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Multiproxy paleoecological evidence of Holocene climatic changes on the Boothia Peninsula, Canadian Arctic

Marie-Claude Fortin, Konrad Gajewski*

Ottawa-Carleton Institute of Biology, Laboratory for Paleoclimatology and Climatology, University of Ottawa, Ottawa, ON K1N 6N5, Canada

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ABSTRACT

A study of chironomid remains in the sediments of Lake JR01 on the Boothia Peninsula in the Central Canadian Arctic provides a high-resolution record of mean July air temperatures for the last 6.9 ka. Diatom and pollen studies have previously been published from this core. Peak Holocene temperatures occurred prior to 5.0 ka, a time when overall aquatic and terrestrial biological production was high. Chironomid-inferred summer air temperatures reached up to 7.5°C during this period. The region of Lake JR01 cooled over the mid- to late-Holocene, with high biological production between 6.1 and 5.4 ka. Biological production decreased again at ~2 ka and the rate of cooling increased in the past 2 ka, with coolest temperatures occurring between 0.46 and 0.36 ka, coinciding with the Little Ice Age. Although biological production increased in the last 150 yr, the reconstructed temperatures do not indicate a warming during this time. During transitions, either warming or cooling, chironomid production increases, suggesting an ecosystem-level response to climate variability, seen at a number of lakes across the Arctic.

Introduction

The composition of lake sediments provides information regarding changes in environmental conditions through time. Multi-proxy studies are particularly important, as the different lines of evidence of past climatic conditions provided by each proxy can be used in comparison to one another, providing a more comprehensive picture of the effect of climatic change on the lake ecosystem through time.

In this study we examine the climatic history over the last 6.9 ka of Lake JR01, located on the Boothia Peninsula in the southern Canadian Arctic, using a multi-proxy approach. Little is known regarding Holocene climatic conditions in this region. Previous studies have analyzed pollen and diatoms in the sediments of Lake JR01 (LeBlanc et al., 2004; Zabenskie and Gajewski, 2007), but quantitative temperature reconstructions are only available from the pollen record (Zabenskie and Gajewski, 2007; Gajewski, 2015a). Although the time-space evolution of the postglacial climates of the Canadian Arctic has been reconstructed (Gajewski, 2015a), these results need verification from high-temporal resolution, well-dated multi-proxy series.

We focus our attention on the chironomids in Lake JR01's sediment record, generating both qualitative estimates of the past biological production of this lake and a chironomid-based mean July air temperature reconstructions using a newly-developed Arctic-wide training set (Fortin et al., 2015). Although there remain gaps in our understanding of the chironomid-temperature relationship, and the importance of indirect limnological variables that co-vary with temperature is not completely known, calibration studies nevertheless consistently identify plausible relationships with chironomid abundance and air temperature (Eggermont and Heiri, 2012). Estimates of past temperatures are assessed and compared to previously-published pollen and diatom analyses of the lake. Taken together, the biological, physical and chemical proxies at Lake JR01 indicate that environmental conditions were warmer and that overall lake production was higher prior to 5.0 ka than they are at present. Furthermore, at Lake JR01 and other lakes across the Arctic, isolated peaks in chironomid production during the Holocene are observed at times of inferred temperature transitions, both into warmer and cooler conditions, indicative of an ecosystem-level response to changes occurring in the lake's environment.

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* Corresponding author.
E-mail address: gajewski@uottawa.ca (K. Gajewski).

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Study site

Lake JR01 is located in the southern Boothia Peninsula in the middle-Arctic vegetation zone (Fig. 1; 69°54′N, 95°4.2′W, 120 m asl, 5.4 m deep). This small lake (0.7 by 0.03 km) is underlain by Precambrian Shield and carbonitic bedrock (Dyke, 1984) and is surrounded by prostrate dwarf shrubs and herbaceous tundra (CAVM, 2003). Two small streams that run through sedge meadows drain into the lake. Water chemistry indicates that this lake is oligotrophic (TP = 0.04 mg l^{-1}) and circumneutral to basic (pH = 8.1) (Hamilton et al., 2001; LeBlanc et al., 2004). Deglaciation in this area occurred around 9.5 cal ka BP (Dyke, 2004).

Methods

A sediment core measuring 485 cm, collected from the central part (5.4 m deep) of ice-covered Lake JR01 was used for this study. Diatom and pollen analysis were previously conducted on this same core (LeBlanc et al., 2004; Zabenskie and Gajewski, 2007).

The core was collected using a Livingstone piston corer (5 cm diameter) and the top 80 cm was collected in a clear plastic tube attached to the drive rods to preserve the sediment water interface. The top 20 cm was extruded in the field at 0.5 cm intervals. The remaining sediment was wrapped in plastic and aluminum foil and stored at 4°C.

Continuous measurements of magnetic susceptibility and sediment loss on ignition, at one or 0.5 cm intervals, were reported in Zabenskie and Gajewski (2007) and followed standard methods (Dean, 1974). For this study, sediment biogenic silica was measured every 0.5–2.0 cm downcore using 0.5 cm^3 samples and a wet alkaline digestion technique (1% Na_2C0_3 base and reduced molybdosilic acid spectrophotometry) (DeMaster, 1981; Conley, 1998; Conley and Schelske, 2001; Fortin and Gajewski, 2009).

Radiocarbon and ^{210}Pb dates were reported in LeBlanc et al. (2004) and Zabenskie and Gajewski (2007). The oldest date at 544 cm was recovered from a second sediment sequence collected from the Lake JR01, which was correlated to the first sequence based on the magnetic susceptibility measurements. This deepest portion of the second core could not, however, be used for further analysis as it contained no microfossils and only contained a layer of organic material (Bryophytes, plant fragments and chironomids) that provided the date. The age model was developed for this paper using BACON (Blaauw and Christen, 2011) on the ^{210}Pb and calibrated ^{14}C dates (Fig. 2). All dates were calibrated using Intcal13 (Reimer et al., 2013) and are reported as ka, 1000 yr before present, with a base of AD 1999, the year in which the sediment core was collected, to avoid the use of negative ages.

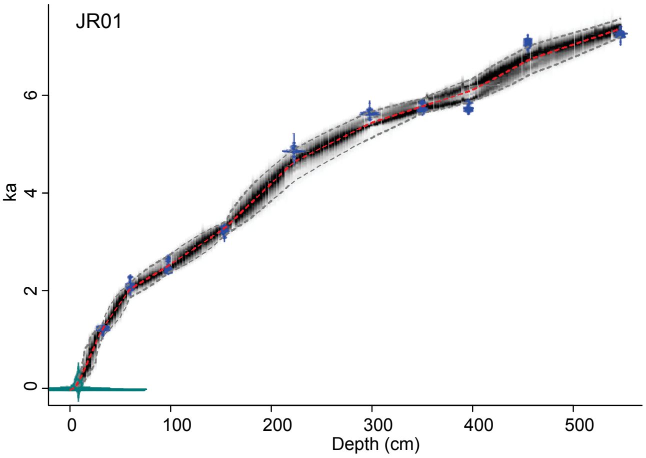


Figure 2. Sediment chronology at Lake JR01, see text for details.

A total of 122 levels was sampled for chironomids, providing over 20,000 whole head capsules (HC) for analysis. Sediment samples were taken every 1–5 cm depending on sediment

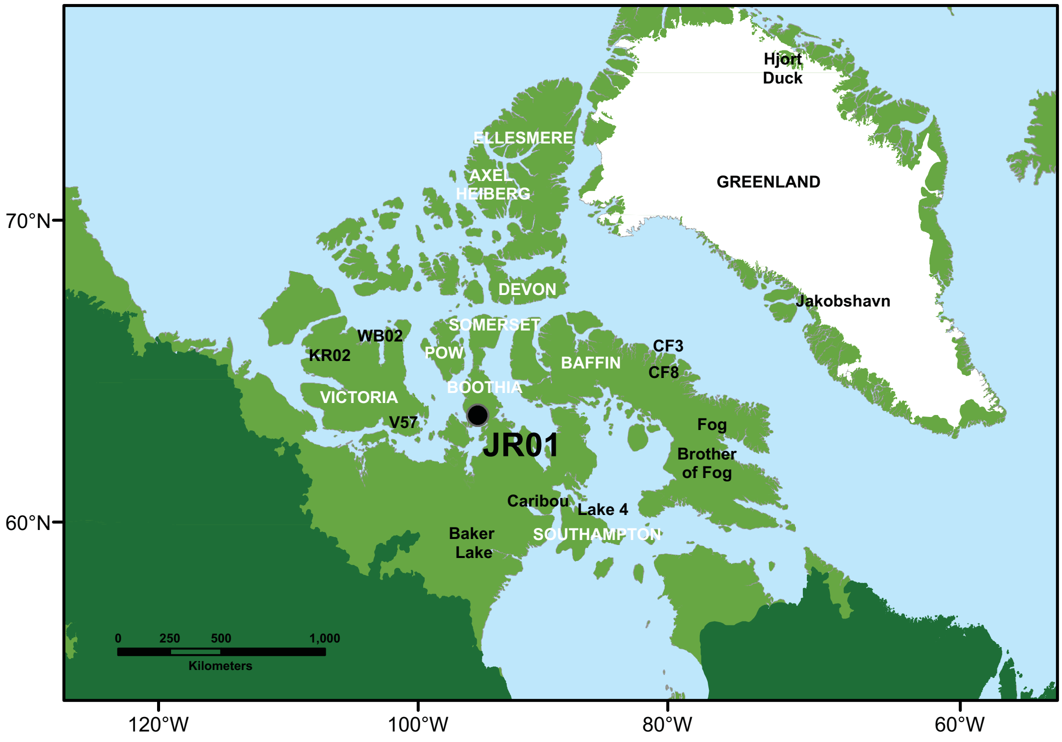


Figure 1. Location of Lake JR01 in the Canadian Arctic. Other studies referenced in the text are also shown (see text for references).

availability, and were processed for chironomid analysis using standard methods (Walker, 2001). The volume of sediment sampled and HC concentrations ranged from 0.1 to 4.0 cm^3 and 24–290 HC cm^{-3} (105–1683 HC dry g^{-1}), respectively. Chironomid volumetric concentrations and concentrations per gram of dry weight had very similar profiles and therefore only volumetric concentrations will be discussed. Although we attempted to obtain a minimum of 50 head capsules per sample (Heiri and Lotter, 2001; Larocque, 2001; Quinlan and Smol, 2001), this was not always possible due to either low HC concentrations or insufficient sediment availability. However, of the 122 levels retained for statistical analysis, only 3 had HC counts below 45 HC.

Head capsules were identified using taxonomic references of Walker (1988, 2000); Barley et al. (2006), Heiri et al. (2004), Larocque and Rolland (2006) and Brooks et al. (2007), and were identified to the lowest level possible. *Tanytarsus* spp., *Micropsectra* spp. and *Paratanytarsus* spp. were identified to the species morphotype level using Heiri et al. (2004). *Heterotrissocladius* spp. identifications to the species level were based on Larocque and Rolland (2006), and *Zalutschia* spA and spB identifications follow Barley et al. (2006).

Mean July air temperatures (JTemp) were estimated based on the JR01 chironomid assemblages using a new collection of modern samples (n = 435) from across Canada and the Canadian Arctic (Fortin et al., 2015). This dataset significantly expands on Barley et al. (2006) by including a greater number of lakes from the Arctic and northern Canada. The training set and calibration procedure is described in Fortin et al., (2015; $r^2_{boot} = 0.70$, $RMSEP_{boot} = 1.93°C$, max bias = 2.22°C). Squared chord distances of the closest analogs in the training set to the downcore assemblages, as well as the geographical location of these analogs, were examined to determine the appropriateness of the training set (Anderson et al., 1989; Birks, 1998; Gajewski et al., 2000; Sawada et al., 2004; Viau et al., 2008).

Principal component analyses (PCA) were conducted separately on the fossil diatom, pollen and chironomid taxonomical data to reveal changes in the community composition of each of these fossil groups through time. The first two axes of each respective PCA explained 28% and 9% of the changes in the chironomid community, 14% and 10% of the changes in the pollen assemblage, and 52% and 17% of the changes in the diatom community. Loadings of the most abundant taxa included in each PCA are presented in Table 1.

Table 1
Loadings of the dominant taxa on the first and second axis of a principal component analysis of the a) chironomid, b) pollen and c) diatom fossil record at Lake JR01.

a.

Chironomid	Axis 1	Axis 2
Abiskomyia	−1.73	0.23
Protanypus	−1.58	−0.33
Tanytarsus spp.	1.46	0.67
Procladius	1.43	−0.61
Pseudodiamesa	−1.38	1.67
Paracladius	−1.37	−1.34
Heterotrissocladius spp.	1.29	−1.19
Mesocricotopus	−1.26	−1.46
Zalutschia spB	−1.25	−1.39
Parakiefferiella nigra-type	−1.25	−0.81
Paratanytarsus spp.	1.20	−0.16
Psectrocladius (Psectrocladius) spp.	1.05	−0.71
Pentaneurini spp.	1.00	−0.94
Corynocera ambigua type	0.92	0.34
Tanyarsina-other	0.84	1.46
Eukiefferiella/Tvetenia spp.	−0.80	0.23
Sergentia	0.66	−0.61
Micropsectra spp.	−0.55	2.39
Corynoneura arctica-type	−0.47	0.66
Cricotopus/Orthocladius spp.	−0.40	−0.26
Zalutschia sp A	−0.35	−0.30
Limnophyes	−0.29	0.78
Hydrobaenus/Oliveridia spp.	−0.26	0.11
Stictochironomus	0.17	−1.61
Corynocera oliveri-type	−0.13	−1.12
Chironomus anthracinus-type	0.08	−0.52
Metriocnemus spp.	0.06	−0.45

b.

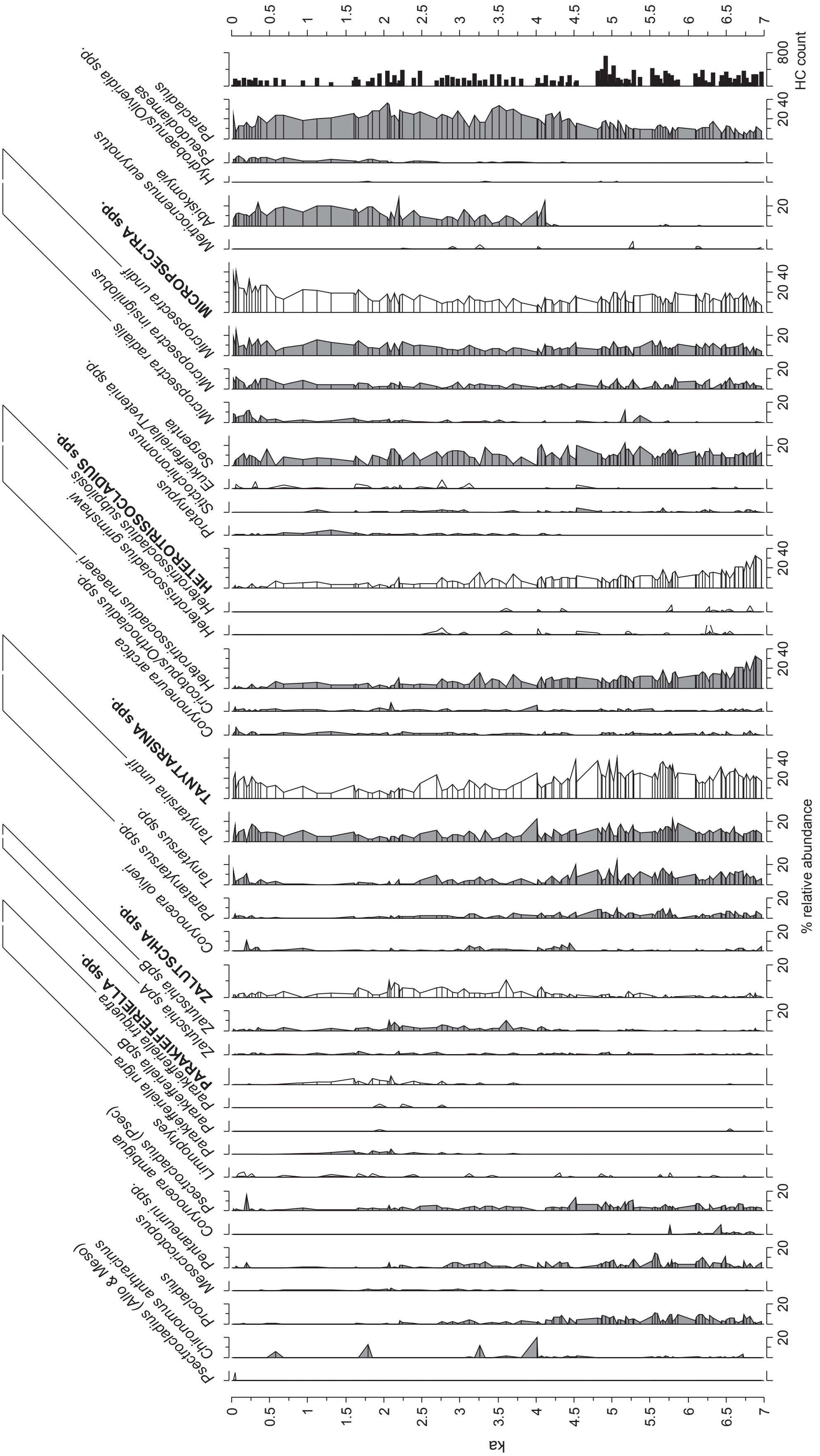
Pollen	Axis 1	Axis 2
Cyperaceae	2.21	−0.06
Ericaceae	−1.67	−0.70
Saxifraga oppositifolia	−1.66	0.44
Brassicaceae	−1.45	−0.40
Polygonum viviparum	1.44	−0.89
Caryophyllaceae	−1.44	−0.61
Salix	1.25	−1.09
Saxifragaceae other	1.09	−1.60
Chenopodiaceae	0.76	1.17
Oxyria	0.62	−0.64
Asteraceae	0.57	1.73
Potentilla	0.46	0.92
Dryas	0.45	−0.13
Poaceae	0.45	−0.79
Rosaceae other	−0.43	−1.98
Ambrosia	−0.36	−0.13
Fabaceae	−0.36	−1.14
Ranunculaceae	0.34	−0.26
Rubus chamaemorus	−0.26	1.18
Artemisia	0.23	0.12
Papaver	−0.10	−1.80
Plantago major	0.00	−0.18

c.

Diatom	Axis 1	Axis 2
Achnanthes rosenstockii	1.34	0.03
Achnanthidium minutissimum spp.	1.30	0.25
Staurosirella pinnata var. *pinnata*	−1.26	−0.25
Pseudostaurosira pseudoconstruens	1.26	−0.07
Staurosira construens var venter	−1.11	0.40
Staurosira aff. elliptica	1.04	−0.25
Pseudostaurosira brevistriata	−0.97	0.44
Staurosira construens form 2	−0.78	1.38
Staurosira construens form 1	−0.53	−1.61
Staurosirella pinnata var acuminata	−0.47	−1.71
Amphora ovalis var. *pediculus*	0.02	−1.74

Results

Heterotrissocladius spp. (optimum 9.2°C, all optima are from Fortin et al., 2015) was the most abundant taxon in the oldest fossil assemblage (Figs. 3 and 4). When *Heterotrissocladius* spp. relative abundance decreased from 6.9 to 6.5 ka, the proportion of both cold- and warm-tolerant taxa already present in the community began to increase. Taxa from the sub-tribe Tanytarsina (called here *Tanytarsina* spp. including all *Paratanytarsus* spp., *Tanytarsus* spp. and *Tanytarsina*-undif.; optimum 9.8°C) and from the sub-tribe Tanypodinae (Pentaneurini spp. and *Procladius* whose optima are 10.6°C and 10.8°C, respectively), became more abundant, and the relative abundance and production of these taxa remained relatively high until ~4.2 ka. Colder-tolerant *Paracladius* (optimum 6.4°C) and taxa from the genus *Micropsectra* (*Micropsectra* spp. including *Micropsectra radialis*, *Micropsectra insignilobus* and *Micropsectra*-undif; optimum 8.0°C) also increased in abundance and production in the mid-Holocene. The relative abundance of *Paracladius* continued to increase until ~3.5 ka, whereas the abundance and production of *Micropsectra* spp. was high between 6.3 ka and 4.8 ka. *Sergentia* and *Psectrocladius (Psectrocladius)* (optima 8.8° and 10.4°C, respectively), were also abundant in the assemblage prior to ~4.2 ka. Prior to ~5.3 ka, the relative


HC count
800
Paracladius
Pseudodiamesa
Hydrobaenus/Oliveridia spp.
Abiskomyia
Metriocnemus eurynotus
MICROPSECTRA spp.
Micropsectra undif
Micropsectra insignilobus
Micropsectra radialis
Sergentia
Eukiefferiella/Tvetenia spp.
Stictochironomus
Protanypus
HETEROTRISSOCLADIUS spp.
Heterotrissocladius subpilosis
Heterotrissocladius grimshawi
Heterotrissocladius maeaeri
Heterotrissocladius spp.
Cricotopus/Orthocladius spp.
Corynoneura arctica
TANYTARSINA spp.
Tanytarsina undif
Tanytarsus spp.
Tanytarsus spp.
Paratanytarsus spp.
Corynocera oliveri
ZALUTSCHIA spp.
Zalutschia spB
Zalutschia spA
PARAKIEFFERIELLA spp.
Parakiefferiella triquetra
Parakiefferiella spB
Parakiefferiella nigra
Paraphyes
Limnophyes
Psectrocladius (Psec)
Corynocera ambigua
Pentaneurini spp.
Mesocricotopus
Procladius
Chironomus anthracinus
Psectrocladius (Allo & Meso)
20 40
20
% relative abundance
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
ka

abundances and concentrations of warm-tolerant chironomid taxa at Lake JR01 were generally at their highest when compared to the rest of the core.

Beginning around 4.8–4.2 ka there was a change in composition of the chironomid, pollen and diatom communities as seen in a transition in the sample scores of the first axes of the respective principal components (Fig. 5). Around this time, the thermophilic chironomid taxa from the earlier Holocene greatly decreased in relative abundance and concentrations, and cold-tolerant *Paracladius* began to dominate the assemblage (Figs. 3 and 4). *Micropsectra* spp. also remained quite abundant from ~4.5 onwards, although less so between 4.5 and 2.5 ka than in the earlier Holocene. At ~4.2 ka, cold stenothermic *Abiskomyia* (optimum 6.2°C) also appeared in the assemblage and remained in high relative abundance until recent times. Although cold-tolerant taxa dominated the assemblage from ~4.5 ka until recent times, taxa tolerant of intermediate and warmer temperatures, such as *Zalutschia* spp. (including *Zalutschia* spA and spB types), *Corynocera oliveri* type, *Protanypus* and *Mesocricotopus* (optimum 10.0°C, 9.9°C, 8.9°C and 10.5°C respectively) all became slightly more abundant than previously in the record and remain in the assemblage until the late Holocene. *Chironomus anthracinus* type (optimum 11.1°C) briefly increased at ~4.0 ka, 3.3 ka, and 1.7 ka, reaching 20%, 10%, and 10% relative abundance at those respective times. *Chironomus anthracinus* type is present in greater relative abundances after disturbances (Brooks et al., 2007). After ~3.5 ka, *Paracladius* dominated the assemblage and its relative abundance stabilized, although its concentration continued to increase for another 2000 yr. From ~3.4 until 600 yr ago there were no major changes in relative abundances other than a slight increase in *Micropsectra* spp. until ~1 ka. After an abrupt increase from 0.5 to 0.3 ka, *Paracladius* and *Abiskomyia* decreased in abundance and *Micropsectra* spp. and *Tanytarsina* spp. increased in relative abundances. During the last 150 yr, the production of cold-tolerant and some warm-tolerant chironomid taxa increased.

The chironomids, pollen and diatoms all show highest accumulation rates in the mid-Holocene (Fig. 6). These results hold true even when alternative age models are considered (not shown; Fortin, 2010). This result is therefore to some extent a function of changes in sedimentation rate, although the large number of dates lends confidence to the age–depth curve. A large peak between 6.2 and 5.2 ka is present in all three proxies. A secondary peak is seen between 3.0 and 2.0 ka.

Sediment organic and biogenic silica contents were highest prior to ~4.8 ka (Fig. 5). Similarly, the concentrations of diatom and pollen fossils reach their highest values prior to ~4.0 ka. Chironomid concentrations show no significant long-term trend, although values were slightly higher prior to ~4.8 ka (Fig. 5). Overall aquatic and terrestrial production, as measured by sediment organic and biogenic silica content as well as pollen and diatom concentrations and accumulation rates, were high between 6.9 and 4.8 ka then decrease from 4.8 to 4.0 ka, and remain low from 4.0ka to 0.15 ka (Figs. 5 and 6). From 150 yr ago to the present, concentrations and accumulation rates of all fossil organisms and sediment BSi content increased (Figs. 5 and 6), representing an increase in overall lacustrine production from the late Holocene minima.

Mean July air temperatures inferred from the fossil chironomid assemblages based on the WAPLS 2-component model and using the modern calibration dataset of Fortin et al. (2015) show a long-term cooling over the record (Fig. 7). Starting at ~0.6 ka, inferred temperatures abruptly decreased, with the coldest temperature occurring between 0.46 and 0.36 ka, then increased at 0.3 ka and then decreased until recent times.

The closest modern analogs to the fossil chironomid assemblages prior to 4.6 ka were lakes located in the more southern Arctic sites of the training set as well as those located in the Fosheim region of Ellesmere Island, an anomalously warm area (Fortin and Gajewski, 2012). After 4.6 ka the fossil assemblages at Lake JR01 more closely resemble those of the more northern lakes of the training set.

The chironomid-based July temperature reconstruction was compared to one done in Gajewski (2015a) based on the pollen assemblages from the same JR01 core published in Zabenskie and Gajewski (2006). Both proxies show a similar long-term cooling, although the pollen-based reconstruction (using the Modern Analog Technique and three analogs) is slightly warmer and more variable that the chironomid based reconstruction (using WAPLS). In both cases, warmest temperatures were reconstructed for the period between 6.9 and 3.20 ka, and the cooling rate accelerated slightly in the past 3.2 ka.

Discussion

Chironomid communities and production

Chironomid taxa present at Lake JR01 over the past 6.9 ka yr are typical of those found in modern-day cold, oligotrophic lakes (Gajewski et al., 2005; Barley et al., 2006; Fortin and Gajewski, 2011; Medeiros and Quinlan, 2011; Fortin et al., 2015). The Holocene chironomid community composition at Lake JR01 is similar to that present in the sediment records from lakes on Baffin Island (Fig. 1; Fog and Brother of Fog Lake, Francis et al., 2006; CF3, Briner et al., 2006; CF8, Axford et al., 2009), Southampton Island (Lake 4 and Caribou, Rolland et al., 2008, 2009), Victoria Island (WB02 and KR02; Fortin and Gajewski, 2010a, 2010b), Northeast Greenland (Duck and Hjort Lake; Schmidt et al., 2011), West Greenland (Jakobshavn area; Axford et al., 2013) and the late Holocene in Lake V57 (Victoria Island; Porinchu et al., 2009) or Baker Lake (Medeiros et al., 2012).

Overall chironomid production during the Holocene is higher at Lake JR01 than at other Arctic lakes, and even at lakes whose inferred temperatures over the Holocene are greater than those for Lake JR01. Pollen concentrations and sediment organic content over the Holocene at Lake JR01 are also quite high for an Arctic lake (Zabenskie and Gajewski, 2007). The higher production at this lake may be due in part to its more southerly location and the result of local-scale environmental influences on this lake, which lead to a relatively dense vegetation cover.

Holocene climatic changes in the Canadian Arctic

The sediment record from Lake JR01 revealed an important transition at ~5.0 ka, which is the time of a major reorganization in the climate of the Canadian Arctic (Gajewski, 2015a). Prior to 5.0 ka, aquatic and terrestrial production, as inferred by pollen and chironomid concentrations and accumulation rates (Gajewski,

Figure 3. Percent relative abundances of all chironomid taxa at Lake JR01. Taxa are plotted in order of decreasing optimal mean July air temperature (°C) (Fortin et al., 2015). Taxa that were subsequently combined for the mean July air temperature reconstruction are grouped together with a bracket. The non-shaded profiles with taxa label in bold and in all capitals represent the sum of the relative abundances of the taxa in the bracket to the left. *Paratanytarsus* spp. includes *Paratanytarsus austriacus*, *Paratanytarsus penicillatus* and *Paratanytarsus* undifferentiated and *Tanytarsus spp*. includes *Tanytarsus lugens*, *Tanytarsus mendax* and *Tanytarsus* undifferentiated. Head capsule (HC) count sums for each level are presented on the far right of the graph.

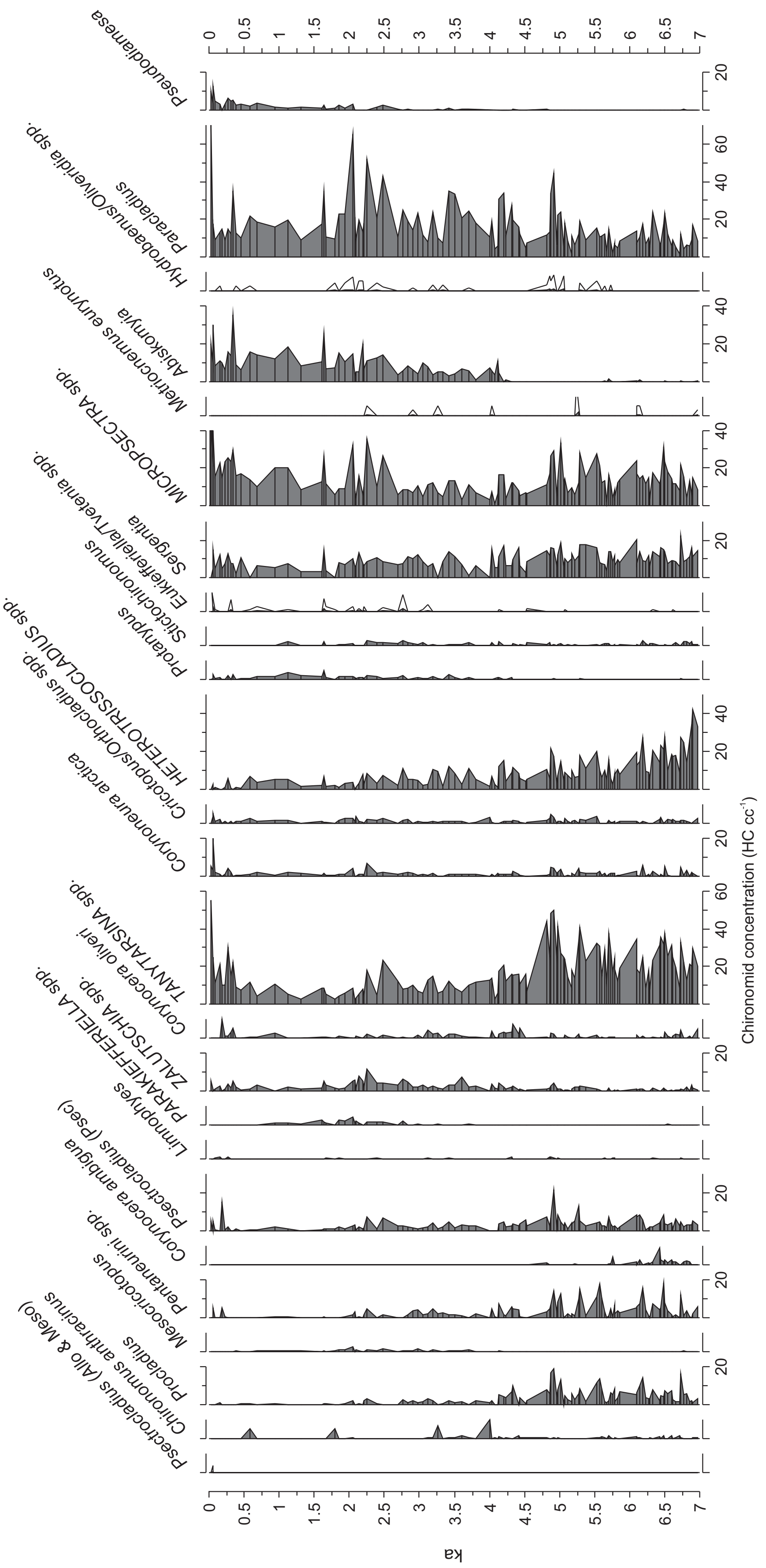


Figure 4. Chironomid concentrations of select chironomid taxa from Lake JR01 during the past 6.9 ka. Taxa are in order of decreasing optimal mean July air temperature (°C).

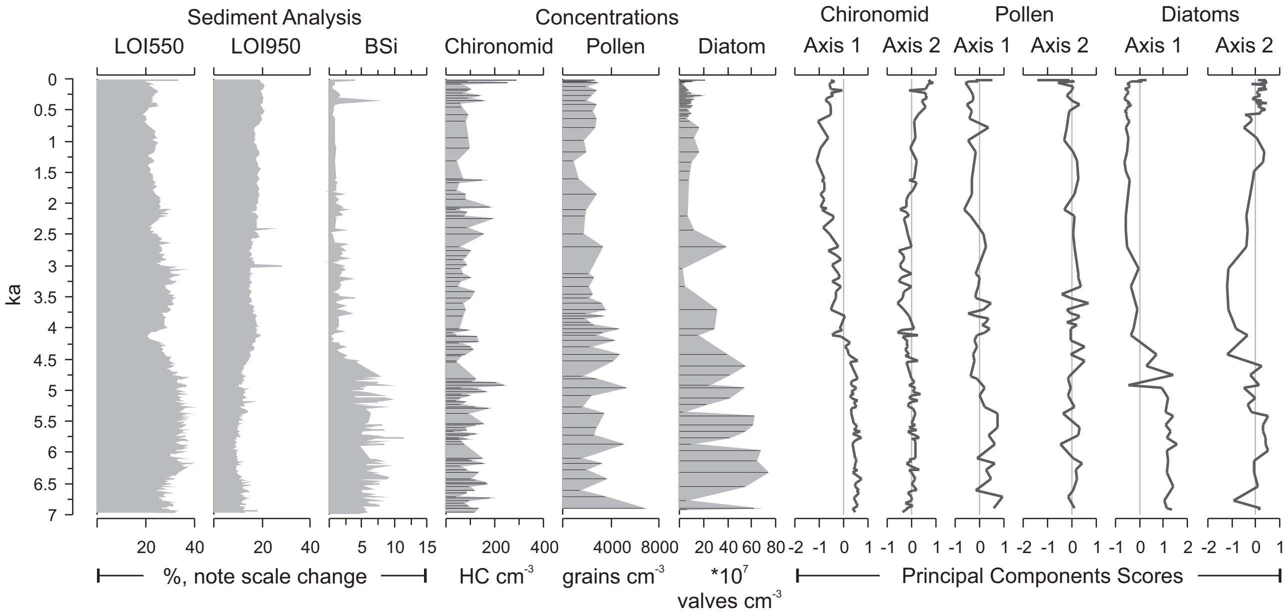


Figure 5. Sediment organic, carbonate and biogenic silica content (%) and chironomid head capsule (HC), pollen grain and diatom valve concentrations at Lake JR01 during the last 6.9 ka. The sample scores for the first and second axis of the respective chironomid, pollen and diatom principal components analysis are plotted on the right.

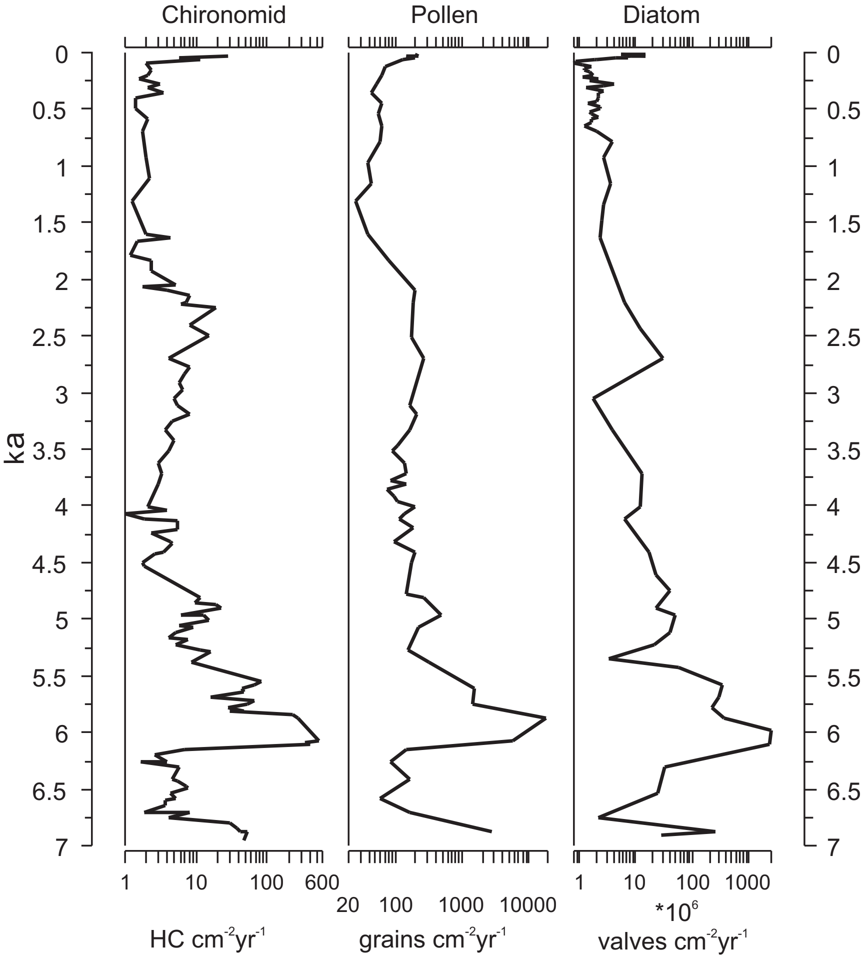


Figure 6. Chironomid head capsules (HC), pollen grain and diatom valve accumulation rates at Lake JR01. Note the log scale.

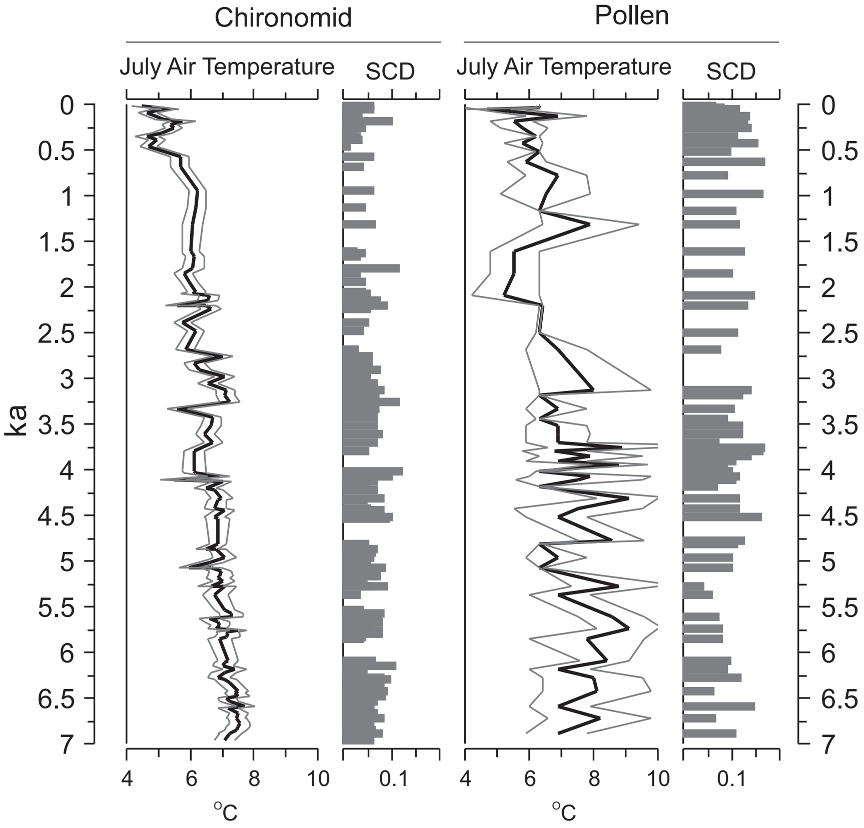


Figure 7. Chironomid-inferred mean July air temperature at Lake JR01 over the last 6.9 ka yr (black line) using a WAPLS-2 component model (Fortin et al., 2015). The standard error of the reconstruction is shown by light gray lines. Pollen-based mean July air temperature reconstruction (Gajewski, 2015a) using pollen assemblages from lake JR01 (Zabenskie and Gajewski, 2007) and the Modern Analog Technique. Gray lines are the standard deviation of the reconstruction based on the top three analogs. The squared chord distance (SCD) of the best analog for the fossil assemblage and the modern data is shown for both the chironomid and pollen records.

1995; Zabenskie and Gajewski, 2007; Peros and Gajewski, 2008; Gajewski, 2015b), were high and chironomid-inferred mean July air temperatures were relatively warm. Temperatures were cool or cooling from ~5.0–1.0 ka, during which time ecosystem production was lower than during the mid-Holocene. Based on the changes in diatom species diversity at 5.0 ka, which is reflected in the PCA scores, a cool period starting at this time was also inferred by LeBlanc et al. (2004), although the magnitude of the change was not estimated using the diatom assemblages due to lack of appropriate modern data. The pollen record showed higher concentrations and accumulation prior to 5.5 ka, and Zabenskie and Gajewski (2007) found warmest conditions between 5 and 3 ka and cooling since 3 ka. A new reconstruction of the pollen record from JR01 (Fig. 7; Gajewski, 2015a) shows warm temperatures from 7.0 to 3.1 ka, and subsequent cooling, as seen in the chironomid record. Based on the chironomid record, climate cooled further from ~1 ka until present times. Minimum temperatures were reached during the Little Ice Age.

The general trends of the chironomid inferred mean July air temperatures at Lake JR01 are similar to those of many other chironomid- and other proxy-based records from across the Arctic. A warm, productive early to mid-Holocene was inferred on Western and Northern Victoria Island (Lakes KR02 and WB02, Podritske and Gajewski, 2007; Peros and Gajewski, 2008; Fortin and Gajewski, 2010a, 2010b; Gajewski, 2015a) using primary production indices as well as pollen, chironomid and diatom records. Warmest temperatures occurred in the early Holocene on Somerset Island, to the north of the Boothia Peninsula (Gajewski, 1995). Records from Baffin Island confirm the presence of a warmer period during the early Holocene (Briner et al., 2006; Francis et al., 2006; Axford et al., 2009), with maximum temperatures between 8.2 and 5.2 ka (Gajewski, 2015a). Ice melt percent was also highest during the early Holocene, as recorded by the Agassiz Ice Core on Ellesmere Island (Fisher et al., 1995).

A cool period occurring at Lake JR01 through the mid- and late Holocene is also interpreted from lake sediment cores on Victoria Island, the northern Boothia Peninsula, Somerset Island, Prince of Wales Island and Baffin Island (Gajewski, 1995; LeBlanc et al., 2004; Briner et al., 2006; Francis et al., 2006; Finkelstein and Gajewski, 2007; Axford et al., 2009; Fortin and Gajewski, 2010a, 2010b; Gajewski, 2015a). At Lake JR01, both the chironomid and pollen records show further cooling in the past ~1 ka, which includes the Little Ice Age, and this is the coldest interval of the Holocene. A cooling occurred at approximately the same time in the chironomid-based records from Southampton Island (between 600 and 300 yr ago, Rolland et al., 2008) and southern Victoria Island (between 900 and 300 yr ago, Porinchu et al., 2009), and in diatom (Wolfe, 2003; LeBlanc et al., 2004; Finkelstein and Gajewski, 2007) and pollen records (Peros and Gajewski, 2009) from across the Arctic.

Temperatures inferred for the past 150 yr at Lake JR01 are cooler than those inferred for the mid-Holocene prior to 5.0 ka, up to 2–3°C cooler based on the chironomid record. A number of other studies from across the Arctic, such as on Victoria, Southampton and Baffin Islands, have found that inferred modern temperatures were equivalent or cooler than those inferred for the early Holocene (Briner et al., 2006; Francis et al., 2006; Rolland et al., 2008; Axford et al., 2009; Fortin and Gajewski, 2010a, b). A recent warming of the past few decades, observed in the Canadian Arctic (and summarized in Kaufman et al., 2009), is not present in either the pollen-inferred temperature records at Lake JR01 nor the chironomid based temperature record, although sediment production proxies as well as fossil concentrations at this lake do increase over the last 150 yr. Gajewski (2015b) has shown that the terrestrial vegetation of the Arctic responds more strongly to Holocene climate variability through changes in biological production rather than diversity. Steward et al. (2013) noted that chironomid communities responded to eutrophication of small ponds below bird nesting sites in the Arctic through production changes rather than changes in community composition. The chironomid response to the recent warming may be similar. Since the temperature reconstruction is based on chironomid percentages, it may be that the chironomid community has not yet sufficiently changed in response to post-Little Ice Age climate warming, although it has increased in production. However, there are too few chironomid samples in the uppermost sediments for definitive conclusions.

Ecosystem variability during Holocene climate changes

The largest change at Lake JR01 occurred around 5.0 ka, a time when the aquatic and surrounding terrestrial ecosystems became less productive (Figs. 5 and 6). This corresponds to a major transition in the climate of the Canadian Arctic and most of Greenland, when the central Canadian Arctic cooled (Gajewski, 2015a). At the start of this transition at ~5.0 ka, chironomid production increased quite significantly for a brief period, with the concentrations of both warm and cold chironomid taxa increasing. This peak is only constrained by two samples, however, a similar phenomenon is also seen at a number of lakes across the Arctic (Fig. 8). At several of the sites for which Holocene chironomid records are available, a peak in chironomid concentration, which is also only identified by one or two samples, is observed at the onset of an environmental change (Fig. 8; Briner et al., 2006; Francis et al., 2006; Axford et al., 2009; Fortin and Gajewski, 2010b). This increase in production may be the chironomid community's response to large changes occurring in the lake's environment at that time. For example, at Lake KR02 on western Victoria Island (Fortin and Gajewski, 2010b) peaks in chironomid production at 6.9ka and 1.6ka coincide with major changes in climate (Fig. 8). As at Lake JR01, both cold- and warm-tolerant taxa increased in abundance and concentrations. At Lake CF8, (Baffin Island, Axford et al., 2009), chironomid concentrations are highest when inferred temperatures rapidly increase at ~10.5 ka and again at ~7.5 ka when inferred temperatures cooled. Similarly, at Lake CF3 (Baffin Island; Briner et al., 2006), chironomid concentrations peak at ~10 ka at the start of a rapid increase in inferred temperatures. Finally, there are spikes in chironomid production at major climate transitions at Fog Lake on Baffin Island at depths of 112 cm, 82 cm and 53 cm, which are depths that are identified in a number of proxies as major transitions (zone boundaries; Francis et al., 2006).

Thus, at all of these sites, there is a spike in chironomid concentration at the onset of large changes in temperatures, both when temperatures are warming and when they are cooling. These increases in chironomid concentrations are always short in duration. They occur at different times at the different sites, as they depend on the local changes in the chironomid community. However, this response at five sites suggests that high-resolution analyses at times of environmental change may provide insight into ecosystem response to environmental change. Finkelstein and Gajewski (2007) reported increased diatom diversity at Lake PW03 on Prescott Island, Nunavut at times of climatic changes, and they suggested this could be explained by the intermediate disturbance hypothesis (Connell, 1978). We hypothesize that the transition between cold and warm taxa may therefore lead to a more

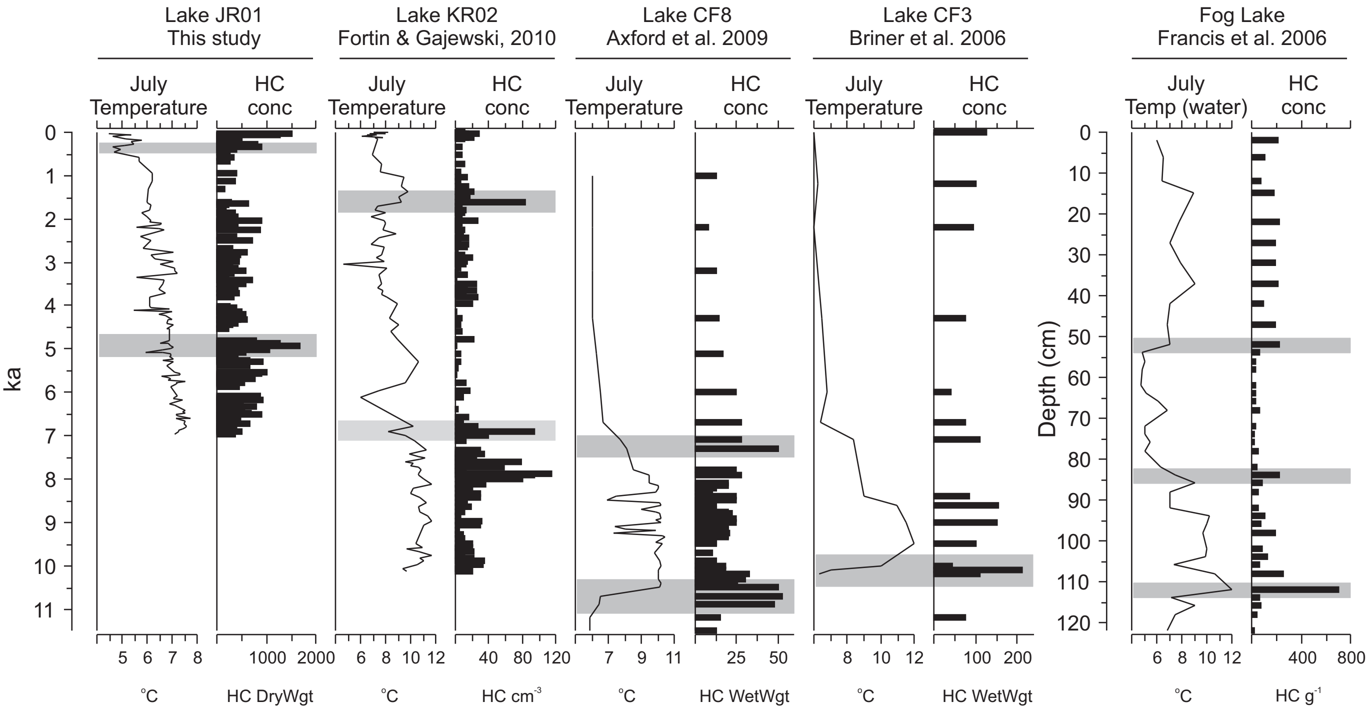


Figure 8. Mean July air temperature and chironomid concentration profiles for Lake JR01 (Boothia Peninsula, Nunavut; this study), Lake KR02 (Western Victoria Island, NWT, Fortin and Gajewski, 2010b), Lake CF8 (Baffin Island, Nunavut; Axford et al., 2009), Lake CF3 (Baffin Island; Briner et al., 2006) and Fog Lake (Baffin Island; Francis et al., 2006). Fog Lake profiles are plotted according to depth; this core is thought to contain the past 52 ka. Gray bands on all profiles represent July Temperature transition zones which correspond to increased chironomid production.

productive non-equilibrium community at times of climatic change. The causes of this are not clear, although in regions such as the Arctic, where communities are limited more by the physical environment than by competitive processes, the combination of colonization and increase in abundance of new species and persistence of older ones may cause temporary increase in production. Jackson and Sax (2009) suggest an increase in diversity would occur when there is rapid migration and delayed extinction, leading to a biodiversity “surplus”. This process may lead to an increase in production as well, as illustrated here. An increase in diversity is not clearly manifested in Lake JR01 (not shown) at the time of the production “spikes”, but there are too few samples to be able to establish a clear relation between production and diversity. Although it is premature to speculate further, this may also indicates that modern chironomid communities may be in a state of disequilibrium due to present climatic changes, and this may need to be considered when using these modern assemblages to infer past conditions. It remains unclear if these findings are applicable outside of the Arctic. Nonetheless, these findings further highlight the complexity of the relationship existing between chironomid community production and composition and environmental change.

Conclusions

At Lake JR01 from the Boothia Peninsula, Nunavut, chironomid-inferred mean July air temperatures were warmest in the mid-Holocene, reaching as high as 7.5°C. Temperatures decreased over the course of the mid- to late-Holocene. Overall terrestrial and aquatic production, as indicated by chironomid, pollen and diatom concentrations and accumulation rates, as well as sediment organic and biogenic content, were higher prior to 5.0 ka than at any other time in the Holocene. The diatom community assemblages during the mid-Holocene also indicate that this was a warm period in the lake's history. Between 5.0 and 1.0 ka, the lake was cooler and less productive. Inferred temperatures, based on both the chironomid and the pollen records, indicate additional cooling between 0.46 and 0.36 ka that corresponds to the Little Ice Age (LIA). Interpretation of changes in the diatom assemblages offers further evidence of a cooling at this time. Indices of both aquatic and terrestrial biological production increased in the last 150 yr, although the reconstructions do not indicate warming. Modern inferred temperatures based on both pollen and chironomids are up to 3°C cooler than those inferred for the mid-Holocene. The overall climatic trends recorded by both the pollen and chironomids at Lake JR01 are comparable to those observed at other sites across the Arctic, offering further evidence that regional-scale climates have influenced Arctic aquatic and terrestrial ecosystems over the Holocene.

Brief periods of greater chironomid production of both warm- and cold-tolerant taxa occurred at Lake JR01 at the onset of periods of climatic and environmental change, regardless of the direction of these changes. Elevated chironomid production is also seen during environmental transitions in the Holocene record of other lakes from across the Arctic. A temporary increase in production may be a consequence of the chironomid community adjustment during environmental transitions.

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