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Arctic coastal freshwater ecosystem responses to a major saltwater intrusion: A landscape-scale palaeolimnological analysis

Joshua R Thienpont,[1] Daniel Johnson,[1] Holly Nesbitt,[1] Steven V Kokelj,[2] Michael FJ Pisaric[3] and John P Smol[1]

Abstract

Because of decreasing sea-ice extent and increasingly frequent Arctic storms, low-lying coastal ecosystems are at heightened risk from marine storm surges. A major Arctic storm event originating in the Beaufort Sea in September 1999 resulted in the flooding of a large area of the outer alluvial plain of the Mackenzie Delta (Northwest Territories, Canada), and has been previously shown to have caused unprecedented impacts on the terrestrial ecosystems on a regional scale. We use diatoms preserved in lake sediment cores to gain a landscape perspective on the impact of the storm on freshwater systems, and to determine if other such events have occurred in the recent past. Our results indicate that five lakes located at the coastal edge of the low-lying Mackenzie Delta show strong, synchronous, and previously unobserved increases in the relative abundance of brackish-water diatom taxa coincident with the timing of the 1999 storm surge. These changes were not observed at a control site located farther inland. The degree to which the storm surge impacted the chemical and biological limnology of the lakes varied, and was not explained by measured physical variables, suggesting the degree of impact is likely related to a combination of factors including distance from the coast, the size:volume ratio of the lake and its catchment, and water residence time. We show that the 1999 storm surge resulted in unmatched broadscale impacts on the freshwater ecosystems of the outer Mackenzie Delta, and that while minimal recovery may be occurring in some of the systems, the lakes studied remain chemically and biologically impacted more than a decade after the inundation event.

Keywords

diatoms, Mackenzie Delta, palaeolimnology, saltwater inundation, storm surge

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Introduction

An increased frequency and intensity of marine storms is an anticipated consequence of climate change (Sepp and Jaagus, 2011). These storms, and the resulting storm surge events, have the potential to cause widespread impacts on sensitive coastal ecosystems, especially those in the circumpolar Arctic, where decreased sea ice and higher sea levels, coupled with increasingly variable storminess, may increase the vulnerability of these ecosystems (Nicholls and Cazenave, 2010; Simmonds and Keay, 2009). In September of 1999, a particularly large storm resulted in a saltwater intrusion event that inundated a large area (>10,000 ha) of the low-lying alluvial plain of the outer Mackenzie Delta (Kokelj et al., 2012; Manson and Solomon, 2007; Pisaric et al., 2011). This saltwater inundation caused significant changes to terrestrial vegetation across the impacted area (Kokelj et al., 2012). Modern limnological analyses suggest that lakes across the outer alluvial plain were impacted by this storm surge event, and that elevated ionic concentrations persist more than a decade after the inundation (Pisaric et al., 2011). Because of a lack of long-term monitoring of limnological conditions, palaeolimnological techniques are necessary in order to infer conditions in the region prior to the 1999 storm surge, and to assess the effects of the storm on these ecosystems (Smol, 2008).

Sedimentary proxy records have been commonly used to infer the impact of large-scale storms (e.g. Liu and Fearn, 2000). Palaeotempestology refers to the science of tracking past tropical cyclone activity using proxy and historical records (Horton and Sawai, 2010), in particular hurricanes/typhoons, and has historically been used to analyze these types of catastrophic storms (e.g. Donnelly and Woodruff, 2007; Liu and Fearn, 1993; Parsons, 1998; Williams, 2009). Similar methods have not been widely applied to smaller-scale storm events, particularly in Arctic regions. In addition, palaeoenvironmental studies of major storm frequency are most commonly applied to coastal marshes, lagoons or lakes that are already saline, not freshwater systems which may have undergone salinization as a result of storm surge events. Palaeolimnological methods provide the potential for assessing both the frequency and impacts of past storm surge events on coastal lakes. Diatoms (algae of the division Bacillariophyta) are a well-suited, and widely used, biological indicator because of their abundance in both freshwater and marine ecosystems, their well-preserved siliceous cell walls, and the fact that many taxa have well defined optima for a wide range of environmental variables, including salinity (Smol and Stoermer, 2010). In a previous study, Pisaric et al. (2011) showed a striking shift from fresh to brackish water diatom taxa as a result of

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[1] Queen's University, Canada
[2] Aboriginal Affairs and Northern Development Canada, Canada
[3] Carleton University, Canada

Corresponding author:
Joshua R Thienpont, Paleoecological Environmental Assessment and Research Laboratory (PEARL), Department of Biology, Queen's University, Kingston ON K7L 3N6, Canada.
Email: joshua.thienpont@queensu.ca

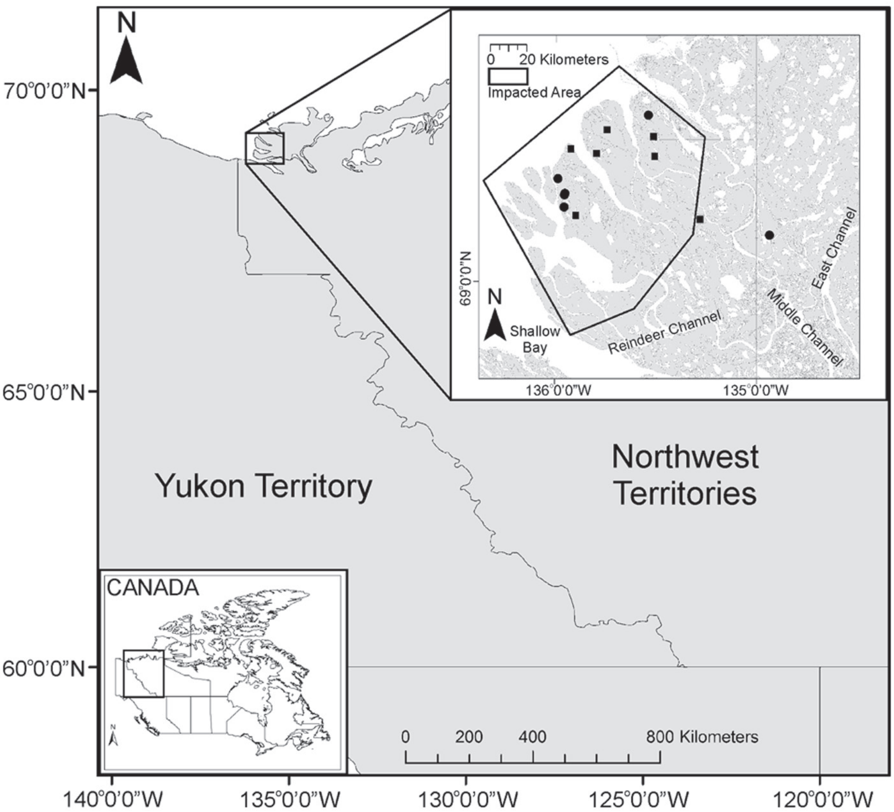

Figure 1. The location of the study area within the outer Mackenzie Delta, shown in the context of Canada. The black outline shows the approximate extent of the impact from the 1999 storm surge based on before and after LANDSAT imagery. Black circles represent sites for modern and palaeolimnological analyses, black squares represent sites where only modern sampling was conducted.

the September 1999 storm surge in a small coastal lake of the outer Mackenzie Delta, and inferred no other saline intrusions in the lake's >1000 year history. However, to date, the impact on the freshwater biology of the region has only been analyzed in this one lake (Deasley et al., 2012; Pisaric et al., 2011), and the geographical extent of the biological impact on freshwater systems of the outer delta remains unknown. While Pisaric et al. (2011) provided the first analysis of the impact of this storm on the limnology of the region, there exists the potential for considerable variation in the response of different lakes across the outer delta, as little is known about the variability in limnological and geological conditions in the lakes of this region. Here, we apply identical palaeolimnological techniques to a broader set of lakes in order to assess the impact this large storm surge event had on freshwater ecosystems at a landscape scale. We hypothesize that all of the low-lying lakes of the outer delta that were inundated by the 1999 storm surge will show increased abundances of brackish-water diatom taxa coincident with this event, though the magnitude of this response may vary as a result of specific conditions in each lake, including the degree to which the storm surge impacted the system.

Methods

Site description

The Mackenzie Delta is Canada's largest delta and the second largest Arctic delta globally, covering approximately 13,000 km^2 on the Beaufort Sea coast of Canada's Northwest Territories (Burn and Kokelj, 2009) (Figure 1). The Delta plain has a maximum elevation of approximately 10 m above sea level (a.s.l.) at its apex more than 200 km from the coast (Rampton, 1988). Owing to the long, gradual slope of the delta, storm surges originating in the Beaufort Sea have the potential to inundate large areas of low-lying alluvial terrain (Mackay, 1963). On 23–24 September 1999, a large-magnitude storm surge resulted in an increase in water level of more than 2 m in the channels of the Mackenzie Delta, and thus is believed to have inundated the low-lying areas within ~20–30 km of the coast. This storm event was the most extreme recorded during the 1990s, based on its duration, wind speed and intensity (Kokelj et al., 2012). Scientific as well as the local indigenous knowledge of the Inuvialuit have shown the storm surge caused widespread increases in soil salinity and vegetation mortality, resulting in a 'dead zone' that is apparent from ground and remote sensing analyses (Figure 1; Kokelj et al., 2012). In order to better understand spatial patterns in the impact of the 1999 storm surge on lakes of the outer delta, sediment cores were obtained from six lakes. Four sites (assigned the code 'DZO' to delineate location within the 'dead zone') are located at the outer edge of the delta, at the leading edge of the impact of the saltwater inundation (Table 1, Figure 1). One additional study lake has ionic chemistry values which appear somewhat elevated from control sites, and is classified as a transition 'T' site. In addition, one site, located ~45 km inland at an upland location which suggests it was not impacted by the 1999 saltwater inundation is considered the control 'C' site for this study (Table 1). The lakes vary in size (3.5–228 ha) and distance from the coast (3.6–43 km). All of the impacted lakes are low-lying in comparison with the control site (Table 1). Ionic concentrations, in particular Na and Cl, in the impacted 'DZO' lakes and the transitional 'T' site, are elevated in comparison with the control location, as well as other lakes studied in the delta and surrounding uplands (Kokelj et al., 2005).

Table 1. Select physical and chemical variables from the six study lakes from which sediment cores were collected.

Lake	Latitude (°N)	Longitude (°W)	Surface area (ha)	Distance from the coast (km)	Current elevation (m a.s.l.)	Cond. (μS/cm)	pH	NO_3 (mg/l)	DOC (mg/l)	Ca (mg/l)	Na (mg/l)	Cl (mg/l)	SO_4 (mg/l)	TP-F (μg/l)	TP-U (μg/l)
DZO-2	69°10′55.5″	135°58′59.1″	126.3	3.57	1	14955	8.08	0.44	8.1	244	2750	5920	716	8.0	16.4
DZO-29	69°09′20.5″	135°56′52.1″	3.5	6.49	1	12722	8.01	0.38	9.8	251	2270	5030	496	10.2	13.7
DZO-30	69°09′12.5″	135°57′02.0″	8.7	7.25	1	6855	8.19	0.27	12.9	125	1120	2530	208	10.7	20.9
DZO-3	69°07′54.1″	135°57′08.1″	22.6	7.86	1	3090	8.63	0.28	13.1	79.9	475	1000	89	15.0	24.8
T-34	69°17′28.6″	135°31′48.4″	75.3	7.58	1	567.8	8.57	0.14	9.5	33.3	57.8	120	44	12.3	18.0
C-28	69°04′05.5″	134°54′52.9″	228.8	43.0	7	240.1	8.5	0.12	9.6	23.9	6.1	7.7	34	9.5	14.8

Cond.: specific conductivity; TP-F: filtered total phosphorus; TP-U: unfiltered total phosphorus.

Lake sampling and sample preparation

Sediment cores were collected from lakes DZO-29, C-28 and T-34 in August of 2009, sampling from the pontoons of a helicopter using a Glew-type (Glew, 1989) gravity corer with an internal diameter of 7.62 cm and extruded using a Glew (1988) vertical extruder. Sediment cores from lakes DZO-2, DZO-3, and DZO-30 were collected using the same methods in July of 2010. Samples for water chemistry analyses were collected from 13 lakes (including the six lakes from which sediment was retrieved) via helicopter during the August 2009 sampling season (Figure 1), with water collected from the centre of the lake, approximately 1.0 m below the surface. Major ion and dissolved organic carbon (DOC) analyses were conducted at the Taiga Laboratory, Yellowknife, NT, with nutrient chemistry analyzed at the National Laboratory for Environmental Testing (NLET) (Burlington ON). Preparation of samples for diatom analyses followed standard procedures (Battarbee et al., 2001). In summary, ~0.3 g of wet sediment was digested using a 1:1 molecular mixture of nitric and sulphuric acid and heated in a water bath (~80°C) for ~4 h in order to facilitate digestion of the organic matrix. Samples were then rinsed daily until neutral (5–7 rinses). Aliquots of diatom slurry were evaporated onto microscope coverslips and mounted to microscope slides using the high-refractive mounting medium Naphrax®. Diatoms were identified and enumerated along transects at 1000× magnification using a Leica DMRB light microscope fitted with differential interference contrast optics and a HCX PL Fluotar objective lens (effective numerical aperture of the combined objective-condenser = 1.3). For each interval a minimum of 300 diatom valves were identified to the lowest possible taxonomic level using standard texts (Campeau et al., 1999a; Cumming et al., 1995; Fallu et al., 2000; Krammer and Lange-Bertalot, 1991, 1997, 1999, 2000). Campeau et al. (1999a) was used in order to assign salinity preferences to diatom taxa, as they analyzed habitat preference for diatom taxa in relation to salinity in the Beaufort Sea region, near to where our study took place.

Geochronology and data analyses

Sediment age determination was conducted using ^{210}Pb and ^{137}Cs radioisotopic techniques (Appleby, 2001). Cores DZO-29 and C-28 were analyzed using gamma emission analysis (Schelske et al., 1994) with an Ortec® germanium-crystal well detector at the Paleoecological Environmental Assessment and Research Lab (Queen's University, Kingston ON, Canada), with dates determined following the constant rate of supply (CRS) model (Appleby and Oldfield, 1978) using the computer program developed by Binford (1990). Because of the relatively short nature of the core, supported ^{210}Pb levels were not reached for C-28 and the average activity of ^{214}Bi was used in order to estimate the background ^{210}Pb activity. Alpha counting was used to determine sediment age for cores DZO-2, -3, and -30 at MyCore Scientific Inc (Deep River ON, Canada), with the CRS model again used for sediment age determination. The sampling resolution of each sediment core analyzed varied between 0.5 and 7.5 years per interval (DZO-2 ~0.5–3.5 yr; DZO-3 ~1–4 yr; DZO-29 ~1–7.5 yr; DZO-30 ~1–2.5 yr; C-28 ~0.5–6.5 yr). The sedimentation rate for each sediment core was modeled based on ^{210}Pb dating techniques (DZO-2 ~47–349 g/m^2 per yr; DZO-3 ~65–466 g/m^2 per yr; DZO-29 ~45–291 g/m^2 per yr; DZO-30 ~31–58 g/m^2 per yr; C-28 ~46–358 g/m^2 per yr).

Relative frequency diagrams of the most common (greater than 5% relative abundance in one interval) diatom taxa were prepared using the computer program TGView 2.0.2 (Grimm, 2004). Constrained incremental sums of squares (CONISS) cluster analyses were conducted on the complete diatom data sets for each lake in order to better elucidate the main biostratigraphic zones of change in the assemblage (Grimm, 1987). Principal components analysis (PCA) was conducted for each sedimentary sequence using the default options in CANOCO for Windows v4.5 (ter Braak and Šmilauer, 2002) following square-root transformation of the diatom relative abundance data. Linear ordination methods were selected as detrended correspondence analysis (DCA) indicated gradient lengths for each assemblage were relatively short (1.2–1.9 standard deviation units). In order to enable a graphical comparison of assemblage changes in the six study lakes over time, PCA was calculated on the combined diatom data set, with sample scores for PCA axis 1 plotted against PCA axis 2. Hill's N2 diversity (Hill, 1973) was conducted for each sediment core using the DCA function in CANOCO. Topographic and line maps were prepared using ArcMAP 10, with topographic data courtesy of the Natural Resources Canada CanVEC data base.

Results

Relationships among limnological variables

Pearson correlation analyses of available chemical and physical variables (Pisaric et al., 2011) were conducted in an attempt to determine if certain physical variables (such as lake area or distance from the coast) might be related to the degree of impact from the storm surge. Highly significant positive correlations (following adjustment using Bonferroni probabilities) were observed among all of the concentrations of major ions, as well as sulphate, nitrate, and specific conductivity (Table 2). In addition a significant positive correlation was observed between the concentrations of dissolved organic carbon (DOC) and filtered total phosphorus (TP-F) (Table 2). No significant correlations were observed between any of the measured chemical variables and physical variables such as lake surface area, depth or estimated distance to the Beaufort Sea coast (Table 2).

Table 2. Pearson correlation matrix[a] for 13 storm surge impacted lakes from the outer Mackenzie Delta sampled for water chemistry in August 2009. Coefficients in bold are significant ($p<0.05$) after adjustment for multiple comparisons using Bonferroni probabilities.

	SA	Depth	Distance	COND	pH	NO_3	DOC	Ca	Na	K	Cl	Mg	SO_4	TP-F
SA	1.000													
Depth	0.015	1.000												
Distance	0.698	0.055	1.000											
COND	−0.217	0.450	−0.422	1.000										
pH	0.614	−0.129	0.447	−0.595	1.000									
NO_3	−0.315	0.287	−0.508	**0.923**	−0.559	1.000								
DOC	−0.364	−0.391	−0.333	−0.131	0.096	0.117	1.000							
Ca	−0.294	0.493	−0.482	**0.985**	−0.635	**0.939**	−0.053	1.000						
Na	−0.193	0.454	−0.404	**0.999**	−0.588	**0.915**	−0.160	**0.981**	1.000					
K	−0.130	0.379	−0.396	**0.986**	−0.556	**0.902**	−0.193	**0.956**	**0.990**	1.000				
Cl	−0.195	0.470	−0.398	**0.999**	−0.592	**0.913**	−0.168	**0.982**	**1.000**	**0.987**	1.000			
Mg	−0.186	0.428	−0.430	**0.995**	−0.574	**0.924**	−0.126	**0.981**	**0.996**	**0.993**	**0.994**	1.000		
SO_4	−0.137	0.370	−0.397	**0.997**	−0.554	**0.881**	−0.155	**0.947**	**0.982**	**0.992**	**0.977**	**0.989**	1.000	
TP-F	−0.206	−0.269	−0.190	−0.164	0.385	0.032	**0.851**	−0.126	−0.182	−0.201	−0.194	−0.144	−0.137	1.000

[a] SA: lake surface area; Distance: estimated shortest distance from Beaufort Sea coast; COND: specific conductivity (μS/cm); DOC: dissolved organic carbon; TP-F: total phosphorus (filtered).

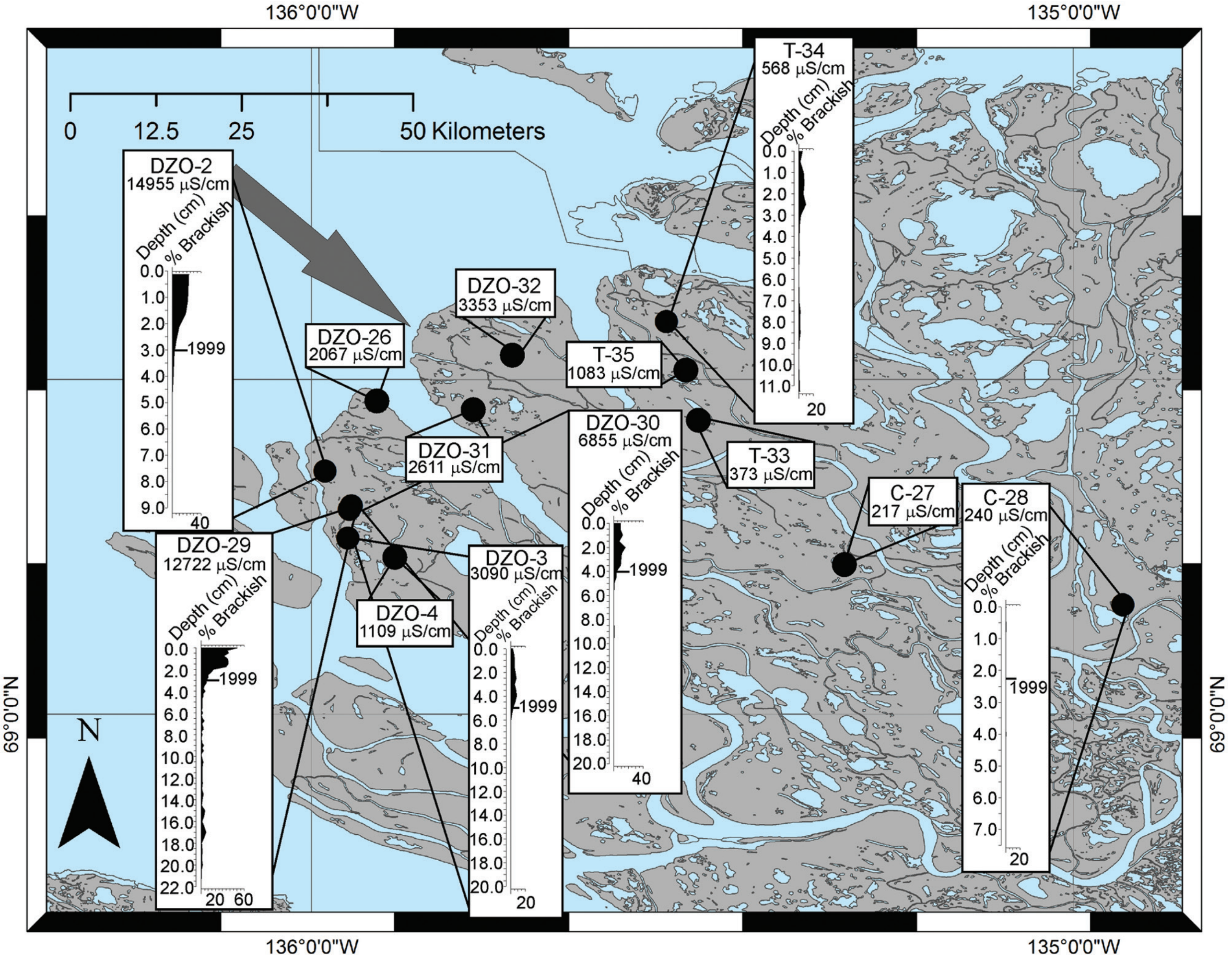

Figure 2. A summary of the impact of the 1999 saltwater inundation on the water chemistry and sedimentary diatom assemblages of 13 lakes from the outer Mackenzie Delta (study area outlined in Figure 1). For each of the 13 lakes sampled, the location and specific conductivity at the time of sampling is indicated below the lake name. For the six lakes from which sediment cores were obtained, the relative abundance of brackish diatom taxa (% Brackish) are displayed relative to depth (cm). The approximate timing of the 1999 storm is included based on ^{210}Pb dating techniques. Grey arrow approximates the NW direction of the winds, which blew saltwater into the delta.

Diatom analyses

Diatom assemblages from the sediment cores in the four impacted DZO lakes and T-34 recorded a consistent appearance and increase in the relative abundance of brackish diatom taxa corresponding to ~1999 based on ^{210}Pb dating techniques (Figure 2). The maximum relative abundance of brackish species varied, ranging from approximately 10% in T-34 to greater than 50% in DZO-29, where brackish taxa dominate the diatom assemblage (Figure 2). The increase in brackish species occurred rapidly in all systems following 1999. Brackish diatom taxa were not observed in appreciable numbers (>3%) in any of the five impacted lakes prior to the inferred 1999 sediment interval. In contrast, our control site C-28, located ~45 km inland, recorded no brackish diatom taxa in any sediment interval of the sediment core, dating back to ~1932 (Figure 2; Pisaric et al., 2011). The relative abundance of brackish diatom taxa in the surface sediment interval of the six study lakes was found to be strongly correlated to measured lakewater specific conductivity recorded at the time of sampling ($r^2 = 0.8$, $p = 0.03$).

Detailed palaeolimnological analysis of sedimentary diatoms from Lake DZO-2 record an assemblage dominated by small benthic taxa of the group *Fragilaria* sensu lato throughout the last ~60 years recorded in this relatively short sediment core (Figure 3a). Increased abundance of freshwater periphytic diatom taxa including *Amphora inariensis* Krammer and *Navicula cryptocephala* Kützing occurred beginning in the late 1980s (Figure 3a). At a core depth of 3.0 cm (~1999 based on ^{210}Pb dating) the appearance of *Craticula halophila* (Grunow) Mann and *Navicula salinarum* Grunow, two taxa classified as mesohalobian in the region (Campeau et al., 1999a), and often found in brackish water habitats, increased in abundance, and represent ~25% relative abundance by ~2004. They continue to represent an important component of the diatom assemblage in the most recent sediments from Lake DZO-2 (Figure 3a).

The diatom assemblage over the last >100 years in Lake DZO-3 has been dominated by small benthic *Fragilaria* sensu lato taxa, as well as by *Amphora pediculus* (Kützing) Grunow (Figure 3b); however, these taxa began to decrease in the 1970s (~7.0 cm), with a corresponding increase in *N. cryptocephala* occurring at this time. At a core depth of ~2.0 cm (between 1995 and 2000 based on ^{210}Pb dating) the brackish taxa *C. halophila* and *N. salinarum* appeared for the first time in the greater than 100 year history of the lake recorded in this sediment core, and increased to a combined maximum abundance of ~15 % (Figure 3b). The abundances of these two taxa were stable for approximately 5 years and then began to decrease slightly until the present; they represent ~5 % of the surface sediment diatom assemblage of Lake DZO-3.

As with the other systems in this study, the diatom assemblage of Lake DZO-30 is dominated by small benthic *Fragilaria* taxa throughout the last few hundred years (Figure 3c). Beginning at a core depth of 16 cm, *A. pediculus* increased in relative abundance, and represented 20% of the assemblage at its most abundant. At a core depth of 4.0 cm (~1999 based on ^{210}Pb dating) the brackish taxa *C. halophila* and *N. salinarum* occurred for the first time in the history of the lake spanned by this sediment core, representing the last few hundred years. Cumulatively, these brackish taxa represented ~25% of the diatom assemblage in this lake at their peak in ~2006. While the relative abundance of *N. salinarum* has decreased over the last 5 years, *C. halophila* has increased, and thus these taxa still represent ~10% of the surface diatom assemblage in Lake DZO-30 (Figure 3c).

The diatom assemblage of T-34, the lake classified as 'transitional' based on elevated ionic concentrations (Na and Cl concentrations were an order of magnitude higher than C-28 when sampled in 2009; Table 1), shows a greater diversity of taxa than three of the four DZO lakes located to the SW (Figure 3d) (Hill's N2 diversity in the surface sediment interval T-34: 23.6; C-28: 26.4; DZO-2: 26.1; DZO-3: 14.78; DZO-29: 12.03; DZO-30: 17.4). Small benthic *Fragilaria* taxa dominate the oldest sediments obtained from the lake. At a core depth of ~10 cm, an increase in the abundance of *A. inariensis, N. cryptocephala, Achnanthidium minutissimum* (Kützing) Czarnecki as well as the cumulative abundance of freshwater *Nitzschia* taxa occurred (Figure 3d). An increase in the abundance of *Diatoma tenue* Agardh was observed at ~4.0 cm. The brackish taxa *C. halophila* and *N. salinarum* increased in abundance at a core depth of 3.0 cm, representing 10% of the relative abundance of diatom taxa. While both taxa were observed in very small abundances in lower sediment intervals, the increase beginning at 3.0 cm was the only sustained occurrence of these two species in this sediment record (Figure 3d). ^{210}Pb dating was not carried out on the T-34 sediment core.

The results of the detailed diatom analyses from lakes DZO-29 and C-28 are described in detail by Pisaric et al. (2011). The oldest intervals in Lake DZO-29 record an assemblage dominated by small benthic fragilarioid taxa, as well as *A. pediculus* (Figure 3e). Increased abundances of *Amphora* taxa were observed over the last ~100 years in DZO-29. While small relative abundances (less than 3%) of the brackish taxa *C. halophila* and *N. salinarum* were found throughout the sediment record, a striking increase was observed coincident with the inferred 1999 interval. These brackish taxa continue to dominate the diatom assemblage of Lake DZO-29 (Figure 3e). In contrast, in our a priori defined control Lake C-28, no brackish water diatom taxa were recorded over the last ~ 90 years (Figure 3f). Instead the assemblage is composed of a diverse group of benthic and periphytic diatom taxa (the most diverse assemblage of the six lakes analyzed in this study) including species of *Achnanthes sensu lato, Amphora, Epithemia, Gomphonema* and *Navicula* sensu lato (Figure 3f).

Principal components analysis (PCA) conducted on the combined diatom data set for all six lakes shows the assemblage of lakes DZO-2, DZO-3, DZO-29 and DZO-30 are more similar to each other throughout the period represented by these sediment cores than to the diatom assemblages from lakes T-34 and C-28 (Figure 4). The diatom assemblage in lake C-28 remained distinct from the impacted lakes throughout the recent past. The most recent sediment intervals in lake T-34 are more similar to the impacted DZO lakes than the bottom-most sediments (Figure 4). Individual PCAs for each lake (PCA axis 1 plotted versus PCA axis 2) show all six lakes have undergone a directional change along the first axis over the recent past. In lakes DZO-2, DZO-3 and DZO-29 a large change along the first axis occurred following the inferred 1999 interval (based on ^{210}Pb dating), a trend that is also observed, though of a smaller magnitude, in lakes DZO-30 and T-34 (Figure 4). Only in control Lake C-28 was no change observed immediately post-1999, instead the main directional change in the assemblage occurred later at this site. In no lake has the assemblage returned to the same diatom assemblage as the bottom-most sediment intervals (Figure 4).

Discussion

Synchronous and unmatched impacts of the 1999 storm surge

The occurrence of brackish diatom taxa in the sediment records of all five impacted lakes, coincident with the timing of the 1999 storm surge, provides strong evidence that the saltwater inundation that resulted from this storm impacted the freshwater ecosystems of the outer Mackenzie Delta at the landscape scale (Figure 2). The synchronous nature and timing of the salinization of these lakes spread across the western outer delta show the widespread impact the storm surge had on freshwater systems of the region, beyond those shown from the previous study conducted on only one lake (DZO-29; Pisaric et al., 2011). These results show that, as with the impacts to terrestrial vegetation and soil geochemistry previously studied at sites across the outer alluvial plain (Kokelj et al., 2012; Pisaric et al., 2011), diatom communities in lakes were also impacted across the region. Palaeolimnological analyses of cladoceran assemblages have shown that the 1999 storm surge event also resulted in the loss of several invertebrate species, illustrating a synchronous impact to the zooplankton community in Lake DZO-29 (Deasley et al., 2012).

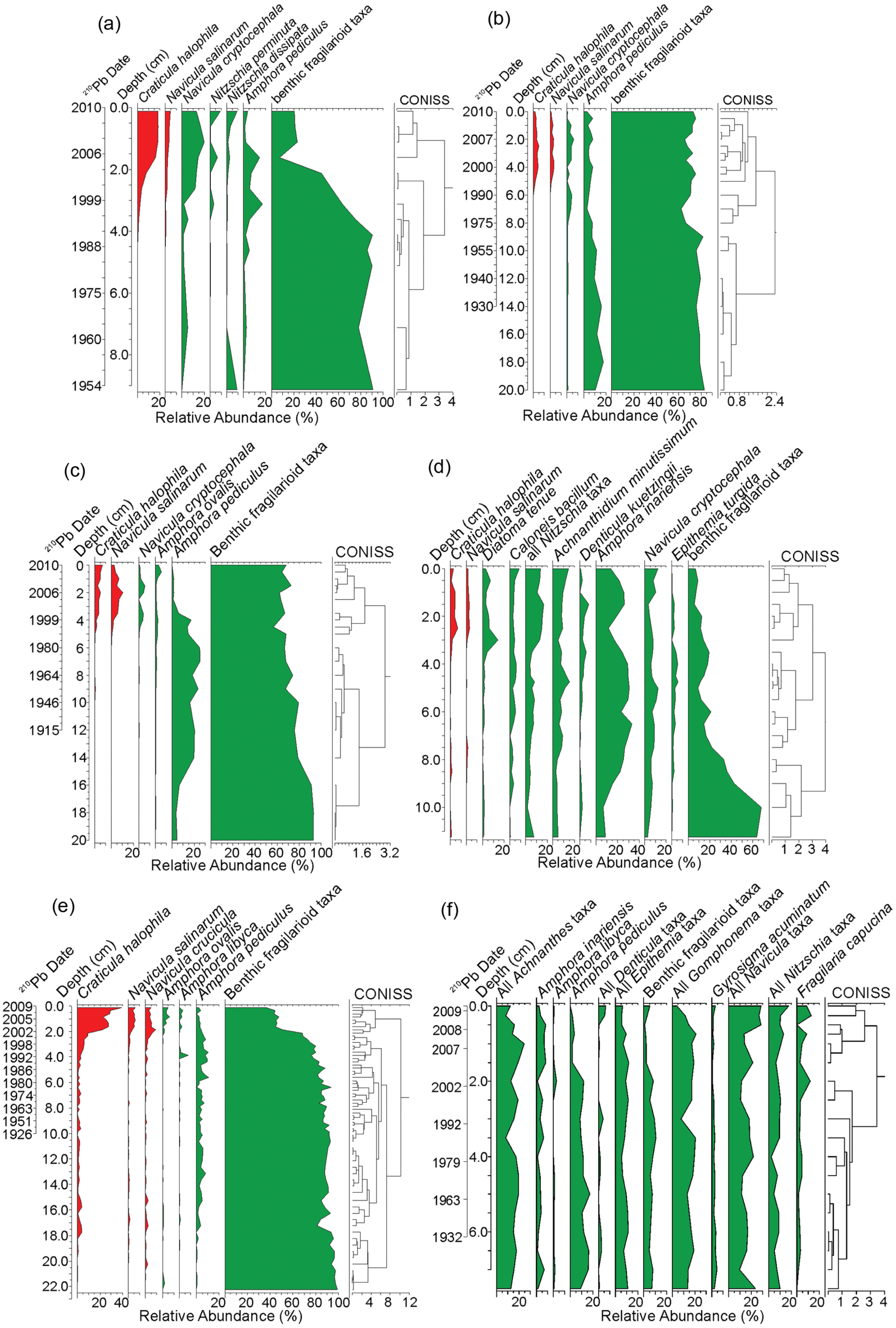

Figure 3. Relative frequency diagrams of the diatom taxa found at greater than 5% relative abundance from (a) impacted Lake DZO-2, (b) impacted Lake DZO-3, (c) impacted lake DZO-30, (d) 'transition' lake T-34, (e) impacted Lake DZO-29 (Pisaric et al., 2011) and (f) control Lake C-28 (Pisaric et al., 2011). Diatom species are organized by principal components analysis axis-1 species scores. Constrained incremental sums of squares (CONISS) cluster analyses are included in order to help delineate the main zones of change in the species assemblage.

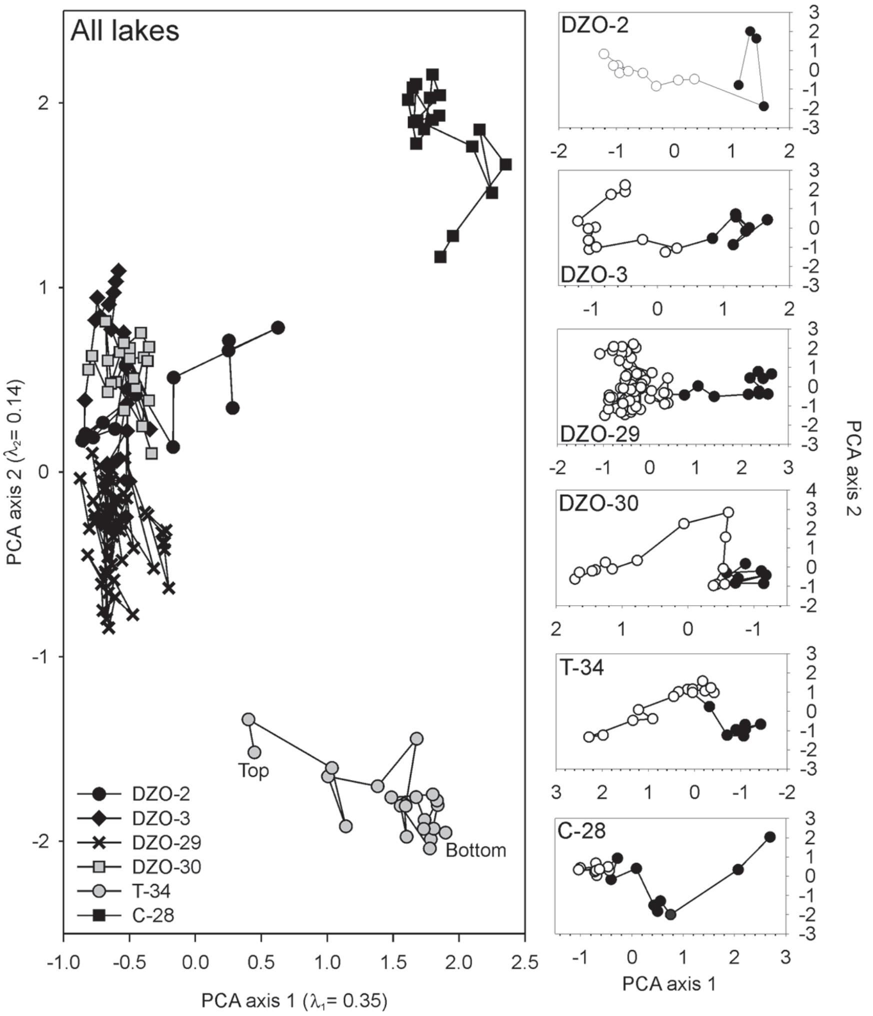

Figure 4. Diatom relative abundance principal components analysis (PCA) axis 1 and axis 2 sample scores for all six study sites, calculated and plotted in a single ordination space, and for each study lake calculated individually. For individual PCA ordinations, the intervals post-1999 (based on ^{210}Pb dating techniques) are included as black circles, with the pre-1999 intervals indicated by white circles. For the combined ordination, eigenvalues (λ) are included in the axis title. Eigenvalues for the individual PCA ordinations were as follows: DZO-2 (λ_1 = 0.50, λ_2 = 0.15), DZO-3 (λ_1 = 0.49, λ_2 = 0.13), DZO-29 (λ_1 = 0.35, λ_2 = 0.15), DZO-30 (λ_1 = 0.39, λ_2 = 0.16), T-34 (λ_1 = 0.30, λ_2 = 0.20), and C-28 (λ_1 = 0.29, λ_2 = 0.17).

The lack of brackish diatom species found in appreciable numbers in the lake sediments of these five lakes at any point prior to 1999 suggests that the impacts this storm had on these systems was unmatched over the period represented by these sediment cores (50–>300 years based on ^{210}Pb dating and extrapolation). This corresponds well with geochemical evidence from permafrost profiles, dendrochronological records and the composition of terrestrial vegetation communities, which suggest the outer delta environment has not been ecologically impacted by other storm surges observed from instrumental gauge records (Kokelj et al., 2012; Manson and Solomon, 2007; Pisaric et al., 2011). Observed declines in sea ice (Comiso et al., 2008) as a result of recent climate warming likely resulted in the 1999 storm surge being the most ecologically significant event on record, because sea ice limits the impact of late-season storms by minimizing the fetch over which strong winds can develop and prevents the movement of saltwater into the normally fresh Mackenzie Delta.

While the timing and nature of the appearance of brackish diatoms among the lakes of the outer delta was remarkably consistent, the magnitude of the abundance of these brackish taxa varied among the five impacted systems (Figure 2). Brackish diatoms represent greater than 50% of the current assemblage of diatom taxa in Lake DZO-29, and thus this system appears to have been the most impacted by the 1999 storm event. Nearby DZO-2 was also heavily impacted, with 25% of the modern assemblage composed of the brackish species *C. halophila* and *N. salinarum* (Figure 3a). At the time of sampling, these lakes had the highest specific conductivity and concentrations of major ions, in particular those associated with saline marine waters (i.e. sodium and chloride) (Table 1). The significant change in the diatom assemblages suggests the biology of lakes DZO-29 and DZO-2 were the most heavily impacted by the 1999 storm of the five lakes studied on the outer Mackenzie Delta alluvial plain. Considering both the current specific conductivity and the abundance of brackish diatoms in the remaining systems, the impact of the storm was most severe on Lake DZO-29, followed by DZO-2, DZO-30, DZO-3 and T-34 (Table 1, Figure 2). Based on principal components analysis of the complete data set, following the 1999 storm surge the diatom assemblage in Lake T-34 became more similar to the assemblage observed in the impacted DZO lakes (Figure 4), suggesting a similar response to the stressor of saltwater intrusion. Pearson correlation analyses conducted on the complete 13 lake chemistry data set showed no significant correlations between any of the measured chemical variables (including specific conductivity as a proxy for the impact of the storm surge, and strongly correlated to the abundance of brackish diatoms in the six lakes analyzed ($r^2 = 0.80$, $p = 0.03$)) and the measured physical variables, including lake area, or estimated distance to the Beaufort Sea coast (Table 2). This suggests that a combination of variables not easily measured in this environment, such as catchment area and water residence time, may have played an important role in modulating the impact of the storm surge on the limnology of these lakes. Further detailed studies of the characteristics of the study lakes and the details of the storm surge itself would be required to elucidate the cause of the chemical and biological variation observed. Nonetheless these data show the impact of this storm was unmatched over the last several hundred years in all of the lakes studied.

Assessing post-storm surge recovery

A single limnological sample of water chemistry several years after the occurrence of the storm event, such as were collected here, cannot provide information on possible chemical or biological recovery. However, detailed palaeolimnological analyses provide the potential for determining if recovery has occurred (Smol, 2008). In the most heavily impacted sites (DZO-29 and DZO-2), the continued abundance of brackish diatoms representing greater than 25% of the species assemblage in the lakes' most recent sediment intervals suggests that no recovery has occurred in these systems (Figure 2). Furthermore, our analyses suggest that, while the initial appearance of brackish diatoms occurred at the time of the saltwater inundation, the abundance of these brackish species increased in the years following 1999, possibly as a result of the gradual influx of solutes from the catchment. Soil Na and Cl concentrations in areas impacted by the storm surge have been shown to be over an order of magnitude greater than in unimpacted alluvium (Kokelj et al., 2012), and thus there is the potential for continued enrichment of the lakes with salts from the terrestrial environment. Slight decreases in the abundance of brackish diatoms observed in lakes DZO-30, DZO-3 and T-34 over the last approximately 5 years suggest that very limited chemical recovery may be occurring in these locations (Figure 2), as ions from the catchments and lakes are gradually flushed by annual flooding and precipitation. This process is likely reduced by the fact that freshwater flooding by the Mackenzie River occurs in spring when solutes are trapped by the frozen active layer, and because at this time the lakes remain capped with ice, preventing their flushing/dilution by floodwaters. In no lake has a return to the pre-impact diatom assemblage been observed (based on PCA; Figure 4), and thus, while small decreases in brackish diatom taxa abundances may be related to declining salt concentrations, it appears that little to no biological recovery to pre-storm surge assemblages has occurred in these lakes. Southern coastal systems impacted by periodic hurricane activity have recorded relatively fast recovery rates among algal (Cebrian et al., 2008) and animal (Stevens et al., 2010) communities following much larger storms, likely as a result of the fact that many southern coastal aquatic ecosystems are brackish or repeatedly exposed to flooding events. The lack of recovery in these freshwater ecosystems a decade after the saltwater inundation illustrates the sensitive nature of these Arctic coastal lakes to episodic flooding by storm surges.

Other diatom assemblage changes

Detailed palaeolimnological analyses of the sediment cores from DZO-2, -3, -30 and T-34 show that small, benthic, oligohalobian-indifferent *Fragilaria* taxa (Campeau et al., 1999a, 1999b) dominate the oldest diatom assemblages of these sites (Figure 3). These taxa are able to tolerate a wide range of harsh conditions such as short growing seasons and low light and are found ubiquitously in Arctic lakes (Smol and Douglas, 2007; Smol et al., 2005). In DZO-2, DZO-3, and DZO-30, located near to each other, increased relative abundances of *Navicula cryptocephala* and freshwater species of *Amphora,* inferred to have occurred early in the 20th century, likely resulted from limnological changes associated with climate warming, which is known to have been significant in this region over the period represented by the instrumental record (Lantz and Kokelj, 2008) and inferred to have begun in the late 19th century based on proxy records (Pisaric et al., 2007). In Lake DZO-29 these changes occur coincident with an increase in whole lake primary production, inferred from sedimentary reflectance estimates of trends in chlorophyll *a* concentrations (Deasley et al., 2012). Increased diatom diversity occurs as a result of longer open-water periods, which allow for the development of more complex periphytic diatom communities. *Amphora inariensis, Amphora pediculus,* and *N. cryptocephala* are common periphytic and epipelic diatoms in many Arctic lakes (Antoniades et al., 2008) known to colonize plant and sediment substrates in the Tuktoyaktuk coastlands region (Campeau et al., 1999a), and to be important taxa in lakes of the Mackenzie Delta with little influence from the river system (Hay et al., 2000). Studies from several regions of the circumpolar Arctic have shown that warming results in increased diversity (Douglas and Smol, 2010) as diatoms have longer to colonize habitats previously unavailable under colder climate conditions.

Estimates of the future impacts of anthropogenic climate change predict decreased Arctic sea-ice extent (Johannessen et al., 2004), increased sea levels in the Arctic Ocean (Nicholls and Cazenave, 2010), and an increase in the frequency and intensity of Arctic storms (Manson and Solomon, 2007; Sepp and Jaagus, 2011). Our results suggest there is significant potential for these changes to result in perturbations to the freshwater ecosystems of the low-lying delta environments of the circumpolar Arctic, which represent some of the largest deltas on the planet. These systems represent some of the most unique and fragile delta ecosystems on Earth (Walker, 1998). The salinization of these environments as a result of increased storm-surge activity could result in major changes to these sensitive systems, which are often considered hot-spots of diversity and productivity in the Arctic. This threat, coupled with the potential impacts of other stressors such as hydrocarbon exploration and development, which is increasing in these regions, must be considered when predicting future changes to the deltaic environments of the circumpolar Arctic.

Conclusions

Sedimentary diatom assemblages show a synchronous appearance of brackish water taxa coincident with the timing of the large storm surge and resulting saltwater inundation event that occurred in September of 1999 in this region of the Mackenzie Delta. At no other point in the history of these lakes (spanning several hundred years) are brackish diatoms found in appreciable numbers, suggesting the impact of this storm surge was unmatched over the recent past. Recent decreases in sea-ice volume in the Beaufort Sea, along with the extreme intensity of the 1999 storm, were likely responsible for the unprecedented impacts observed in these ecosystems. In the most impacted lake, no biological recovery has occurred, and in fact the lakes have exhibited increases in the abundance of brackish taxa as salts likely continue to enter the lake from the impacted/salinized terrestrial environment. In the sites impacted to a lesser extent, slight decreases in brackish species suggest limited chemical recovery may be occurring, but that the systems are still affected over a decade after the 1999 storm. Our research suggests that, for the sensitive coastal freshwater systems of the north, saltwater inundation represents a severe and possibly ecosystem-altering threat, which is predicted to increase as a result of future rapid climate change. Diatom-based palaeolimnological methods are useful for tracking storm-surge events in the Arctic, similar to the approaches used in palaeotempestology for tracking tropical cyclone activity.

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References

Antoniades D, Hamilton PB, Douglas MSV et al. (2008) *Diatoms of North America: The Freshwater Floras of Prince Patrick, Ellef Ringnes and Northern Ellesmere Islands from the Canadian Arctic Archipelago.* Koenigstein: Koeltz Scientific Books.

Appleby PG (2001) Chronostratigraphic techniques in recent sediments. In: Last WM and Smol JP (eds) *Tracking Environmental Changes Using Lake Sediments. Vol 1: Basin Analysis, Coring and Chronological Techniques*. Dordrecht: Kluwer Academic Press, pp. 171–204.

Appleby PG and Oldfield F (1978) The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediments. *Catena* 5: 1–8.

Battarbee RW, Jones VJ, Flower RJ et al. (2001) Diatoms. In: Smol JP, Birks HJB and Last WM (eds) *Tracking Environmental Change Using Lake Sediments. Vol 3: Terrestrial, Algal and Siliceous Indicators*. Dordrecht: Kluwer Academic Press, pp. 155–202.

Binford MW (1990) Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. *Journal of Paleolimnology* 3: 253–267.

Burn CR and Kokelj SV (2009) The environment and permafrost of the Mackenzie Delta area. *Permafrost and Periglacial Processes* 20: 83–105.

Campeau S, Héquette A and Pienitz R (1999b) Diatoms as quantitative paleodepth indicators in coastal areas of the southeastern Beaufort Sea, Arctic Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology* 146: 67–97.

Campeau S, Pienitz R and Héquette A (1999a) *Diatoms from the Beaufort Sea Coast, Southern Arctic Ocean (Canada).* Berlin: Gebrüder Borntraeger.

Cebrian J, Foster CD, Plutchak R et al. (2008) The impact of Hurricane Ivan on the primary productivity and metabolism of marsh tidal creeks in the North Central Gulf of Mexico. *Aquatic Ecology* 42: 391–404.

Comiso JC, Parkinson CL, Gersten R et al. (2008) Accelerated declines in the Arctic sea ice cover. *Geophysical Research Letters* 35: L01703, doi: 10.1029/2007GL031972.

Cumming BF, Wilson SE, Hall RI et al. (1995) *Diatoms from British Columbia (Canada) Lakes and their Relationship to Salinity, Nutrients and Other Limnological Variables.* Berlin: J. Cramer Press.

Deasley K, Korosi JB, Thienpont JR et al. (2012) Investigating the response of Cladocera to a major saltwater intrusion event in an Arctic lake from the outer Mackenzie Delta (NT, Canada). *Journal of Paleolimnology* 48: 287–296.

Donnelly JP and Woodruff JD (2007) Intense hurricane activity over the past 5,000 years controlled by El Ninõ and the West African monsoon. *Nature* 447: 465–468.

Douglas MSV and Smol JP (2010) Freshwater diatoms as indicators of environmental change in the High Arctic. In: Smol JP and Stoermer EF (eds) *The Diatoms: Applications for the Environmental and Earth Sciences 2nd Edition.* Cambridge: Cambridge University Press, pp. 249–266.

Fallu M-A, Allaire N and Pienitz R (2000) *Freshwater Diatoms from Northern Québec and Labrador (Canada): Species–Environment Relationships in Lakes of Boreal Forest, Forest–Tundra and Tundra Regions.* Berlin: J. Cramer Press.

Glew JR (1988) A portable extruding device for close interval sectioning of unconsolidated core samples. *Journal of Paleolimnology* 1: 235–239.

Glew JR (1989) A new trigger mechanism for sediment samplers. *Journal of Paleolimnology* 2: 241–243.

Grimm EC (1987) CONISS – A FORTRAN-77 program for stratigraphically constrained cluster-analysis by the method of incremental sum of squares. *Computers & Geosciences* 13: 13–35.

Grimm EC (2004) *TGView v.2.0.2 Computer Program*. Springfield: Illinois State Museum, Research and Collections Center.

Hay MB, Michelutti N and Smol JP (2000) Ecological patterns of diatom assemblages from Mackenzie Delta lakes, Northwest Territories, Canada. *Canadian Journal of Botany* 78: 19–33.

Hill MO (1973) Diversity and evenness – Unifying notation and its consequences. *Ecology* 54: 427–432.

Horton BP and Sawai Y (2010) Diatoms as indicators of former sea levels, earthquakes, tsunamis, and hurricanes. In: Smol JP and Stoermer EF (eds) *The Diatoms: Applications for the Earth and Environmental Sciences 2nd Edition.* Cambridge: Cambridge University Press, pp. 357–273.

Johannessen OM, Bengtsson L, Miles MW et al. (2004) Arctic climate change: Observed and modelled temperature and sea-ice variability. *Tellus* 56A: 328–341.

Kokelj SV, Jenkins RE, Burn CR et al. (2005) The influence of thermokarst disturbance on the water quality of small upland lakes, Mackenzie Delta region, Northwest Territories, Canada. *Permafrost and Periglacial Processes* 16: 343–353.

Kokelj SV, Lantz TC, Solomon S et al. (2012) Utilizing multiple sources of knowledge to investigate northern environmental change: Regional ecological impacts of a storm surge in the outer Mackenzie Delta, N.W.T. *Arctic* in press.

Krammer K and Lange-Bertalot H (1991) Bacillariophyceae 4. Teil: Achnanthaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema Gesamtliteraturverzeichnis Teil 1-4. In: Ettel H, Gerloff J, Heynig H et al. (eds) *Süßwasserflora von Mitteleuropa 2/4.* Berlin: Spektrum Akademischer Verlag.

Krammer K and Lange-Bertalot H (1997) Bacillariophyceae 2. Teil: Bacillariaceae, Epithemiacaeae, Surirellaceae. In: Ettel H, Gerloff J, Heynig H et al. (eds) *Süßwasserflora von Mitteleuropa 2/2*. Berlin: Spektrum Akademischer Verlag.

Krammer K and Lange-Bertalot H (1999) Bacillariophyceae 1. Teil: Naviculaceae. In: Ettel H, Gerloff J, Heynig H et al. (eds) *Süßwasserflora von Mitteleuropa 2/1*. Berlin: Spektrum Akademischer Verlag.

Krammer K and Lange-Bertalot H (2000) Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettel H, Gerloff J, Heynig H et al. (eds) *Süßwasserflora von Mitteleuropa 2/3*. Berlin: Spektrum Akademischer Verlag.

Lantz TC and Kokelj SV (2008) Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. *Geophysical Research Letters*, 35: L06502, doi:10.1029/2007GL032433.

Liu K-B and Fearn ML (1993) Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* 21: 793–796.

Liu K-B and Fearn ML (2000) Reconstruction of prehistoric landfall frequencies of catastrophic hurricanes in NW Florida from lake sediment records. *Quaternary Research* 54: 238–245.

Mackay JR (1963) *The Mackenzie Delta Area, N.W.T*. Ottawa: Department of Mines and Technical Surveys.

Manson GK and Solomon SM (2007) Past and future forcing of Beaufort Sea coastal change. *Atmosphere-Ocean*, 45: 107–122.

Nicholls RJ and Cazenave A (2010) Sea-level rise and its impact on coastal zones. *Science* 328: 1517–1520.

Parsons ML (1998) Salt marsh sedimentary record of the landfall of Hurricane Andrew on the Louisiana coast: Diatoms and other paleoindicators. *Journal of Coastal Research* 14: 939–950.

Pisaric MFJ, Carey SK, Kokelj SV et al. (2007) Anomalous 20th century tree growth, Mackenzie Delta, Northwest Territories, Canada. *Geophysical Research Letters* 34: L05714, doi:10.1029/2006GL029139.

Pisaric MFJ, Thienpont JR, Kokelj SV et al. (2011) Impacts of a recent storm surge on an Arctic delta ecosystem examined in the context of the last millennium. *Proceedings of the National Academy of Sciences (USA)* 108: 8960–8965.

Rampton VN (1988) *Quaternary Geology of the Tuktoyaktuk Coastlands, Northwest Territories*. Ottawa: Geological Survey of Canada.

Schelske CL, Peplow A, Brenner M et al. (1994) Low-background gamma counting: Applications for ^{210}Pb dating of sediments. *Journal of Paleolimnology* 10: 115–128.

Sepp M and Jaagus J (2011) Changes in the activity and tracks of Arctic cyclones. *Climatic Change* 205: 577–595.

Simmonds I and Keay K (2009) Extraordinary September Arctic sea ice reductions and their relationships with storm behaviour over 1979–2008. *Geophysical Research Letters* 36: L19715, doi: 10.1029/2009GL039810.

Smol JP (2008) *Pollution of Lakes and Rivers: A Paleoenvironmental Perspective 2nd Edition*. Oxford: Blackwell Publishing.

Smol JP and Douglas MSV (2007) From controversy to consensus: Making the case for recent climate change in the Arctic using lake sediments. *Frontiers in Ecology and the Environment* 5: 466–474.

Smol JP and Stoermer EF (2010) *The Diatoms: Applications for the Environmental and Earth Sciences 2nd Edition.* Cambridge: Cambridge University Press, pp. 1–686.

Smol JP, Wolfe AP, Birks HJB et al. (2005) Climate driven regime shifts in the biological communities of Arctic lakes. *Proceedings of the National Academy of Sciences USA* 102: 4397–4402.

Stevens PW, Blewett DA, Champeau TR et al. (2010) Posthurricane recovery of riverine fauna reflected in the diet of an apex predator. *Estuaries and Coasts* 33: 59–66.

ter Braak CJF and Šmilauer P (2002) *CANOCO Reference Manual and CANODRAW for WINDOWS Users Guide: Software for Canonical Community Ordination (Version 4.5).* Ithaca NY: Microcomputer Power.

Walker HJ (1998) Arctic Deltas. *Journal of Coastal Research* 14: 718–738.

Williams HFL (2009) Stratigraphy, sedimentology, and microfossil content of Hurricane Rita storm surge deposits in southwest Louisiana. *Journal of Coastal Research* 25: 1041–1051.