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A 2000 year midge-based paleotemperature reconstruction from the Canadian Arctic archipelago

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Abstract A lake sediment core recovered from Lake V57 on Victoria Island, Nunavut, Canada, spanning the last 2000 years, was analyzed for sub-fossil midge remains and organic-matter content (estimated by loss-on-ignition (LOI)). Significant changes in midge community composition occurred during the last 2000 years, with a distinct midge community appearing after 1600 AD. The chironomid community between 0 and 1600 AD was dominated by *Heterotrissocladius*, *Tanytarsus*, *Abiskomyia*, and *Paracladius*. At approximately 1600 AD, *Heterotrissocladius* decreased in relative abundance and taxa such as *Corynocera ambigua*, *C. oliveri*, *Psectrocladius sordidellus* type, and Pentanneurini increased in relative abundance. Previously published midge-based inference models for average July air temperature (AJAT) and summer surface–water temperature (SSWT) were applied to the subfossil midge stratigraphy. The AJAT reconstruction indicates relatively cool conditions existed between 1100 and 1600 AD, with exceptional warming occuring after 1600 AD, as lake productivity inferred from organic-matter content increased concomitantly with midge-inferred AJAT and SSWT. The cooler conditions between 1200 and 1600 AD, and the pattern of warming over recent centuries inferred from Lake V57 is broadly consistent with temperature-sensitive biogenic silica records from other sites in the central Canadian Arctic and the treeline zone to the south suggesting a regionally synchronous response to climate forcing.

Keywords Holocene climate change · Chironomids · Paleolimnology · Air temperature · Arctic · Paleoclimate · Midges

This is one of fourteen papers published in a special issue dedicated to reconstructing late Holocene climate change from Arctic lake sediments. The special issue is a contribution to the International Polar Year and was edited by Darrell Kaufman.

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Introduction

The Arctic is experiencing a dramatic reduction in sea ice (Serreze et al. 2003, Rothrock et al. 1999), reduced snow cover (Serreze et al. 2000) and permafrost (Stroeve et al. 2005), and retreat of glaciers (Wang et al. 2007). In addition, changes in geochemical fluxes and nutrient cycling (Frey et al. 2007) and aquatic ecosystem structure and composition (Ruhland et al. 2008; Smol et al. 2005) have been recently documented. All of these changes appear to be linked to increasing temperatures, which have now exceeded those experienced over the preceding 100 years of instrumental records (Hansen et al. 2006; Rigor et al. 2000). The past 2000 years includes episodes of prolonged increased radiative forcing during the Medieval Climate Oscillation (MCO, ~800–1300 AD) and decreased radiative forcing during the Little Ice Age (LIA, 1450–1850 AD) (Hoyt and Schatten 1998a, b; Crowley 2000). A more detailed understanding of the temporal and spatial patterns of Arctic climate change in response to past and present prolonged changes in radiative forcing is necessary so that the accuracy of future scenarios can be evaluated and strategies to cope with the impacts of greenhouse gas forcing can be developed.

Lacustrine records that supply quantitative temperature estimates can provide a context against which the increases in temperature that characterize much of the Arctic during the late twentieth and early twenty-first century can be compared. However, the paleolimnological approach is predicated on our ability to accurately characterize the relationship between the proxies (biological, physical, and geochemical) and specific climate variables (Birks 1995). It is critical that we understand the response of aquatic ecosystems and various biological proxies to climate forcing prior to using these sedimentary archives describe the potential future response of these systems to climate change (Livingstone et al. 2005). As such, there has been a dramatic increase in the number of paleolimnological studies utilizing the remains of sub-fossil midges to develop high-resolution (sub-decadal to sub-centennial) quantitative reconstructions of late Holocene (pre-instrumental) thermal conditions (Brooks and Birks 2004; Porinchu et al. 2007; Thomas et al. 2008).

Increasingly, midge-based temperature reconstructions are being evaluated by the degree of concurrence that exists between them and other independent reconstructions, whether proxy-based or observational. These comparative studies have not only improved our understanding of chironomid paleoecology but they have also helped to identify additional processes and dynamics that may have influenced sub-fossil midge communities, and thereby have helped to refine down-core temperature reconstructions. For example, Anderson et al. (2008) determined that the relative role of the processes associated with both the direct and indirect effects of climate change varied during the Holocene, as did their influence on the ecological trajectory of biotic communities present in a low-Arctic lake in southwest Greenland. Additional studies have identified that changes in land-use, vegetation and hydrology can influence midge-based temperature reconstructions (Heiri et al. 2003, Engels et al. 2008). Increased integration of site-specific conditions and the development of regional syntheses that rely on multiple proxies and produce high-resolution, quantitative reconstructions of late Holocene climate will improve our understanding of how the direct and indirect effects of climate change are manifested in Arctic lakes.

Aquatic ecosystems in the Arctic are very sensitive to climate change, as small increases in temperature can dramatically reduce snow cover, the duration and thickness of ice cover, and affect the timing of ice-melt, all of which can directly impact the limnology and ecology of Arctic lakes (Karst-Riddoch et al. 2005; Livingstone et al. 2005). The primary purpose of this paper is to present a paleolimnological record and quantitative air and water temperature estimates for the past 2000 years for a small lake (unofficially designated Lake V57) on Victoria Island, one of the largest islands in the Canadian Arctic archipelago, and determine whether the impacts of known climatic events such as the MCO, LIA, and late twentieth century warming are evidenced in this region. The results from Lake V57 are compared to other temperature sensitive paleolimnological records from adjacent areas of the central Canadian Arctic and the treeline zone to the south to assess the geographic extent of changes in temperature during the last 2000 years as reflected in these paleolimnological records.

Study area

Victoria Island (Fig. 1) is underlain by Paleozoic carbonate and mantled with drumlinoid ridges composed of till (Dyke 2004). The region was covered by the Laurentide Ice Sheet, with de-glaciation rapidly occurring in the early Holocene (~9 ka) (Dyke 2004). The region is underlain by deep, continuous permafrost rich in ice content (Natural Resources

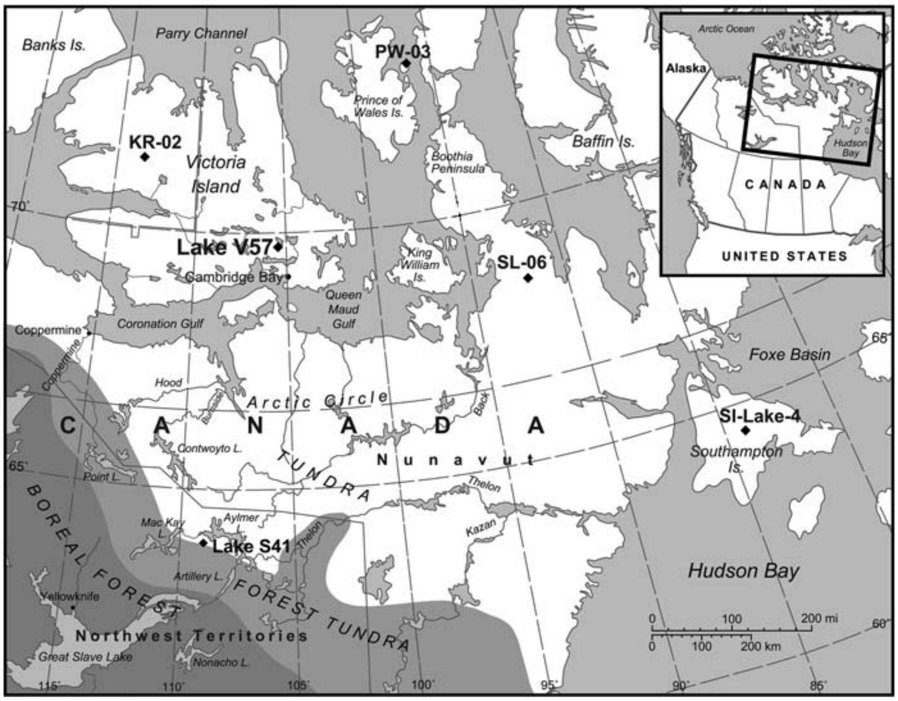

Fig. 1 Study area and location of Lake V57. Additional sites discussed in the text also indicated: Lake S41 (MacDonald et al. this volume); Lake KR-02 (Peros and Gajewski this volume); Lake PW-03 (Finkelstein and Gaiewski 2007); SI-Lake-4 (Rolland et al. 2008); Lake SL-06 (Peros and Gajewski this volume)

Canada 1995). Well-developed turbic cryosols are present on glacial deposits. Numerous small lakes fill depressions in glacial till or coarse-grained glacio-lacustrine deposits (Fulton 1995). The southeast quadrant of Victoria Island is characterized by a low arctic climate (Environment Canada 2008a). The nearest meteorological station to the study site, Lake V57, is located in Cambridge Bay, NU (69.1°N, 105.13°W, 27 m asl). Mean annual temperature at Cambridge Bay for the period 1971–2000 is −14.4°C, with mean July temperature of 8.4°C, and mean winter temperature (DJF) of −28.5°C (Environment Canada 2008b). Mean annual precipitation varies between 100 and 200 mm for the region. Vegetation in southern Victoria Island is dominated by *Betula nana* (dwarf birch), *Salix* (willow), *Ledum* (northern Labrador tea), *Dryas*, and *Vaccinium.* Lake V57 is a small (9 ha), relatively deep (6.90 m), weakly alkaline (pH = 8.20) lake located in south-eastern Victoria Island (69°39.408′ N, 105°21.436′ W). At the time of sediment collection, August 11, 2004, measured surface water temperature was 9.4°C. Vegetation in the vicinity of Lake V57 consists of sedge-dominated, prostrate dwarf-shrub tundra with un-vegetated, barren areas common on upland surfaces.

Methods

Replicate sediment cores were recovered from the approximate center of Lake V57 using a modified Livingstone corer (Wright 1967). The sediment–water interface was undisturbed during sediment recovery. The sediment core analyzed from Lake V57 measured 77 cm and was sub-sectioned in the field at 0.25 cm intervals. The sediment was stored in Whirl-paks and kept cool and in the dark during transport to the lab at The Ohio State University. Measurement of limnological variables, such as water temperature, was made approximately a week prior to sediment collection using a YSI multi-meter.

Chronological control for the core is based on three AMS ^{14}C ages on *Drepanocladus* fragments (Table 1). A radiocarbon age was also obtained on modern *Drepanocladus* collected in the littoral zone of Lake V57 to ascertain whether radiocarbon ages associated with downcore *Drepanocladus* samples may be influenced by hard-water effects commonly associated with carbonate terrain. Analysis was conducted at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS). Ages were converted to calendar years using CALIB 5.0.2 and the IntCal04 calibration dataset (Reimer et al.

Table 1 Radiocarbon dating results[a]

Depth (cm)	NOSAMS #	^{14}C yr BP	±	1−σ range (cal BP)	Median probability age (cal BP)
Littoral (surface)	OS-54853	>modern			
5.0–5.25	OS-55924	550	35	1393–1422	540
7.0–8.0	OS-54936	1600	30	1918–1950	1480
10.5	OS-59013	2630	35	2841–2869	2760

[a] National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS)

2004; Stuiver et al. 2005). Ages are reported relative to AD 1950 (cal yr BP) using the median probability age and an age-depth model developed using a spline-fit approach (Heegaard et al. 2005).

Chironomid analysis follows Walker (2001). Subfossil midge remains were analyzed at 0.25–0.50 cm resolution, with a minimum of 40 head capsules analyzed at each interval (Heiri and Lotter 2001; Quinlan and Smol 2001). Identifications were based on Wiederholm (1983), Brooks et al. (2007) and an extensive reference collection of sub-fossil midge remains housed at The Ohio State University. The volume of sediment processed in order to yield a sufficient number of head capsules varied from 0.5 to 2.5 ml. The average number of head capsules recovered varied between 22.5 and 164 ml^{-1} of sediment. Loss-on-ignition (LOI) analysis followed Heiri et al. (2001).

A midge-based inference model for average July air temperature (AJAT) and summer surface–water temperature (SSWT) was recently developed for use in the central Canadian Arctic (Porinchu et al. this volume). The AJAT inference model is based on 77 lakes and 50 midge taxa; the SSWT inference model includes 75 lakes and 50 taxa. A two-component WA-PLS model provides the most robust performance statistics for AJAT, with an $r^2_{\mathrm{jack}} = 0.77$, RMSEP = 1.0°C, maximum bias of 1.4°C, and no trend apparent in the residuals (negative trend $r^2 = 0.22$, $P < 0.0001$). The most robust SSWT inference model, based on a one-component WA-PLS approach, provides an $r^2_{\mathrm{jack}} = 0.75$, a RMSEP = 1.4°C, and maximum bias of 2.3°C (Porinchu et al. this volume). One means of assessing the reliability of a quantitative paleoenvironmental reconstruction is to determine for each subfossil assemblage the total percentage of taxa present downcore that do not appear in the modern calibration dataset. According to Birks (1998), reconstructions that are based on subfossil assemblages that have >95% of the subfossil taxa present in the calibration set are very reliable; reconstructions with >90% of the subfossil taxa present in the calibration set are considered reliable. An additional method of assessing the reliability of inference model estimates involves determining the number of rare taxa present in downcore samples. A taxon is classified as rare if it has an effective number of occurrences or Hill's N2 ≤ 5 (Hill 1973). Taxa with Hill's N2 values ≥ 5 in a training set can be considered well represented and will likely provide reliable estimates of temperature optima (Brooks and Birks 2001).

The chironomid percentage diagram was plotted using C2 (Juggins 2003) and based on the relative abundance of all identifiable midge remains. Numerical zonation of 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 inference models and the sample specific errors (1.1–1.2°C) associated with the reconstruction were developed using C2 (Juggins 2003). Indirect gradient analysis (DCA) and direct gradient analysis (RDA) were implemented by the program CANOCO version 4.0 (ter Braak and Šmilauer 2002).

Results[1]

The radiocarbon activity of modern (living) *Drepanocladus* retrieved from the littoral zone of Lake V57 is higher than modern (fraction of modern = 1.0872), suggesting that that the hard-water effects commonly

[1] The data presented in this paper are available on-line through the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/canada/nu/v57midge2008.txt).

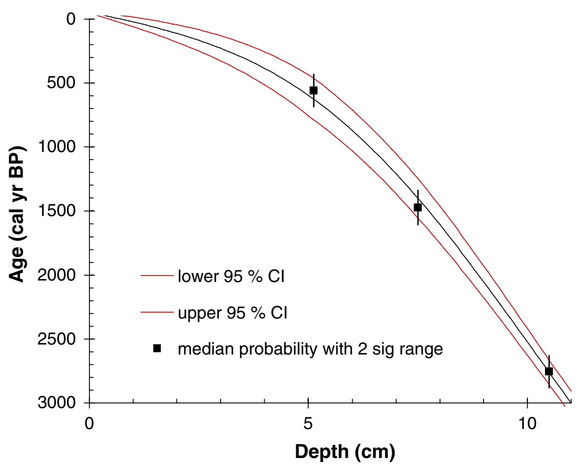

Fig. 2 Age-depth model for the sediment core from Lake V57. Spline fit ($k = 3$; Heegaard et al. 2005) through three calibrated ^{14}C ages (Table 1) and the age of the surface sediment (2005 = −55 cal yr BP). Error bars are entire 1-sigma age ranges. CI = 95% confidence intervals

associated with dating aquatic macrophytes in carbonate terrain is negligible (MacDonald et al. 1991). The age model with 95% confidence intervals is presented in Fig. 2. It indicates that the last 2000 years in Lake V57 is captured by the upper 8.5 cm of sediment. Over this interval, the average width of the 95% confidence intervals is ±110 years.

The uppermost sediment (0–4 cm) consists of dark reddish-brown, organic-rich mud with abundant chironomid tubes at mud–water interface. The sediment color is increasingly lighter with depth. Moss layers (*Drepanocladus* spp.) are present between 4.0 and 9.0 cm. Organic-matter content, as estimated by LOI analysis, increases from 15% to 19% between 0 and ~1650 AD, with a peak of 22% at 1200 AD (Fig. 5). LOI increases rapidly between ~1650 AD, when LOI values are ~18%, and 1900 AD when LOI values are ~50% higher than at 1650 AD, reaching a value of 27%. The interval from 1900 AD to present is characterized by a variable, but overall trend of increasing organic content.

The chironomid stratigraphy was partitioned into three statistically significant zones (Fig. 3). Zone V57-1 spans the interval between 0 AD and ~1600 AD. This zone is characterized by high relative abundances of taxa such as *Heterotrissocladius*, *Tanytarsus*, and *Micropsectra*. Cold stenothermic taxa such as *Parakiefferiella nigra* type, *Abiskomyia*, *Pseudodiamesa*, and *Zalutschia* sp. *A*. are present, albeit at low levels. *Sergentia*, a taxon commonly associated with the profundal of cold, mesotrophic-oligotrophic Arctic lakes is also present (Wiederholm 1983). The overlying zone, V57-2, spans the interval 1600 AD to ~1850 AD. This zone is dominated by *Corynocera ambigua* type, *Psectrocladius sordidellus* type, and *Microspectra*. *P. nigra* type, *Abiskomyia*, *Pseudodiamesa*, and *Zalutschia* sp. *A*. are extirpated from Lake V57 during this interval. The relative contribution of *Paracladius*, *Hydrobaenus/Oliverida*, *Orthocladius*, *Corynoneura*, *and* Pentaneurini decreases in Zone V57-2, whereas, the relative abundance of *Paratanytarsus*, *Procladius*, and *Stictochironomus* increase. The midge community in the uppermost zone, which spans the late ninetieth and twentieth centuries, is characterized by a relatively high proportion of *Tanytarsus* and *C. ambigua* type, and increases in *C. oliveri* type, *Hydrobaenus/Oliveridia*, *Orthocladius*, and Pentaneurini, and a reduction in *Heterotrissocladius*, *Paracladius*, and *Paratanytarus.*

The subfossil midge assemblages from Lake V57 were plotted passively against the assemblages in the modern training set using redundancy analysis (RDA) in order to determine if the composition of downcore midge communities are well represented in the central Canadian training set (Fig. 4) (Porinchu et al. this volume). The RDA bi-plot indicates that the composition of the late Holocene midge community in Lake V57 is located within the ordination space captured by the calibration set; the subfossil assemblages are associated with the deepest and coldest calibration set lakes. De-trended correspondence analysis (DCA) reveals that rapid turnover of midge community composition occurred at ~1600 and 1900 AD (Fig. 5).

Twenty-seven chironomid taxa were recovered from Lake V57, of which 24 (90%) are present in the central Canadian training set (Porinchu et al. this volume). The relative abundance of the three subfossil taxa that are in the Lake V57 core but absent from the training set, *Monodiamesa*, *Doithrix/Psuedorthocladius*, and *TAC* totals between 0.0 and 7.3%. The subfossil midge taxa in Lake V57 are well represented in the central Canadian training set, with only two samples having a relative abundance of rare taxa ($N2 < 5$) greater than 5% (range = 0.7–7.3%; mean = 2.4%). Therefore, the quantitative

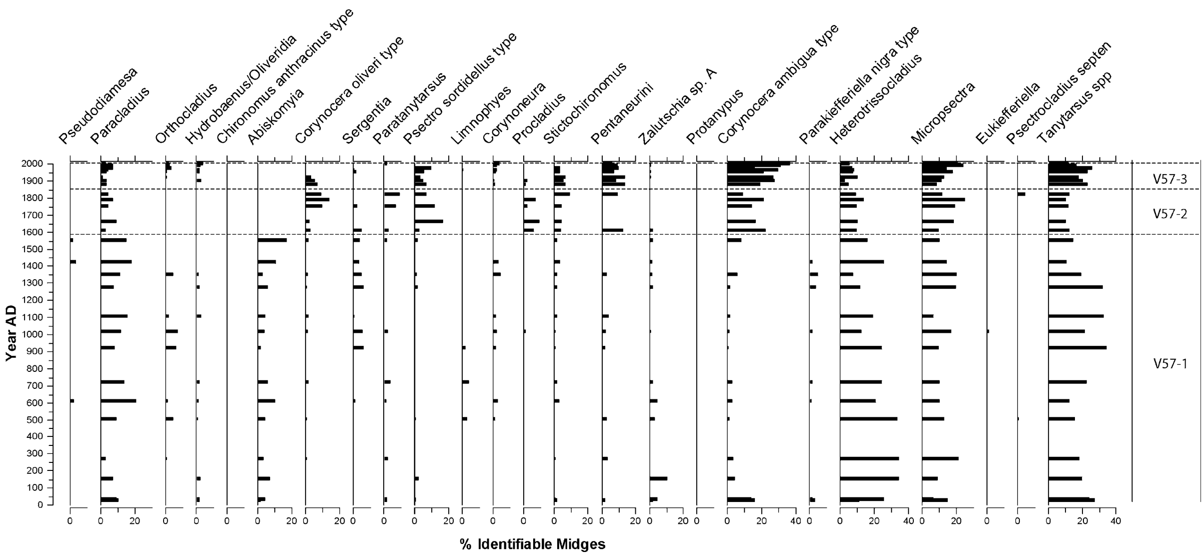

Fig. 3 Chironomid percentage diagram of taxa present in Lake V57. Taxa arranged by their AJAT optima (Porinchu et al. this volume)

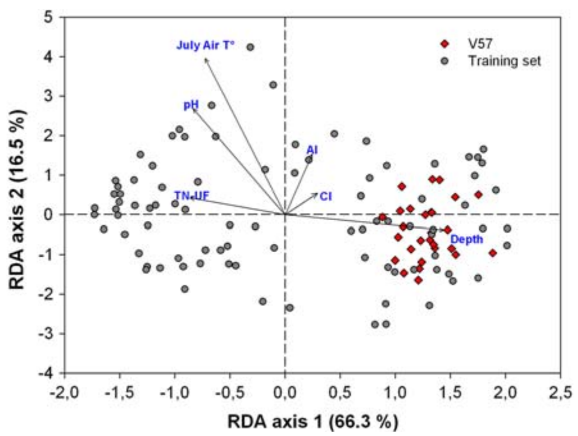

Fig. 4 Redundancy analysis (RDA) passively plotting midge assemblages from Lake V57 with chironomid assemblages in the central Canadian calibration set. The arrows represent the vectors of the six environmental variables that capture a statistically significant amount of variance in the distribution of chironomids in the calibration set (Porinchu et al. this volume)

temperature reconstructions (AJAT, SSWT) can be considered robust.

Application of a two-component WA-PLS inference model for AJAT and a one-component WA-PLS inference model for SSWT to the subfossil chironomid stratigraphy from Lake V57 reveals that the average inferred AJAT is 7.8°C and the average inferred SSWT is 10.0°C (Fig. 5). The trends in the air and water temperature regimes are similar for the last 2000 years, with the exception of the late twentieth century. Between 0 and 500 AD, inferred temperatures averaged 8°C and 10.5°C for AJAT and SSWT, respectively. The interval between 500 and 1600 AD was characterized by an extended period of below average air and water temperatures. Beginning at ~1600 AD the interval of low water temperature was followed by fluctuating, up-ward-trending temperature, with a maximum of 9.1°C and 10.8°C at 1900 AD for AJAT and SSWT, respectively. The reconstructed temperature range captured by variations in the midge community in Lake V57 was 2.8°C (6.4–9.0°C) and 1.8°C (9.2–11.0°C) for AJAT and SSWT, respectively.

Discussion

The midge stratigraphy and the results from the DCA indicate that the midge community in Lake V57 underwent major shifts in community composition within the past 2000 years. However, dating uncertainties related to radiocarbon-based chronologies (MacDonald et al. 1991), time-averaging by bioturbation and low sedimentation rates hamper the resolution of the reconstruction.

The most prominent change in the Lake V57 midge stratigraphy is the shift to more thermophilous taxa after ~1600 AD. Average MJAT and SSWT for

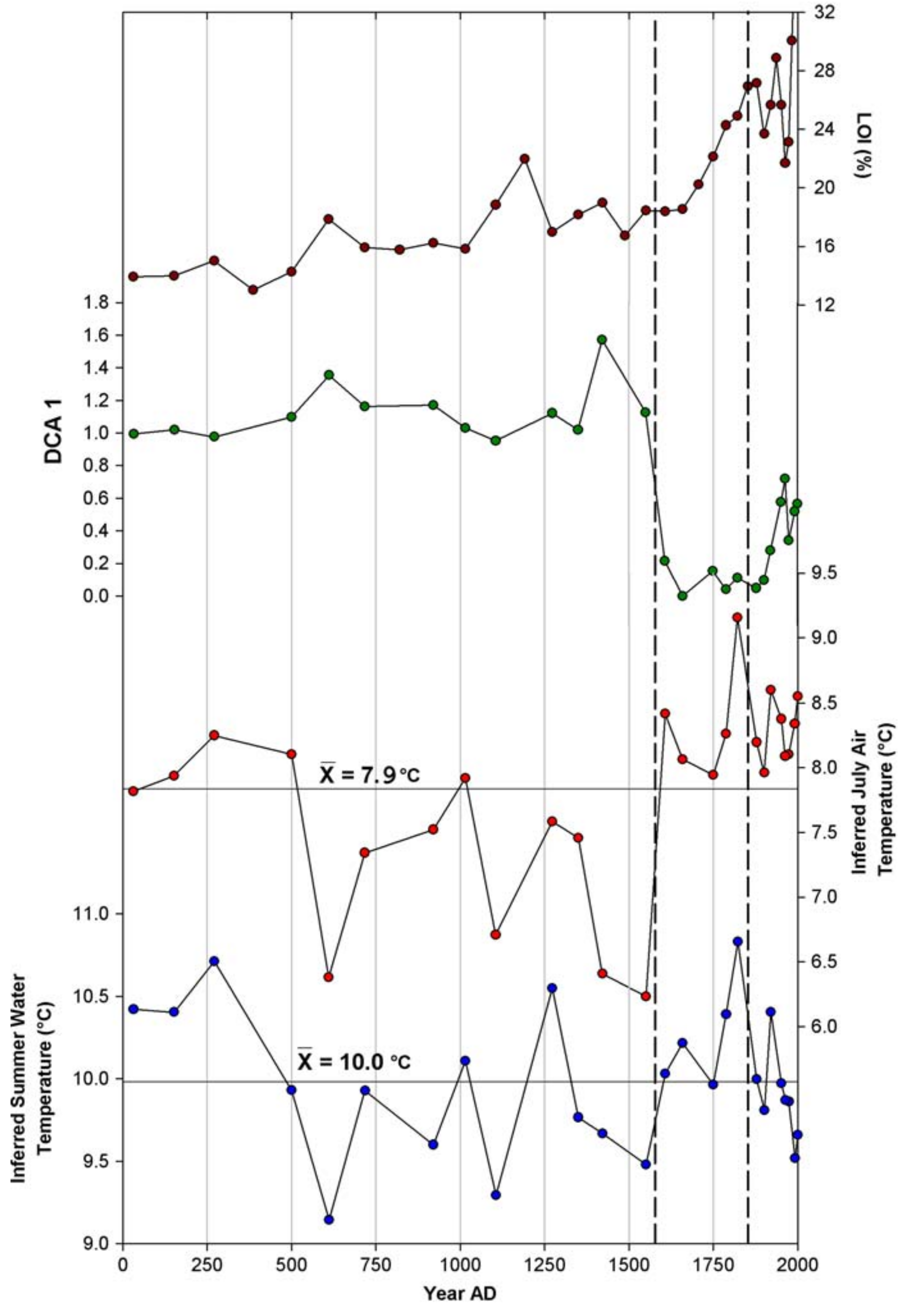

Fig. 5 Organic-matter content determined by loss on ignition (LOI), de-trended correspondence analysis (DCA) Axis 1 scores, and midge-based AJAT and SSWT inferences for sediment core from Lake V57

the interval between 1000 AD and 2000 AD is 7.9°C and 10.0°C, respectively. Higher-than-average AJAT and SSWT estimates typify the early portion of the record, reflecting the high relative abundance of *C. amibgua* type, *Micropsectra*, and *Zalutschia* sp. *A*. These taxa have high AJAT optima in the central Canadian training set (Porinchu et al. this volume) and have previously been associated with warm subarctic and Arctic lakes (Porinchu and Cwynar 2000; Larocque et al. 2006). An increase in *Abiskomyia*, *Paracladius*, and *C. oliveri* type, taxa with relatively low AJAT and SSWT optima (Porinchu et al. this volume), and a decrease in *C. ambigua* type characterizes the interval between ~500 and ~1600 AD. *Abiskomyia*, *Paracladius*, and *C. oliveri* type are commonly associated with cold tundra lakes and ponds in North America, Fennoscandia, and Eurasia (Olander et al. 1999; Brooks and Birks 2000; Porinchu and Cwynar 2000; Larocque et al. 2006; Porinchu et al. this volume). *Paracladius* has the lowest AJAT optimum (7.6°C) and narrowest tolerance (1.01°C) of any taxa present in more than five lakes in the central Canadian training set (Porinchu et al. this volume). The early part of the LIA (1400–1600 AD) includes the highest abundance of the cold stenothermous taxa, *Abiskomyia* and *Pseudodiamesa*, corresponding to the lowest midge-inferred AJAT estimate at ~1550 AD.

Both air and water temperatures remain below the series means from ~1000 to 1600 AD. This interval of below-average water and air temperature is terminated by a two-stage increase in temperature at ~1600 and ~1750 AD. The initial increase in temperature is associated with a 4-fold increase in *C. ambigua* type. Brodersen and Lindegaard (1999) note that *C. ambigua* type, often associated with Arctic and subarctic lakes, is also common in temperate lakes. A sharp delineation in the distribution of *Corynocera* occurs across treeline in northeast Siberia, with *C. ambigua* type only found south of treeline and *C. oliveri* type most abundant north of treeline. Porinchu and Cwynar (2000) suggested that the distribution of *Corynocera* in northeast Siberia could serve as an indicator of relative warmth. Warming, which begins at ~1600 AD in midge-inferred reconstruction from Lake V57, is interrupted by a short interval of depressed temperature, signified by an increase in *Paratanytarsus*, a taxon with a relatively low AJAT optima (9°C) (Porinchu et al. this volume). The most recent portion of the record is dominated by taxa with relatively high temperature optima in the central Canadian training set, e.g. *C. ambigua* type; however, the midge-inferred AJAT estimates decrease, but to a lesser extent than the SSWT inferences, with AJAT increasing slightly in the late twentieth century. Chironomid-based air and water temperature estimates from a treeline lake south of Lake V57 also show a pattern of decreased temperature in the twentieth century (MacDonald et al. this volume).

The decrease in chironomid-inferred AJAT and SSWT at Lake V57 during much of the twentieth century is difficult to reconcile with the well-documented increase in the mean annual temperature over much of the Northern Hemisphere (Hansen et al. 2006; Rigor et al. 2000). The increase in average global temperatures began in the late ninetieth century, but increased markedly in the late twentieth century and in much of the Arctic (ACIA 2004; IPCC 2007). A recent meta-analysis of more than 200 diatom-based paleolimnological studies reveals that geographically consistent changes in diatom community composition characterize temperate, subarctic and Arctic lakes during the late twentieth century (Ruhland et al. 2008). Ruhland et al. (2008) suggest that an increase in the relative abundance of *Cyclotella*, a planktonic species, and the concomitant decrease *Fragilaria*, a benthic species, may be related to an increase in the length of the ice-free period. A decrease in the duration of ice cover may facilitate the development of, or strengthen the thermal stratification in Arctic lakes (Smol pers. comm.; MacDonald et al. this volume).

Stratification may explain why *Micropsectra*, a taxa associated with the profundal of cold, Arctic lakes (Brooks et al. 2007), concomitantly increases with littoral, thermophilous taxa such as *Orthocladius*, *Psectrocladius sordidellus* type, and *Corynoneura* (Brooks et al. 2007) in the uppermost sediment in Lake V57. The appearance of profundal chironomid taxa, such as *Sergentia*, in the upper sediment of a well-sheltered, moderately deep, sub-alpine lake in the Snake Range, Nevada, may similarly be due to strengthening of stratification under warmer conditions (Reinemann 2008). One approach to test whether stratification may be playing a role is to calculate the difference between the $SSWT_{optima}$ and $AJAT_{optima}$ for individual taxa. This difference will likely be greater for profundal taxa, e.g. *Micropsectra*, which are isolated from warmer surface waters than for taxa typically associated with the littoral zone, e.g. *Psectrocladius*, which will be more directly affected by air temperature. Table 2 reports the $SSWT_{optima}$ and $AJAT_{optima}$ for taxa commonly identified as preferring littoral or profundal environments (Brooks et al. 2007) from Lake V57. These taxa have Hill's N2 values > 9 and therefore their temperature estimates are likely reliable (Brooks and Birks 2001). The average offset between SSWT and AJAT ($SSWT_{optima}$–$AJAT_{optima}$) for littoral and profundal taxa is 0.95°C and 1.33°C, respectively (Table 2). The recent concomitant increases in littoral and profundal taxa may be due, in part, to the differential effects of thermal stratification on specific

Table 2 AJAT and SSWT optima of Lake V57 taxa commonly associated with profundal or littoral environments (Brooks et al. 2007)

	Profundal/littoral	N2-AJAT	$AJAT_{optima}$	N2-SSWT	$SSWT_{optimum}$	SSWT–AJAT
Paratanytarsus	L	52.11	9.01	49.10	9.91	0.90
Corynoneura	L	35.64	9.07	34.23	9.92	0.85
Limnophyes	L	23.22	9.07	21.17	9.80	0.74
Orthocladius	L	29.83	8.28	27.25	9.12	0.83
Zalutschia sp. *A.*	L	32.55	9.53	32.15	10.17	0.64
Zalutschia sp. *B.*	L	18.10	10.18	17.39	11.16	0.97
P. septentrionalis	L	18.53	11.95	18.64	13.40	1.45
P. sordidellus	L	60.15	9.02	58.55	10.24	1.22
Average						0.95
C. anthracinus	P	27.75	8.46	27.37	9.38	0.92
Sergentia	P	34.11	8.84	33.80	10.29	1.45
Stictochironomus	P	28.29	9.30	26.48	10.89	1.59
Micropsectra	P	38.08	10.23	39.02	11.44	1.21
Heterotrissocladius	P	32.36	10.01	30.49	11.36	1.35
Protanypus	P	9.37	10.90	10.15	12.48	1.58
Procladius	P	56.00	9.24	55.29	10.45	1.21
Average						1.33

N2: Hill's N2; $AJAT_{optima}$, $SSWT_{optima}$, SSWT–AJAT reported in °C; AJAT: average July air temperature; SSWT: summer surface–water temperature

taxa, and this may account for divergence of the midge-inferred temperature profiles from regional instrumental records during the late twentieth century.

A composite diagram of quantitative air temperature estimates from Lake V57 and biogenic silica (BSi) records available from the central Canadian Arctic has been assembled from a number of sources (Fig. 5). BSi has been used effectively as a proxy of paleo-productivity (Hu et al. 2003) and air temperature (McKay et al. 2008). The comparison reveals a striking correspondence in the pattern of BSi variability in this region (Finkelstein and Gaiewski 2007; Peros and Gajewski this volume), especially during the last millennium (Fig. 6). Between 800 and ~1200 AD, and ~1800 AD to present, lake productivity and/or temperature, as inferred from BSi, were generally high, whereas the interval between ~1200 and 1800 AD was typified by lower lake productivity and/or temperatures (Finkelstein and Gaiewski 2007). A similar, three-phase pattern in BSi values was reported for Lake S41, a small treeline zone a lake located ~250 km northwest of Yellowknife, Canada (MacDonald et al. this volume). At Lake S41, high BSi values typify 500–1100 AD and from 1800 AD onward, and low BSi values characterize the interval between 1200 and 1800 AD.

MacDonald et al. (this volume) found a correspondence between solar variability, hemispheric temperatures, and the BSi content at Lake S41 over the past 2000 years. The combination of widespread increased temperatures in the central Canadian Arctic related to a more active sun during both the period preceding and following the LIA, possibly coupled with increased photosynthetic gain by diatoms and lake productivity, might explain the similarity in the BSi records from lakes throughout the region. The variable and muted chironomid-based temperature reconstruction for Lake V57 may relate to the impact of increasing lake stratification on the profundal chironomid fauna. MacDonald et al. (this volume) argue that increased stratification developed due to earlier ice-free conditions and warmer summer temperatures could reduce temperature and oxygen in the hypolimnion, thus reducing chironomid respiration rates (Brodersen et al. 2004, 2008) and attenuating the impacts of increases in air temperature as reflected in the chironomid record.

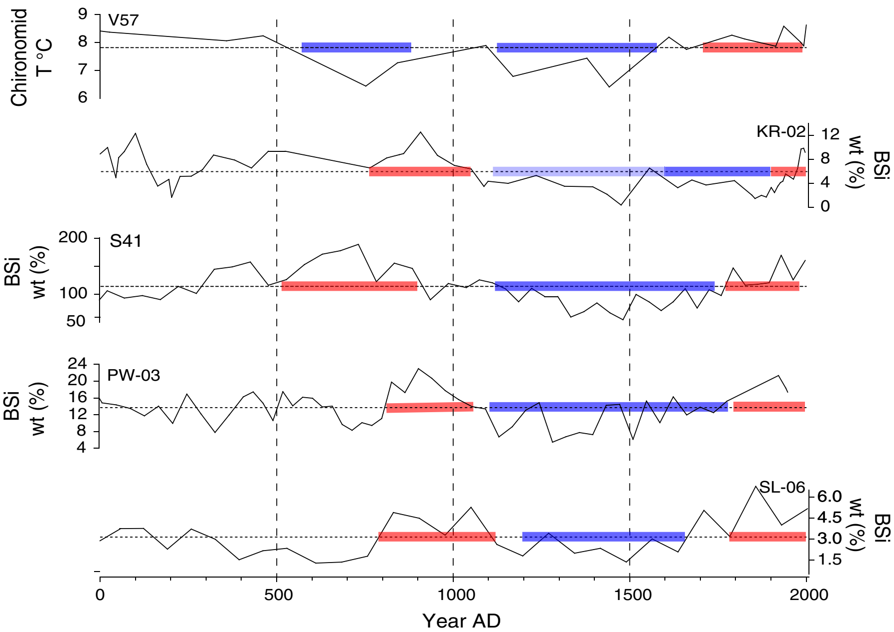

Fig. 6 Midge-inferred AJAT reconstruction from Lake V57, and biogenic-silica (BSi) records from other sites in the central Canadian Arctic (Fig. 1): Lake PW-03 (Finkelstein and Gajewski 2007); Lake KR-02 (Podritske and Gajewski 2007); Lake SL-06 (Peros and Gajewski this volume); SI-Lake-4 (Rolland et al. 2008); Lake S41 (MacDonald et al. this volume). Red bars indicate above-average warmth, as inferred from midge and BSi values; blue bars indicate below-average temperature

Conclusions

The most striking features of the LOI and chironomid stratigraphy at Lake V57 are an increase in lake productivity, as estimated by LOI, and a trend towards a more thermophilous community after 1600 AD. The post-1600 AD interval is notable. The shift to a more thermophilous midge community is typified by increases in *C. ambigua* type and *P. sordidellus* type, and decreases in cold-water taxa such as *Heterotrissocladius* and *C. oliveri* type. The changes in the midge community occur concomitantly with higher midge-inferred AJAT and SSWT. The pattern of warming over recent centuries that equals or exceeds MCO conditions is consistent with temperature reconstructions or temperature sensitive BSi records from a number of sites in the central Canadian Arctic and the treeline zone to the south. However, there is poor representation of twentieth century warming in the SSWT estimates, and a divergence between AJAT and SSWT that in the uppermost sediment. A possible explanation for the apparent decrease in the temperature sensitivity of chironomid-based inference models may be the development or strengthened stratification of Lake V57, resulting from late twentieth century increases in temperature. This increase in temperature may result in a longer ice-free period and warmer spring and summer epilimnion temperatures, and less oxygen and lower temperatures in the hypolimnion, which in turn may alter the relationship between air temperature and profundal midge taxa.

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