. Modern analogues and goodness-of-fit to temperature were assessed following methods described in Birks (1998). To provide an indication of how well a fossil assemblage was represented

in the modern calibration set, we calculated the proportion of taxa from each fossil assemblage represented in the modern calibration set (Birks, 1998). When the proportion was lower than 70%, we defined the fossil sample as having no modern analogue. Canonical correspondence analysis (CCA) of the modern and the fossil data was carried out with the environmental variable of interest (e.g., July temperature) as the sole constraining variable to assess the fit of the fossil assemblages to the environmental variable of interest (Birks et al., 1990). We used the residual distance (square residual length, SqRL) of the modern samples as a criterion of fit: any fossil sample with a residual distance equal to or larger than the residual distance of the extreme 10% of the calibration set samples is considered to have a 'poor' fit to the environmental variable (Birks et al., 1990).

Results

Core chronology

The chronology of the studied core is presented in Figure 2. Humic acid dates were systematically older than expected and have therefore been rejected to establish our age model. Compared to the macrofossil date at 13–14 cm, this difference is in the order of 1600 yr after calibration. Lead activities obtained on core 1G and macrofossil-derived ^{14}C dates from core 2G were used to develop an age model of this sedimentary sequence:

$$y = 2.0979 + 0.0318x - 4.0746*10^{-5}x^2 + 3.1295*10^{-8}x^3 \qquad (1)$$

Neither LOI (%) nor water content could be used for core correlation (not available for core 1G), so this age model might present errors in the upper part of the core as lead dates were not from the core that provided the macrofossil-derived ^{14}C dates. However, this error should be low considering that compaction was low in both studied cores (less that 3 cm for the whole core), and because both cores were sampled at the same date and location.

Sedimentological analyses

Grey values derived from the X-ray analysis are presented in Figure 3, with smoothed data for the XRF profiles of major chemical elements (Fe, Rb, Zr, Sr, Ca, K). This figure also includes the LOI, C/N

Table 2b

^{210}Pb ages from core 1G.

Depth (cm)	Excess ^{210}Pb (pCi g^{-1})	Dates (AD)
0.06	7.072	2004
0.30	7.072	2001
0.71	6.973	1994
1.17	5.937	1984
1.97	5.545	1958
2.55	2.766	1933
3.35	0.964	1906

Processed by the National Water Research Institute, Canada Center for Inland Waters, Burlington, Ontario, Report 05-03.
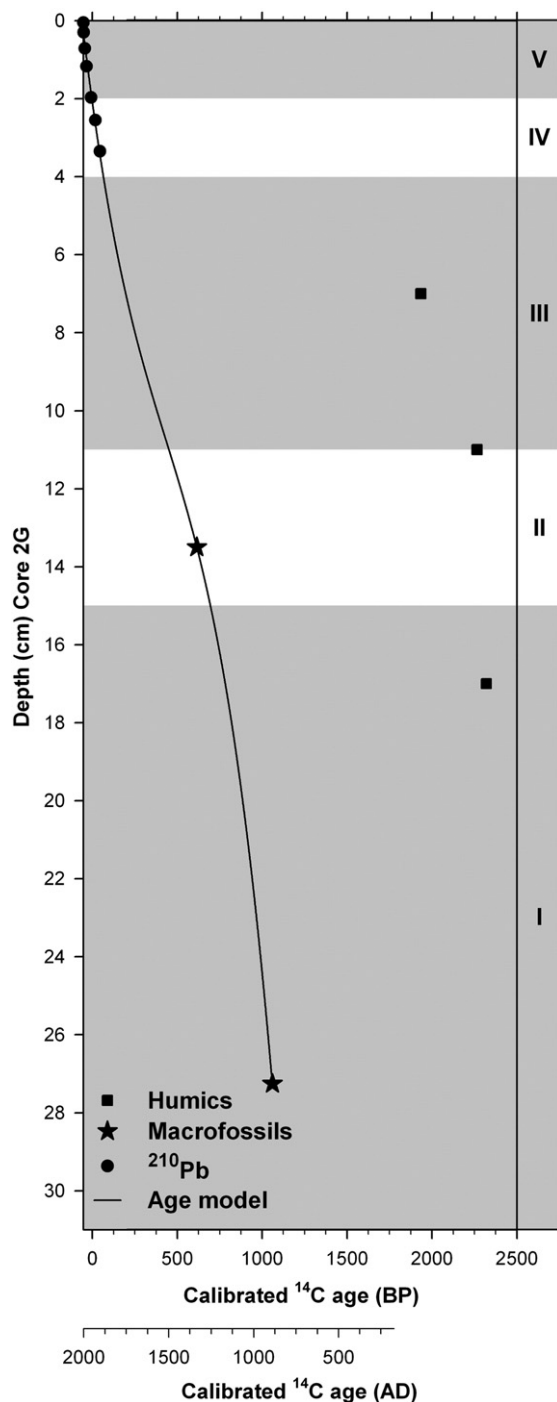
Figure 2. Calibrated depth–age model derived from the AMS macrofossil dates from core 2G and ^{210}Pb dates from core 1G. Zones are derived from the chironomid analysis.

values and a two-dimensional diagram of the grain size analysis. Sediment grain size distribution is well-sorted, highly dissymmetric, and leptokurtic (higher peak around the mode than the normal distribution) with a single mode at ~30 μm, in the very coarse silts range. This distribution was relatively constant through time but with a tendency towards smaller particles in the uppermost and most recent part of the core. LOI and the C/N ratio presented similar trends, with a constant but slow increase through time, and a particularly sharp increase between 16 and 12 cm characterized by the highest values in the entire core.

Sediment relative density was estimated by the grey values derived from the X-ray positive image of the core. Intervals with lighter grey values were observed at 28 and 23 cm and between 16–12 cm and 4–0 cm. The smoothed curve (negative exponential method) derived from these data varied inversely compared with the XRF profiles of major chemical elements. The PCA (Fig. 4) confirmed this observation as variables were located in the same area along axis 1, but at the opposite end on the axis 2, except for iron (Fe) which did not reveal any signs of influence from the observed grey values.

Chironomid stratigraphy

The stratigraphic distribution of selected midges are presented on Figure 5a (concentration) and 5b (relative abundance). Both stratigraphies providing complementary information, the concentration diagram will be mainly discussed, unless there are discrepancies between the two graphs. Based on the program ZONE, the succession of chironomid assemblages was divided into five zones. This analysis especially revealed one major event (Zone II), where initially low abundant taxa in Zone I developed rapidly and dominated the chironomid population. The mean value of the chironomid head capsule concentration (HC) was ~50 head capsules per gram of dry sediment in the entire core. The 43 identified taxa were mainly cold-adapted specimens. *Heterotrissocladius subpilosus*-group, widely encountered in arctic oligotrophic lakes (Walker and Paterson, 1983; Olander et al., 1999), was regularly represented and its constant abundance of ~10 specimens per gram of dry sediment represented more than 20% of the chironomids picked throughout the core. The Hill's N1 diversity index along the core had a mean value of ~11.

Chironomid zone I covered half of the core from 31 to 15 cm core depth (cal yr AD 850–1250). This zone was mainly dominated by *H. subpilosus*-group. Although not statistically significant to create a zone, changes in the chironomid assemblages occurred at 27 cm (cal yr AD 900) and at 23 cm (cal yr AD 980). At 27 cm, HC concentrations and Hill's N1 diversity index increased due to an increase of *Coryno-neura*, typically encountered in the littoral zone of shallow tundra lakes and on aquatic plants (Oliver and Roussel, 1983; Schmäh, 1993; Walker and MacDonald, 1995). This event also corresponded to an increase of *Cricotopus*, *H. subpilosus*-group, *Tanytarsus* with and without spur and *Sergentia*, a mesotrophic (Merilaïnen et al., 2000) and profundal taxon (Francis, 2001). At 23 cm, the Hill's N1 diversity index was just slightly higher than the average but the HC concentration almost reached its peak. At that depth, taxa found at 27 cm depth (*Corynoneura*, *H. subpilosus*, *Tanytarsus* with and without spur) increased again, but with the addition of *H. grimshawi*-group, a cold-stenotherm (Brooks and Birks, 2001), acidophilic (Pinder and Morley, 1995), oligotrophic (Brodin, 1986), high-alpine (Heiri et al., 2003) taxon, *Mesocricotopus*, a cold-stenotherm and oligotrophic taxon (Levesque et al., 1996; Walker et al., 1997), *M. radialis*-type, a high-alpine (Heiri et al., 2003) cold indicator (Brooks and Birks, 2000) and *Orthocladius*, found in medium to large arctic lakes (Oliver and Roussel, 1983).

The lower part of chironomid Zone II, between 15 and 13 cm (cal yr AD 1250–1365), was characterized by a rise of the abundance of almost all the identified taxa, and an increase in the HC concentration and the Hill's N1 diversity index. The most abundant taxa (>20 HC/g) were *Corynoneura* and *Micropsectra radialis*-type. The other abundant taxa (up to 20 HC/g) were *Orthocladius* and *Cricotopus*, which are often associated with the littoral zone, aquatic plants and more productive environments (Oliver and Roussel, 1983; Simola et al., 1996). This event also corresponded to a short appearance of *Diamesa* which lives in running/lotic waters but is also known to feed on algae in lakes (Oliver and Roussel, 1983). Two other taxa, *Limnophyes* and *Zalutschia* sp., were also identified in this zone, but with relatively low concentration (~4 HC/g). They are often associated with the littoral zone, aquatic plants and more productive environments (Oliver and Roussel, 1983; Quinlan and Smol, 2002). In the upper part of this zone (13–11 cm, cal yr AD 1365–1500), the abundance of
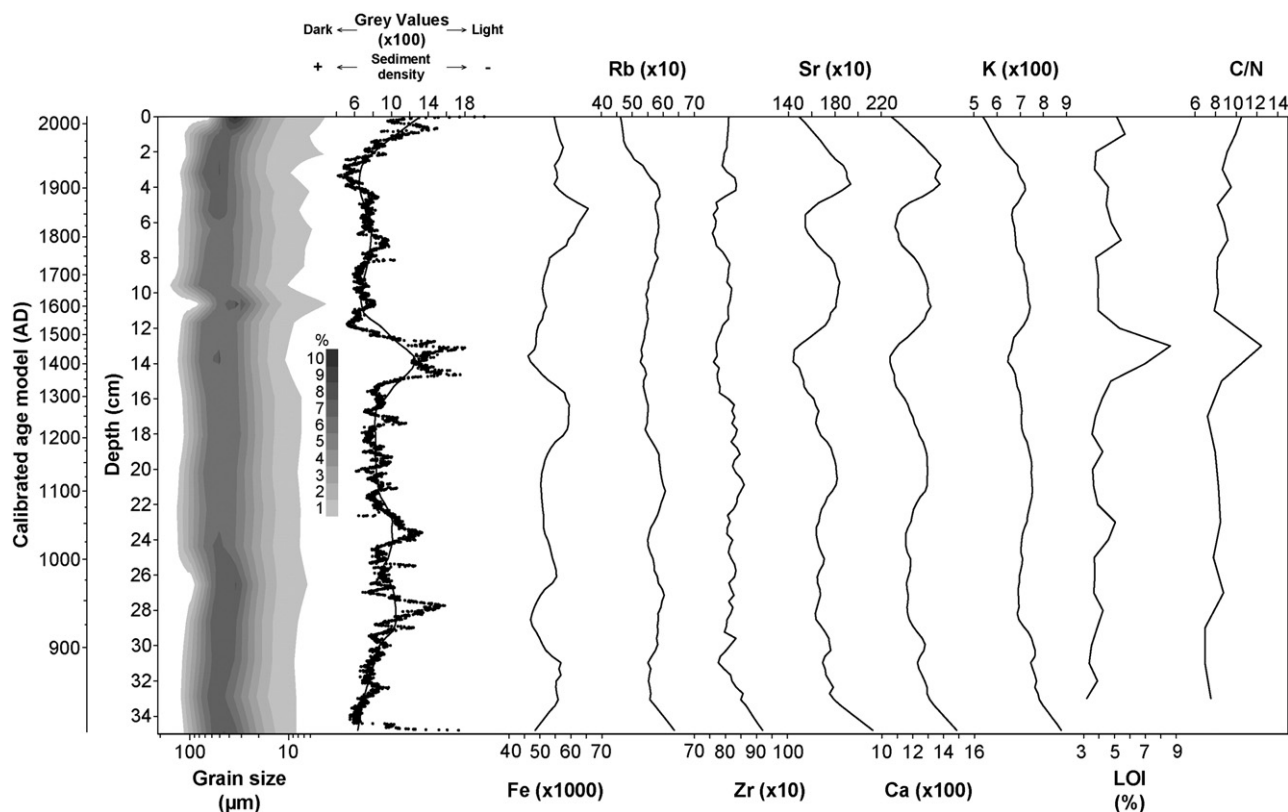
Figure 3. Variations of the grey values derived from the X-ray analysis of the core. High and low values correspond to light greys (low sediment density) and dark greys (high sediment density) respectively. Also provided, XRF profiles of major chemical elements and a two-dimensional graphic of the grain size frequency distribution (%), with frequencies represented along a proportional grey scale from light (low %) to dark (high %), LOI (550 °C) and C/N ratio.

most taxa decreased, as well as the HC concentrations and the Hill's N1 diversity index.

Chironomid zone III (11–4 cm, cal yr AD 1500–1885), closely reflected the same trends observed in Zone I, namely that *H. subpilosus*-group dominated the assemblages and the Hill's N1 diversity indexes was below or just above the average.

In chironomid zone IV (4–2 cm, cal yr AD 1885–2004), *H. grimshawi*-group and *H. subpilosus*-group had HC concentrations lower than 10 per gram of dry sediment, whereas *Corynoneura* and *Cricotopus* dominated the assemblages. The Hill's N1 diversity index was slightly higher than the average but increased towards the upper end of the zone. HC concentration was low at ca. 25 HC/g. *H. grimshawi*-group and *H. subpilosus*-group increased again in zone V, with an increase in *H. brundini*-group, *Mesocricotopus*, *Tanytarsus* sp. and *Tanytarsus* with spur. *Corynoneura* and *Cricotopus* were also present with concentration at ca. 10 HC/g. Hill's N1 diversity index was slightly higher than in the previous zone and the HC concentration almost doubled (from 25 to 50 HC/g).

Temperature inferences

The inferred August air temperatures are presented on Figure 6, with the RMSEP limit of the model and the five zones derived from the chironomid analysis. The inferred values varied between 6.5 and 10.1 °C around a mean value of 8.4 °C. Taking into account the RMSEP of the model (1.26 °C), this temperature range showed significant variations of the inferred temperatures between the highest (2 cm core depth) and lowest (17 cm core depth) values. All samples except one (16 cm) had good modern analogues and good-fit to temperature.

Zone I (31–15 cm) showed mainly low amplitude variations of the inferred temperature. This main trend was interrupted by two high-magnitude cooler events at 31 and 17 cm, which corresponded to the

coldest values inferred for the whole core with lowest values more than 1.5 °C colder than the average. Inferred temperatures in zone II (15–11 cm) were above the average except at 11 cm were they remained slightly lower. In zone III, the variability of inferred temperature increased with colder than average temperatures (by 0.7–1.2 °C) at 9 and 8 cm and warmer than average temperatures (by 0.9 °C) at 7 and 6 cm. Based on the RMSEP limit, these values were however not statistically different. In zone IV the inferred temperatures rapidly increased above the average, and reached the highest value (10.1 °C) at 2 cm core depth. The inferred temperature then decreased to the average in zone V, with the inferred temperature in the surface sample (8.4 °C) being close to the mean inferred value and the summer (July/August) temperature climate normal (8.3 °C; 1971–
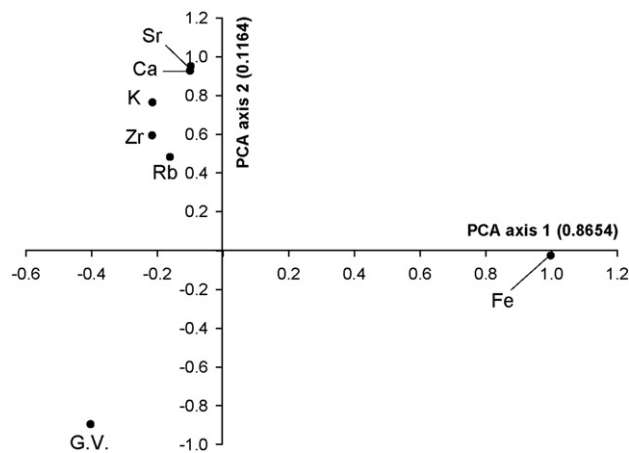

Figure 4. PCA analysis of the grey values (G.V.) derived from the X-ray analysis and of the major chemical elements measured by the XRF analysis.
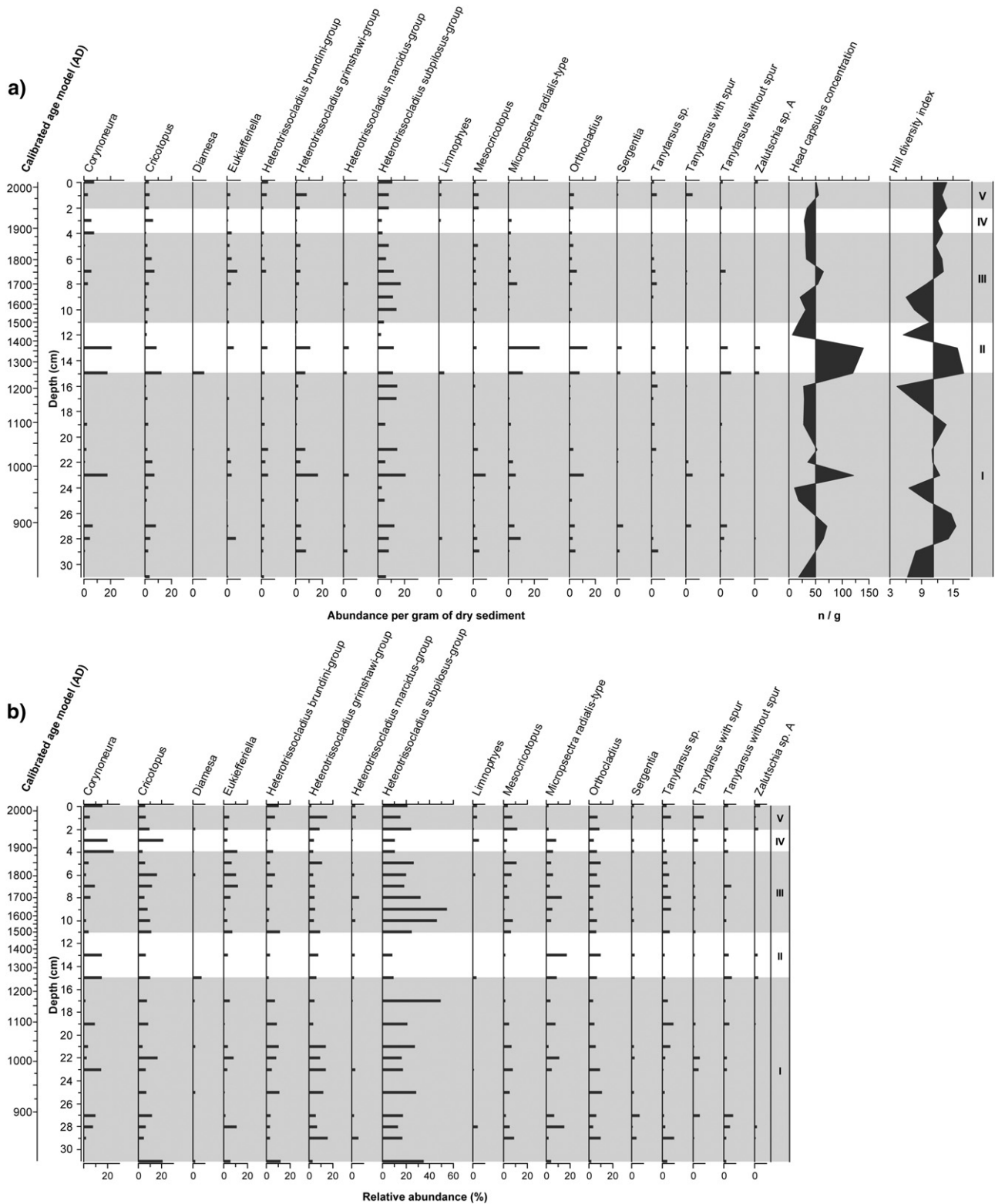
Figure 5. Chironomid stratigraphy (in abundance per gram of dry sediment (a) and relative abundance % (b)). Head capsule concentration and Hill's diversity index are also provided.

2000) and warmer than the august temperature climate normal (7.3 °C; 1971–2000) (Environment Canada, 2002).

Discussion

This study presented the environmental portrait of a northern Southampton Island lake during the last millennium. Both biological and sedimentological analyses revealed that this geographical area was perturbed by short-lived environmental changes in the lake ecosystem. The concomitant changes in both types of analyses suggest that climate affected simultaneously the chironomid assemblages and the sedimentology. This multi-proxy approach is unusual (Rolland et al., 2008) and enhances the need of such studies to better understand the link between biological and sedimentological processes.
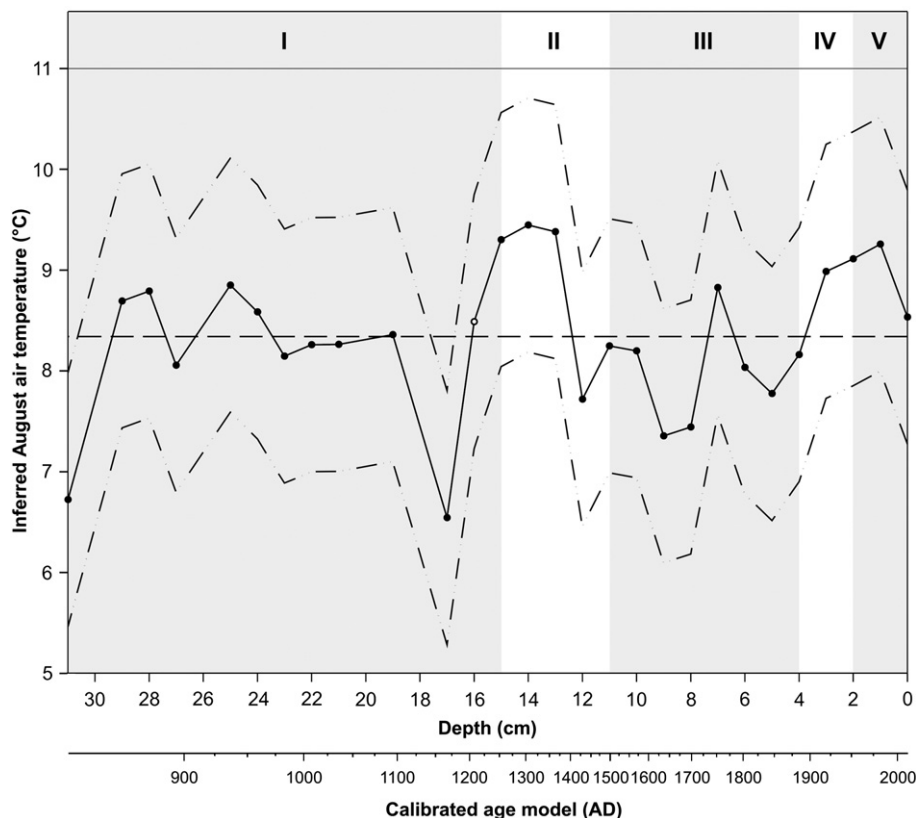
Figure 6. Chironomid-based August air temperature (°C). All samples except one (empty circle) had good modern analogues and good-fit to temperature. The model root mean square error of prediction (RMSEP) and the climate normal (1971–1990) (8.3 °C) for the whole core are represented as long dash/dot/dash and short dash lines respectively. Zones are derived from the chironomid analysis.

Sedimentary processes through the Late Holocene

The sedimentological information of this study was used as a complement to better understand the biological diversity and succession of the chironomid assemblages over time. Grain size is usually highly affected by changes in the hydrological regime of a lake, which includes precipitation rates and the amount of water inputs during snow melt periods (Last, 2001). In Lake 4, the grain size analysis did not present any major shifts in sediment textural properties and grain population though the entire core. Although the analytical resolution was set at 1 cm intervals, this revealed that, on a long-term perspective, hydrological inputs to the lake were almost constant during the studied period of time. On the contrary, the variations observed in the grey values of the radiographic profile clearly revealed that the sediment density was variable. Sediment density reflected the amount of detrital and organic input within the lake ecosystem. The observed increase of grey values at 28 cm, 23 cm, 16–12 cm and 4–0 cm, characterized higher organic sediment content, with higher porosity to X-rays. Taking into account the constant amount and size of grain particles entering the lake, the higher organic content might have originated mainly from the lake itself (autochthonous) or from a greater influx of terrestrial organic matter, a hypothesis supported by the increase of the C/N ratio. The ITRAX results strengthen this hypothesis as all the selected chemical elements (except Fe) were negatively correlated to the grey values (Fig. 4). A constant input of particles would have, in theory, provided a constant amount of detritic material inside the lake basin and hence constant detrital elements (PCA2) concentrations. However, we observe a decrease of the elements concomitant with lower density values. This suggests that detrital sedimentary input remained constant but has been diluted by higher organic matter fluxes.

Chironomids

The fossil assemblages were mainly composed of cold oligotrophic chironomid taxa. The latter were commonly found in the Canadian Arctic and northern Europe (Walker et al., 1997; Larocque et al., 2001). The most abundant, *H. subpilosus*-group, was also abundantly found in another lake on Southampton Island (Rolland et al., 2008). This strictly profundal (Simola et al., 1996) lake dweller had a more or less constant concentration throughout the core. Physiologically, chironomids rely upon their living substrata, which must be suitable for their biological requirements (Armitage, 1995). Combined with the stable grain size profile, the regular presence of *H. subpilosus*-group means that its habitat and/or its physiological needs did not change significantly during the period covered by this sedimentary sequence. By contrast, all the identified taxa with increased concentrations in zone II, such as *Corynoneura*, *Orthocladius*, *Limnophyes* and *Zalutschia* sp. A, are related to aquatic plants, the littoral zone and more productive environments (Oliver and Roussel, 1983; Quinlan and Smol, 2002). Their presence and the lower sediment density (as measured by X-rays) undoubtedly characterized changes in the littoral zone and trophic state of the lake. Arctic lakes are highly influenced by their winter ice cover which determines the timing and duration of the primary production period (Rühland et al., 2003; Smol et al., 2005). Although ice algae may develop under a thin ice cover and feed part of the trophic network (and by extrapolation chironomids) of a lake, a reduced ice-free season might not be sufficient to provide food and habitats to the littoral chironomid community (Douglas and Smol, 1999; Perren et al., 2003; Rouse et al., 1997). Therefore, the increased chironomid head capsule concentrations in zone II were probably the results of a longer ice-free season, which might have started earlier or ended later during the summer period.

Based on *in situ* lake water column measurements (Table 1) and Laperrière (2006) fossil diatom assemblages identified along core 1G, the high-occurrence of taxa belonging to the *Heterotrissocladius*-group and especially *H. grimshawi*-group (Pinder and Morley, 1995), revealed that the lake was mainly acid throughout the reconstructed period of time. This acidity is mainly derived from the surrounding watershed as outlined by geological surveys (Heywood and Sanford, 1976). This relatively low pH might have restricted the development of other chironomid taxa, as Walker et al. (2003) revealed that pH was an important variable explaining the distribution of freshwater midges in lakes from the Yukon and Northwest Territories.

Temperature inferences and comparison with regional paleoclimate data

The top-core paleotemperature records from this northern Southampton Island lake revealed a close match between modern inferred temperatures and average summer temperatures reported for this area between 1971 and 2000. This profile also presented several short-lived departures from this average. The interpretation of every inferred variable is always dependent on the RMSEP of the model used in its reconstruction (Lepš and Šmilauer, 2003). In this study, almost all inferences were constrained within the limit of the model which, in theory, means that all the observed variations cannot be statistically differentiated. However, in the case of temperature changes exceeding 1 °C in this core, chironomid-based inferred temperatures should provide reliable scenarios of paleoclimate at this site (Larocque and Hall, 2004). Based on the variations in the abundance of the *H. subpilosus*-group, the inference model used for this paleotemperature seemed to have been strongly influenced by this taxon which has the lowest temperature optimum in the training set (Larocque et al., 2006). The relatively low number of Low and High-Arctic lakes in this transfer function might explain the overriding influence of this taxon on the temperature reconstruction and might have biased the high-amplitude events by giving more emphasis to the lowest but also less emphasis on highest inferred values. Taking into account these limitations, only a general portrait of the lake conditions can be provided, but our general interpretations were supported by other paleolimnological data from the mid- and eastern High-Arctic.

Indeed, the 1 °C temperature increase between cal yr AD 1160–1360 may correspond to the one found in the study of varved sediments from Donard Lake, west of Baffin Island, Moore et al. (2001). They found a rapid increase of the inferred summer temperatures between cal yr AD 1195 and 1220 followed by an extended warmer period until cal yr AD 1375. Based on this high-resolution record, the authors associated this warmer period with the Medieval Warm Period (MWP) which was about 0.5 °C warmer than their average inferred summer temperature before cal yr AD 1195. Despite the low number of samples analysed in our core for this period, the inferred records observed in Lake 4, with temperatures ~1 °C higher than average, presented the same tendencies as in Donard Lake and correspond to a MWP. Archaeological and anthropological studies of Thule, also named Sadlirmiut on Southampton Island, revealed that this tribe took advantage of the MWP to migrate from northern Alaska to the eastern Canadian Arctic (Coltrain et al., 2004). Southampton Island has a rich archaeological site in Native Point, where high-numbers of bowhead whale skeletal remains from the Thule era were dated between cal yr AD 1000–1350 (Coltrain et al., 2004). Coltrain et al. (2004) suggested that the high-number of bowhead whale skeletal remains corresponded to longer ice-free seasons in the Hudson Bay that promoted whale hunting by the Thule. Such longer ice-free seasons might also have existed in freshwater ecosystems on this island and may have controlled the sedimentological and biological processes in our study site during this period. The presence of this native tribe and the changes in our temperature reconstruction, clearly suggest that the Southampton Island experienced a warmer period during the 13th century.

Although the inferred temperatures in zone III between cal yr AD 1364–1695 were lower but not statistically different from the ones observed in zone II, they reflected a shift to a cooler environment over approximately 300 yr. The LIA has been reported from pollen analyses in northern Quebec and Labrador between AD 1570–1870 (Gajewski and Atkinson, 2003). In their study of Donard Lake, Moore et al. (2001) concluded that the LIA occurred between cal yr AD 1375–1800 and was characterized by a rapid decrease of ~0.7 °C in the summer temperatures compared to the MWP. Our record from Southampton Island presented a similar trend, with a minimum inferred value ca. 2 °C colder than the maximum observed during the MWP but this cooler event ended earlier (cal yr AD 1695) and was followed by a second warm period between cal yr AD 1750–1800. The three minima registered in Donard lake during the LIA, with the coolest period being around cal yr AD 1645–1715 (possibly corresponding to the Maunder Minimum), agrees with our results. This cooling was still described as modest, being less than 1 °C (Bradley and Jones, 1993; Jones et al., 1998; Mann et al., 1999). Here, an excursion of about 1 °C from the average was inferred using chironomids, and the similarity in the climate patterns suggest that this cooling episode corresponded to the LIA.

The LIA was described as the coldest period of the last millennium (Mann et al., 1998; Jones et al., 1998). This was not the case at our site. Another cold event at cal yr AD 1175 was identified in our record when the inferred temperature was almost 2 °C colder than the average. A pre-medieval cold period has been described elsewhere (Cowling et al., 2001), although the amplitude of the temperature decrease was slightly smaller than that of the LIA.

In the two upper zones, the increase in the inferred temperatures might reveal recent changes that are due to non-natural forces. Although sediments were less compact near the water/sediment interface and this higher water content could have prevented a good relationship between sedimentology and chironomid-inferred temperatures, our results revealed that both variables are generally close but the relationship between both variables is not as high as the one observed during the MWP. Similar results were observed in Europe with inferred summer MWP temperatures that were the same as those measured into the last quarter of the 20th century (Goosse et al., 2006). The record from Southampton Island does not reveal such high-amplitude climate changes as observed elsewhere in the Canadian High Arctic, but undoubtedly this island is actually experiencing environmental changes. Although the MWP mainly resulted from natural climate forces, the recent lacustrine changes might be the result of increasing greenhouse warming and subsequent changes in the physical environment such as longer ice-free seasons. Based on the reconstructed lake state during the MWP, such warming might affect the lake community by increasing its productivity and, in a long-term perspective, will shift the lake to a mesotrophic state. Such situations underline the importance of long-term monitoring programs in this remote area and the development of new frameworks that focus on the way this environment will be affected by global warming.

Conclusions and perspectives

The paleolimnological study of this northern Southampton Island lake provides information and extends the spatial understanding of Northern Hemisphere climatic events (Medieval Warm Period and Little Ice Age) in the Foxe Basin region. Both chironomid-based August air temperature inferences and sedimentological assemblages suggest that Southampton Island was affected by a regional warming between cal yr AD 1160–1360 and a regional cooling between cal yr AD 1360–1700. These results compare well with both archaeological studies made on Southampton Island and paleoclimatic studies conducted on the southern part of Baffin Island. In the present study, the information extracted based on the biological indicators (chironomids) was supported by a large range of sedimentological analyses. Such results

confirm the importance of including sedimentological proxies when interpreting chironomid analysis as they provided an extended overview of the past hydrological and geochemical status of the lake which has affected its biological community. The large number of lakes covering the arctic landscape provides a real opportunity to improve our knowledge of past natural climates in still poorly studied arctic regions and develop new frameworks for the evolution of such freshwater ecosystems under the now called "Anthropocene."

Acknowledgments

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