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ORIGINAL PAPER

Paleolimnological evidence of the response of the central Canadian treeline zone to radiative forcing and hemispheric patterns of temperature change over the past 2000 years

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Abstract Instrumental climate records from the central Canadian treeline zone display a pattern of variation similar to general Northern Hemisphere temperature trends. To examine whether this general correspondence extends back beyond the instrumental record, we obtained a sediment core from Lake S41, a small lake in the Northwest Territories of Canada at 63°43.11′ N, 109°19.07′ W. A radiocarbon-based chronology was developed for the core. The sediments were analyzed for organic-matter content by loss-on-ignition (LOI), biogenic-silica content (BSi), and chironomid community composition to reconstruct July air temperature and summer water temperature. The paleolimnological records were compared with records of atmospheric CO_2 concentration, solar variability, and hemispheric temperature variations over the past 2000 years. The results of the analyses suggest that widely-documented long-term variations in Northern Hemisphere temperature associated with radiative forcing, namely the cooling following the medieval period during the Little Ice Age (LIA), and twentieth century warming, are represented in the central Canadian treeline zone. There is also evidence of a brief episode of warming during the eighteenth century. As evidenced by LOI and BSi, the twentieth century warming is typified by increased lake productivity relative to the LIA. Depending upon the measure, the increased productivity of the twentieth century nearly equals or exceeds that of any other period in the past 2000 years. In contrast, the rate of chironomid head capsule accumulation decreased and remained low during the twentieth century. Although the chironomid-inferred temperature reconstructions indicate cooling during the LIA, they present no evidence of greatly increased temperatures during the twentieth century. Warming during the twentieth century might have enhanced lake stratification, and the response of the chironomid fauna to warming was attenuated by decreased oxygen and lower temperatures in the hypolimnion of the more stratification-prone lake.

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Introduction

Instrumental climate records, paleoclimatological records and other paleoenvironmental data indicate that the northern high latitudes have been experiencing a general warming for more than a century (e.g. Douglas et al. 1994; Overpeck et al. 1997; Hansen et al. 1999, 2006; Briffa et al. 2001; Smol et al. 2005; Lugina et al. 2006). The instrumental records show that the northern treeline zone in central Canada (Fig. 1), like many other high-latitude regions, has exhibited a strong positive response to general hemispheric and global temperature increases, with particularly high temperatures over the past two to three decades (Fig. 2) (Hansen et al. 1999, 2006; Rigor et al. 2000; Lugina et al. 2006). The recent warming trend has been most strongly expressed in spring (March, April, May) with some warming also apparent in summer (June, July, August) and winter (December, January, February) (Rigor et al. 2000). Climate model simulations suggest that temperature increases due to global warming should continue to be particularly pronounced in the treeline zone

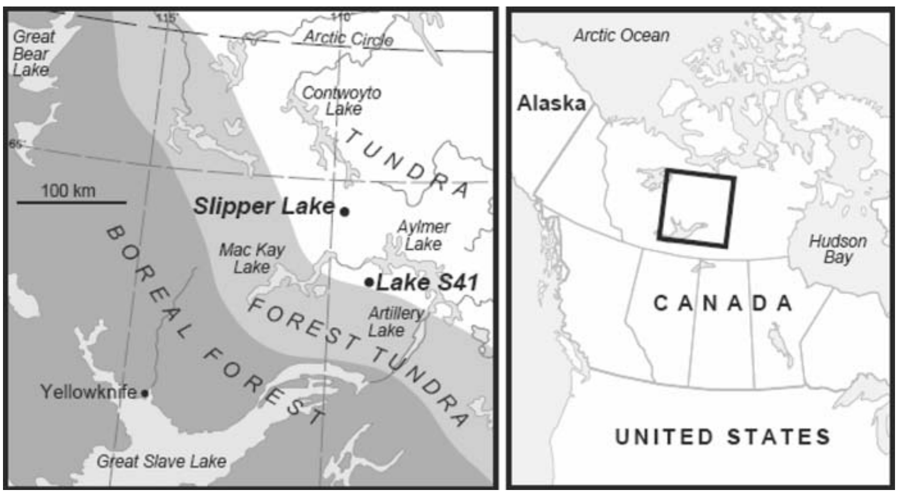

Fig. 1 Location of Lake S41, Slipper Lake, and the treeline zone north of Yellowknife, Northwest Territories

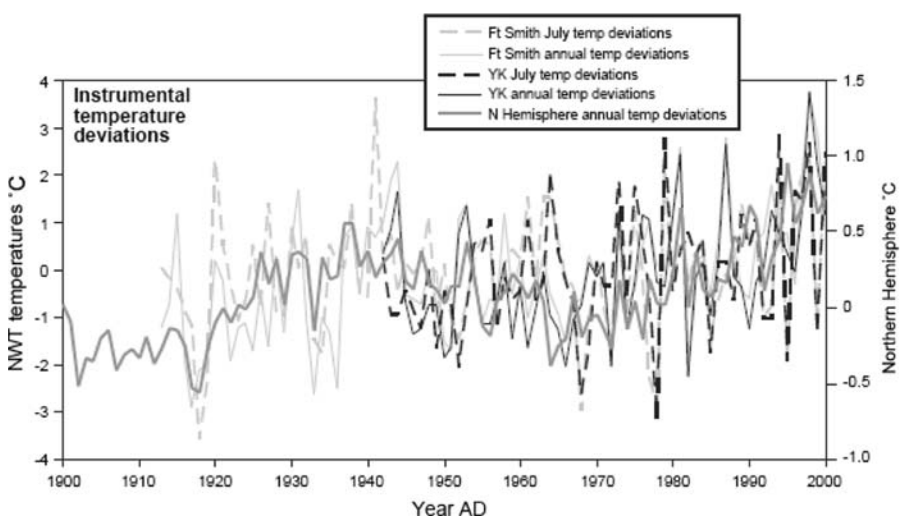

Fig. 2 Comparison of instrumental climate records from Fort Smith and Yellowknife, NWT, and average Northern Hemisphere deviations in July and annual temperatures (data from Environment Canada Adjusted Historical Climate Data Base; Lugina et al. 2006). The instrumental meteorological record from Fort Smith, located 300 km south of Yellowknife, is the longest in the region

(Arctic Climate Change Assessment 2004; Intergovernmental Panel on Climate Change 2007). In turn, if temperatures continue to increase, the boreal forest is likely to extend northward into areas now occupied by tundra (Arctic Climate Change Assessment 2004). Such an extension would decrease albedo at high latitude and provide a positive feedback further enhancing global warming (Bonan et al. 1995; Foley et al. 2003; Woodward et al. 1998; Levis et al. 1999, 2000). A persistent linkage between global warming and increased temperatures in the central Canadian treeline zone could serve to exacerbate the global impacts of warming.

Paleoclimatic records provide one means of testing the long-term persistence of the linkage between global and hemispheric temperature variations and temperatures in the treeline zone. Long records of past temperatures and ecosystem response can also be used to serve as a benchmark of natural climatic and environmental variability against which to compare the warming of the twentieth and early twenty-first centuries. Climate change can have large impacts on Arctic hydroecological systems and lake sediments provide archives of such changes (e.g. Smol et al. 2005; Prowse et al. 2006).

In this paper we provide a preliminary study of proxy indicators of past temperature analyzed from the sediments of a small lake located in the treeline zone of central Canada. The study region lies north of Yellowknife, Northwest Territories (NWT) (Fig. 1). Summer temperature gradients across the treeline zone in this region are steep and paleoenvironmental study sites along this ecotone between boreal forest and tundra have been shown to possess temperature-sensitive records (Moser and MacDonald 1990; MacDonald et al. 1993; Pienitz et al. 1999; Huang et al. 2004; Rühland et al. 2003; Rühland and Smol 2005). The proxies that we examine are lake sediment organic-matter content as represented by loss-on-ignition (LOI) (Heiri et al. 2001), biogenic-silica content (BSi) (Mortlock and Froelich 1989), fossil chironomid community composition, and chironomid-inferred water and air temperatures (Walker et al. 1997; Francis et al. 2006; Barley et al. 2006; Porinchu et al. in press). We also include previously published LOI and fossil diatom data (Rühland and Smol 2005) from another small lake within the same region. The treeline paleolimnological records are compared to previously published records of two climatic forcing agents, solar activity as represented by sunspots, atmospheric CO_2 concentrations (Hoyt and Schatten 1998a, b; Solanki et al. 2004; Monnin et al. 2004; Keeling et al. 2004), and regional and hemispheric temperature variations (Szeicz and MacDonald 1995; Moberg et al. 2005) that span the last 400–2000 years. Our intent is to assess whether widely recorded thermal events such as the widespread cooling typical of the Little Ice Age (LIA ~1300–1850 AD) and the recent warming of the twentieth century are captured in the lake records and thus expressed in this region. The cooling of the LIA was likely a result of decreased insolation coupled with increased volcanic activity relative to the earlier period, which included widespread warming during medieval times (Crowley 2000). The increasing temperatures in recent centuries likely reflect both the influence of solar and volcanic forcing, and increased greenhouse gas concentrations (Crowley 2000), with the latter factor becoming increasingly important through the twentieth and twenty-first centuries.

Study area

Lake S41 (unofficial designation) is located in the NWT at 63°43.11′ N 109°19.07′ W and ~418 m asl (Fig. 1). The small water body is less than 0.3 ha with a maximum depth about 4.4 m. The lake lies at the southern edge of the arctic tundra biome, adjacent to the forest-tundra ecotone. The regional bedrock is dominated by granodiorite and gneiss with metamorphosed volcanic rock with granitoid intrusions (Padgham and Fyson 1992; Wilkinson et al. 2001). The region was glaciated during the last glacial maximum and earlier glaciations. Glacial-erosional features and deposits of till and glaciofluvial sediment are common. Regional deglaciation occurred around 10,000–9000 cal year BP (Dyke et al. 2003). Continuous permafrost is present throughout the area and soils are poorly developed (Clayton et al. 1977). The action of glaciation coupled with permafrost has produced highly deranged drainage patterns with abundant lakes.

The study area is typified by short cool summers, long cold winters, and relatively low precipitation (http://atlas.nrcan.gc.ca/site/english/sitemap/index.html). There is a steep gradient in July temperatures in the region from about ~12.5°C in the forest-tundra zone to 8°C farther north in the tundra zone. The mean January temperature in the area of Lake S41 is −27.5°C. The region is relatively dry with total mean annual precipitation of ~200 mm. Although continuous snow cover typically extends from October through May, the average maximum snow depth is generally less than 20–40 cm. Lakes in the region are often ice-covered for much of the year, with an average open-water period of only 90 days (Wedel et al. 1990).

Vegetation is typical of the extreme northern edge of the forest-tundra zone. Scattered small stands and individual elfin-growth and krummholtz *Picea glauca* and *Picea mariana* (white and black spruce) are widely interspersed within the dominant cover of tundra. The tundra vegetation cover can be discontinuous on rocky substrates and is dominated by lichens, mosses, sedges, grasses, and diverse herbs. Small shrubs, most typically *Betula glandulosa* (dwarf birch), *Salix* (willow), and various ericoids are common.

Methods

Lake S41 was cored at its deepest location on April 27, 2005 from the ice cover. The depth of the ice was approximately 2 m and the water depth was 2.4 m. The coring was done using a modified Livingstone piston corer fitted with a clear plastic core barrel. The core collected the intact water-sediment interface and 45 cm of underlying sediment. The core was subsampled through vertical extrusion at 0.50-cm intervals. The barrel was kept upright and still during transport and extrusion so as to not mix the sediments. Subsamples were placed in sealed plastic bags and stored in a cold room after return to UCLA.

The lower 5 cm of the core contained a plug of sediment with anomalously high organic-matter content that underlies a section of very low-organic sediment separated by a sharp break at ~38 cm depth. We discounted the lower organic-rich section as possible contamination introduced during coring. The chronology for the core was developed by AMS radiocarbon dating of four samples from the upper 33 cm of the core. AMS analyses were conducted at the University of California, Irvine. Due to a paucity of terrestrial macrofossils, the ^{14}C ages were obtained from bulk organic sediment (Table 1). Because the surrounding lithology is dominated by igneous rock, we assumed that the ^{14}C-dating uncertainties associated with hard-water effects (MacDonald et al. 1991) are negligible. Radiocarbon ages were calibrated to calendar years before 1950 AD (cal year BP) using CALIB 5.0.2 and the IntCal04 calibration dataset (Reimer et al. 2004; Stuvier et al. 2005). The median probability ages were used to develop an age-depth model and 95% confidence intervals based upon a spline-fit routine following Heegaard et al. (2005). The chronology suggests that the last 2000 years are represented by the upper 25 cm of sediments, and we focused our analyses on this section of the core. Due to the slow sedimentation rate, the past 200 years are encompassed by only seven of our 0.5-cm-thick sediment subsamples. With such few intervals and low volumes of available sediment, ^{210}Pb dating of the upper core was not feasible. Instead, the ^{14}C-based chronology was extrapolated to the sediment surface, which was fixed at 2005 AD.

LOI analysis was performed on each 0.5-cm subsample to examine changes in the organic content of the sediments (Heiri et al. 2001). Although it may be influenced by many factors (Smol 2008), organic content can often be related to lake and/or watershed productivity, and has been shown to be positively related to temperature in the study area (MacDonald et al. 1993; Pienitz et al. 1999). Subsamples of 1 ml of sediment were combusted at 550°C for 1 h. BSi is an indicator of lake productivity based upon

Table 1 Radiocarbon ages from Lake S41

Depth (cm)	UCI Lab #	^{14}C age (year BP)	±	1-Sigma age range (cal year BP)	Median age (cal year BP)
7.0–7.5	25833	375	15	336–493	463
13.4–14.0	25841	1045	20	934–960	950
23.0–23.5	25836	1985	15	1898–1999	1933
32.5–33.0	25835	2765	20	2798–2917	2857

All ages based on AMS analyses of bulk sediment siliceous algae productivity (typically diatoms and chrysophytes), which in turn is likely positively correlated with summer temperature in the study region (MacDonald et al. 1993; Pienitz et al. 1999). Aside from warmer water temperatures, another key driver of this response may be increased planktonic diatoms due to a longer ice-free period when climate is warm (Smol 1988). BSi was measured at 0.5-cm resolution for the entire core. Wet alkaline extraction (10% Na_2CO_3), molybdate-blue reduction, and spectrophotometry were used to process the samples and determine BSi concentrations (Mortlock and Froelich 1989).

Chironomid community composition in small lakes within the study region has been shown to be sensitive to the changing mean annual temperatures and changing environmental conditions of the treeline ecotone (Walker and MacDonald 1995; Porinchu et al. in press). Recently, a number of chironomid-based inference models for water and air temperature have been developed for the Canadian Arctic (Walker et al. 1997; Francis et al. 2006; Barley et al. 2006; Porinchu et al. in press). The chironomid remains from the Lake S41 sediments were analysed to elucidate changes in community composition and head capsule accumulation rates over the past 2000 years, and to apply a chironomid-temperature transfer function model to infer past temperatures. Chironomid analysis followed standard procedures, as outlined by Walker (2001), and Porinchu and MacDonald (2003). A midge-based inference model for average July air temperature (T_{jul}) and summer surface water temperature (T_{ssw}) was recently developed for the central Canadian Arctic (Porinchu et al. in press). The lakes used in the training set are distributed from the forested treeline region northward to tundra regions on Victoria Island. The T_{jul} inference model is based on 77 lakes and 50 midge taxa; the T_{ssw} inference model is based on 75 lakes and 50 taxa (Porinchu et al. in press). A two-component weighted-averaging partial least squares (WA-PLS) model provides the most robust performance statistics for T_{jul}, with an $r_{jack}^2 = 0.77$, root-mean-squared error of prediction (RMSEP) = 1.03°C, a maximum bias of 1.37°C, and no strong trend apparent in the residuals (negative trend $r^2 = 0.22$, $p < 0.0001$). The most robust T_{ssw} inference model, based on a one-component WA-PLS approach, provides an $r_{jack}^2 = 0.75$, a RMSEP = 1.39°C, and maximum bias of 2.33°C (Porinchu et al. in press).

A minimum of 40 head capsules (Heiri and Lotter 2001; Quinlan and Smol 2001) were identified and enumerated in each sample, with the exception of three samples that had low abundances (10.25, 11.25, and 16.75 cm). In some cases two adjacent 0.5-cm subsamples were combined to reach a total of 40 head capsules. A total of 26 chironomid taxa were identified in sediment of Lake S41, all of which are contained in the training set (Porinchu et al. in press). Chironomid abundance data are expressed as percentages using the computer program C2 (Juggins 2003). Numerical zonation of the chironomid percentage diagram, based on optimal sum-of-squares partitioning, was implemented using ZONE version 1.2 (Juggins 1991). The statistical significance of the zones was assessed using BSTICK (Bennett 1996). The WA-PLS temperature-inference models and the sample-specific errors (1.1–1.2°C) associated with the reconstruction were developed using C2 (Juggins 2003). Detrended correspondence analysis (DCA) was undertaken to assess the timing and magnitude of compositional turnover in the chironomid fauna (Birks 1998; Smol et al. 2005). This analysis was based on all taxa present in each sample and used square-root-transformed midge percentage data to optimize the 'signal-to-noise' ratio and to stabilize variances (Prentice 1980).

Results[1]

Based upon the ^{14}C chronology, the average sedimentation rate over the past 2000 years was about 0.14 mm year^{-1}; the temporal resolution of the 0.5-cm subsamples ranges from ~50 years in the lower part of the core to ~30 years at the top (Fig. 3). The uncertainty in the age model averages ±90 years based on the 95% confidence intervals evaluated at each 1 mm depth.

The sediment is massive, organic-rich mud. LOI and BSi variations over the past 2000 years at Lake S41 are positively correlated ($r = 0.41$, $p \leq 0.05$). Values for both decline during the general period of the LIA and reach their lowest values between

[1] All of the data from Lake S41 presented in this study are available on-line through the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/canada/nwt/s41-2008.txt).

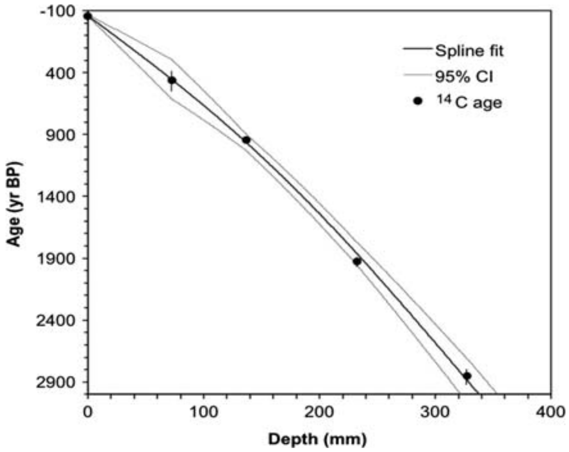

Fig. 3 Age-depth model for sediment core from Lake S41. Spline fit ($k = 3$; Heegaard et al. 2005) through four ^{14}C ages (Table 1) and the age of the surface sediment (2005 = −55 cal year BP). Error bars are entire 1-sigma age ranges. CI = 95% confidence intervals

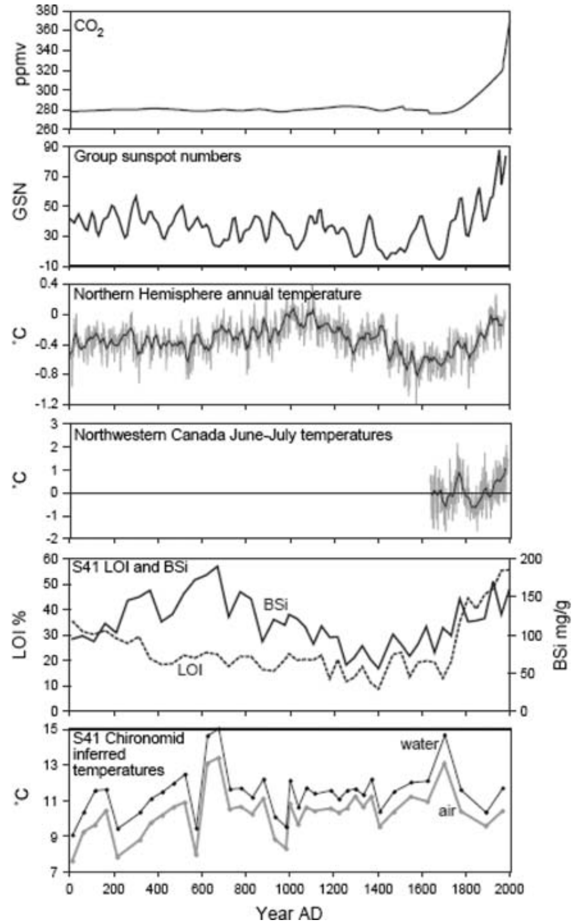

Fig. 4 Comparison of atmospheric CO_2 concentrations (data from Monnin et al. 2004; Keeling et al. 2004), solar activity as indicated by decadal group sunspot numbers (GSN; data from Solanki et al. 2004; Hoyt and Schatten 1998a, b), Northern Hemisphere annual temperature deviations (dark line is 11-year running average; data from Moberg et al. 2005), northwestern Canada tree-ring-inferred June-July temperature deviations (data from Szeicz and MacDonald 1995), productivity indicators from Lake S41 including organic-matter content analyzed by loss on ignition (LOI), biogenic-silica content (BSi), and chironomid-inferred summer surface lake water and average July air temperatures from Lake S41

~1200 and 1700 AD. LOI and BSi then increase to values greater than or nearly equal to those of medieval times during the twentieth century (Fig. 4).

The chironomid fauna is similar to that found in other small lakes within the treeline zone of the region (Walker and MacDonald 1995; Porinchu et al. in press). The faunal assemblage was subdivided into three distinct zones (Fig. 5). Zone S41-1 spans the first millennium (~0–1100 AD) and is dominated by *Corynocera ambigua* type, which comprises approximately 70% of the entire midge community. Other important constituents include *Tanytarsus* spp., *Sergentia,* and *Parakiefferiella bathophila* type, and thermophilous taxa such as *Dicrotendipes, Polypedilum* and *Microtendipes*. The next zone (S41-2), from ~1100–1400 AD, is characterized by the abrupt decrease in the relative abundance of *C. ambigua* type and an increase in taxa such as *Sergentia, Paratanytarsus* and *Psectrocladius eptentrionalis* type. In addition, *Parakiefferiella bathophila* type is absent in this zone, whereas *Cladotanytarsus mancus* is present at the base of this zone. Thermophilous taxa such as *Dicrotendipes, Polypedilum* and *Microtendipes* are rare to absent in this zone. *C. ambigua* type, *Sergentia,* and *P. septentrionalis* type continue to decrease in abundance in the uppermost zone (S41-3, ~1400 AD—present). Taxa such as *Psectrocladius sordidellus* type and *Tanytarsus* spp. increase two- to three-fold in this interval and reach their highest abundance in the upper portion of the core. Thermophilous taxa such as *Dicrotendipes, Polypedilum,* and *Microtendipes* reappear, albeit at low levels, following 1700 AD.

The chironomid-inferred reconstructions of air and water temperatures (Fig. 4) produce average values that are consistent with the average air temperatures of the treeline zone recorded by instrumental records

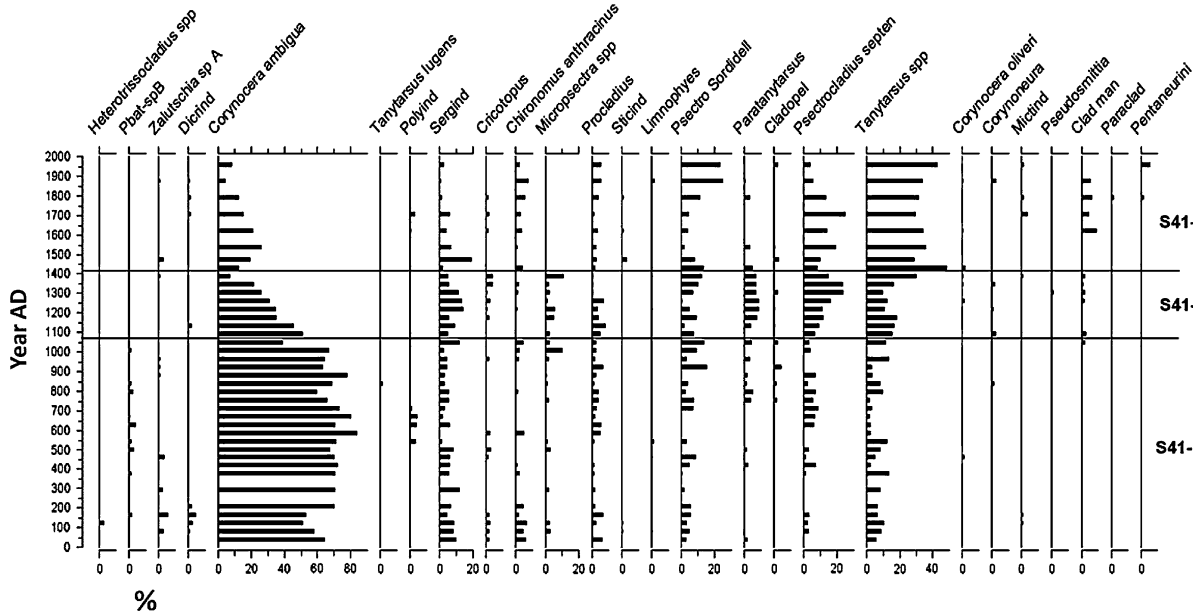

Fig. 5 Relative precentages of fossil chironomid abundances for Lake S41. S41-1, -2, and -3 refer to chironomid assemblage zones discussed in text. Abbreviations for chironomid taxa: *Pbat-spB* = *Parakiefferiella* cf. *bathophila-Parakiefferiella sp.B*, *Dicro* = *Dicrotendipes*, *Polyind* = *Polypedilum*, *Sergind* = *Sergentia*, *Sticind* = *Stictochironomus*, *Psectrocladius sordidell* = *Psectrocladius semicirculatus/sordidellus*, *Psectrocladius septen* = *Psectrocladius septentrionalis*, *Mictind* = *Microtendipes*, *Clad man* = *Cladotanytarsus*, *Paraclad* = *Paracladius*

(~12.5–8°C). The average chironomid-inferred T_{jul} for the past 2000 years is 10.3°C, with individual sample estimates ranging from 7.5 to 13.5°C. A peak in air and water temperatures occurs in the period 600 to 700 AD and is consistent with a peak in BSi in this section of the core. Temperatures remain relatively low from 900 AD to present, except for an individual peak at ~1700 AD. Unlike the LOI and BSi records, the chironomid-inferred temperatures do not show any indication of unusually strong recent warming relative to LIA or earlier values.

The first two DCA axes account for 15.5% (Axis 1) and 8% (Axis 2) of the total variance in the chironomid faunal composition. The ordination of the first two axes suggests that, between ~1050 and 1400 AD, compositional turnover as captured by the first two DCA axes was driven by a common forcing factor, indicated by the existence of similar trends of decreasing values after ~1050 AD for both axes (Fig. 6). Overall, there appears to be a general and statistically significant correspondence between the DCA Axis 1 and the BSi record ($r = 0.52, p \leq 0.05$), and between DCA Axis 2 and the BSi and LOI records ($r = 0.47$ and $r = 0.42$, $p \leq 0.05$). At ~1500 AD faunal turnover occurs, with *Micropsectra* and *Paratanytarsus* eliminated or greatly reduced in relative abundance, and taxa such as *Stictochironomus, Polypedilum,* and *Microtendipes* reappearing. At the same time, the previous relationship between overall productivity as represented by LOI or BSi appears to decouple from the chironomid community composition as represented by the DCA axes. The decoupling is particularly marked for DCA Axis 1. The DCA analysis suggests that faunal turnover and the relationship between temperature, lake productivity and chironomid community composition in the post-1500 AD interval may be confounded by additional forcing factors affecting the chironomids.

Discussion

Detailed temporal comparisons between the Lake S41 proxy records and hemispheric temperature changes, and global radiative forcing over the past 2000 years, are difficult due to the uncertainty in the ^{14}C-derived chronology, the relatively coarse resolution of the sampling, and the potential for smoothing of the

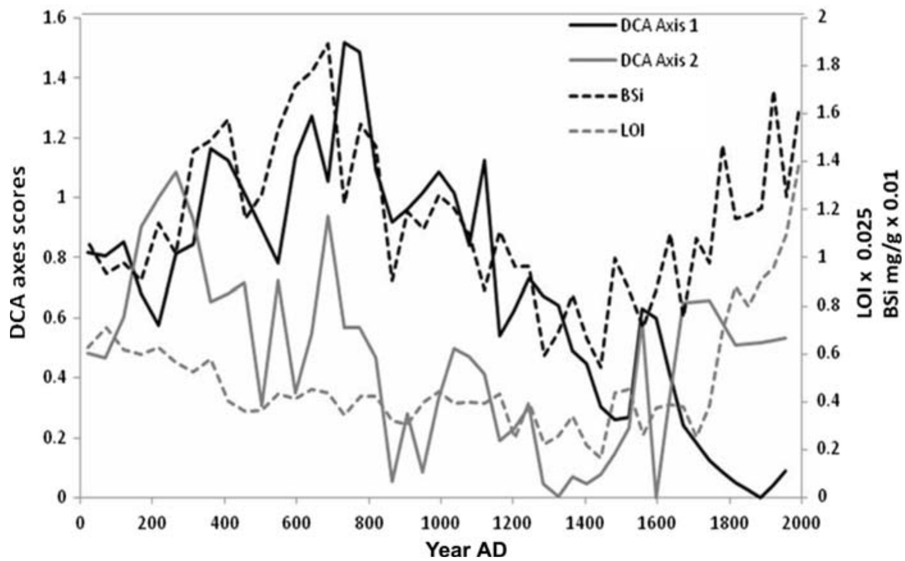

Fig. 6 First two detrended correspondence analysis (DCA) axes scores for chironomid compositional changes (solid lines), along with loss on ignition (LOI) and biogenic-silica content (BSi) from Lake S41

sediment-based climatic signal at Lake S41. However, the records of LOI, BSi, and chironomid community composition from the core exhibit a general correspondence between global radiative forcing by solar variability and greenhouse gas concentrations, resulting hemispheric temperature patterns, and climatic and limnic environmental change in the central Canadian treeline zone (Fig. 4). The LOI and BSi records from Lake S41 provide indications of shifts in lake productivity that are consistent with warmer and more productive conditions prior to the LIA, a decline in temperatures and productivity during the LIA, and warming and increased productivity that equals or surpasses the pre-LIA conditions during the twentieth century (Fig. 4). These shifts correspond roughly to the timing of long-term variations in solar activity and hemispheric temperatures. The pronounced increase in productivity during the twentieth century also corresponds with increasing concentrations of atmospheric CO_2 (Fig. 4). One anomaly is the peak in pre-LIA BSi and chironomid-inferred temperature in our record (~600–800 AD) that precedes the peak in Northern Hemisphere temperatures during the so-called Medieval Warm Period (MWP ~800–1300 AD). The causes of this are unclear and may reflect the coarse resolution of our record and uncertainties in ^{14}C-based chronological control.

An interesting feature in our records is an increase in BSi and temperature during the eighteenth century. This coincides with an increase in Northern Hemisphere temperatures and regional temperatures which is represented by a northwestern Canadian tree-ring reconstruction (Fig. 4). It appears that increased insolation during this time produced increased hemispheric temperatures, with a contemporaneous response in central and northwestern Canada.

The midge community at Lake S41 underwent significant compositional turnover during the last two millennia. The relative abundance of *Corynocera ambigua* type, which comprised approximately 75% of the midge community between 0 and 1050 AD, was reduced to approximately 10% by 1900 AD. *C. ambigua* type was replaced by *Tanytarsus* spp., *Psectrocladius septentrionalis* type, *Psectrocladius sordidellus* type, and to a lesser extent by taxa such as *Dicrotendipes, Microtendipes,* and *Polypedilum* in the upper sediment. In the central Canadian Arctic, *C. ambigua* type is most commonly associated with lakes in southern Arctic tundra; *C. ambigua* type is rare in the boreal forest (Porinchu et al. in press). Taxa such as *Microtendipes* and *Polypedilum* are most commonly encountered in sediment from sites located in the boreal forest or forest tundra. *Dicrotendipes*, which also reappears in the upper zone, is generally considered a thermophilous taxon and is more commonly associated with sites located south of treeline (Oliver and Roussel 1983; Walker and MacDonald 1995; Porinchu and Cwynar 2000; Larocque et al. 2006). Although the modern distribution of *Dicrotendipes* in this region extends northwards to eastern Victoria Island, Porinchu et al. (in press) have suggested that the presence of this taxon on Victoria Island may be due to recent regional warming. The increase or reappearance of thermophilous taxa in the uppermost sediment suggests that twentieth-century warming is reflected in chironomid community composition. However, the chironomid-inferred temperature reconstructions from Lake S41 do not provide strong evidence of recent warming. In addition, the DCA analysis (Fig. 6) does not show unprecedented high values during the twentieth century, but indicates a decoupling between the chironomid community response and measures of lake productivity. The similar variations in the two DCA axes and the variations in BSi and LOI suggest a relationship between lake productivity and shifts in the chironomid community composition, particularly during the first 1500 years of the record. It is possible that the general lake and watershed productivity as measured by organic-matter content, the siliceous algae productivity as measured by BSi, and the midge fauna community composition were responding to the direct effects of climate (most likely temperature change) on limnological conditions at the site during the early record. The chironomid-inferred temperature reconstructions for Lake S41 are anomalous both in terms of the productivity records from the core, and instrumental and paleoclimatic records of recent warming (Figs. 2 and 3).

Confirmatory evidence for increased lake productivity during the twentieth century is scarce from the study area. The temporal resolution of most other paleolimnological records from the central Canadian treeline region is too coarse to compare to the Lake S41 record (Moser and MacDonald 1990; MacDonald et al. 1993; Huang et al. 2004). The best available data come from Slipper Lake (Rühland and Smol 2005), some 120 km northwest of Lake S41 (Fig. 1). Based upon both ^{14}C and ^{210}Pb ages, the Slipper Lake record offers a temporal resolution of about 20 years in the nineteenth and twentieth centuries, and ~200 years prior to that. The LOI record from Slipper Lake (Fig. 7) suggests slightly higher levels of productivity prior to the LIA when Lake S41 also experienced enhanced productivity, a decrease during the early LIA, and then increased productivity that reached unprecedented levels during the twentieth

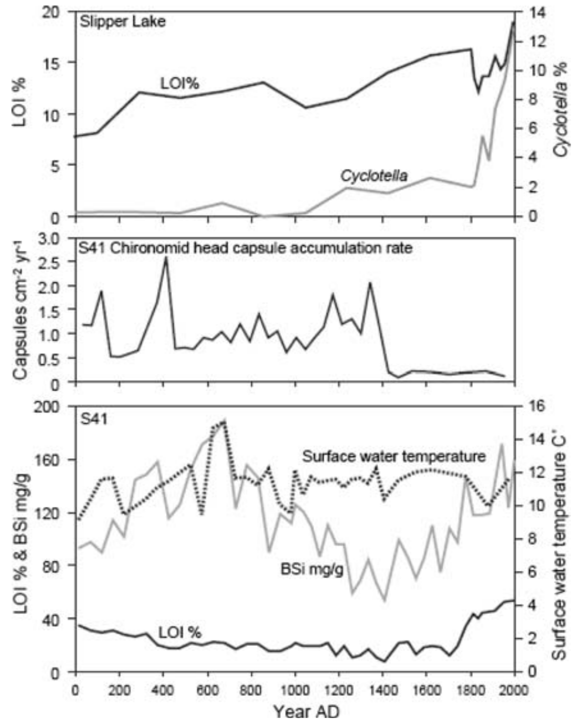

Fig. 7 Organic-matter content determined by loss on ignition (LOI) and relative abundance of diatoms of the *Cyclotella stelligera* complex from Slipper Lake (data from Rühland and Smol 2005) compared with the accumulation rate of chironomid head capsules from Lake S41, and the LOI, biogenic-silica content (BSi), and chironomid-inferred summer surface water temperature from Lake S41

century. Rühland and Smol (2005) noted that the abundance of planktonic diatoms of the *Cyclotella stelligera* complex (*C. stelligera, C. pseudostelligera*) also reached unprecedented levels during the twentieth century (Fig. 5). They suggest that the high relative abundance of *Cyclotella stelligera* complex diatoms likely reflects increased thermal stratification of lake water during the summer, coupled with a longer ice-free period and longer growing season. The increase in *Cyclotella stelligera*-complex and other planktonic species relative to benthic forms rose to unprecedented levels during the twentieth century. This phenomenon is widespread in Canadian Arctic lakes and suggests that increased warming, a longer ice-free period, and greater thermal stratification may be important hallmarks of the limnological impact of recent warming at high latitudes (Sorvari et al. 2002; Rühland et al. 2003; Smol and Douglas 2007; Rühland et al. in press; Smol et al. 2005;

J. P. Smol pers. comm.). A review by Kling et al. (2003) indicates that increased lake stratification and oxygen depletion of profoundal waters is an expected outcome of global climate warming in regions with seasonally stratified lakes.

It is also possible that lake depths increased during twentieth-century warming and this may have contributed to stratification and cooler, less oxygenated benthic environments. Relatively continuous precipitation records from Fort Smith and Yellowknife only extend back to the 1940s, but they show a long-term trend of increased precipitation since that time. Paleolimnological data indicate that the Holocene thermal maximum in the study area experienced increased positive hydrological balance. Warming temperatures could decrease dominance by dry polar airmasses and more frequent incursions of moister southern airmasses.

The Slipper Lake record not only provides additional evidence supporting the conclusion that twentieth-century warming equaled or exceeded that of any period of the past 2000 years, but may provide insights into why the chironomid-inferred temperature reconstructions from Lake S41 lack evidence of twentieth-century warming. The recent shift to an increase in the *Cyclotella stelligera* complex at Slipper Lake suggests that decreased ice cover and increased thermal stratification have been important features of the twentieth century (Fig. 7). Although Lake S41 is relatively shallow (~4–5 m), it is also very small. Its ratio of depth to fetch (~4.4 m depth to 80 m maximum length) making it prone to at least intermittent stratification (Larsen and MacDonald 1993). Stratification would also be promoted by a longer ice-free period and warming. A prolonged period of ice-free conditions and warming accompanied by increased stratification would enhance planktonic diatom productivity as is evident in the BSi content at Lake S41 and in the diatom record at Slipper Lake. However, increased stratification would also keep bottom water colder and less oxygenated which could mask the impact of warming air temperature on benthic chironomid taxa (J. P. Smol pers. comm.). A slight increase in the relative abundance of *Sergentia* in the uppermost sample of S41, a taxon typically associated with cold, oligotrophic Arctic lakes (Walker et al. 1997; Francis et al. 2006) or the bottom waters of deep, temperate lakes (Porinchu et al. 2002), is consistent with cold, oxygen-depleted benthic waters.

Therefore, changes in oxygen availability and nutrient cycling due to changes in lake stratification or depth during the twentieth century could confound the relationship between air temperature, general lake productivity, and benthic chironomid response that is suggested by the DCA results. As an example, Little et al. (2000) have shown that changes in lake stratification due to eutrophication and the development of an anoxic hypolimnion, produced a decoupling of diatom and chironomid response to environmental change at a site in Ontario. Recent work has shown that chironomid respiration rates are sensitive to both decreases in temperature and oxygen (Broderson et al. 2008), and stronger stratification could cause stress on chironomids. It is notable in this regard that the accumulation rate of chironomid head capsules decreases at Lake S41 at the same time that other indicators provide evidence for increased productivity and stratification due to recent warming of the region (Figs. 4–7). The decrease in head capsule accumulation rate suggests a decrease in the benthic chironomid populations, consistent with increased stress. Clearly, research on differences in seasonal temperature responses during the twentieth century compared to earlier warm episodes, coupled with more studies of chironomid physiological responses to temperature, are required and will be a valuable addition to the paleolimnological literature.

Conclusions

The evidence presented here suggests a positive relationship between low-frequency Northern Hemisphere temperature trends linked to global-scale variations in radiative forcing and lake productivity in the central Canadian treeline zone during the past 2000 years. Lake productivity appears to have decreased during the LIA. This was followed by increasing productivity during the late 19th and 20th centuries that, based upon both Lake S41 and Slipper Lake, appears to roughly equal or surpass that of any other period during the past 2000 years. The high productivity during the past century corresponds with increased solar activity, increased greenhouse-gas concentrations, and general warming of the Northern Hemisphere. As lake productivity in the region is positively related to temperature, the changes in productivity observed at our site likely reflect local changes in temperature at the central Canadian treeline zone related to global radiative forcing and hemispheric trends. There is also evidence from the region of increased lake-water stratification during the twentieth century. The degree of stratification may exceed that experienced over the past two millennia. Chironomid-inferred air and water temperatures show a decrease during the LIA, but do not indicate any strong increase in temperature over the past century. There also appears to be a decoupling in the earlier relationship between lake productivity as measured by LOI and BSi, and the chironomid community composition. It is possible that the muted response in the chironomid-based temperature estimates and this apparent decoupling may reflect the response of the benthic chironomid fauna to cooling and decreased levels of oxygen in the hypolimnion caused by increased lake stratification during the twentieth century.

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