

Investigating the response of Cladocera to a major saltwater intrusion event in an Arctic lake from the outer Mackenzie Delta (NT, Canada)

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Abstract An increase in the frequency and intensity of marine storm surges is a predicted consequence of climate warming, and therefore it is important to better understand the biological responses to such events in coastal regions. In late September 1999, a major storm surge resulted in a saltwater intrusion event over a large area of the Mackenzie Delta (NT, Canada) front,

causing rapid salinization of lakes on the alluvial plain. Due to a lack of long-term ecological monitoring data in the region, the impacts that the saltwater intrusion event had on the biota of affected lakes were unknown. We used high-resolution paleolimnological approaches to reconstruct past assemblage changes in Cladocera from impacted Lake DZO-29 (unofficial name) in order to determine how different cladoceran species responded to a major increase in lake salinity following the 1999 storm surge. *Camptocercus* were extirpated from the lake following the saltwater intrusion and have not recovered. We also observed an initial decrease in *Alona* relative abundance following the marine flooding, likely reflecting a loss of *A. quadrangularis*, *A. barbulata*, and *A. costata* from the lake. *A. circumfimbriata*, *Chydorus biovatus*, *C. brevilabris*, and *Bosmina* spp. were abundant both before and after the saltwater intrusion, and *Paralona pigra* was present following the storm surge, but not prior to it. The most notable shift in Cladocera in the recent sedimentary record, however, occurred much earlier, with an increase in pelagic *Bosmina* taxa and a subsequent decrease in the benthic/littoral taxa *Chydorus* and *Camptocercus*, an assemblage shift that is consistent with a response to climate warming in this region, and strongly correlated to other changes in the lake inferred to be as a result of regional warming.

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Introduction

In September of 1999 an intense storm in the Beaufort Sea resulted in a saltwater intrusion event that impacted a large area of the outer Mackenzie Delta front (Manson and Solomon 2007; Pisaric et al. 2011). The 1999 saltwater intrusion moved seawater ~30 km inland, flooded over 10,000 ha of pristine Arctic habitat, and drastically altered the terrestrial and aquatic ecology of this area (Pisaric et al. 2011; Kokelj et al. in press). Modern water chemistry analyses revealed that concentrations of sodium and chloride are still elevated in the impacted lakes, as well as the surrounding terrestrial soils more than a decade later, suggesting little or no chemical recovery has occurred (Pisaric et al. 2011).

A previous investigation into the impacts of this storm surge event on the freshwater ecosystems of the Delta recorded striking changes in the sedimentary diatom assemblages of a coastal lake immediately following the 1999 intrusion (Pisaric et al. 2011). No other major diatom changes were inferred related to lakewater salinity throughout the lake's history prior to the 1999 storm, indicating that the impact of this intrusion was unmatched within the ~1,000 year history of this lake ecosystem (Pisaric et al. 2011). However, the impact that this saltwater intrusion event had on higher trophic levels, if any, has not been investigated. For example, the Cladocera (Branchiopoda, Crustacea) are a group of aquatic invertebrates common in most freshwater ecosystems, and are useful indicators of changes within an ecosystem's structure because they are key grazers on algae, and an important food source for fish and invertebrate predators. In addition, cladoceran assemblages contain representatives from virtually all habitats within the lake (Korhola and Rautio 2001; Jeppesen et al. 2011).

Cladocera are generally considered to have limited osmoregulatory abilities (Frey 1993), and many cladoceran taxa are confined to freshwater, although there are still several taxa able to inhabit brackish waters or even marine habitats (Bowman and Abele 1982). For example, in Canadian lakes, *Alona circumfimbriata* is distributed across a wide salinity gradient, and can live in very brackish waters (Chengalath 1982). *Daphnia* tend to be sensitive to high salinity, but clones of *Daphnia pulex* have been recovered from high salinity ponds in the Canadian low Arctic near Churchill, Manitoba (Weider and Hebert 1987). Physiological

stress resulting from high salinity can affect the body size, feeding rates, and life history traits of Cladocera (Achuthankutty et al. 2000; Martínez-Jerónimo and Martínez-Jerónimo 2007), and previous studies have observed a negative correlation between cladoceran species diversity and lakewater salinity (Chengalath 1982; Hammer and Forró 1992; Bos et al. 1999). Saltwater inundations from storm surges like the one that occurred in the Mackenzie Delta have the potential to negatively impact the cladoceran community in freshwater coastal lakes if the species historically present in these lakes are not adapted to tolerate large and sudden changes in lakewater salinity.

Relatively little is known about the distribution of Cladocera across salinity gradients in Canadian Arctic and Subarctic regions, with almost no data available for the vast outer Mackenzie Delta region, where salinity changes may be common. Sweetman and Smol (2006a) examined the distribution of Cladocera subfossil remains along a north–south transect in Alaska, USA, and found that differences in species assemblage existed between tundra and forest-tundra lakes, which appeared to be related to differences in lake depth and total phosphorus (TP). Similarly, Sweetman et al. (2010) examined cladoceran remains in 50 lakes located across the Canadian Arctic treeline from the Northwest Territories to Nunavut and found that Cladocera species assemblages were significantly related to surface water temperature, dissolved organic carbon (DOC), and TP. In both Sweetman and Smol (2006a) and Sweetman et al. (2010), lake specific conductivity values were much lower than those for lakes in the inundated region of the Mackenzie Delta ($2.5\text{--}478\text{ }\mu\text{S cm}^{-1}$ vs. $570\text{--}15,000\text{ }\mu\text{S cm}^{-1}$; Pisaric et al. 2011).

Cladocera leave chitinous exoskeletons preserved in lake sediments that can be identified to the genus or species level (Korhola and Rautio 2001). Therefore, cladoceran assemblages preserved in lake sediments have the potential to track long-term changes in northern lake ecosystems, which can be of particular value in the absence of long-term monitoring data (Smol 2008). Salinity has been highlighted as a significant variable influencing subfossil zooplankton community composition and cladoceran species richness in shallow, brackish lakes from Denmark, although nutrients and fish abundance were also important (Amsinck et al. 2005). Cladocera subfossils have also successfully tracked periods of brackish

transgressions of the Baltic Sea in a coastal lake in Finland, and these periods were characterized by a reduced diversity of littoral cladocerans, although *Alona rectangula*, *Alona affinis*, and *Chydorus sphaericus* s.l. were tolerant of increased salinity (Sarmaja-Korjonen and Hyvärinen 2002). In North America, Bos et al. (1999) documented clear relationships between cladoceran taxa and lakewater salinity for athalassic lakes in the interior of British Columbia. Cladocera subfossils, therefore, have the potential to be effective indicators of saltwater intrusion events in

coastal lakes in the Mackenzie Delta, providing information on the biological responses of this key group of aquatic invertebrates.

In this study, we analyzed cladoceran remains in the same sediment slices previously analyzed for diatoms (Pisarcic et al. 2011) from a lake (Fig. 1) in the Mackenzie Delta (NT) that is known to have experienced a large increase in lakewater salinity following the 1999 saltwater intrusion. Our objectives are to evaluate the usefulness of cladoceran subfossils for tracking saltwater intrusion events, and to assess the

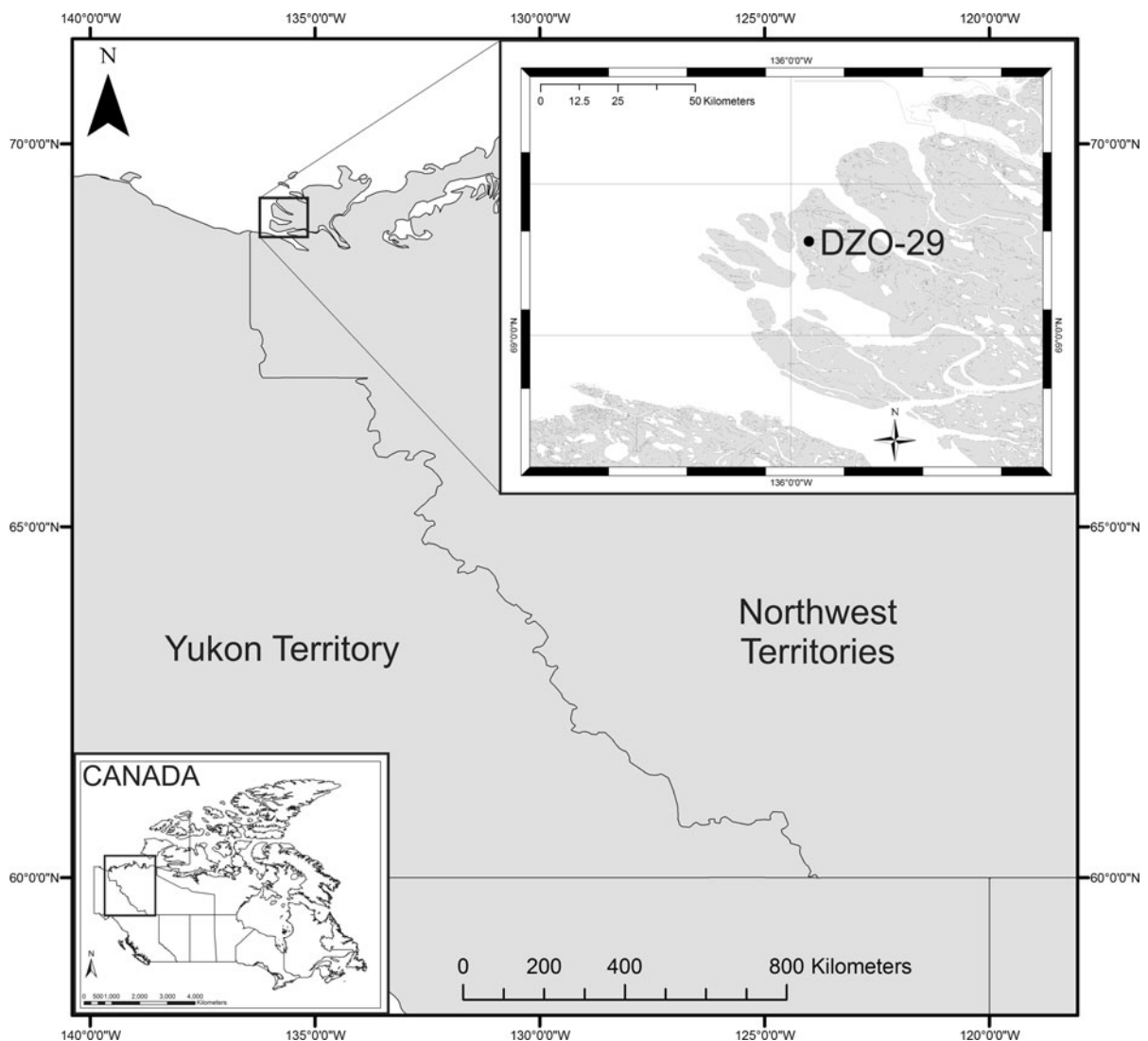


Fig. 1 Map of lake DZO-29 located near the Beaufort Sea coast, outer northwest Mackenzie Delta, with insets showing the location of the region in the context of the Northwest Territories and Canada

resilience of different cladoceran taxa to large and sudden increases in lakewater salinity, increasing our understanding of cladoceran salinity tolerances in coastal Arctic lakes that are vulnerable to marine storm surges.

Study site description

The Mackenzie Delta, located in the Northwest Territories, Canada, is approximately 210 km long and 62 km wide, spanning an area of almost 13,000 km², making it Canada's largest delta, and the second largest Arctic delta globally (Fig. 1) (Burn and Kokelj 2009). The maximum elevation of the Mackenzie Delta is ~10m above sea level and gradually slopes downwards to the Beaufort Sea coast. The delta is a Holocene feature comprised of sediments deposited by the Mackenzie and Peel Rivers (Rampton 1988). Storm surges originating in the Beaufort Sea can inundate hundreds of lakes and vast areas of low-lying alluvial terrain in the outer Mackenzie Delta (Mackay 1963).

Our study lake (DZO-29, unofficial name, 69°09'20.5"N, 135°56'52.12"W), which is located ~5 km southeast of Ellice Island, is on the northwest perimeter of the Mackenzie Delta adjacent to the Beaufort Sea (Fig. 1). This lake was selected because it is located within the area impacted by the 1999 saltwater intrusion event, and is known to have experienced an increase in lakewater salinity inferred from sedimentary diatoms, where brackish taxa showed a substantial increase in relative abundance after 1999 (Pisaric et al. 2011). The lake has a maximum depth of 4.1 m, is small (~5.5 ha), exhibits limited aquatic macrophyte growth, and the current ionic chemistry of the lake is elevated in comparison to other lakes in the Mackenzie Delta not impacted by the inundation (Na⁺ 2,270 mg/L, Cl⁻ 5,030 mg/L, specific conductivity 12,722 µS/cm; Pisaric et al. 2011). Profiles of lakewater salinity taken during several seasons of the year suggest conductivity varies little on an annual scale, as the potential for freshwater flushing of the system is limited by the fact that ice seals the lake during the peak flow of the Mackenzie River in the spring. This likely explains why little chemical recovery of the lakes in the region has occurred since 1999 (Pisaric et al. 2011; J. Thienpont unpublished data).

Methods

Sediment coring and radiometric dating

A 22–5-cm gravity sediment core was collected on August 21, 2009, from the pontoons of a helicopter using a Glew-type gravity corer (Glew 1989), which was then sectioned into 0.25-cm intervals using a Glew (1988) vertical extruder and stored below 4°C. Select intervals were dated using ²¹⁰Pb and ¹³⁷Cs radioisotopes (Pisaric et al. 2011) following standard procedures for gamma decay analysis (Schelske et al. 1994; Appleby 2001). The same sediment core slices that were used for the diatom-based assessment conducted by Pisaric et al. (2011) were used in this investigation, ensuring that direct comparisons of changes in different paleolimnological indicators could be conducted.

Laboratory and statistical analyses

Sediments were prepared for analysis of cladoceran remains using standard procedures outlined in Korhola and Rautio (2001). Briefly, 1.5 g of wet sediment for each interval was deflocculated in 10% KOH solution at ~70°C for 30 min, then rinsed through a 38-µm sieve. The residue retained on the sieve was transferred to a vial using deionized water, then pipetted onto slides and mounted using glycerin jelly. Due to a lack of available sediment, the top 1 cm of sediment was combined. Headshields, carapaces, postabdomens, postabdominal claws, expodite segments, and ephippia were enumerated using a Leica DMRB microscope with bright field optics, and the most abundant type of remain for each species was used to determine the number of individuals in a sample. A minimum of 70 individuals was counted for each interval (Kurek et al. 2010). Identification of subfossil remains was based on descriptions in Sweetman and Smol (2006b) and Szeroczyńska and Sarmaja-Korjonen (2007). For each interval, the total number of cladoceran individuals per gram of dry sediment was calculated to estimate changes in cladoceran density over time. Counts of individuals were then converted to relative abundances, and species that did not occur in at least 2 samples with at least 2% relative abundance were removed from further analysis. A stratigraphic profile was prepared using TGView 2.0.2 (Grimm 2004), and a constrained incremental sum of

squares (CONISS) cluster analysis was included in order to elucidate major zones of changes in sedimentary cladoceran species assemblages (Grimm 1987). The significance of the CONISS zones was determined with the broken stick model (Bennett 1996) using the vegan (Oksanen et al. 2010) and rioja (Juggins 2009) packages for the R software environment (R Development Core Team 2011).

Whole lake primary production was estimated using visual reflectance spectroscopically inferred chlorophyll *a* (VRS-chl *a*), a technique that infers both chlorophyll *a* and its diagenetic products (Michellutti et al. 2010). In order to facilitate the direct comparison of changes in the cladoceran assemblage with diatom species changes, principal components analysis axes 1 and 2 site scores were calculated using CANOCO v4.5 (ter Braak and Šmilauer 2002).

Results

Sixteen cladoceran taxa were identified in the sediments of Lake DZO-29, including *Leptodora kindtii* Ficke 1844, *Bosmina* Baird 1846, *Alona quadrangularis* O.F. Müller 1775, *A. barbulata* Megard 1967, *A. circumfimbriata* Megard 1967, *A. guttata* Sars 1862, *A. costata* Sars 1862, *A. intermedia* Sars 1862, *Leydigia leydigi* Schoedler 1863, *Chydorus biovatus* Frey 1985, *Chydorus brevilabris* Frey 1980, *Paralona pigra* Sars 1861, *Alonella nana* Baird 1850, *Acroperus harpae* Baird 1834, *Eurycerus bullatifrons* Frey 1975, and *Camptocercus* spp. Baird 1843. *Camptocercus* taxa in North America are poorly described (Smirnov 1998), but at least two species of *Camptocercus* have been identified based on subfossil shells from the Alaska region (Sweetman and Smol 2006b). The carapaces we recovered here superficially resemble *C. rectirostris* from Europe. Unfortunately, due to a high density of microscopic organic particles present on the slides, it was difficult to observe the characteristic headpore arrangement on several *Alona* headshields, and for relative abundance calculations, *Alona* had to be grouped together. For the same reason, *C. biovatus* and *C. brevilabris* were also grouped in relative abundance calculations, as well as *Bosmina longirostris* and *Eubosmina longispina* (Fig. 2).

A significant shift in the cladoceran assemblage was identified by the broken stick model at a core depth of 2.25 cm, which corresponds to ~1999 based

on ^{210}Pb dating, and corresponds well to the timing of the major change in the first principal components axis based on the diatom assemblage, although this change in the cladoceran assemblage was secondary to a major assemblage shift at 13.5 cm (Fig. 2). In the decades prior to the 1999 saltwater intrusion event, the cladoceran assemblage of DZO-29 was dominated by *Bosmina* spp., *Alona* spp., and *C. biovatus/brevilabris*, and had smaller but appreciable abundances of *A. harpae* and *Camptocercus*. *Bosmina*, *Alona*, and *C. biovatus/brevilabris* remained dominant after the saltwater intrusion; although a small decrease in *Alona* relative abundance accompanied by an increase in *Bosmina* was observed. *A. quadrangularis*, *A. barbulata* and *A. costata* were not identified in the sediments following the saltwater intrusion. In the 0–1-cm interval, *Alona* and *Bosmina* returned to their pre-impact abundances. *Camptocercus* spp. disappeared from the sedimentary record immediately following the 1999 intrusion, although it had been declining since a core depth of 18.25 cm (Fig. 2). *P. pigra* had been absent from the sedimentary record above a core depth of 14 cm, but reappeared in low abundances after the saline intrusion. *A. harpae* remains were recorded in low abundances before and after the 1999 intrusion, but were not recorded in the 0–1-cm sediment interval.

Another significant change in the cladoceran assemblage occurred at a core depth of 17 cm, where *Camptocercus* decreased and *Chydorus* spp. increased (Fig. 2). The most significant change in the cladoceran assemblage, however, occurred at a core depth of 13.5 cm (Fig. 2). Below 13.5 cm, the pelagic *Bosmina* spp. were present in lower abundances (11%), whereas benthic species, including *Alona* spp., *Camptocercus* spp., and *C. biovatus/brevilabris*, were all present in relatively high abundances (17, 22 and 38% respectively). Above 13.5 cm, a large relative increase in *Bosmina* spp. (from 11 to 22%) was observed, and *Bosmina* spp. continued to increase to approximately 50% relative abundance within the lake. A corresponding decrease in the benthic taxa *Camptocercus* and *C. biovatus/brevilabris* occurred above a core depth of 13.5 cm. As is common in all sedimentary profiles, larger errors associated with older ^{210}Pb dates make it difficult to assess the precise timing of the increase in *Bosmina* observed.

The density of cladoceran individuals per gram of dry sediment showed a steady increase beginning

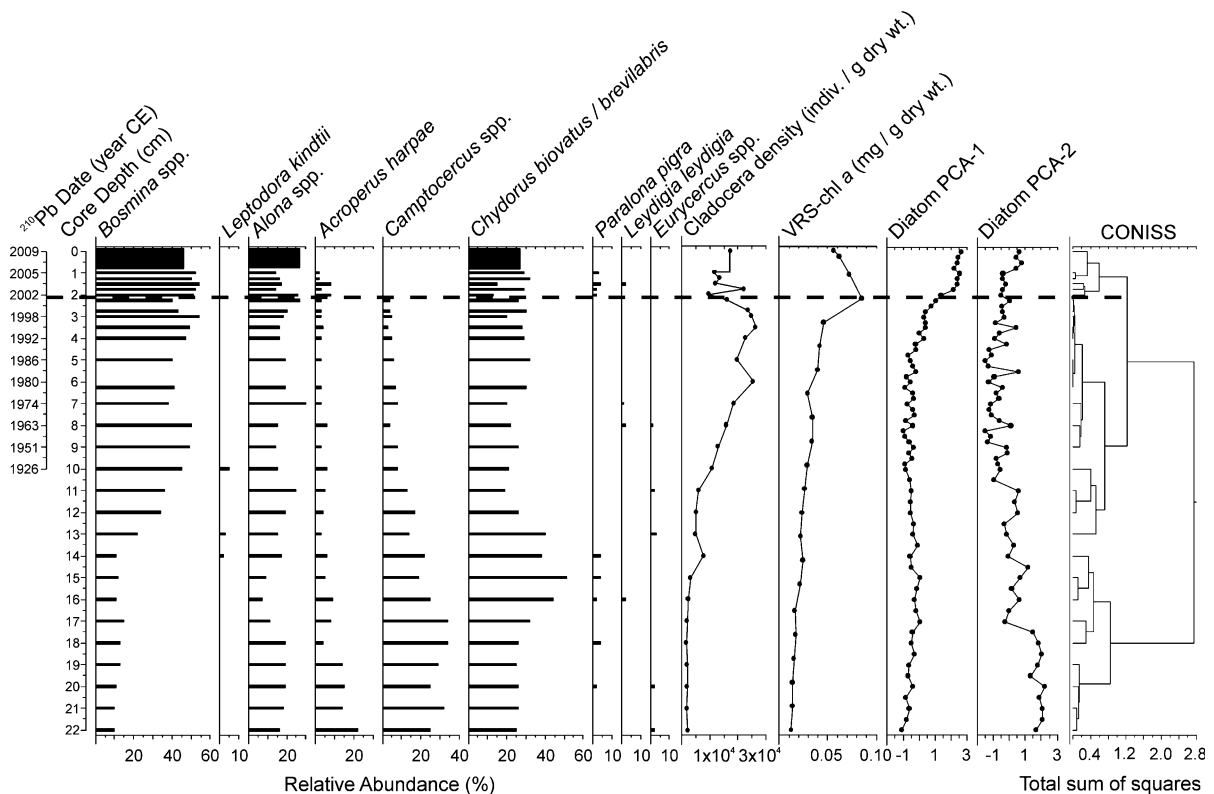


Fig. 2 Relative abundance diagram of subfossil cladoceran taxa in DZO-29. Constrained incremental sum of squares (CONISS) cluster analysis is shown, with three significant zones determined by breakpoint analysis using the broken stick model. The density of cladoceran remains (individuals per gram dry sediment) is included, as well as an estimate of whole lake

production as inferred from sedimentary visual reflectance spectroscopy chlorophyll *a* (VRS-chl *a*) (mg/g dry sediment). A summary of the diatom data analyzed in Pisarcic et al. (2011) is included using principal components analysis axis 1 and 2 site scores, in order to illustrate the timing of changes in the diatom assemblage

at a core depth of 15 cm, and continued until 3 cm (Fig. 2). There was an initial decrease in cladoceran density following the storm surge (~2.5 cm), which persisted for ~3 years (Fig. 2). The cladoceran density was found to be variable in the most recent sediments, but was always elevated relative to the earliest sediment core intervals examined (Fig. 2).

Similar to cladoceran density, there was a steady increase in VRS-chl *a*, from ~15 cm onwards, and cladoceran density and VRS-chl *a* inferences were significantly correlated (Pearson correlation, $R = 0.50$, $p = 0.02$). VRS-Chl *a* peaked at 2.0 cm, corresponding to when the cladoceran density decreased, and showed a steady decline above 2.0 cm, but remained elevated relative to the oldest sediment intervals. Diatom PCA axis-2, which tracks secondary changes in the diatom assemblage, changed at approximately 17 cm, and was significantly correlated to the

increase in cladoceran density which began at approximately the same sediment interval (Pearson correlation, $R = -0.68$, $p < 0.001$).

Discussion

The Cladocera species assemblage in DZO-29 was significantly impacted by the 1999 saltwater intrusion. Since the late nineteenth century, the dominant cladocerans in DZO-29 were *Bosmina* spp. in the pelagic zone, and *Alona* spp. and *C. biovatus/brevibrabris* in the littoral/benthic areas of the lake. These species remained dominant after the 1999 saltwater intrusion event, although *Alona* spp. showed a decrease in relative abundance. This decrease likely reflects the loss of *A. quadrangularis*, *A. barbulata*, and *A. costata*, which were not recorded in the

sediments post-1999 and were likely extirpated from the lake along with *Camptocercus*. This is consistent with Bos et al. (1999), where *A. quadrangularis*, *A. barbulata*, and *Camptocercus* were generally restricted to fresh waters in athalassic lakes from the British Columbia (Canada) interior. Similarly, *Camptocercus* and *A. quadrangularis* were absent from Lake Ruokolampi, Finland, during periods of brackish-water transgressions of the Littorina Sea in the Baltic (Sarmaja-Korjonen and Hyvärinen 2002). The subfossil cladoceran density data suggest that the 1999 saltwater intrusion of the outer Mackenzie Delta did not result in a drastic, long-lasting impact on cladoceran biomass. However, the reproducibility of concentration data for Cladocera and other indicators in paleolimnology is problematic (Kattel et al. 2007; Heiri 2004), and the interpretation of concentration data is not straightforward (Battarbee et al. 2001). Therefore, these data should be viewed critically and with caution (Smol 2008).

Chydorus brevilabris, *A. circumfimbriata*, and *Bosmina* were abundant both before and after the saline intrusion, and continued to survive and reproduce even after the lake switched rapidly from a freshwater to a brackish system (as shown by diatom PCA axis-1; Pisaric et al. 2011). In Finnish Lake Ruokolampi, *C. sphaericus* and *A. rectangula* remained abundant during the Littorina transgression (Sarmaja-Korjonen and Hyvärinen 2002). These European taxa are similar to *C. brevilabris* and *A. circumfimbriata*, respectively, in North America (Frey 1980), suggesting these species groups are well adapted to tolerate fluctuating salinities. Similarly, these taxa displayed higher salinity tolerances relative to other cladoceran species in Bos et al. (1999). Based on Bos et al. (1999), however, the current conductivity levels in DZO-29 ($\sim 13,000 \mu\text{S cm}^{-1}$) should be too high to support *Bosmina* and *C. brevilabris* (neither taxa found above conductivity of $5,800 \mu\text{S cm}^{-1}$; Bos et al. 1999), yet both of these taxa were recorded in appreciable abundances before and after the 1999 saltwater intrusion. This could suggest that the distribution of these taxa in British Columbia were limited by factors other than salinity (Bos and Cumming 2003), or that cryptic differences exist between morphologically similar species in interior British Columbia lakes compared to coastal lakes in the Mackenzie Delta. This highlights the importance of studying the local ecology of cladoceran species, as

differences in ecology might exist between seemingly identical species in different regions.

Paralona pigra reappeared in Lake DZO-29 following the marine storm surge, suggesting the changes that occurred in the lake following the saltwater inundation favoured its re-establishment. This contrasts with Sarmaja-Korjonen and Hyvärinen (2002), where *P. pigra* (referred to as *Chydorus piger*) disappeared from Lake Ruokolampi when the water became more brackish during the Littorina Sea transgression. This could indicate that the salinity tolerances for *P. pigra* differ between these two regions. Alternatively, the response of *P. pigra* to saltwater intrusion or transgression events may be indirect, and instead *P. pigra* is appearing or disappearing in response to other factors such as changes in habitat. *P. pigra* is a benthic taxon that usually crawls on the surface of the bottom sediments. In Finland, it is often associated with early-lake development when sediments are high in mineral particles (Sarmaja-Korjonen 2002), and in Canada it shows a preference for sandy or rocky substrates in vegetation-free zones (Chengalath 1982). No visible stratigraphic changes were observed in the sediment core of Lake DZO-29, nor were there any changes in magnetic susceptibility, and loss-on-ignition analysis showed a small increase in percent organic matter following the storm surge, although this was short-lived (J. Vermaire, Carleton University, Ottawa, Canada, pers. commun.). Based on these results, the saltwater intrusion likely did not result in increased mineral or sand content of the sediments that would favor an increase in *P. pigra*. The intrusion may have caused a reduction in the extent of coverage by rooted aquatic macrophytes, providing more benthic habitat for this taxon, but no monitoring data are available on macrophytes before the storm occurred.

Earlier changes in the cladoceran assemblage of Lake DZO-29 suggest a gradual shift from benthic to pelagic primary production. Between a core depth of 17 and 14 cm, *Camptocercus* decreased in relative abundance, and *C. brevilabris/biovatus* increased. *C. brevilabris* displays more plasticity in habitat preference, and while it is typically a littoral or benthic taxon, it can also exploit the pelagic zone of a lake (Chengalath 1982; Paterson 1993; Dole-Olivier et al. 2000). In contrast, *Camptocercus* are poor swimmers, and are strictly benthic (Dole-Olivier et al. 2000). At a core depth of 13.5 cm, the open-water taxa

Bosmina spp. increased in relative abundance, while *Chydorus* and *Camptocercus* decreased. Coincident with the timing of these cladoceran assemblage changes, the sedimentary diatom community experienced a shift (inferred from PCA axis-2 site scores), the onset of a gradual increase in VRS-inferred chlorophyll *a* was observed, and the density of cladoceran remains in the sediments also increased. The coincident change in the diatom assemblage was driven primarily by an increase in the relative abundance of periphytic taxa, notably species of the genus *Amphora*, as well as decreases in the relative abundance of small benthic fragilarioid taxa (Pisaric et al. 2011). These changes, along with overall increases in whole lake primary production inferred from VRS-chl *a*, have been shown as a response to warming in other Arctic regions (Smol and Douglas 2007; Michelutti et al. 2010).

As the duration of the ice-free period is lengthened by earlier spring thaw and later freeze-up in the fall, the period of time during which algal communities are able to thrive is increased, accounting for the increased overall lake production inferred from sedimentary VRS-chl *a* (Michelutti et al. 2005). Similarly we would also expect an increase in secondary production, which is supported by our observation of increasing density of cladoceran individuals preserved in the sediments, although we stress again that we believe concentration data should be viewed with caution in paleolimnological studies. In addition to increased production, a longer productive season and increased temperatures may result in increased thermal stability in the lake, which could promote the development of the planktonic algal community. While no planktonic diatom taxa were observed in the sediment core (Pisaric et al. 2011), other algal taxa (e.g. green algae), which often thrive during the summer, are likely exploiting this increased planktonic habitat. The shift in the cladoceran assemblage towards planktonic *Bosmina* from obligate benthic *Camptocercus* (with a transition period favoring *Chydorus*, which has plastic habitat preferences) may be a response to this gradual increase in planktonic primary production, and also to decreased ice cover which would provide more available pelagic habitat. Due to the remote nature of these lakes, recent climate warming is the dominant stressor impacting aquatic biological communities, and while eutrophication could result in increased production as inferred in this study, changes resulting from warming

are more plausible, and if there were any increases in nutrients in this lake, it would likely be related to climate and could not be linked to cultural eutrophication.

These data provide the first paleolimnological evidence of changes in cladoceran assemblages related to climate warming in the Canadian Arctic. Sweetman et al. (2008) examined 50 lakes in the central Canadian Arctic treeline region, and found no consistent pattern of increases in planktonic cladocerans like *Bosmina* in recent sediments of lakes known to have experienced warming, and suggest that Cladocera in these lakes have not yet surpassed an environmental threshold related to warming. The Mackenzie Delta region has experienced among the most extensive warming trends in the Canadian Arctic (Bégin et al. 2000; Lantz and Kokelj 2008), and our data suggest that, unlike treeline lakes in the central Canadian Arctic, Lake DZO-29 in the Mackenzie Delta has surpassed a critical environmental threshold in response to climate warming.

Conclusions

As the frequency and severity of storms and resulting saltwater intrusions are expected to increase with rising sea levels and climate change, assessing the ecological impacts of fluctuating salinity on aquatic ecosystems is critical. Changes in the relative abundances of Cladocera in coastal Lake DZO-29 (Mackenzie Delta, NT) tracked a severe 1999 saltwater intrusion event, which is known to have resulted in a shift from a freshwater to a brackish diatom flora with no subsequent recovery. Specifically, *Camptocercus*, *A. quadrangularis*, *A. barbulata*, and *A. costata* were likely extirpated, and *P. pigra* recolonized the lake following the saltwater intrusion. *C. brevilabris/biovatus*, *Bosmina*, and *Alona circumfimbriata* were abundant before and after the storm surge, suggesting that these taxa are well adapted to tolerate sudden and dramatic changes in lakewater salinity. Earlier changes in cladoceran relative abundance suggest a gradual shift from benthic to pelagic production, consistent with post-1850 climate warming in this region, which is also reflected by increased whole lake primary production.

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