Quantitative estimates of recent environmental changes in the Canadian High Arctic inferred from diatoms in lake and pond sediments

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Abstract

Diatoms were examined in three lacustrine sediment records from Alert, northern Ellesmere Island, and from Isachsen, Ellef Ringnes Island. Diatom assemblages changed markedly since the mid-19th century following relatively stable community composition that spanned centuries to millennia. Three different assemblages, primarily composed of *Fragilaria pinnata*, *Diadesmis* spp., or *Pinnularia* spp., dominated the pre-1850 period at the three sites, but were replaced with different, more diverse assemblages in recent sediments. These species shifts occurred in the mid- to late-19th century in the Isachsen sites, and in the mid- to late-20th century in our Alert site. This difference in timing appears to be a result of the different sensitivities of lakes and ponds to environmental change, rather than of site-specific chemical properties. Reconstructions of pH using diatom inference models indicated increases from 0.5 to 0.8 pH units at these sites over this period of assemblage change. The diatom-inferred pH record from Alert showed agreement with measured climate data from Alert over the last ∼30 years. These marked community changes suggest that these sensitive high arctic sites have recently crossed important ecological thresholds due to environmental change, most likely related to recent warming.

Introduction

Arctic regions are highly sensitive to environmental change, and it is now generally recognized that climate changes are amplified in high latitude regions due to feedback mechanisms (Houghton et al. 2001). Unfortunately, due to logistical restraints, long-term meteorological data are lacking from most arctic regions. The first meteorological stations in the Canadian High Arctic were only established in 1947, and just five stations monitored this vast region. Consequently, little is known about long-term natural climate variability in the region. Therefore, proxy-based climate reconstructions using natural archives are required to determine the timing, nature, and rate of any environmental and climatic changes that have occurred prior to the establishment of instrumental monitoring stations.

High arctic landscapes are typically dominated by lakes and ponds. Although most high arctic lakes are remote and therefore largely isolated

from direct human impacts, dramatic changes in these freshwater systems are predicted to occur due to future regional environmental changes (Rouse et al. 1997). For example, climate changes may have both direct (e.g., temperature, snow cover) and indirect (e.g., dissolved organic carbon, pH) effects on Arctic freshwater sites. Many of these limnological changes can be tracked using biological indicators (Smol and Cumming 2000).

Diatoms are siliceous algae that preserve well in lake sediments and are sensitive to changes in environmental conditions. As a dominant component of periphyton in high arctic lakes and ponds, diatoms are ideal microfossils in paleolimnological studies (Stoermer and Smol 1999). Although the High Arctic has historically been neglected in diatom studies, considerable effort has recently been devoted to understanding modern high arctic diatom distributions and autecology (e.g., Douglas and Smol 1993, 1995; Lim et al. 2001a, b; Michelutti et al. 2003a; Antoniades et al. 2004, 2005; Jones and Birks 2004).

Qualitative studies detailing the response of diatom assemblages and other indicators to environmental change have been completed for several high arctic regions (e.g., Smol 1983; Douglas et al. 1994; Doubleday et al. 1995; Gajewski et al. 1997; Smith 2002; Michelutti et al. 2003b; Birks et al. 2004a, b; Jones and Birks 2004; Smith et al. 2004). However, the Canadian High Arctic Archipelago alone encompasses over 1.42 million km^2, and further study is needed in order to understand the timing and spatial variability of any recent environmental changes. In addition, as previous studies were concerned primarily with interpretations of floristic change, quantitative inferences of limnological changes are rare (Joynt and Wolfe 2001; Wolfe 2002).

Through the analysis of diatom sedimentary records, this study had several objectives: (1) to determine the extent and timing of diatom responses to recent environmental change in two regions of the High Arctic; (2) to use paleolimnological methods to establish quantitative estimates of the degree of limnological change of environmental change; and (3) to determine whether any correlations exist between changes in these diatom records and measured climate data.
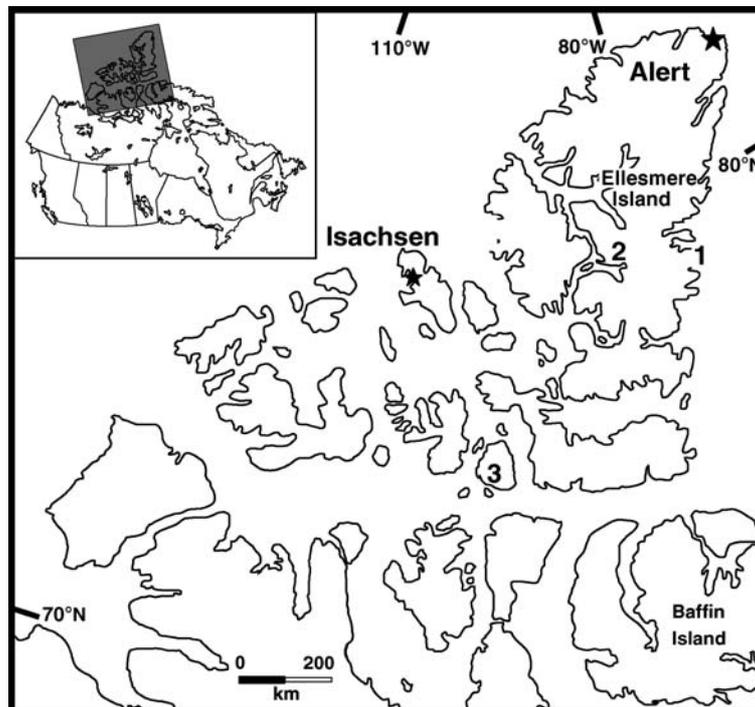

Figure 1. Location map of Alert and Isachsen in the Canadian Arctic Archipelago. Numbers indicate locations of other studies referred to in the text. 1 = Cape Herschel, eastern Ellesmere Island (Douglas et al. 1994). 2 = Sawtooth Lake, west-central Ellesmere Island (Perren et al. 2003). 3 = Char Lake, Cornwallis Island (Michelutti et al. 2003b) (Modified from Antoniades et al. 2005).

Methods

Site descriptions

Alert (82°30′ N, 62°20′ W) is located on the northeastern tip of Ellesmere Island in the Canadian Arctic Archipelago (Figure 1). The climate of the region is extremely cold and dry, with mean annual temperature and precipitation of −18.0°C and 154 mm, respectively (Meteorological Service of Canada 2002). As only two months of the year have average temperatures above freezing (i.e., July–August), the ice-free season for lakes and ponds is extremely short. Larger lakes in the area may retain perennial ice cover throughout the summer.

Self Pond (82°26.5′ N, 62°01.6′ W) is situated at 137 m asl, approximately 8 km southeast of the Alert military base (Figure 2). It is a small (16.6 ha), relatively shallow (8 m) lake that is alkaline and mesotrophic (Table 1). Self Pond is underlain by Ordovician to Silurian carbonates and mudstones (Christie 1964), and has an ephemeral inflow and one small outflow stream. The local vegetation is restricted to pockets of herbaceous plants and mosses growing between tundra polygons. Additional details concerning Alert's regional limnology and geology are summarized in Antoniades et al. (2003a, 2005).
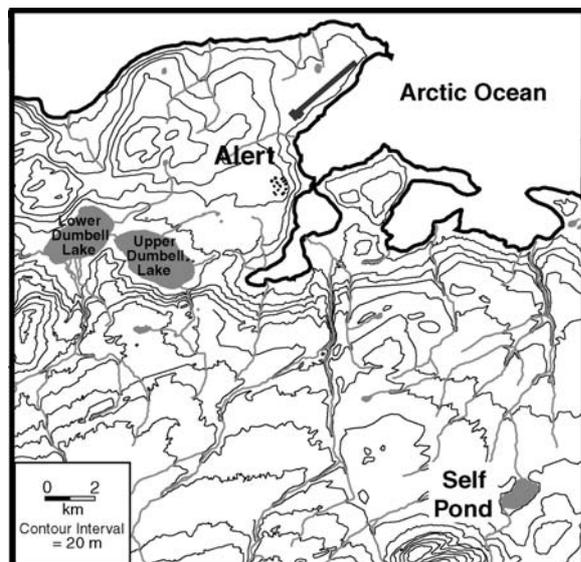
Table 1. Selected water chemistry variables from study sites.

	Self Pond	I-F	I-O
Area (ha)	16.6	0.07	0.78
Depth (m)	8	0.3	0.35
Elevation (m asl)	137	12	69
pH	8.3	5.9	6.9
TP (μg/l)	12.1	10.2	10.9
TN (mg/l)	0.202	0.117	0.376
Specific Conductivity (μS/cm)	135	58	17
DOC (mg/l)	0.9	1.3	1.7
DIC (mg/l)	12.1	0.9	1.8

TP – Total phosphorus; TN – Total nitrogen; DOC – Dissolved organic carbon; DIC – Dissolved inorganic carbon.

Ellef Ringnes Island is located along the northwestern margin of the Canadian Arctic Archipelago (Figure 1). Isachsen (78°47′ N, 103°32′ W) is located on its west coast, and has the coldest, cloudiest summers in the High Arctic (Maxwell 1981). Average annual temperature and precipitation are −19.0°C and 102 mm, respectively. Because of the extreme summer climate and poor soils, land surfaces around Isachsen are virtually devoid of vegetation (Nahir 1996).

Sites I-F and I-O (unofficial names) are shallow tundra ponds located near the former Isachsen weather station (Figure 3). I-F (78 °47.5′ N, 103 °26.2′ W) is situated approximately 400 m inland from the Arctic Ocean at 12 m asl, and is underlain by black shale and glaciomarine sediments (Heywood 1957). It is a small (0.07 ha),
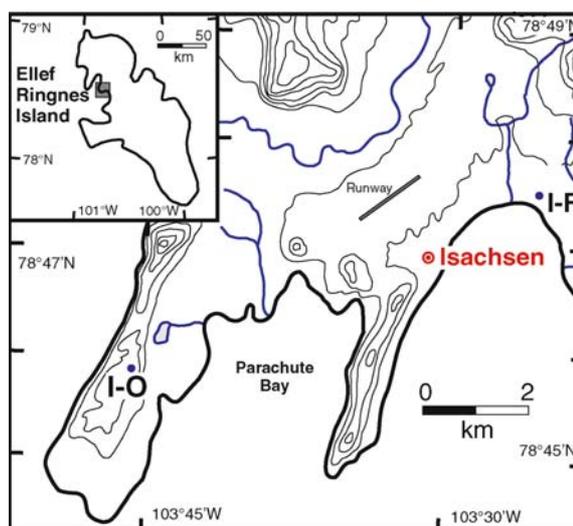

Figure 2. Map detail of Self Pond and the Alert area. Location of military buildings and airstrip are also noted.

Figure 3. Map detail of Ponds I-F, I-O, and the Isachsen area. Contour interval = 30.5 m.

shallow (0.3 m) pond whose size shrank noticeably due to evaporation over the course of the 1996 field season (Table 1). Sparse patches of moss were present surrounding I-F, and moss and emergent grasses were present within the pond itself. I-F was mesotrophic, dilute, poorly buffered, and weakly acidic when sampled on July 23, 1996 (Table 1).

I-O (78°45.8′ N, 103°45.3′ W) is 6 km southwest of the former Isachsen weather station (abandoned since its closure in 1979), on an elevated ridge of gabbroic rock at 69 m asl (Heywood 1957). I-O is a shallow (0.35 m) tundra pond of moderate size (0.78 ha). Although the catchment was largely unvegetated, I-O had well developed aquatic moss growth around its fringes. Small meltwater streams from large adjacent snowbanks were flowing into I-O when sampled on July 26, 1996. I-O was marginally mesotrophic, dilute, poorly buffered, and circumneutral (Table 1).

Sampling and analysis

In addition to retrieving sediment cores, water samples were collected at each of our sites for detailed chemistry analysis. A more comprehensive discussion of regional differences in water chemistry and diatom assemblages from the Alert and Isachsen regions is published elsewhere (Antoniades et al. 2003 a, b, 2004, 2005).

A 16 cm sediment core was taken from Self Pond on August 2, 2000, using a gravity corer (Glew 1991). The core was extruded on site, with the upper 8 cm sectioned into 0.5 cm intervals, and the remainder sectioned at 1.0 cm intervals using a Glew (1988) extruder. At Isachsen, sediment cores of 30 cm (I-F) and 35.5 cm (I-O) were taken on July 26 and 30, 1996, respectively. These cores were extracted by inserting core tubes into the pond bottoms and withdrawing the sediments under suction. The upper 3.0 cm (I-F) and 2.5 cm (I-O) were sectioned at 0.5 cm intervals, below which both cores were extruded in 1.0 cm sections.

Samples from Self Pond and I-O were analyzed for ^{210}Pb by alpha spectrometry at Mycore Scientific Inc., Deep River, Ontario, while the I-F core was analyzed for ^{210}Pb by gamma spectrometry in PEARL at Queen's University, Kingston, Ontario. Both Isachsen cores were also analyzed

for ^{137}Cs by gamma spectrometry at Queen's University. ^{210}Pb ages were calculated using the constant rate of supply model (CRS) (Appleby 2001).

Sediments were prepared for diatom analysis by microwave digestion using techniques described by Parr et al. (2004); however, our digestions were carried out at a maximum temperature of 160 °C. The cleaned diatom samples were dried on glass cover slips and mounted in Naphrax$^{®}$ mounting medium. Diatoms were identified and enumerated at 1000× using a Leica DMRB microscope equipped with Nomarski DIC optics, and taxonomic identifications primarily followed Krammer and Lange Bertalot (1986–1991); Lange-Bertalot and Genkal (1999) and Foged (1981). Self Pond samples were enumerated to 1000 valves, while 300 valves were typically enumerated in Isachsen core samples. However, I-F and I-O sediments had extremely high ratios of inorganic siliciclastic particles to diatoms, and in the lower portions of the core, counting entire coverslips often did not yield this minimum number. As such, while every effort was made to enumerate at least 300 valves per sample, some low diversity samples in the lower portions of the cores were only counted to a minimum of 100 valves.

Statistical analyses

The degree of diatom community turnover within the sediment cores was analyzed using detrended correspondence analysis (DCA) with the computer program Canoco version 4.0 (ter Braak 1998). Quantitative records of pH and specific conductivity were reconstructed from diatom profiles using weighted averaging (WA) and weighted averaging partial least squares (WAPLS) inference models developed in Antoniades et al. (2005). These models were based on a 90 site calibration set that consisted of lakes and ponds from Alert, Isachsen, and Mould Bay, Prince Patrick Island. Diverse limnological gradients were present, with ranges from 3–1400 m in diameter, 0.25–45 m in depth, 10–2130 μS in specific conductivity, and 5.1–8.9 in pH. pH was reconstructed with a WA model (root mean square error of prediction (RMSEP) = 0.42, bootstrapped coefficient of determination (r^2) = 0.72), while specific conductivity was inferred with a two component WAPLS

model (RMSEP $= 0.28$ $_{log}$COND, $r^2 = 0.70$). All reconstructions and model generation were done using the computer program C^2 version 1.3 (Juggins 2003). Changes in species diversity were measured with Hill's (1973) N2, which weights species according to their abundances when calculating diversity values. These proxy records were then compared with measured climate records from the Alert weather station of the Meteorological Service of Canada (MSC).

Results

Chronologies

Self Pond's average sedimentation rate of 0.0084 g·cm^{-2}·yr^{-1} $\pm$ 0.002 was extremely high relative to those reported from most other Canadian High Arctic lakes (e.g., Douglas and Smol 2000; Michelutti et al. 2003b), and suggests that Self Pond contains a high-resolution sedimentary record relative to these other sites. Unsupported ^{210}Pb declined exponentially with depth in the Self Pond core, reaching background levels (mean = 0.42 Bq/g) at a depth of 8 cm. Extrapolation of the chronology beyond 8 cm based on a uniform sedimentation rate suggests that the 16 cm core represents approximately 330 years of sediment accumulation.

Both Isachsen cores were characterized by unusual ^{210}Pb profiles. I-O's sediments contained no inventory of unsupported ^{210}Pb, as activity fell within the restricted range of 0.009 to 0.014 Bq/g (mean = 0.012 Bq/g). A highly irregular ^{210}Pb profile in the I-F core suggested the possibility of highly variable sedimentation rates, sediment mixing, or both. Assigning an age of ~1850 to the inflection point of the ^{210}Pb curve (i.e., 3.5 cm) yielded a sedimentation rate of 1 cm accumulation per 42 years. A well-defined ^{137}Cs peak was also recorded in the 0.5–1.0 cm interval of the I-F core. Assigning the year 1963 to the center of this interval indicated a sedimentation rate of 1 cm per 44 years. Although the assumption of uniform sedimentation is tenuous, the close agreement of the rates calculated with ^{137}Cs and ^{210}Pb profiles suggests that our assumptions are reasonable. A ^{137}Cs peak was also present in the 0.5–1.0 cm interval of the I-O core, and if similar sedimentation rates are inferred, these cores represent approximately 1300 (I-F) and 1600 (I-O) years of sediment accumulation.

Paleolimnological records

Thirty-nine diatom taxa were identified in the Self Pond core. Eleven of these were present at >1% relative abundance in any one interval, and only five taxa were defined as common (i.e., exceeding 1% relative abundance in three core sections) (Table 2a). Low diversity diatom assemblages were thus characteristic throughout much of Self Pond's stratigraphic record (Figure 4). *Fragilaria pinnata* Ehrenberg dominated the core, exceeding 90% relative abundance in every interval prior to 1980. From ~1918 to ~1980, slight decreases in *F. pinnata* and *F. construens* var. *venter* (Ehrenberg) Grunow abundances were offset by gradual increases in *F. construens* var. *construens* (Ehrenberg) Grunow, *Achnanthes minutissima* Kützing, and *Cymbella* sp. A3. Over this period, trends in diatom-inferred limnological variables mirrored these subtle species shifts. pH remained stable at ~7.3 within the lower portions of the core, and increased slightly to 7.5 through the mid-20th century, while inferred specific conductivity was below 10 μS cm^{-1}. After ca. 1980, *F. pinnata* steadily and dramatically decreased in relative frequency, and was replaced by *F. construens* var. *construens*, *A. minutissima*, and *Cymbella* sp. A3. Species diversity (as measured by Hill's N2), which was low throughout the core (i.e., 1.3–3.2), also increased sharply after 1980. Analysis of diatom assemblages by detrended correspondence analysis (DCA) indicated that DCA axis 1 scores were also relatively unchanged prior to ~1918, dropped gradually until ~1980, and steeply thereafter (Figure 4). Similar trends in diatom-inferred pH (DI-pH) and specific conductivity were again present, with sharp rises to 8.0 and 60 μS cm^{-1}, respectively.

Fifty-five diatom taxa were identified in the sediments of I-F (Table 2b), of which 21 were defined as common. Several *Pinnularia* taxa and *Orthoseira roseana* (Rabenhorst) O'Meara dominated the core prior to the mid-19th century (Figure 5). These five taxa comprised between 70 and 88% of enumerated diatoms below the 3 cm level of the I-F core. Above 3 cm, diversity increased dramatically, and *Pinnularia* spp. were replaced by taxa including *Caloneis aerophila*

Table 2. Common taxa from sediment cores (present > 1% relative abundance in ≥ 3 core sections).

| Taxon	# Occur.	Max. Abund.
(a) Self Pond		
Achnanthes minutissima Kützing	10	39.7
Cymbella sp. A3	10	4.9
Fragilaria construens var. *construens* (Ehrenberg) Grunow	6	2.7
F. construens var. *venter* (Ehrenberg) Grunow	19	17.4
F. pinnata Ehrenberg	24	98.4
(b) I-F		
Caloneis aerophila Bock	33	24.5
C. subclevei Krammer	3	1.9
Diadesmis contenta (Grunow) Mann	3	5.6
D. gallica W. Smith	3	2.0
D. paracontenta Lange-Bertalot & Werum	16	2.8
D. perpusilla (Grunow) Mann	16	23.7
Fragilaria brevistriata Grunow	4	5.7
Hantzschia amphioxys (Ehrenberg) Grunow	4	1.4
Navicula mutica Kützing	4	1.9
Neidium bergii (Cleve) Krammer	15	3.8
Nitzschia normannii Grunow in Van Heurck	7	9.4
N. perminuta (Grunow) Peragallo	8	17.4
Orthoseira roseana (Rabenhorst) O'Meara	26	5.8
Pinnularia borealis Ehrenberg	32	30.1
P. brandelii Cleve	4	4.1
P. divergentissima (Grunow) Cleve	4	0.9
P. intermedia (Lagerstedt) Cleve	33	47.8
P. obscura Krasske	33	20.1
P. subrostrata (A. Cleve) Cleve-Euler	33	9.9
Stauroneis anceps Ehrenberg	10	5.3
(c) I-O		
Achnanthes delicatula Kützing	12	2.9
A. helvetica Hustedt	9	7.6
A. marginulata Grunow in Cleve & Grunow	15	6.0
Caloneis aerophila Bock	31	10.0
C. silicula (Ehrenberg) Cleve	7	2.3
Diadesmis contenta (Grunow) Mann	3	3.0
D. gallica W. Smith	39	25.9
D. paracontenta Lange-Bertalot & Werum	39	39.1
D. perpusilla (Grunow) Mann	30	7.1
Encyonema silesiacum (Bleisch) Mann	28	14.7
Eunotia praerupta Ehrenberg	4	2.0
Fragilaria capucina Desmazières	12	4.9
F. construens var. *venter* (Ehrenberg) Grunow	6	5.0
F. pinnata Ehrenberg	6	4.0
N. cryptocephala Kützing	15	6.8
N. gandrupii Krasske	27	7.7
N. gerloffii Schimanski	4	4.1
N. nivaloides Bock	4	2.4
N. pseudoscutiformis Hustedt	39	29.0
N. schoenfeldii Hustedt	13	2.8
Neidium affine (Ehrenberg) Pfitzer	3	1.8
N. ampliatum (Ehrenberg) Krammer	6	2.9
N. bergii (Cleve) Krammer	9	3.9
Nitzschia perminuta (Grunow) Peragallo	37	23.6
Pinnularia borealis Ehrenberg	5	1.9
P. brebissonii Kützing	6	2.9
P. intermedia (Lagerstedt) Cleve	9	3.1
Stauroneis anceps Ehrenberg	26	5.8
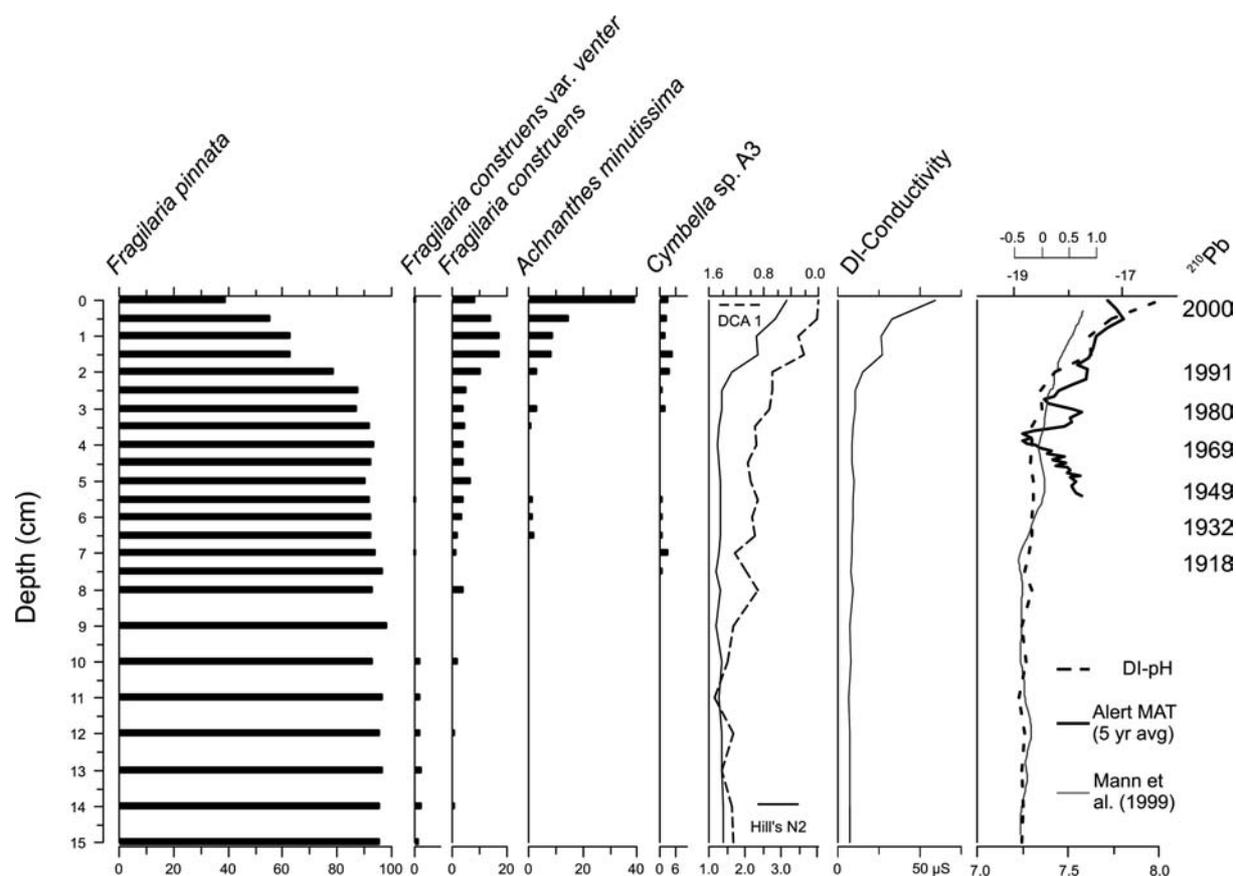
Figure 4. Self Pond (Alert, Ellesmere Island) diatom stratigraphy (selected taxa shown). Mann et al. line refers to multiproxy reconstruction of Northern Hemisphere mean temperature. Data from Mann et al. (1999). See text for discussion of prediction errors.

Bock, *Diadesmis perpusilla* (Grunow) Mann, *Nitzschia perminuta* (Grunow) Peragallo, *N. normannii* Grunow, and *Stauroneis anceps* Ehrenberg (Figure 5). DCA axis 1 scores again closely mirrored these trends in diversity, with stable values below 3 cm, and a marked decrease above this level (Figure 5). Not surprisingly, diatom models inferred relatively stable pH and specific conductivity below 3 cm; DI-pH increased from 5.6 to 6.0 in the upper 3 cm of the core, and DI-conductivity decreased from 90 to 55 μS cm^{-1}.

The sedimentary record of I-O showed higher species diversity and greater variability in downcore diatom assemblages than our other two sites (Figure 6). Eighty-eight diatom taxa were identified from I-O, with 28 common taxa (Table 2c). The majority of I-O's record was dominated by moss epiphytes, including *Diadesmis gallica* W. Smith, *D. contenta* (Grunow) Mann, and *Navicula pseudoscutiformis* Hustedt, and by gradually increasing concentrations of *Nitzschia perminuta*. While species diversity increased upwards throughout the core, the most pronounced increase occurred only in the upper 2.0 cm of sediment. These recent sediments were characterized by diatom assemblages with low abundances of numerous *Achnanthes* and *Navicula* species. DCA axis 1 scores also showed a gradual increase throughout most of the core, but again dropped sharply above the 2 cm level (Figure 6). Similarly, diatom reconstructions of pH and conductivity indicated two zones within the core: one of rapid change from 0–2.0 cm, and one of gradual increase below this horizon. DI-pH ranged from 6.4 to 7.2, while conductivity ranged from 11 to 46 μS cm^{-1}. More than half of the increase in diatom-inferred limnological variables occurred within the top 2.0 cm of the core.

Standard errors of prediction (SEP) were large in each of our reconstructions relative to the
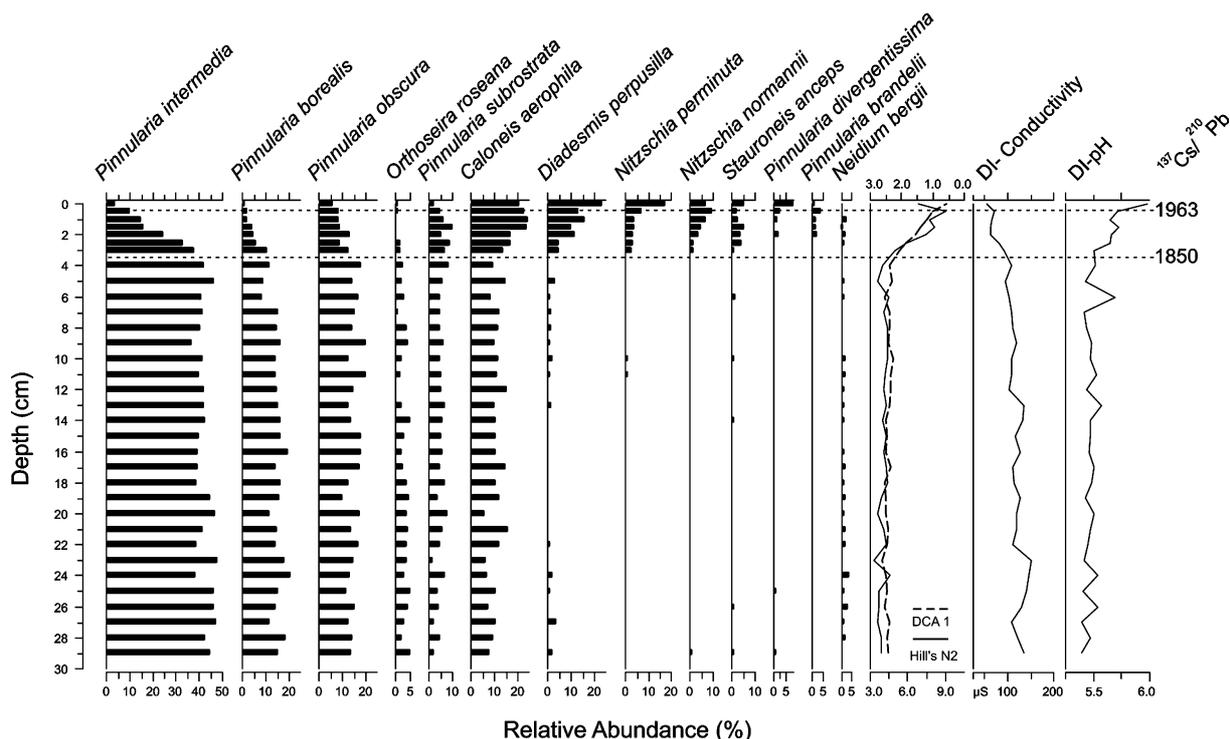
Figure 5. Pond I-F (Isachsen, Ellef Ringnes Island) diatom stratigraphy (selected taxa shown). See text for discussion of prediction errors.
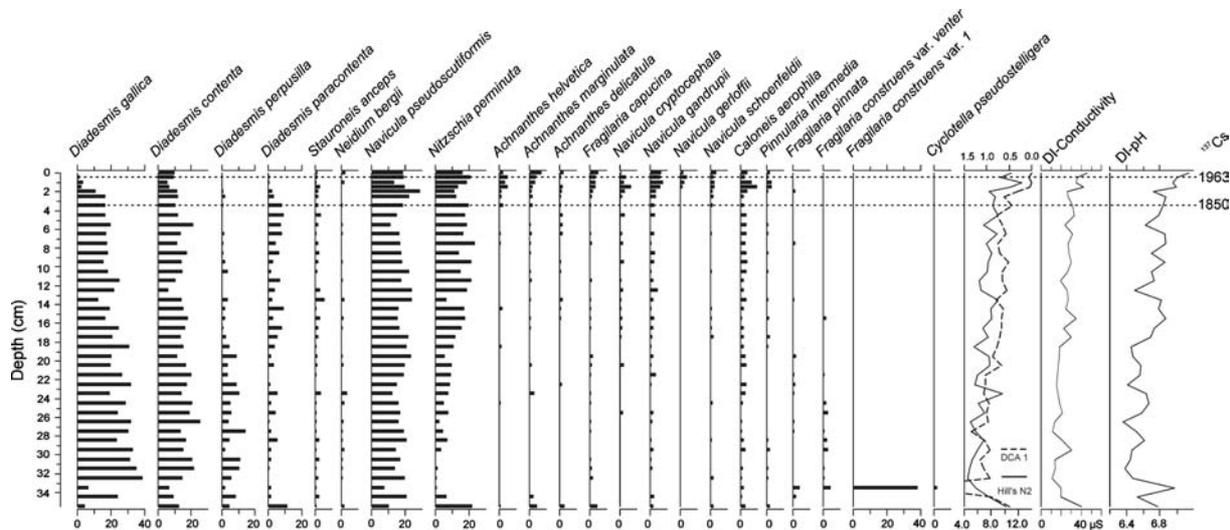

Figure 6. Pond I-O (Isachsen, Ellef Ringnes Island) diatom stratigraphy (selected taxa shown). See text for discussion of prediction errors.

magnitude of inferred limnological change. However, our goal was to track overall trends in inferred variables, and we acknowledge that

inferring absolute values may not be realistic with this dataset. At Self Pond, SEP varied from ± 73 to ± 119% of the range of reconstructed pH, and

± 47 to ± 93% of the range of reconstructed conductivity. Errors greatly decreased in the upper several cm of the Self Pond core. SEP from the I-F and I-O core reconstructions were of similar magnitude (I-F: pH ± 83–88%, COND ± 72–77%; I-O: ± 54–57%, COND ± 49–63%).

Discussion

The striking similarities between our diatom profiles and those of earlier high arctic paleolimnological studies (e.g., Douglas et al. 1994; Perren et al. 2003) suggest similar ecological responses to recent climate changes. However, important differences exist between these records. Most significant, perhaps, are the taxonomic differences between our diatom assemblages and those elsewhere in the High Arctic. Dramatic recent diatom shifts, such as those seen in I-F and I-O, have previously been recorded from the High Arctic only in sites with strongly *Fragilaria*-dominated assemblages (e.g., Douglas et al. 1994; Michelutti et al. 2003b; Perren et al. 2003). The presence of similar community change in sites dominated by *Diadesmis* spp. and *Pinnularia* spp. confirms that the cause of these shifts cannot be taxon or community specific, and that they likely result from larger forcing mechanisms, such as climate.

The biostratigraphic patterns present in the three cores resemble those described elsewhere in the Canadian High Arctic (Douglas et al. 1994; Michelutti et al. 2003b; Perren et al. 2003). However, the timing of species shifts is spatially asynchronous, although we acknowledge that assigning accurate dates to high arctic cores is often problematic. The difference in timing of community change appears to be related to site size rather than to physicochemical characteristics such as pH, and may result from differing thresholds in larger vs. smaller sites.

Studies of shallow high arctic ponds indicate that the transition from low to higher diversity diatom assemblages occurred in the mid- to late-19th century at sites with a wide range of pH values (i.e., I-F, I-O, also Douglas et al. 1994). The concurrent timing suggests a similar response to regional climate forcing factors. By contrast, studies of larger lakes suggest slower response rates to these environmental fluctuations, as shown by delayed community shifts due to recent environmental change. The later onset of species shifts (i.e., ~1920) and the recent acceleration of community change observed in Self Pond agrees with observations from other, larger lakes from west-central Ellesmere and Cornwallis islands (Perren et al. 2003; Michelutti et al. 2003b), but not those from sites on northeastern Ellesmere Island (Smith 2002). In addition, these large sites appear unaffected by the pronounced mid-19th century changes observed from Isachsen (this study) and eastern Ellesmere Island ponds (Douglas et al. 1994). This serves to highlight the sensitivity of shallow ponds and their utility as early indicators of environmental change (Douglas and Smol 1999).

Furthermore, an absence of diatoms below 1.5 cm of the sedimentary record of Lower Dumbell Lake, 10 km northeast of Self Pond, was hypothesized to result from permanent ice cover under a colder climate regime (Doubleday et al. 1995). Contrasted with the persistence of diatoms in Self Pond, a smaller, shallower lake, this absence further reinforces the importance of lake size in determining the rate of response to environmental change. It is also noteworthy that Doubleday et al. (1995) sampled Lower Dumbell Lake in 1992, preceding the most dramatic changes in Self Pond's sedimentary record (Figure 4). Further analysis of recent changes in the diatom assemblages of Lower Dumbell Lake may help to clarify any differences in limnological response to environmental change between these sites.

The relatively high temporal resolution of Self Pond's stratigraphic record allows for a more detailed comparison of trends in temperature, from the nearby Alert Meteorological Station, and DI-pH. During the first two decades of the 50 year (i.e., ~1950 to ~1970) Alert climate record, a cooling trend does not appear to be reflected in diatom assemblages. The diatom communities at these sites are likely already those ideally adapted to extreme cold conditions. As such, these assemblages may have been unable to show any significant response to further cooling. DI-pH rose slowly during the ca. 1970's, indicating muted diatom response to warming, and during the last ca. 20 years a steady increase in temperature is reflected by a strong rise in DI-pH. The agreement between temperature and pH trends (Figure 4) suggests that Self Pond diatom communities are sensitively recording environmental changes, and

that ecological thresholds were passed during the lake's recent history.

Temperature variations are thought to affect high arctic diatom communities primarily through effects on the extent and duration of ice cover, which in turn influence benthic productivity and habitat availability, as well as other limnological variables (Smol 1983, 1988). Also, warming may affect lakewater chemistry through several climate-mediated effects, including increases in snowmelt and nutrient inflows, changing permafrost active depths, and the control of changing ice cover on lake-atmosphere interactions (Sommaruga-Wögrath et al. 1997; Koinig et al. 1998; Douglas and Smol 1999; Schmidt et al. 2004). As such, the higher pH and diatom diversity observed in our sites are among the expected effects of temperature increases. While community responses to changes in ice cover have been identified in sites across the pH spectrum, the close linkage of temperature and pH in arctic and alpine lakes has previously been identified only in poorly buffered, acidic sites (Sommaruga-Wögrath et al. 1997; Koinig et al. 1998; Wolfe 2002). However, temperature and pH appear to be linked in Self Pond despite its alkaline nature.

Despite the relationship that has been demonstrated between air temperature and pH in poorly buffered, oligotrophic alpine and arctic lakes (Sommaruga-Wögrath et al. 1997; Wolfe 2002), the sensitivity of high arctic ponds to environmental change does not appear to be strongly related to pH levels. The century-scale stability in diatom communities observed in acidic sites (i.e., I-F, pH = 5.9) was also apparent in far more alkaline Cape Herschel sites (pH = 8.1–8.4; Douglas et al. 1994). The extremity of high arctic climates may have historically precluded compositional change in lakes and ponds; however the magnitude of recent climate change appears to have exceeded natural thresholds within these ecosystems.

Assuming that the mechanisms controlling the pH-temperature relationship in arctic lakes are correctly understood, it is unclear why Self Pond reacts so sensitively to changes in temperature. However, the magnitude of change in DI-pH at Self Pond (i.e., 0.8 pH units) is of similar magnitude to those calculated in acidic Baffin Island lakes (i.e., 0.7 pH; Wolfe 2002). The changes in temperature and DI-pH from Alert also mirror records of global climate change (Figure 4; Mann et al. 1999), but the magnitude of recent changes is greater in our sites, confirming the heightened susceptibility of the high arctic to environmental change. Although the linkage of pH and temperature variations in alpine lakes deteriorated in the early 20th century due to increased atmospheric acid deposition (Wolfe 2002) pH and temperature in Self Pond appear to be coupled only in the last ~30 years. We acknowledge that the prediction errors associated with each of our reconstructions were large in relation to the magnitude of diatom-inferred limnological changes, largely due to the lack of modern analogues for historical diatom communities. However, the consistent trends, as well as the concurrent indications of dramatic changes in DI-variables, DCA scores, and diversity measures, reinforce our interpretations and the significance of these recent shifts in biotic communities.

Conclusions

Analyses of sediment cores from Ellef Ringnes and northern Ellesmere islands record dramatic shifts in diatom assemblages in recent sediments. Three different dominant communities were affected by these changes, which led to species replacements and large increases in diversity. The onset of these changes occurred in the mid-19th century in the Isachsen ponds, and in ~1920 in Self Pond. DI-pH records from Self Pond show an agreement with temperature over the last three decades. These large changes in historically stable systems suggest that lakes and ponds in the Canadian High Arctic have crossed significant ecological thresholds in the recent past due to climate warming.

References

Antoniades D., Douglas M.S.V. and Smol J.P. 2003a. Comparative physical and chemical limnology of two Canadian High Arctic regions: Alert (Ellesmere Island, NU) and Mould Bay (Prince Patrick Island, NWT). Arch. Hydrobiol. 158: 485–516.

Antoniades D., Douglas M.S.V. and Smol J.P. 2003b. The physical and chemical limnology of 24 ponds and one lake from Isachsen, Ellef Ringnes Island, Canadian High Arctic. Int. Rev. Hydrobiol. 88: 519–538.

Antoniades D., Douglas M.S.V. and Smol J.P. 2004. Diatom species-environment relationships and inference models from Isachsen, Ellef Ringnes Island, Canadian High Arctic. Hydrobiologia 529: 1–18.

Antoniades D., Douglas M.S.V. and Smol J.P. 2005. Diatom autecology and inference model development from the Canadian High Arctic Archipelago. J. Phycol. In press.

Appleby P.G. 2001. Chronostratigraphic techniques in recent sediments. In: Last W.M. and Smol J.P. (eds), Tracking Environmental Change using Lake Sediments. Volume 1: Basin Analysis, Coring, and Chronological Techniques. Kluwer, Dordrecht, pp. 171–203.

Birks H.J.B., Jones V.J. and Rose N.L. 2004a. Environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – an introduction. J. Paleolimnol. 31: 403–410.

Birks H.J.B., Jones V.J. and Rose N.L. 2004b. Recent environmental change and atmospheric contamination on Svalbard as recorded in lake sediments – synthesis and general conclusions. J. Paleolimnol. 31: 531–546.

Christie R.L. 1964. Geological reconnaissance of Northeastern Ellesmere Island, District of Franklin. Geol. Surv. Can. Memoir 331: 79.

Doubleday N.C., Douglas M.S.V. and Smol J.P. 1995. Paleo-environmental studies of black carbon deposition in the High Arctic: a case study from Northern Ellesmere Island. Sci. Total Environ. 160(161): 661–668.

Douglas M.S.V. and Smol J.P. 1993. Freshwater diatoms from high arctic ponds (Cape Herschel, Ellesmere Island, N.W.T.). Nova Hedwigia 54: 511–552.

Douglas M.S.V. and Smol J.P. 1995. Periphytic diatom assemblages from high arctic ponds. J. Phycol. 31: 60–69.

Douglas M.S.V. and Smol J.P. 1999. Freshwater diatoms as indicators of environmental change in the High Arctic. In: Stoermer E.F. and Smol J.P. (eds), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, pp. 227–244.

Douglas M.S.V. and Smol J.P. 2000. Eutrophication and recovery in the High Arctic: Meretta Lake (Cornwallis Island, Nunavut, Canada) revisited. Hydrobiologia 431: 194–204.

Douglas M.S.V., Smol J.P. and Blake W.,Jr. 1994. Marked post-18th century environmental change in high-Arctic ecosystems. Science 266: 416–419.

Foged N. 1981. Diatoms in Alaska. Bibliotheca Phycologica, vol. 53, J. Cramer, Vaduz, pp. 317.

Gajewski K., Hamilton P.B. and McNeely R. 1997. A high resolution proxy-climate record from an arctic lake with annually-laminated sediments on Devon Island, Nunavut, Canada. J. Paleolimol. 17: 215–225.

Glew J. 1988. A portable extruding device for close interval sectioning of unconsolidated core samples. J. Paleolimnol. 2: 241–243.

Glew J. 1991. Miniature gravity corer for recovering short sediment cores. J. Paleolimnol. 5: 285–287.

Heywood W.W. 1957. Isachsen area, Ellef Ringnes Island, District of Franklin, Northwest Territories. Geological Survey of Canada Paper 56–58.

Hill M.O. 1973. Diversity and evenness – Unifying notation and its consequences. Ecology 54: 427–432.

Houghton J.T., Ding Y., Griggs D.J., Noguer M., van der Linden P.J. and Xiaosu D. (eds) 2001. Climate Change 2001: The Scientific Basis Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, pp. 944.

Jones V.J. and Birks H.J.B. 2004. Lake-sediment records of recent environmental change on Svalbard: results from diatom analysis. J. Paleolimnol. 31: 445–466.

Joynt E.H. and Wolfe A.P. 2001. Paleoenvironmental inference models from sediment diatom assemblages in Baffin Island Lakes (Nunavut, Canada) and reconstruction of summer water temperature. Can. J. Fish. Aquat. Sci. 58: 1222–1243.

Juggins S. 2003. C^2 : software for ecological and palaeoecological data analysis and visualisation. Department of Geography, University of Newcastle, Version 1.3.

Koinig K.A., Schmidt R., Sommaruga-Wögrath S., Tessadri R. and Psenner R. 1998. Climate change as the primary cause for pH shifts in a high alpine lake. Water Air Soil Poll. 104: 167–180.

Krammer K. and Lange-Bertalot H. 1986–1991. Bacillariophyceae. In: Ettl H., Gerloff J., Heynig H. and Mollenhauer D. (eds), Süßwasserflora von Mitteleuropa, Band 2(1–4). Gustav Fischer Verlag, Stuttgart, pp. 2485.

Lange-Bertalot H. and Genkal S.I. 1999. Diatoms from Siberia I: Islands in the Arctic Ocean (Yugorsky-Shar Strait). A.R.G. Gantner Verlag, Vaduz, pp. 304.

Lim D.S.S., Douglas M.S.V. and Smol J.P. 2001a. Diatoms and their relationship to environmental variables from lakes and ponds on Bathurst Island, Nunavut, Canadian High Arctic. Hydrobiologia 450: 215–230.

Lim D.S.S., Kwan C. and Douglas M.S.V. 2001b. Periphytic diatom assemblages from Bathurst Island, Nunavut, Canadian High Arctic: an examination of community relationships and habitat preferences. J. Phycol. 37: 379–392.

Mann M.E., Bradley R.S. and Hughes M.K. 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. Geophys. Res. Lett. 26: 759–762.

Maxwell J.B. 1981. Climatic regions of the Canadian Arctic Islands. Arctic 34: 224–240.

Meteorological Service of Canada 2002. Canadian Climate Normals 1971–2000. Environment Canada, Ottawa, Ontario.

Michelutti N., Holtham A.J., Douglas M.S.V. and Smol J.P. 2003a. Periphytic diatom assemblages from ultra-oligotrophic and UV transparent lakes and ponds on Victoria Island and comparisons with other diatom surveys in the Canadian Arctic. J. Phycol. 39: 465–480.

Michelutti N., Douglas M.S.V. and Smol J.P. 2003b. Diatom response to recent climatic change in a high arctic lake (Char Lake, Cornwallis Island, Nunavut). Global Planet. Change 38: 257–271.

Nahir M. 1996. Isachsen High Arctic Weather Station Decommissioning and Cleanup: Environmental Screening Report. Public Works and Government Services Canada, Edmonton.

Parr J.F., Taffs K.H and Lane C.M. 2004. A microwave digestion technique for the extraction of fossil diatoms from coastal lake and swamp sediments. J. Paleolimnol. 31: 383–390.

Perren B.B., Bradley R.S. and Francus P. 2003. Rapid lacustrine response to recent high arctic warming: a diatom record from Sawtooth Lake, Ellesmere Island, Nunavut. Arct. Antarct. Alp. Res. 35: 271–278.

Rouse W.R., Douglas M.S.V., Hecky R.E., Hershey A.E., Kling G.W., Lesack L., Marsh P., McDonald M., Nicholson B.J., Roulet N.T. and Smol J.P. 1997. Effects of climate change on the waters of Arctic and Subarctic North America. Hydrol. Process. 11: 973–902.

Schmidt R., Kamenik C., Kaiblinger C. and Hetzel M. 2004. Tracking Holocene environmental changes in an alpine lake sediment core: application of regional diatom calibration, geochemistry, and pollen. J. Paleolimnol. 32: 177–196.

Smith I.R. 2002. Diatom-based Holocene paleoenvironmental records from continental sites on northeastern Ellesmere Island, high Arctic, Canada. J. Paleolimnol. 27: 9–28.

Smith S.V., Bradley R.S. and Abbott M.B. 2004. A 300 year record of environmental change from Lake Tuborg, Ellesmere Island, Nunavut, Canada. J. Paleolim. 32: 137–148.

Smol J.P. 1983. Paleophycology of a high arctic lake near Cape Herschel, Ellesmere Island. Can. J. Bot. 61: 2195–2204.

Smol J.P. 1988. Paleoclimate proxy data from freshwater arctic diatoms. Verh. Int. Verein. Limnol. 23: 837–844.

Smol J.P. and Cumming B.F. 2000. Tracking long-term changes in climate using algal indicators in lake sediments. J. Phycol. 36: 986–1011.

Sommaruga-Wögrath S., Koinig K.A., Schmidt R., Sommaruga R., Tessadri R. and Psenner R. 1997. Temperature effects on the acidity of remote alpine lakes. Nature 387: 64–67.

Stoermer E.F. and Smol J.P. (eds) 1999. The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge, pp. 482.

ter Braak C.J.F. 1998. CANOCO and CANOPost, Version 4 for Windows. Microcomputer Power: Ithaca, NY, USA.

Wolfe A.P. 2002. Climate modulates the acidity of Arctic lakes on millennial time scales. Geology 30: 215–218.