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Interglacial and Holocene temperature reconstructions based on midge remains in sediments of two lakes from Baffin Island, Nunavut, Arctic Canada

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Abstract

Midge remains (Insecta: Diptera: Chironomidae and Chaoboridae) from two upland lake basins on the Cumberland Peninsula of Baffin Island were analyzed and the results used in a transfer function to reconstruct paleotemperatures. This upland region remained ice-free throughout the last glacial cycle and the two lake basins retain sediments deposited during the previous interglacial period as well as during the Holocene period, but they did not accumulate sediment during most of the glacial period. Midge remains are abundant and well preserved at both sites. Midge-inferred summer surface water temperatures and mean July air temperatures were estimated using an inference model built on modern samples spanning a geographic range extending from Devon Island, Canada to Maine, USA. Data from twenty-nine new surface samples from Baffin Island were added to an existing inference model. The new weighted averaging (WA) model for summer surface water temperature yields $r^2_{jack}=0.88$ and RMSEP=2.22 °C for summer water temperatures, and $r^2_{jack}=0.88$ and RMSEP=1.53 °C for mean July air temperatures. Reconstructions at both sites indicate that summer temperatures during the last interglacial were higher than at any time in the Holocene, and 5 to 10 °C higher than present. Peak Holocene temperatures occurred in the first half of the period, and have decreased since about the mid-Holocene.

Keywords: Chironomidae; Transfer function; Paleotemperature reconstruction; Last interglacial; Baffin Island; Climate change

1. Introduction

Instrumental records show that the Earth has warmed ca. 0.6 °C over the past century (Hansen et al., 1999), with the most dramatic increase since the 1960s. The Arctic has recently experienced a similar warming pattern (Overpeck et al., 1997), except the magnitude is greater, with average annual temperature increases of 2 to 5 °C across most of the Arctic since the 1960s (Serreze et al., 2000), although the pattern of warming exhibits strong spatial variability. Supporting observations of this increasing warmth include: decreases in Arctic sea ice and snow cover, negative glacier mass balance, and increases in permafrost and ocean temperatures (summarized at http://nsidc.org/sotc/).

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The short time span of direct observations limits our ability to evaluate the role of natural climate variability and greenhouse gas forcing in explaining these observations, but the pattern of change is consistent with General Circulation Modeling (GCM) simulations of the consequences of increased greenhouse gases. These simulations predict the greatest sensitivity to greenhouse warming will occur in the Arctic. Strong positive feedbacks to warming in the Arctic, particularly through sea-ice reduction and shortened duration of seasonal snow cover, amplify global warming in the Arctic and have global implications (http://nsidc.org/sotc/).

The first several millennia of the present interglacial (ca. 12 to 7 ka[1]) and the last interglacial (ca. 130 to 115 ka) are two intervals widely preserved throughout the globe, when ice volumes were higher than at present, sea levels rose rapidly until about 7 ka, and summer temperatures were generally warmer than present. Although by no means perfect analogs to future greenhouse warmings, they offer rare glimpses of how Earth's climate system operates in it warmest modes. Climate reconstructions for the Arctic during peak warmth of the Holocene (CAPE, 2001; Kaufman et al., 2004) suggest that the timing and magnitude of warmth relative to present have strong spatial variability across the Arctic, despite hemispherically symmetric forcing. Consequently, future greenhouse warming may also exhibit strong spatial variations.

The last interglacial offers a glimpse of the world even warmer than during the Holocene thermal maximum. Understanding climate dynamics during peak warmth of the last interglacial requires a representative spatial distribution of sites. In northern North America and across much of northern Europe, such a strategy is complicated by extensive glacial erosion during the last ice age.

Lacustrine sediments offer one of the best archives of climate change in terrestrial Arctic environments. On eastern Baffin Island, recent research has shown that coastal uplands of northern Cumberland Sound remained above the limit of erosive continental or local glaciers throughout the last glacial cycle (the Foxe [=Wisconsin] Glaciation; ca. 115 ka to 12 ka), although relatively fast-moving outlet glaciers from the Laurentide ice sheet occupied the adjacent fiords (Miller et al., 2002). The sediment record is not complete; in all cases a major depositional hiatus separates the two interglacial sediment infills, presumably reflecting perennially frozen conditions during the glacial stage (Miller et al., 2002).

Midge remains (principally chironomids, also known as non-biting midges) have been analyzed from sediment cores from two of these upland lakes, Fog Lake and Brother of Fog Lake (Fig. 1), and are used to reconstruct quantitatively lake water temperatures and mean July air temperatures for the Holocene and last interglacial periods. Other analyses of these cores include diatoms from the Fog Lake core (Wolfe et al., 2000; Wolfe, 2003), and pollen analysis of Fog and Brother of Fog lakes (Fréchette et al., in press).

Midge remains in lacustrine sediment have been shown to be a valuable tool for paleotemperature reconstructions (Walker et al., 1997; Lotter et al., 1999; Battarbee, 2000; Brooks and Birks, 2001). The larval stages of non-biting midges (Diptera: Chironomidae) are aquatic and have chitinous head capsules that are shed with molting. These head capsules are abundant and very well preserved in lake sediments, and retain features that allow identification to the genus level (Walker, 2001). Mandibles of Chaoboridae (phantom midges) were also found.

Quantitative temperature reconstructions of summer surface water temperatures and July air temperatures are made possible by the application of multivariate models of modern calibration sets. The calibration set used in this study includes that published by Walker et al. (1997), with additional modern sites from Baffin Island. This study provides the first quantitative estimates of terrestrial summer temperatures during the last interglacial in the eastern Canadian Arctic. The study has not

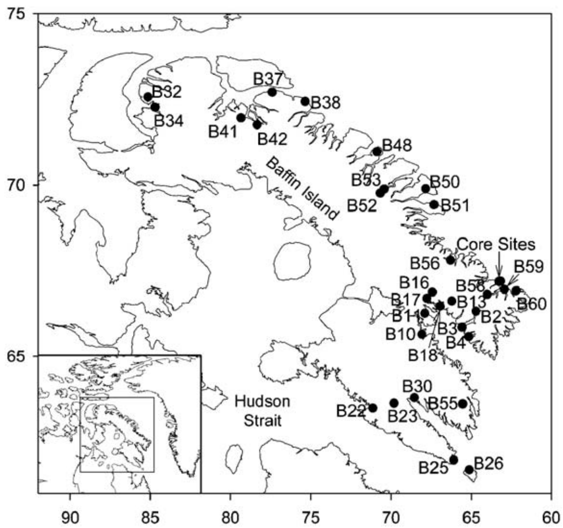


Fig. 1. Map of Baffin Island showing 30 sites comprising the modern calibration set, and the two coring sites.

[1] All ages expressed in calendar years before present (ka), with present taken to be 1950 AD.

only provided quantitative temperature estimates, but also a valuable record of the changing midge fauna in the Arctic, especially during the last interglacial period.

2. Core site descriptions

Fog Lake (unofficial name) (67°11′N, 63°15′W) is located on the Cumberland Peninsula of Baffin Island (Fig. 1). It lies in the uplands of Merchants Bay at 460 m asl, above lateral moraines dated by cosmogenic isotopes at >35 ka (Steig et al., 1998; Miller et al., 2002). The lake is small, about 150 m in diameter, with a maximum water depth of 9.6 m. It receives inflow primarily as slopewash during snowmelt from a small (2.3 km^2) watershed. In most years, Fog Lake is only ice-free during the month of August.

Brother of Fog Lake (unofficial name) is situated 11 km NE of Fog Lake (67°11.5′N, 63°08′W, elevation of 360 m asl), in a similar setting above the highest lateral moraines in adjacent Merchants Bay. The lake is larger (350 × 500 m^2) and deeper (16 m maximum water depth) than Fog Lake, and it has a larger drainage area (ca. 5 km^2) with a small stream entering the lake from the south. The lake is at a lower elevation and in a more open valley than Fog Lake, so it has a longer ice-free season.

3. Methods

3.1. Coring and dating

Cores were collected in May 1996 and May 1998 with a sledge-mounted percussion coring system (Nesje, 1992). Details of the coring and sedimentological analyses for Fog Lake can be obtained from Wolfe et al. (2000). Similar methods were used at Brother of Fog Lake.

Fog Lake core 96FOG-05 recovered 137 cm of sediment from 9.6 m water depth in a 7 cm diameter core, from which samples for midge (as well as pollen and diatom) analyses were taken. Radiocarbon dating was carried out on this core. A companion core, 96FOG-04, taken only a few meters away, has similar magnetic susceptibility allowing direct correlation between cores, and was used

Table 1
New sites added to the surface training set from Baffin Island

Lake	Latitude	Longitude	Elevation (m)	Max. depth (m)	Lake area (km^2)	Summer water temperature (°C)	July air temperature (°C)
B2	66.31	64.69	574	3.8	0.19	5.20	6.6
B3	65.85	65.56	115	17.1	0.63	5.84	6.7
B4	65.57	65.16	92	3.8	0.02	4.34	6.8
B10	65.64	68.06	197	23.4	0.11	6.56	7.1
B11	66.25	67.88	85	43.8	0.19	7.67	6.8
B13	66.61	66.20	377	8.0	0.46	8.66	6.1
B16	66.87	67.41	459	17.0	0.29	6.49	6.1
B17	66.69	67.75	246	7.1	0.11	8.96	6.5
B18	66.46	66.93	7	11.8	0.10	10.39	6.7
B22	63.48	71.11	203	6.8	0.31	9.32	7.7
B23	63.62	69.80	623	13.4	0.28	5.73	6.9
B25	61.96	66.08	52	35.5	0.15	6.47	5.8
B26	61.68	65.12	322	3.7	0.02	5.72	5.3
B30	63.78	68.54	156	4.9	0.04	8.54	6.8
B32	72.56	85.12	533	12.7	0.06	6.08	5.5
B34	72.27	84.68	61	10.5	0.03	8.70	5.8
B37	72.7	77.38	686	8.4	0.20	5.05	5.0
B38	72.43	75.34	107	4.1	0.32	7.66	5.5
B41	71.95	79.33	64	3.6	0.15	9.91	5.8
B42	71.75	78.32	646	10.4	0.15	6.13	5.8
B48	70.96	70.86	134	13.2	0.09	7.88	5.0
B50	69.89	67.82	159	13.6	0.14	6.28	5.8
B51	69.42	67.31	207	21.0	0.08	3.47	5.7
B52	69.76	70.65	579	14.6	0.33	7.17	5.5
B53	69.88	70.41	113	4.8	0.09	10.94	5.5
B55	63.60	65.52	597	17.9	0.65	2.75	5.0
B56	67.8	66.28	79	6.5	0.16	7.91	5.4
B58	66.8	63.96	18.3	11.0	0.2	9.84	5.7
B59	66.95	62.9	201	14.7	0.18	5.20	7.1
B60	66.91	62.17	152	18.2	0.08	4.24	6.3

Details of the remaining sites in the training set are given in Walker et al. (1997).

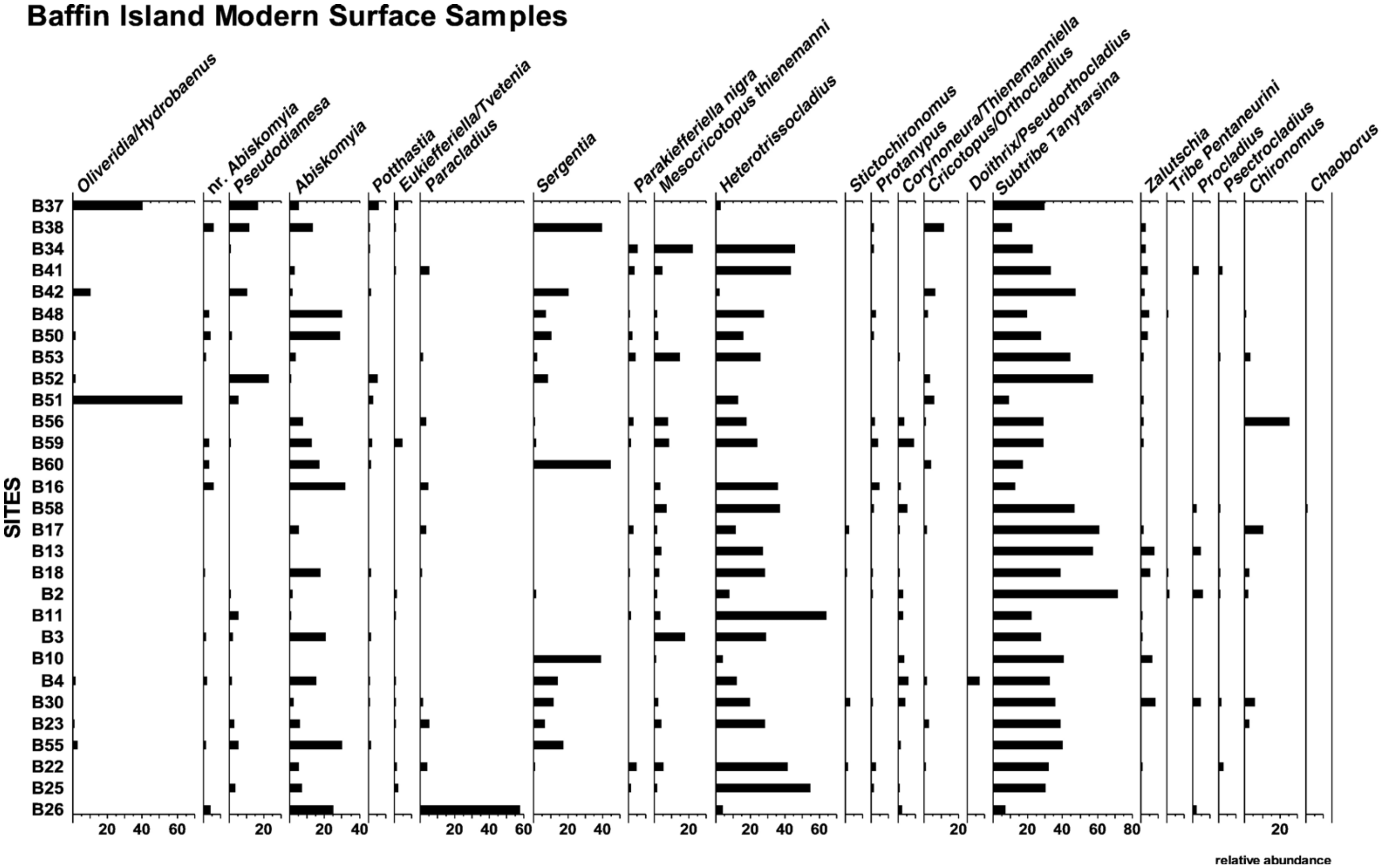


Fig. 2. Relative abundances of selected taxa recovered from Baffin Island modern surface samples. Sites are arranged from north to south, and taxa are arranged according to their temperature optima, with cold-water taxa on the left side of the diagram.

for luminescence and radiocarbon dating. A complete discussion of the chronology of the Fog Lake sediment core is in Wolfe et al. (2000) and Miller et al. (2002).

To ensure the most complete recovery of last interglacial sediment, Brother of Fog core 98BRO-05 was allowed to penetrate 0.5 m of Holocene gyttja before the piston was released, allowing deeper sediment to be recovered in a single drive. The 7-cm-diameter core recovered 190 cm of sediment from 16.0 m water depth. Dating was by radiocarbon and luminescence methods, all on core 98BRO-05, with one additional date from nearby core 98BRO-04. The chronology is presented in Miller et al. (2002). A surface core (98BRO-03) was also taken to recover the most recent sediments.

3.2. Surface sampling

Lakes sampled for the modern Baffin Island calibration set are a subset of those used to construct inference models using Baffin Island diatoms (Joynt and Wolfe, 2001) and pollen (Kerwin et al., 2004). The samples were collected during the summers of 1994, 1995, and 1996. Details of sampling methods can be obtained from Joynt and Wolfe (2001). Limnological data were also collected at the time of sediment sampling. Water temperatures were measured using a SeaCat® profiler and are integrations of temperatures for the water column in each lake. Because there is very little temperature variation with depth in these lakes in summer (Wolfe, unpublished data), we feel these measurements are comparable to summer surface water temperatures. Midge remains were enumerated in the surface sediments from 30 sites (Table 1). Mean July air temperatures for the Baffin sites were calculated by averaging the four nearest-neighbor grid points of a 25-km grid of climatology for North America, using 30-year climate normals 1951–1980, and corrected for elevation (Thompson et al., 1999). We combined data from these sites with the calibration set of Walker et al. (1997) in order to include sites representing a wide range of summer temperatures. The Walker et al. (1997) sites range from northern Labrador to the southern Maritimes (Canada) and Maine (USA); and also included four sites from Devon and Baffin islands. Details of these sites are in Walker et al. (1997). Water temperatures for these sites were also taken in summer. Mean July air temperatures were estimated from climate atlases (Thomas, 1953; Houde, 1978; McCalla, 1991). Midge taxonomy of the Baffin

Table 2
Comparison of WA and WA–PLS model results for summer water and mean July air temperatures

	r^2_{app}	r^2_{jack}	$RMSE_{app}$	$RMSEP_{jack}$	Ave. bias	Ave. $bias_{jack}$	Max. bias	Max. $bias_{jack}$
Summer water temperature								
Classical deshrinking								
WA	0.87	0.84	2.49	2.67	0.00	−0.03	3.55	3.79
WA_{tol}	0.91	0.88	2.01	2.25	0.00	−0.08	3.59	3.32
Inverse deshrinking								
WA	0.87	0.84	2.32	2.55	0.00	−0.02	4.04	4.85
WA_{tol}	0.91	0.88	1.92	2.22	0.00	−0.07	3.25	4.01
WA–PLS								
Component 1	0.87	0.84	2.33	2.55	0.01	−0.02	3.84	4.64
Component 2	0.92	0.87	1.79	2.26	0.01	−0.01	1.69	3.07
Component 3	0.94	0.84	1.51	2.60	0.03	−0.13	1.62	3.65
Component 4	0.95	0.83	1.41	2.74	0.03	−0.04	1.30	3.80
Mean July air temperature								
Classical deshrinking								
WA	0.89	0.87	1.58	1.67	0.00	−0.02	0.74	0.88
WA_{tol}	0.92	0.88	1.28	1.60	0.00	−0.07	1.20	1.75
Inverse deshrinking								
WA	0.89	0.87	1.49	1.60	0.00	−0.02	1.44	1.77
WA_{tol}	0.92	0.88	1.23	1.53	0.00	−0.06	1.24	1.47
WA–PLS								
Component 1	0.89	0.87	1.49	1.60	0.00	−0.02	1.37	1.70
Component 2	0.91	0.86	1.31	1.65	0.01	0.01	0.77	1.44
Component 3	0.93	0.84	1.15	1.76	0.02	0.04	0.70	1.73
Component 4	0.94	0.83	1.08	1.85	0.02	0.03	0.84	2.03

WA results include inverse versus classical deshrinking, with and without tolerance downweighting (tol). Species data were square-root transformed.

Island sites was harmonized with the existing calibration set.

3.3. Midge analysis and modeling

Midge analysis followed Walker (2001). Aliquots of wet sediment (1 to 2 cm^3) were deflocculated in 10% HCl and warm 5% KOH and rinsed on a 100-μm sieve. The material was sorted under a dissecting microscope at 50× using a Bogorov sorting tray (Gannon, 1971). All head capsules were removed and mounted permanently on microscope slides for identification at 400× to 1000×. Baffin Island surface samples had been freeze-dried, and after 1-g aliquots were rehydrated, they were treated in the same manner as core samples. Identification of chironomid remains to the highest possible taxonomic resolution was done using the keys of Oliver and Roussel (1983), Wiederholm (1983), Epler (1992, 2001), and Walker (1988, 2000).

The inference model for summer surface water and July air temperature and down-core reconstructions were accomplished using the computer program C2 (Juggins, 2003). The data were screened for outliers prior to analysis. Sites that yielded less than 50 head capsules were excluded (Heiri and Lotter, 2001; Quinlan and Smol, 2001). This resulted in lake B32 being excluded from the calibration set. Rare taxa were also removed from the calibration set: taxa that occurred at less than 2 sites, or never made up greater than 2% relative abundance were removed. The resulting calibration set had a total of 68 sites and 44 taxa. The calibration set does not include Fog and Brother of Fog lakes. All species data were square-root transformed. Model results were cross validated by jack knifing or leave-one-out cross validation (Birks, 1995). Sample-

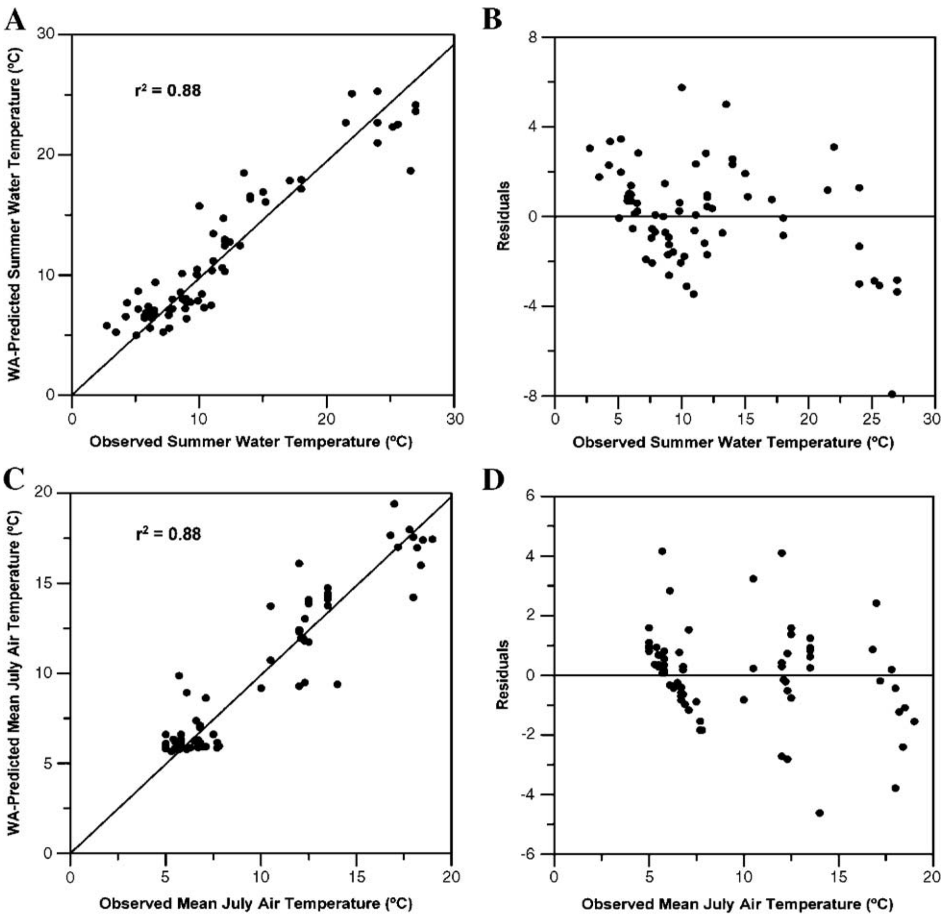


Fig. 3. Inference model results showing: (A) the relationship between observed summer surface water temperature (67 sites) and temperatures predicted (jackknifed values) by the WA model; (B) the relationship between observed summer water temperature and residuals (observed − predicted); (C) the relationship between observed mean July air temperatures and temperatures predicted (jackknifed values) by the WA model; (D) the relationship between observed mean July air temperatures and residuals.

specific error estimates in the reconstructions were cross validated by bootstrapping using the program C2.

In order to determine whether the modern calibration model had adequate analogs for the fossil assemblages, modern analog testing (MAT) was performed using the computer program C2, with squared chord distance as the dissimilarity coefficient (Overpeck et al., 1985). Confidence intervals were based on minimum DC distance within the calibration set following Laing et al. (1999). Fossil assemblages above the 95% confidence interval were considered to have no analogs in the calibration set, samples between 75% and 95% were considered to have fair analogs.

4. Results

4.1. Modern calibration set

A total of 30 midge taxa were recovered from the modern Baffin samples. Distributions of the most abundant taxa are presented in Fig. 2. The twenty-nine Baffin surface sites had a range of summer surface water temperatures from 2.75 to 10.94 °C. and July air temperatures from 5.0 to 7.7 °C (Table 1). The complete calibration set represents a summer water temperature range of 2.75 to 27.0 °C, and a mean July air temperature range from 5.0 to 19.0 °C, and is comprised of 68 sites and 44 taxa. Detrended correspondence analysis (DCA) was used to determine the compositional gradient length for the calibration data set (results not shown). The gradient length is 2.83 standard deviation units, indicating that the use of unimodal regression models is appropriate (Birks, 1995). Detrended canonical correspondence analysis (DCCA) was also performed to determine the gradient lengths for both temperature variables. The gradient length for summer water temperature was 2.82 standard deviation units, and for July air temperature 2.62 standard deviation units, again indicating that unimodal-based methods for regression and calibration are appropriate (Birks, 1995). Results of the regression model testing are given in Table 2. The model that best explained the variance in the data set proved to be a weighted averaging (WA) model with inverse deshrinking and tolerance downweighting for both summer water temperature and July air temperature. The choice of this model was based on the combination of high r^2_{jack} value, together with low values for the root mean square error of prediction (RMSEP) and bias. Comparison of the observed and predicted temperatures for all sites, plus residuals (observed − predicted) are shown in Fig. 3. Regression coefficients are given in Table 3. After screening, 44 midge taxa were retained in the WA model. These taxa are listed in Table 4 along with their temperature optima and tolerance ranges.

Table 3
Deshrinking regression coefficients used for calculating paleotemperatures for the of the WA models

	Intercept (a)	Slope (b)
Summer water temperature		
Classical deshrinking		
WA	6.88	0.44
WA_{tol}	3.69	0.64
Inverse deshrinking		
WA	−11.93	1.96
WA_{tol}	−4.19	1.42
Mean July air temperature		
Classical deshrinking		
WA	5.63	0.46
WA_{tol}	2.01	0.77
Inverse deshrinking		
WA	−9.84	1.94
WA_{tol}	−1.63	1.19

For method of calculation, see Walker et al. (1997).

4.2. Sediment cores

Fog Lake core 96FOG-05 has five stratigraphic units (Fig. 4A) as defined by Wolfe et al. (2000). Unit I (137–121 cm) is a stony diamicton. Unit II (121–111 cm) is laminated silt and clay, with 10% organic matter. The unit represents lacustrine sediment deposited in a proglacial setting. Unit III (111–82 cm) is compact (de-watered) gyttja with mosses. Organic content varies from 4 to 19%. An AMS ^{14}C date on a bryophyte macrofossil near the base of this unit is >52,200 ^{14}C year BP. Luminescence age estimates based on thermoluminescence (TL) and infrared-stimulated luminescence (IRSL) from Unit III in adjacent core 96FOG-04 indicate that the unit is at least 90 ka old (Table 5). Unit IV (82–51 cm) is stratified, highly minerogenic sediment (organic content <3%), indicative of rapidly deposited sediment in a lacustrine environment. Radiocarbon dating has been done on humic acids, aquatic moss macrofossils and chironomid chitin. Three radiocarbon dates on macrofossils from Unit IV at 56.5 cm, 62 m, and 66.5 cm depth are 8130±50, 8370±60, and 8030±50, respectively (Wolfe et al., 2000). Unit IV was previously thought to have been deposited during the Foxe Glaciation, but we now interpret the unit to represent early post-glacial time when the lake was first ice-free, soils were not yet well developed in the catchment, and melt from thick snowbeds of the last glaciation provided a relatively high flux of sediment to the lake. Unit V (51–

Table 4
WA optima and tolerances (jackknifed) for summer water and mean July air temperatures, number of occurrences, and Hill's N_2 for midge taxa (Chironomidae, Ceratopogonidae, and Chaoboridae) retained in the WA model

Taxon	Water temperature Optima	Water temperature Tolerance	Air temperature Optima	Air temperature Tolerance	Number of occurrences	Hill's N_2
Oliveridia/*Hydrobaenus*	5.4	2.1	6.0	1.2	12	6.5
Orthocladiinae # 14	5.9	0.5	6.5	0.8	2	1.9
nr *Abiskomyia*	6.2	2.1	5.9	0.7	13	11.9
Pseudodiamesa	6.2	1.6	5.9	0.9	21	15.9
Abiskomyia	6.9	2.1	6.2	0.8	29	23.2
Potthastia	6.9	3.4	6.9	2.6	16	14.1
Eukiefferiella/*Tvetenia*	7.1	2.2	6.8	2.2	14	11.5
Paracladius	7.2	1.8	5.8	0.9	14	9.3
Sergentia	8.2	3.9	8.0	3.2	36	26.1
Parakiefferiella nigra	8.5	1.6	6.3	0.9	18	16.3
Mesocricotopus thienemanni	8.5	2.0	6.9	1.8	30	22.5
Heterotrissocladius	9.9	3.9	8.7	3.3	58	47.0
Stictochironomus	10.2	2.3	9.8	3.1	17	13.6
Protanypus	10.4	3.9	9.2	3.4	34	29.9
Corynoneura/*Thienemanniella*	10.8	6.1	9.4	4.3	38	32.5
Smittia/*Pseudosmittia*	10.9	4.0	10.3	3.9	9	8.1
Cricotopus/*Orthocladius*	11.0	6.1	9.5	4.2	38	32.3
Doithrix/*Pseudorthocladius*	11.5	6.7	10.6	3.5	6	4.2
Subtribe Tanytarsina	11.6	6.2	9.9	4.3	68	65.0
Limnophyes	14.0	4.7	11.6	3.0	6	5.7
Zalutschia	14.2	7.4	10.9	5.0	36	27.5
Tribe Pentaneurini	15.9	5.3	13.6	2.9	30	23.9
Procladius	15.9	6.5	13.0	4.1	35	30.8
Stempellina	16.8	5.3	14.2	2.4	16	15.0
Psectrocladius	16.8	6.4	13.7	3.6	37	27.1
Microtendipes	16.9	5.3	14.1	2.5	23	19.3
Chironomus	17.5	8.3	13.1	5.4	27	17.5
Stempellinella/*Zavrelia*	17.6	5.7	14.8	2.8	14	13.0
Pagastiella	17.8	5.6	14.4	2.8	14	12.1
Heterotanytarsus	18.4	5.0	14.6	2.6	16	12.7
Dicrotendipes	18.8	5.6	15.1	2.7	24	20.9
Family Ceratopogonidae	19.2	4.6	15.3	2.7	5	4.8
Cladopelma	20.3	5.9	15.6	2.9	20	17.0
Cryptochironomus	20.6	5.5	15.8	2.7	12	10.5
Tribelos	21.3	6.5	16.2	3.2	10	6.3
Parakiefferiella cf. *bathophila*	22.0	4.5	16.7	2.4	10	8.0
Polypedilum	22.3	4.8	16.7	2.5	15	12.3
Endochironomus	22.3	2.9	17.1	1.0	2	1.4
Lauterborniella/*Zavreliella*	22.8	4.3	17.0	2.2	9	8.6
Zalutschia zalutschicola	22.9	6.0	16.7	3.3	2	1.8
Chaoborus	23.1	5.5	16.5	3.6	9	6.8
Labrundinia	23.5	1.1	17.6	0.6	3	2.9
Pseudochironomus	24.1	2.1	17.8	0.8	9	8.0
Parachironomus	24.7	2.7	17.6	1.6	7	6.2

0 cm) is uniform olive gyttja, and represents deposition during most of the Holocene period.

Brother of Fog Lake core 98BRO-05 and companion core 98BRO-04, that captures the full Holocene, record six lithostratigraphic units (Fig. 4B) that have broad similarities to those from Fog Lake. Unit I (240–204 cm) is organic-rich silt with some aquatic moss fragments and pebbles. Unit II (204–185 cm) is a sand layer, overlain by Unit III (185–130 cm), a gyttja with moss fragments and occasional thin sand layers. Moss fragments from the top of Unit III have an AMS ^{14}C date >60 ka (Miller et al., 2002). We consider Units I–III in 98BRO-05 to represent lacustrine sedimentation during an interglacial regime; these units are correlative with Unit III, and possibly Unit II, in core 96FOG-05. IRSL ages from two samples within Unit III of 98BRO-05 yielded maximum limiting ages, rather than clear finite ages. Full solar reset IRSL ages for UIC812 and

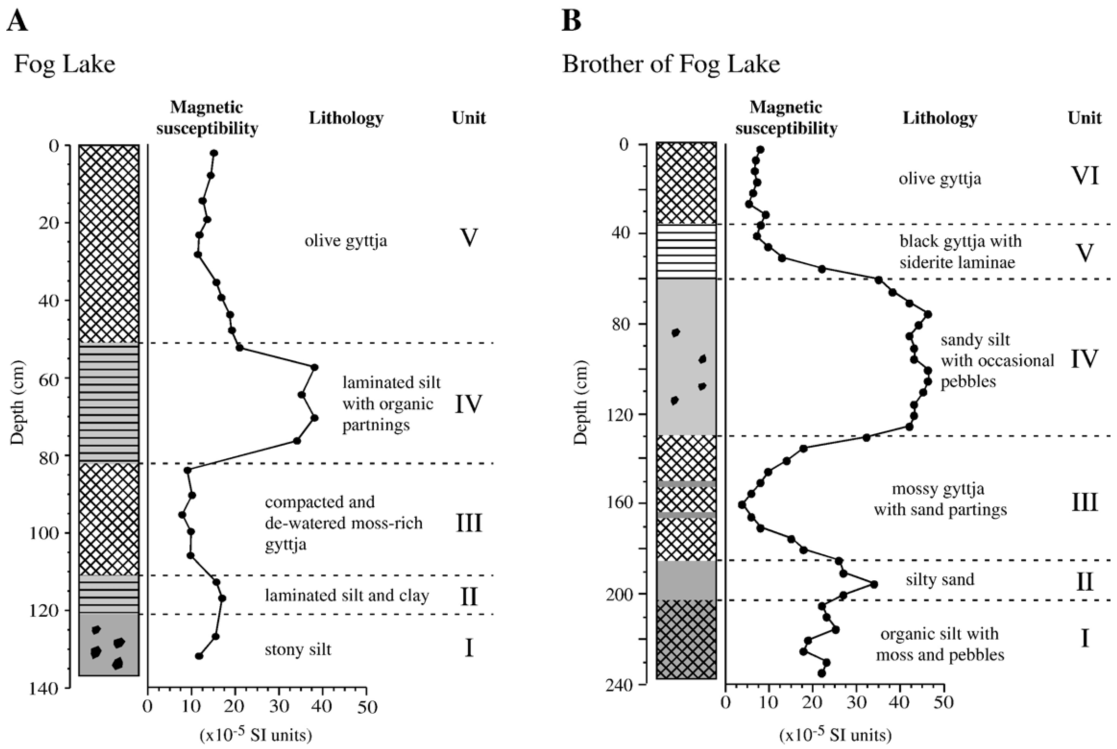


Fig. 4. Lithology and magnetic susceptibility of cores from both sites.

UIC813 (Table 5) are ca. 212 and 185 ka and for 1-h sunlight exposure are ca. 145 and 122 ka, respectively. The significant difference in age between the full-solar reset and 1-h sunlight exposure was not documented with Fog Lake sediment. Additional IRSL analyses of 98BRO-05 sediment indicate a clear resistance of luminescence to solar resetting, with >20% of the natural luminescence retained after 10 min of light exposure. Usually <5% of the natural IRSL signal is retained after 1 to 2 min of light exposure, indicating a population of charges stored in "deep" thermally stable traps that were not solar reset with sediment transport and deposition. It appears that the sediments from Unit III were deposited with an appreciable amount (>20% of the natural) of inherited luminescence. Consequently, the IRSL ages calculated after 1-h light exposure might still be maximum ages, suggesting that the sediment is at least no older than the last interglacial (ca. 125 ka).

Table 5
Dose rate and equivalent dose (De) data and resultant infrared stimulated luminescence age estimates for lacustrine sediments from core 98BRO-05
Composite core depths and core unit are given in parentheses

Core	98BRO-05	98BRO-05	98BRO-05	98BRO-05
Core Level	132–135 cm	96–99 cm	70–72 cm	31–33 cm
(Composite core level, UNIT)	(179–182 cm, III)	(143–146 cm, III)	(117–119, IV)	(78–80 cm, IV)
Laboratory number	UIC812	UIC813	UIC814	UIC815
Uranium (ppm)	2.93±0.45	2.07±0.36	4.50±0.86	3.91±0.71
Thorium (ppm)	8.49±1.19	7.42±0.97	17.40±2.48	15.77±1.97
Potassium (K_2O)	1.79±0.02	1.33±0.02	3.20±0.04	3.05±0.03
Moisture content (%)	55±5	55±5	40±5	40±5
Organic content (%)	12±2	12±2	5±1	5±1
Dose rate (Gy/ka)	2.20±0.17	1.87±0.15	5.05±0.36	4.87±0.31
IRSL De (Gy), full solar reset	466.02±2.07	345.06±0.86	Saturated	1101.87±16.38
IRSL De (Gy); 1 h sunlight	320.61±5.96	229.05±2.80	Saturated	1080.56±15.30
IRSL age (ka) full solar reset	<212±19	<185±6	Non-calculable	<226±20
IRSL age (ka) 1 h sunlight	≤145±10	≤122±10	Non-calculable	<222±20

Unit IV (130–62 cm) is a thick sequence of stratified sandy silt, with low organic content and occasional pebbles. We interpret Unit IV to represent rapid accumulation of fluvially transported sediment delivered episodically, presumably at about the Pleistocene–Holocene transition. This interpretation is supported by IRSL dating. Two samples from Unit IV were processed for luminescence dating. Sample UIC814 is saturated and UIC815 yields an equivalent dose of > 1 kGy, both indicating great antiquity (> 200 ka old) (Table 5). Such extremely old ages probably reflect incomplete or no solar resetting of these sediments prior to deposition. Elevated inherited luminescence, especially with OSL stimulation, indicates rapid and massive deposition of sediments, which largely precludes even short (minutes) light exposure. The depositional environment of Unit IV is similar to that of Unit IV in core 96FOG-05. As in Unit IV at Fog Lake, ^{14}C dating has been inconclusive. Two humic acid samples from Unit IV (76 and 105 cm depth) are 37.8 and 36.9 ka, respectively, but a single date on chironomid chitin extracted from Unit IV has a ^{14}C age of 19 ka (23.1 ka cal year BP). Humic acids extracted from the correlative unit in companion core 98BRO-03 are 27.5 ka (Table 6). The dramatic differences in ^{14}C activity in chironomids and humic acids from the same levels suggests that much of the organic material in Unit IV is reworked, as the catchment was flushed during the transition from glacial to interglacial conditions. Many chironomids are detritivores, and the age of 23.1 ka on their head capsules may reflect a strong dependence on reworked (interglacial) organic material delivered to the lake, supplemented by modest amounts of contemporary detritus. Reworking is supported by pollen analysis of several levels in Unit IV that exhibit similar characteristics to the underlying interglacial beds, suggesting the pollen is reworked (Fréchette et al., in press). In a recent work comparing ^{14}C ages from chironomid head capsules and bulk sediments from the same core, Fallu et al. (2004) also found that dates based on chironomid remains were consistently younger. They suggest that the bulk sediments contained old organic carbon from the watershed, and that the chironomid larvae were selecting higher quality food sources derived from both aquatic and terrestrial producers, and feeding very little on old, refractory organic matter. At this point, no definitive age can be assigned to Unit IV, but it contains abundant reworked material.

Unit V (62–37 cm) is a black gyttja with siderite laminae of early Holocene age, representing lacustrine deposition without significant fluvial input under reducing conditions, possibly with the lake ice-covered throughout most years. Unit VI (37–0 cm) is weakly stratified to massive olive gyttja of Holocene age, similar to Unit V in Fog Lake. No ^{14}C dating has been undertaken in Units V or VI.

4.3. Chironomidae: Fog Lake

Twenty-eight chironomid taxa were recovered from the Fog Lake core, plus mandibles of *Chaoborus* (Chaoboridae). Relative abundance of the most common taxa are shown in Fig. 5. No levels of Unit I were analyzed for midge remains because these sediments are not of lacustrine origin.

Units II and III represent the previous interglacial period. Unit III has the greatest abundance of warmer water taxa, such as *Chironomus* and *Psectrocladius*. *Heterotrissocladius* is also abundant, and *Chaoborus* mandibles are also present. Temperature reconstructions indicate that this time period was warmer than the Holocene (Fig. 6). Unit II, although more minerogenic than Unit III, also has warmer water taxa such as *Chironomus*, and was also probably deposited during the previous interglacial.

Unit IV (early Holocene) is overwhelmingly dominated by *Oliveridia*/*Hydrobaenus*. These insects are tolerant of cold temperatures, and can survive in the low organic, high mineral content sediments that were entering the lake at that time. On Svalbard, Brooks and Birks (2004) found three lakes dominated by *Oliveridia*, including one glacier-fed lake in which *Oliveridia* was the only taxon present. *Pseudodiamesa* is also abundant in this unit, while *Heterotrissocladius* and *Chironomus* are low in

Table 6
Radiocarbon dates on organic material from Brother of Fog Lake

Core	Depth (cm)	Composite core depth (cm)	Core unit	Material dated	Laboratory ID	δ^{13}C	Conventional radiocarbon age
98BRO-05A	30–31	77–79	IV	Humic acids	NSRL-10617	(−25‰) [a]	33,300 ± 320
98BRO-05A	65–66	112–113	IV	Humic acids	NSRL-10618	−24.1‰	32,200 ± 440
98BRO-05A	87–88	134–135	III	Aquatic moss macrofossil	NSRL-10131	−30.3‰	60,000 ± 1900
98BRO-03B	4–5	4–5	VI	Humic acids	NSRL-10130	−25.5‰	23,600 ± 130

NSRL = INSTAAR, University of Colorado, for carbon extraction and target preparation; measured at Woods Hole Oceanographic Institution.
[a] Estimated; insufficient sample for measurement.

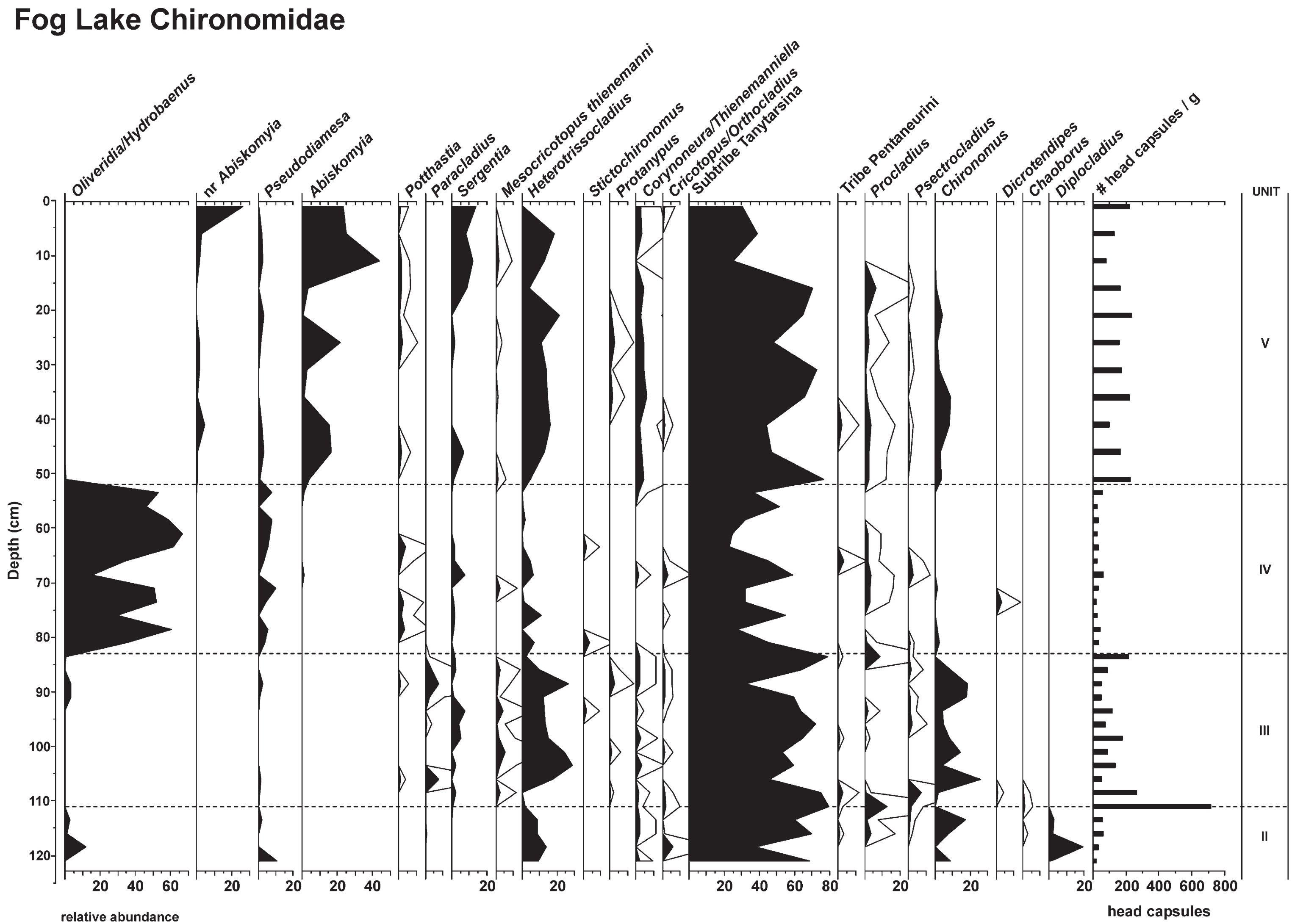
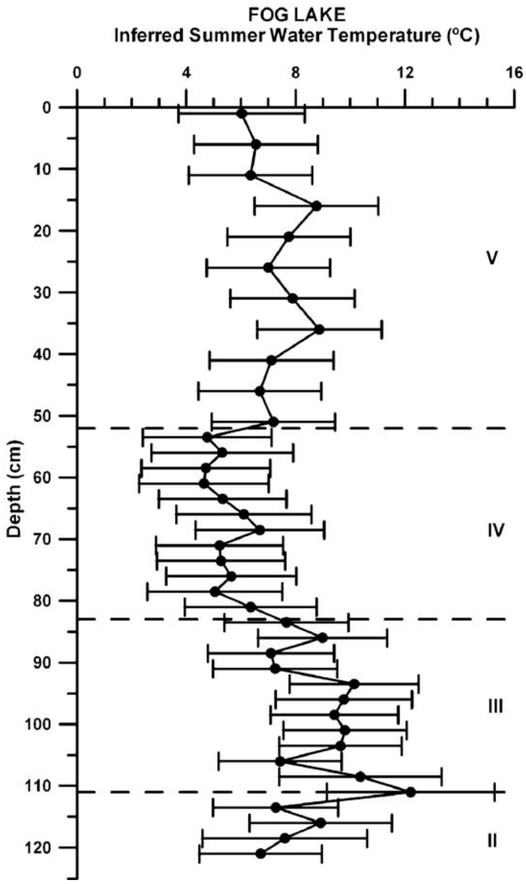


Fig. 5. Relative abundances of the selected taxa recovered from the Fog Lake core, and concentration of head capsules. Taxa are arranged according to their temperature optima, with cold-water taxa on the left of the diagram. Zones refer to the lithological units of the core. The taxon “nr *Abiskomyia*” is possibly an early instar of that genus.



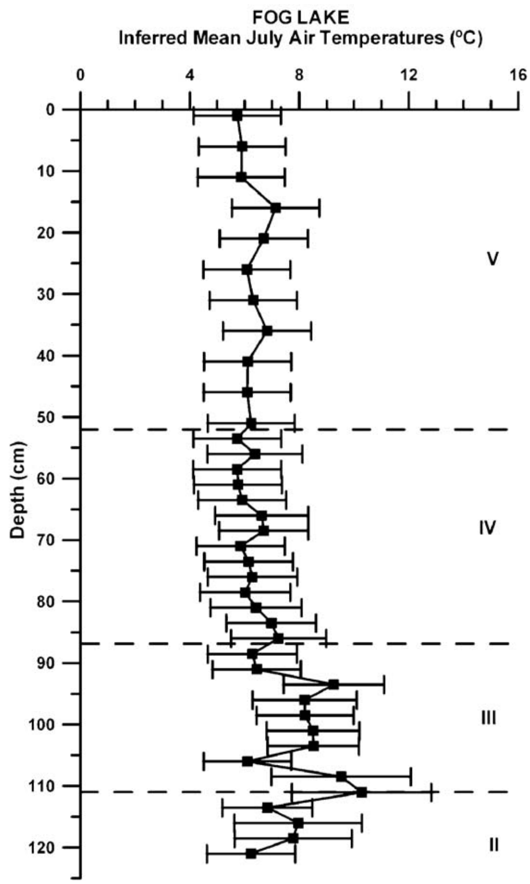


Fig. 6. Midge-inferred summer water and mean July air temperature estimates with associated error estimates for the Fog Lake core. Errors were estimated by bootstrapping. Zones refer to the lithological units.

abundance. Total head capsule concentration (Fig. 5) during this period was extremely low, resulting from low lake productivity, high mineral sedimentation rate, or a combination of the two factors.

In the later Holocene (Unit V), the assemblage is dominated by *Abiskomyia*, *Sergentia* and *Heterotrissocladius*, and the Tanytarsina. *Procladius* and *Chironomus* are also fairly abundant in the early Holocene. Estimated water and air temperatures indicate that peak temperatures occurred in the first half of the Holocene, and a steady decline in temperatures occurred during the second half of this period (Fig. 6).

4.4. Chironomidae: Brother of Fog Lake

The chironomid fauna of Brother of Fog Lake shows similar changes over time to those of Fog Lake, but in general, there is a greater diversity of taxa in the Brother of Fog Lake core (Fig. 7).

Units I, II, and III, representing the last interglacial, are dominated by warm-water taxa such as *Chironomus* and *Dicrotendipes*, in addition to the Tanytarsina. Other warm-water taxa present include *Endochironomus*, *Chaoborus*, and *Glyptotendipes*. Temperature estimates are very warm, 15 to 16 °C, especially in Unit III. Head capsule concentrations are also high (Fig. 7), suggesting a warm, highly productive lake. The interglacial period in Brother of Fog Lake has a greater diversity of warm-water taxa than does Fog Lake. Brother of Fog Lake is 100 m lower in elevation than Fog Lake, which may account for warmer temperatures at that site, or possibly equivalent units within the interglacial are not in the Fog Lake core. An as yet unidentified taxon was present in Units I and II of this core. It appears to be a member of the subfamily Orthocladiinae, and is referred to as Unknown 17 (author's designation). An example is shown in Fig. 8. Although it resembles *Abiskomyia* in some respects, the differences seem great enough to give it a separate designation.

Unit IV is dominated by *Sergentia*, *Heterotrissocladius*, *Corynoneura*/*Thienemanniella* and the Tanytarsina.

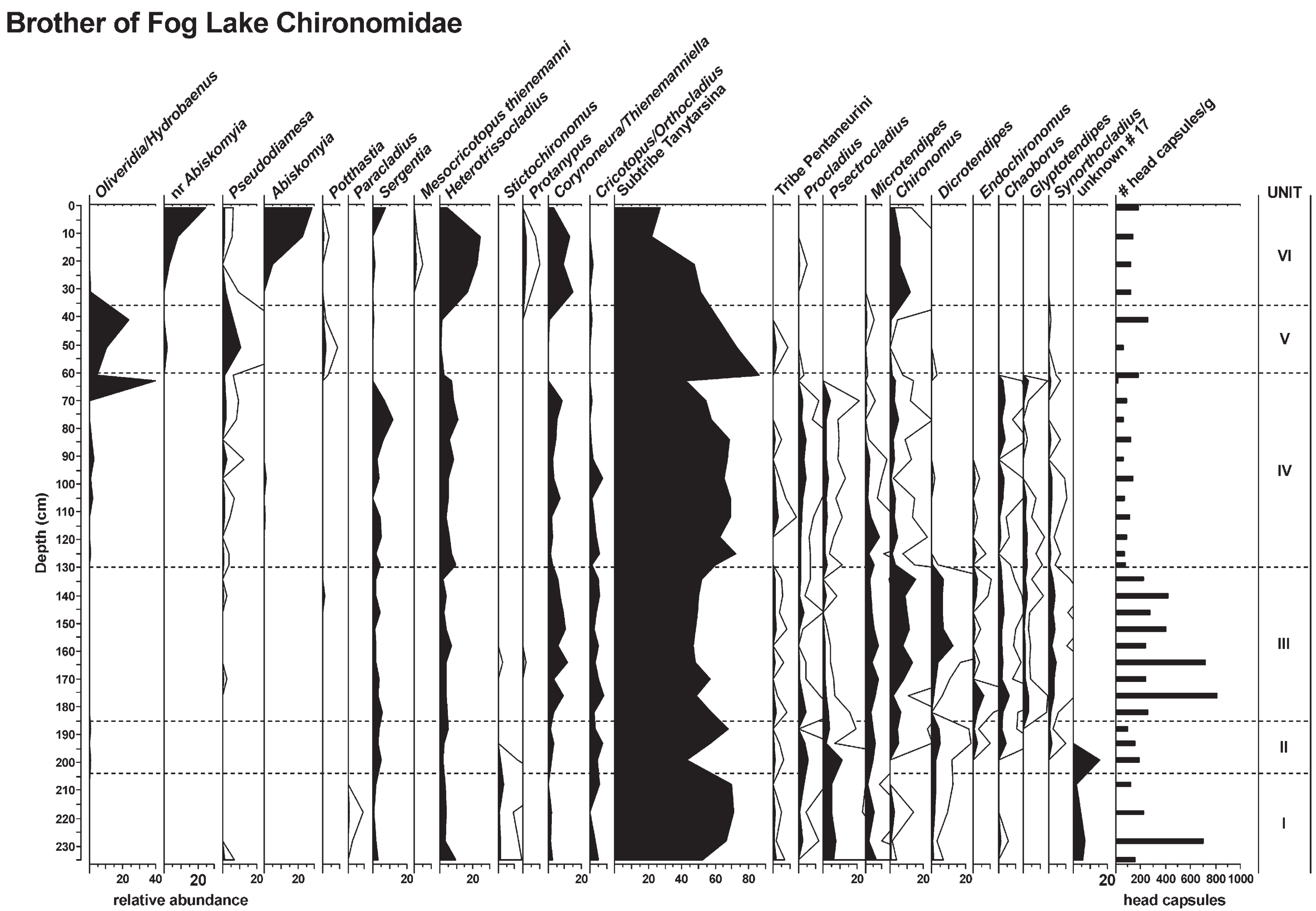


Fig. 7. Relative abundances of selected taxa recovered from the Brother of Fog Lake core, and concentration of head capsules. Taxa are arranged according to their temperature optima, with cold-water taxa on the left of the diagram. Roman numerals refer to the lithological units of the core. The taxon “nr *Abiskomyia*” is possibly an early instar of that genus.

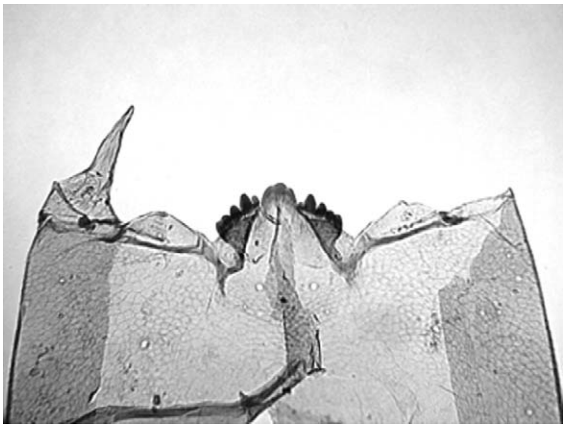


Fig. 8. Head capsule of Unknown 17 (author's designation) from Brother of Fog Lake, 171 cm depth. Only one antennal pedestal was present on this specimen. The first lateral tooth on the right side of the mentum appears to be broken off. The reticulate pattern was present in all specimens.

This unit includes midges normally found south of tree line, such as *Microtendipes*, *Endochironomus*, *Glyptotendipes*, and *Chaoborus*, resulting in warmer-than-present estimated temperatures, but the abundance of reworked carbon and pollen suggests that some of the chironomids might also be reworked from the underlying interglacial units.

The Holocene (Unit VI), is again dominated by *Abiskomyia*, *Heterotrissocladius*, and *Chironomus*. *Corynoneura*/*Thienemanniella* is also abundant. As in Fog Lake, temperature reconstructions indicate warmth in the early Holocene with gradual cooling to the present (Fig. 9). Unit V, although lithologically distinct from Unit IV in Fog Lake, has a similar fauna, dominated by *Oliveridia*/*Hydrobaenus*, *Pseudodiamesa*, and subtribe Tanytarsina (Figs. 5 and 7). Both diversity and head capsule abundance are low in this unit, suggesting low productivity (or possibly rapid sedimentation). This unit has the coldest estimated temperatures.

4.5. Modern analog testing

In the Fog Lake core, only one sample (at 118.5 cm) fell outside the 95% confidence interval and is considered

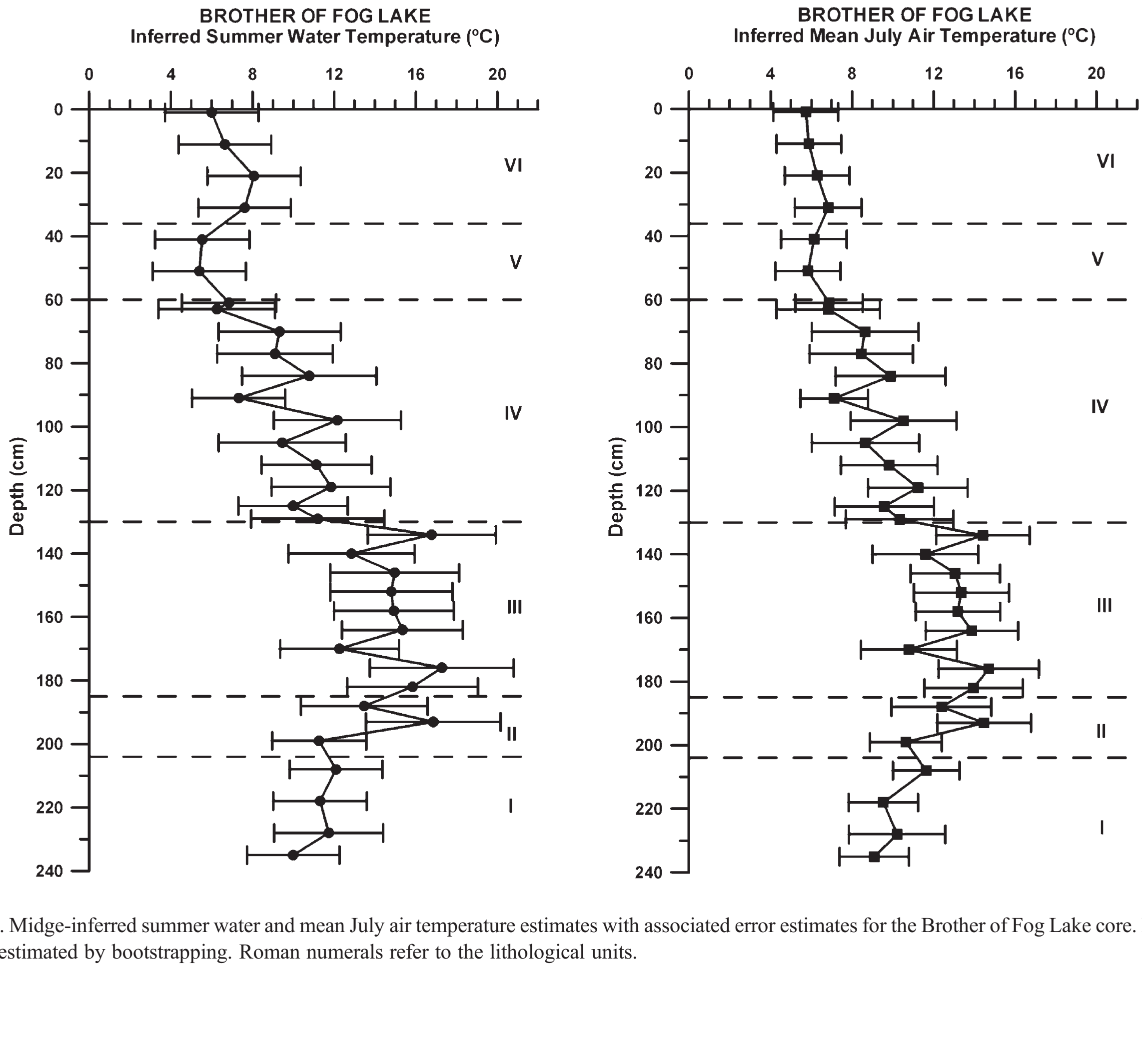


Fig. 9. Midge-inferred summer water and mean July air temperature estimates with associated error estimates for the Brother of Fog Lake core. Errors were estimated by bootstrapping. Roman numerals refer to the lithological units.

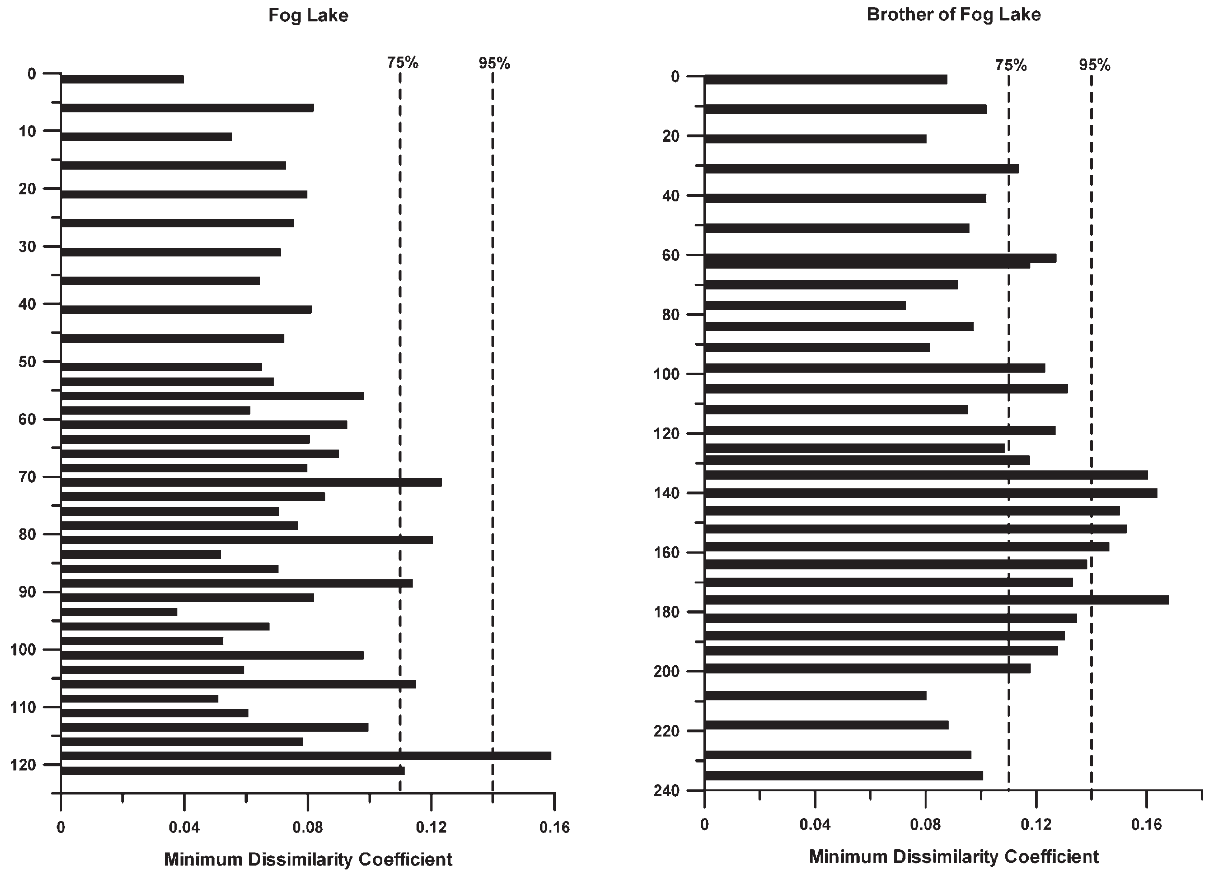


Fig. 10. Analogs between midge assemblages in the sediment cores and calibration model. Samples with dissimilarity coefficients greater than the 95% cutoff are considered to have no analogs in the calibration set. Samples with dissimilarity coefficients between 75% and 95% are considered to have fair analogs.

to have no analog in the calibration set (Fig. 10). In this sample, *Diplocladius* was abundant (19%), and *Diplocladius* was not present in the calibration set. Although *Diplocladius* was present in nearby levels of the Fog Lake core (Unit II), it was not in such high abundance (Fig. 5).

In Brother of Fog Lake, six samples fall outside the 95% confidence interval. These samples are in Unit III, which we believe to be the previous interglacial sediments. *Synorthocladius* was fairly abundant during this period, and was not present in the modern calibration set. The other taxon that does not occur in the modern calibration set is the orthoclad Unknown 17, which occurred in Units I and II. However, samples in these Units are considered to have good analogs in the calibration set.

5. Discussion

Capturing intact records of the last interglacial in the eastern Canadian Arctic has been difficult because of the rare preservation of intact sedimentary sequences in an environment dominated by the Laurentide Ice Sheet for most of the Foxe Glaciation. To date, cores recovered from seven lakes along eastern Baffin Island contained stratified interglacial sediments below Holocene and minerogenic layers, all with ^{14}C dates on plant macrofossils that are at or beyond the limits of ^{14}C dating (summarized in Miller et al., 2002). Three of these lakes (Fog, Brother of Fog, and Robinson; Miller et al., 1999) have luminescence ages suggesting the interglacial layers were deposited between 90 and 130 ka ago. Based on the more continuous ice core records from Greenland (NGRIP Members, 2004), Devon Island and Ellesmere Island (Koerner, 1989), the only time the adjacent regions were as warm as the Holocene was during the last interglacial (sensu stricto); the summer insolation peak between about 130 and 120 ka. Based on their limiting luminescence and ^{14}C ages, and the results from nearby ice cores, we conclude that these layers in Fog and Brother of Fog lakes must be from the last interglacial (sensu stricto), with ages bracketed by ca. 130 and 120 ka. The lack of significant sedimentation events between the last interglacial and the Holocene evidenced in all 7 lakes suggests that summer temperatures cooled rapidly at the end of the last interglacial and did not recover again until the early Holocene, when rapid sedimentation occurred as melting of extensive snowbanks on an unstable landscape resulted in rapid accumulation of minerogenic sediment in 4 of the lakes. This minerogenic sediment (Unit IV in both Fog and Brother of Fog lakes) is dominated by macro fauna and organic carbon reworked from the preserved last interglacial landscape and lake sediments, making the deposit difficult to date precisely, and rendering biotic proxies unreliable.

The lack of any other sediment accumulation between the last and present interglacials suggests that the lakes were perennially frozen throughout the Foxe Glaciation. At present, the lakes are ice-free only 1 to 2 months each year. A summer temperature depression of only 4 to 5 °C would keep average air temperature below freezing throughout the summer (mean July air temperature for the Cumberland Peninsula is 4.6 ± 1.7 °C (Environment Canada, 2004)). Consequently, we focus our interpretations on the interglacials, during which the lakes accumulated gyttja typical of high-latitude shield lakes in small catchments.

Inferred summer surface water temperatures and mean July air temperatures, plus error estimates for both cores are shown in Figs. 6 and 9. The consistent trends evident in both cores include a warm period in the first half of the Holocene, followed by gradual cooling up to the present time. This is consistent with estimates of summer warmth and pH using diatoms in Fog Lake (Wolfe et al., 2000) and with indications from pollen analysis (Fréchette et al., in press). During the last interglacial, summer water temperature estimates are warmer than at any time during the Holocene period at both sites. At Fog Lake, water temperature estimates for the interglacial are approximately 9 to 12 °C, compared with 5 °C at present. At Brother of Fog Lake, water temperature estimates for the last interglacial range as high as 16 °C, and throughout the peak of the interglacial average between 14 and 15 °C, whereas present temperatures are estimated to be only 6 °C. Summer water temperatures are typically higher than mean summer air temperatures at the same site by several degrees (Livingstone et al., 1999). Inferred July air temperatures during the last interglacial at Fog Lake average about 8 °C, which is in line with July air temperature inferred from pollen (Fréchette et al., in press). Midge inferred July air temperatures for the last interglacial at Brother of Fog Lake, however, are much higher than pollen inferred temperatures. Temperature estimates based on pollen averaged 7 to 8 °C, whereas estimates based on midge remains averaged about 13 °C. It should be noted that fossil midge assemblages from the last interglacial in the Brother of Fog core had only fair to poor analogs with the modern training set (Fig. 10).

These results indicate that this period was indeed a very warm time for the Canadian Arctic. Pollen in the interglacial units of both cores is dominated by birch and alder at much higher levels than at any time in the Holocene (Fréchette et al., in press), supporting our interpretation of much warmer summers than during the present interglacial. Diatom analysis of the Fog Lake core (Wolfe et al., 2000) also indicates warm summer conditions.

Comparison of these paleoclimate records with other records from this region is difficult, as few published records exist, especially for interglacial sediments. Fossil midge assemblages in an interglacial deposit near Thule, Greenland (Brodersen and Bennike, 2003) contained taxa that indicate a glacier-fed stream environment, and thus are not really comparable to the sites on Baffin Island. Macrofossils from the same deposit at Thule and sediment samples from Jameson Land in eastern Greenland yielded temperature estimates 4 to 5 °C higher than present for the last interglacial (Bennike and Böcher, 1992, 1994). The North GRIP ice core record also indicates that the previous interglacial temperatures were about 5 °C higher than present based on oxygen isotopes (NGRIP Members, 2004). In this study, the midge-inferred air temperature estimates are 4 to 9 °C higher than present. In Holocene sediments, midge-inferred summer water temperatures from a site in arctic Québec, Canada were warmer than at the Baffin Island sites, but show the same trend, that is, warmer conditions in the early and mid-Holocene and recent cooling (Fallu et al., 2005).

In both cores, fossil assemblages had good or fair analogs in the modern calibration set (Fig. 10). In Unit III of Brother of Fog six levels were found to have no analogs, possibly due to the presence of *Synorthcladius*. This no-analog situation might call into question the temperature reconstruction for this Unit, however because it is consistent with the interpretation of the same time period in Fog Lake, we feel confident that the temperature reconstruction reflects actual conditions at the time. Additionally, Lotter et al. (1999) found that even in situations with poor analogs, models were able to predict actual temperatures reliably, implying that the models may still be used in no-analog situations.

An advantage of using chironomids to infer past summer temperatures is the ability to use modern calibration sets to construct transfer functions and arrive at quantitative estimates. Chironomid reconstructions have been shown to be one of the most promising of biological proxies for paleotemperatures (Battarbee, 2000). Additionally, new work using the oxygen isotopic signature of chironomid head capsules has shown that two independent temperature proxy records may be obtained from the chironomid remains. Application of this technique to head capsules from the Fog Lake core support the conclusions reported in this paper for temperature estimates downcore (Wooller et al., 2004).

6. Conclusions

Quantitative temperature reconstructions from many terrestrial sites in the Arctic will provide important data for climate modelers. In this study, we present quantitative reconstructions based on midge remains that are the first of their kind for the previous interglacial period. Midges are widely distributed in the Arctic, are rapid colonizers, and may prove to be one of the best temperature proxies for Arctic sites. Our reconstructions illustrate that the previous interglacial in this region of the Canadian Arctic was warmer than at any time during the Holocene period. Results of midge-inferred quantitative temperature reconstructions also agree well with qualitative proxies from the same core, such as pollen and diatoms. All proxies indicate a very warm previous interglacial, and a warm period in the first half of the Holocene followed by gradual cooling up to the present.

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