Impacts of a recent storm surge on an Arctic delta ecosystem examined in the context of the last millennium

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One of the most ominous predictions related to recent climatic warming is that low-lying coastal environments will be inundated by higher sea levels. The threat is especially acute in polar regions because reductions in extent and duration of sea ice cover increase the risk of storm surge occurrence. The Mackenzie Delta of northwest Canada is an ecologically significant ecosystem adapted to freshwater flooding during spring breakup. Marine storm surges during the open-water season, which move saltwater into the delta, can have major impacts on terrestrial and aquatic systems. We examined growth rings of alder shrubs (*Alnus viridis* subsp. *fruticosa*) and diatoms preserved in dated lake sediment cores to show that a recent marine storm surge in 1999 caused widespread ecological changes across a broad extent of the outer Mackenzie Delta. For example, diatom assemblages record a striking shift from freshwater to brackish species following the inundation event. What is of particular significance is that the magnitude of this recent ecological impact is unmatched over the >1,000-year history of this lake ecosystem. We infer that no biological recovery has occurred in this lake, while large areas of terrestrial vegetation remain dramatically altered over a decade later, suggesting that these systems may be on a new ecological trajectory. As climate continues to warm and sea ice declines, similar changes will likely be repeated in other coastal areas of the circumpolar Arctic. Given the magnitude of ecological changes recorded in this study, such impacts may prove to be long lasting or possibly irreversible.

paleoecology | paleolimnology | dendrochronology | limnology | salinization

Recent climatic warming is predicted to have the most adverse effects on low-lying coastal environments through inundation by rising sea levels (1). Arctic coastlines are especially vulnerable (2) due to sea level rise (3), reductions in sea ice extent and duration (4–6), and increasingly variable storm activity (7, 8). During the 20th century, average global sea level has risen at a rate of about 1.7–3 mm/y (1) and is expected to rise an additional 0.22 to 0.44 m above 1990 levels by the end of this century (1). As sea level rises, the impacts of storm surge flooding in low-lying coastal environments will be exacerbated (9). Historical records of climate and environmental change in many Arctic regions are either nonexistent or of very short duration. Determining the frequency and magnitude of storm surges using instrumental tidal records is similarly limited by the spatial and temporal extent of these data (10). In the western Canadian Arctic, the frequency and magnitude of storm surge occurrence have been examined using tidal records from Tuktoyaktuk (1961-present) and log debris lines (10). Traditional knowledge of local indigenous people (the Inuvialuit) suggests an increase in storms that are accompanied by high winds, especially from the east and northwest (11). Coupled with observations of the Inuvialuit, satellite data confirm that summer sea ice extent has declined nearly 50% between 1978 and 2003 across large portions of the Beaufort Sea (12). The greater extent and seasonal duration of open water, coupled with rising sea levels and more variable storm activity, increase the vulnerability of low-lying alluvial environments throughout the Arctic to inundation by marine storm surges. While instrumental records and traditional knowledge are important in assessing recent storm surge activity, they provide limited insight into the frequency and magnitude of large-scale storm surge events. Further, instrumental records cannot be used to determine if recent changes and their ecological impacts are outside the envelope of natural variability at centennial to millennial time scales. Understanding the frequency and magnitude of past storm surge events is critical to predicting ecosystem changes and managing resource development under changing climatic conditions. Here, we present annually resolved dendrochronological records from green alder shrubs (*Alnus viridis* subsp. *fruticosa*) and high-resolution, contiguously sampled subfossil diatom records from radiometrically dated lake sediment cores to provide compelling insights into the importance of past storm surge events during the last ∼1,000 y in the outer Mackenzie Delta, Northwest Territories, Canada. This region is a wetland of global significance that is underlain by rich hydrocarbon reserves. In particular we focus on a storm surge event that occurred in late September 1999. Our data suggest that saltwater inundations of this magnitude, and the associated ecological impacts, have not occurred in at least the last millennium.

Results and Discussion

To determine the impact, if any, of past storm surges on ecosystems in the outer Mackenzie Delta, we developed growth-ring chronologies from green alder shrubs growing at varying distances from the coastline (Fig. 1 and Fig. 2*A*). A total of 107 samples were collected from 10 sites across the study area in 2006 and 2007 (Fig. 1 and Fig. 2*B*). Chronologies were developed for samples grouped by health status: living healthy, living stressed, or dead. The three chronologies were highly correlated with one another during the common period of overlap (1950–2003) (Fig. 2*A*). Although the living healthy shrubs were obtained from

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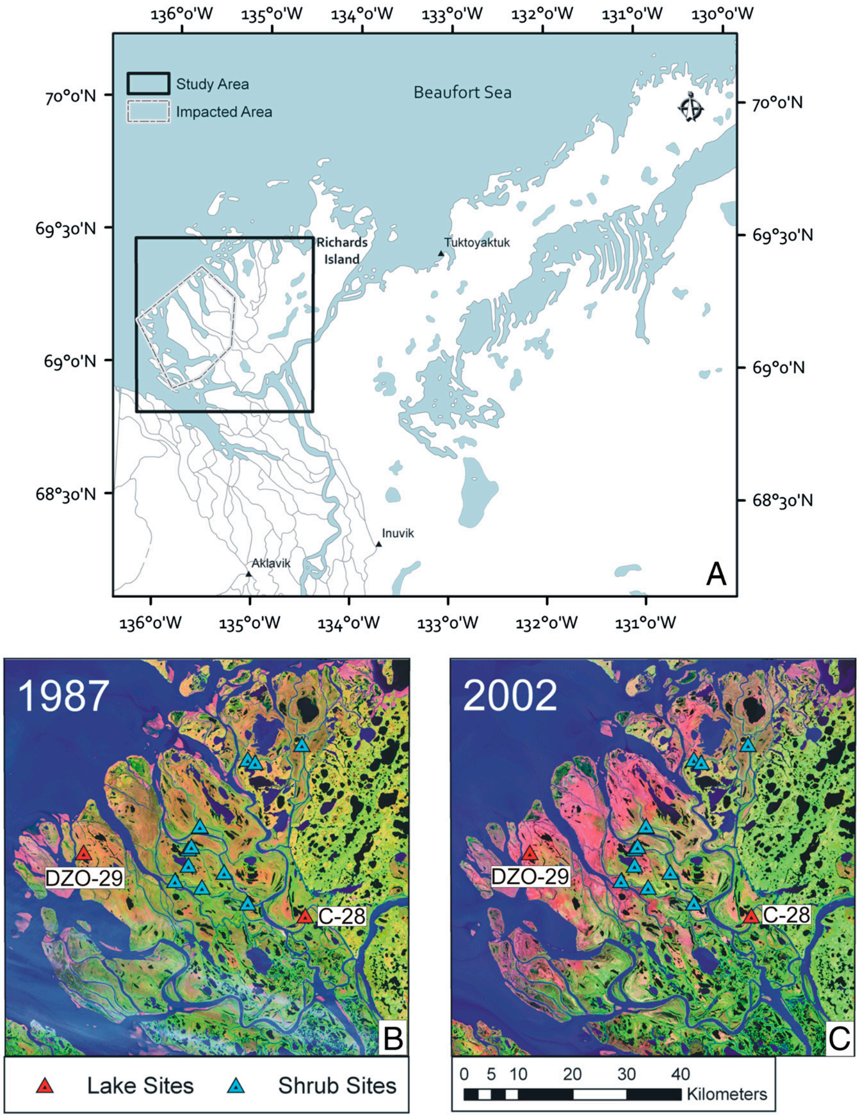

Fig. 1. Study area and sites. (*A*): Study area in the Mackenzie Delta region (solid square). An impacted area defined using changes evident on satellite imagery and field reconnaissance is shown by the dashed line. (*B*): LANDSAT image (August 2, 1987) of the study area showing the location of alder shrub sampling sites, and lakes C-28 and DZO-29. (*C*): LANDSAT image (July 18, 2002) showing the large change in reflectance in the impacted zone several years after the 1999 storm surge. Standard Top of Atmosphere corrections were applied to both images, which are displayed using Bands 7, 4, and 2. Apparent differences between the two LANDSAT images are due to changes in water level, and do not reflect increased channel width or redeposition of features following the 1999 storm surge event. The exposed surfaces, such as those near the coast or within some of the channels are sandbars with elevations generally <20 cm. Water levels in the Mackenzie Delta progressively decline during the open-water season, reaching lowest flows in August and September. Thus, differences in the two images reflect these gradual changes in water level during the summer season and the variability between flows in 1987 vs. 2002. Gauge data from Reindeer Station (within ~2 km of DZO-29) recorded water levels of 9.4 m on August 2, 1987, and 9.6 m on July 18, 2002. Therefore, features that are apparent in the 1987 image were submerged in 2002 and do not suggest that the proximity of Lakes DZO-29 and C-28 changed with respect to the major river channels. Decreased proximity to the channel could have increased their susceptibility to recent storm surges, but our analyses of the LANDSAT images show no significant differences in channel width between the two images.

areas beyond the apparent extent of the saline incursion during the 1999 storm, they were growing on the alluvial plain and likely were flooded during the storm event. As a result, all three chronologies exhibited an abrupt decrease in ring-width after 1999. Previously known surge events also impacted alder growth (Fig. 2*A*); however, these impacts were of relatively short duration (1–2 y). A major storm surge in September 1944 predates the instrumental gauge record, but is known from the accounts of Tuktoyaktuk residents. The dead shrub chronology had a significant decrease in growth that persisted for approximately 8 y following the 1944 event (Fig. 2*A*).

In addition to growth declines in alder, large-scale mortality of shrubs also resulted from the 1999 storm surge (Fig. 2*C*). Approximately 53% of alder shrub mortality occurred in 1999–2000. An additional 37% of sampled shrubs died between 2001–2004, reflecting individuals that were able to survive the initial disturbance event, but then perished in response to changes in environmental conditions that resulted. A decade later, soils in many impacted areas still have exceedingly high chloride concentrations, inhibiting the reestablishment of vegetation communities (Fig. S1).

While the dendrochronological record can be used to assess the terrestrial impacts of storm surges over the last ~80 y, lake sediments provide a much longer record of past ecosystem change (13). Lake sediments were collected from two small, closed-basin ponds (DZO-29, C-28; unofficial names) in the low-lying alluvial plain of the outer Mackenzie Delta (Fig. 1). DZO-29 (69.155694°N, 135.947811°W) is located ~6 km from the coast

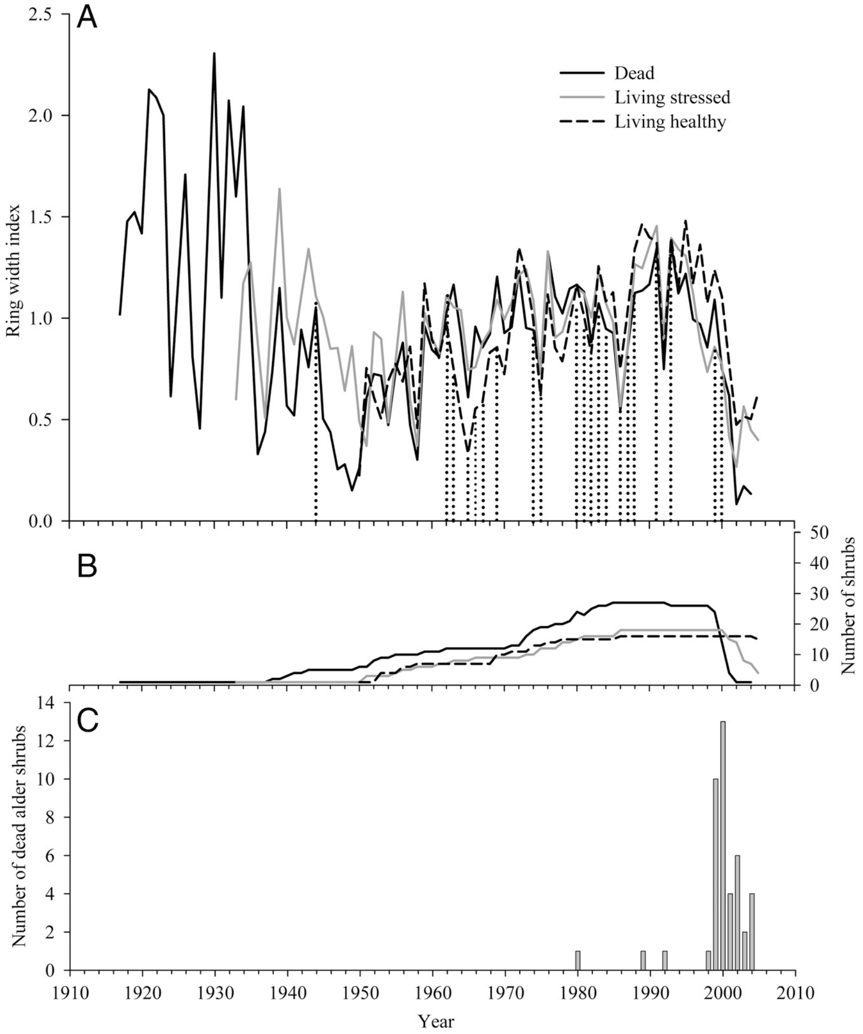

Fig. 2. Alder shrub ring-width chronologies and mortality data. (*A*): Growth chronologies for the living healthy, living stressed, and dead chronologies. Vertical dashed lines represent known open-water season storm surge events with dominant wind direction from the northwest (>6 h in duration and storm surges at least 0.7 m in height) based on the instrumental record from Tuktoyaktuk (2). The 1944 event that predates the instrumental record, but is known from accounts of residents of Tuktoyaktuk, is also indicated. (*B*): Number of samples in each of the alder shrub growth chronologies through time [line formatting is the same as in (*A*)]. (*C*): Alder shrub mortality data as determined by dating dead alder shrubs collected from areas impacted by the 1999 storm surge event.

in the surge impacted zone as indicated by before and after LANDSAT imagery (Fig. 1) and the relatively high ionic concentrations of the water (Cl^- 5,030 mg/L; Na^+ 2,270 mg/L) (Table S1). Lake C-28 (69.082065°N, 134.935284°W) is located ~45 km from the coast, beyond the impacted zone (Fig. 1) and serves as a control site for our study. C-28 ionic concentrations ($Cl^- = 7.7$ mg/L; $Na^+ = 6.1$ mg/L) were far less than lakes in the impacted zone (Table S1) and are comparable to freshwater lakes sampled away from the coast (14). In both lakes, high-resolution gravity sediment cores were collected in order to sample the lakes' most recent histories. In addition, in order to obtain a longer-term perspective of marine surge events, a 1.4 m long piston core was recovered from DZO-29. Although the coring procedure for a long core such as this would sacrifice a few centimeters of the surface sediment, the collection of the high-resolution gravity core from DZO-29 provides a combined sedimentary sequence spanning the last millennium. To ensure a complete record of past storm surge impacts, we sampled the gravity and piston cores contiguously at the highest resolution possible for subfossil diatoms (i.e., every sediment sample in the core was analyzed contiguously for diatoms, and so there were no gaps in the sedimentary record).

Diatoms can effectively track past marine intrusions into lacustrine habitats, because these algae are diverse, well preserved, and have well-defined salinity optima (15). The modern diatom assemblage in the high-resolution surface core from DZO-29 is dominated by a combination of brackish water diatom taxa including *Craticula halophila, Navicula salinarum*, and *Navicula crucicula* (Fig. 3*A*). This assemblage reflects the contemporary limnological conditions, which show elevated ionic concentrations in the lake water. These brackish taxa (16–18) were present in trace abundances throughout the last millennium [as shown in both the surface core (last 2–400 y) and the longer piston core (last thousand years)] (Fig. 3*B*), as would be expected given the lake's proximity to the marine environment. Contiguous sampling throughout the entire length of both sediment cores demonstrates that small benthic fragilarioid taxa, which characterize typical freshwater Arctic lakes and ponds (19), dominate the diatom assemblage often approaching 100% relative abundance during much of the last millennium (Fig. 3 *A* and *B*). For a period of time, substantial increases in the abundances of various groups of freshwater, periphytic diatom taxa are observed in the lower half of the piston core from DZO-29 and represent successional changes of taxa common in other inland

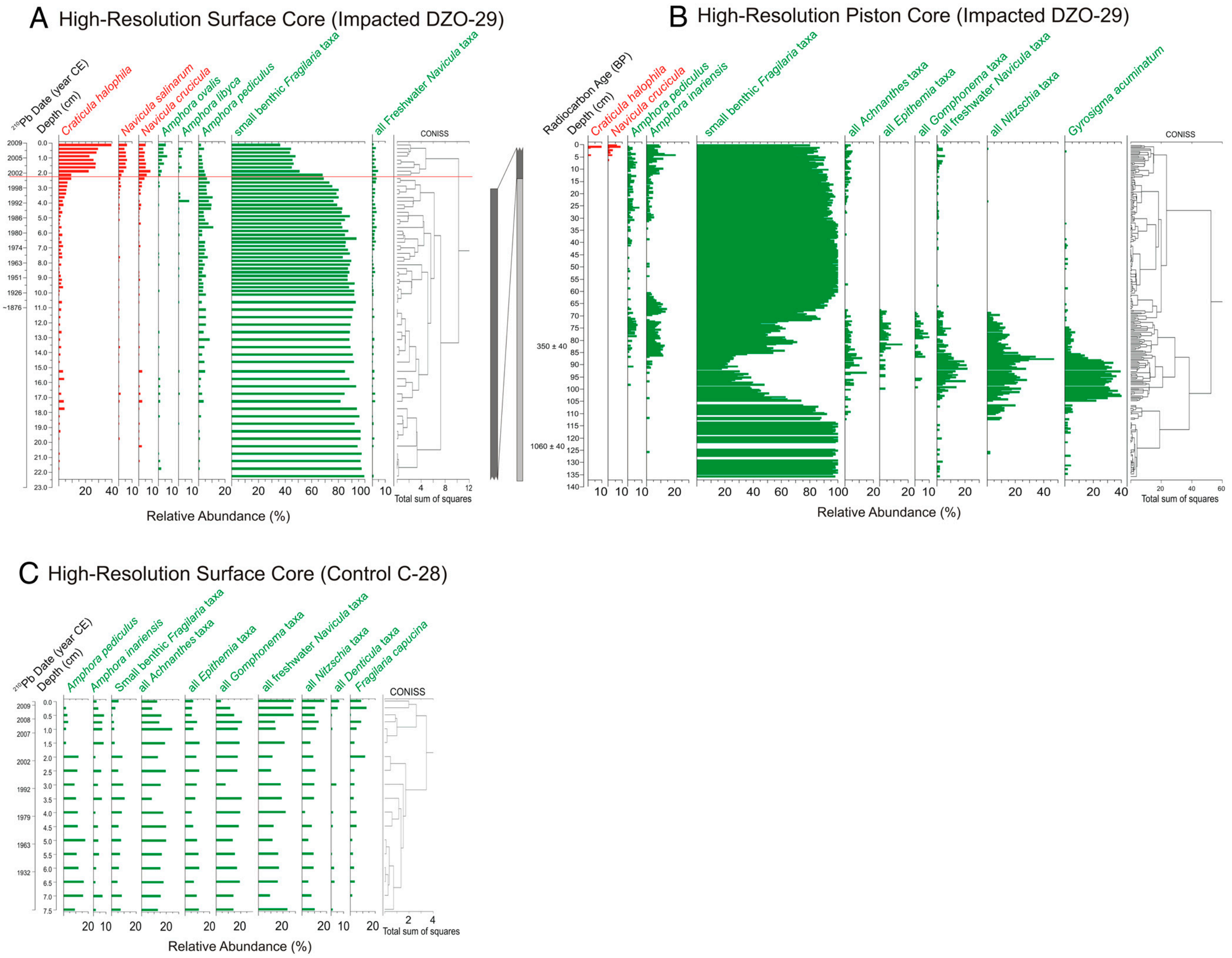

Fig. 3. Stratigraphic profiles showing the relative abundances of the most common diatom taxa. (*A*): High-resolution surface sediment core from Lake DZO-29 (impacted site), and (*B*): high-resolution sedimentary intervals from the DZO-29 piston core, which likely dates back to the lake's formation. Diatom taxa classified as brackish are presented in red, with freshwater taxa identified in green. The age chronology of the gravity core was developed using the unsupported ^{210}Pb activity, which reached background levels at 11-cm, indicating an approximate date of 1876 (Fig. S2). Two calibrated AMS ^{14}C dates provide dating control in the deeper sediments. Gray bars between (*A*) and (*B*) indicate the approximate overlap between the gravity and piston cores. Gaps in the DZO-29 piston core record (*B*) represent intervals in which too few diatom valves were present to provide a statistically robust estimate of the overall species assemblage. Nonetheless, the diatom valves present were all from freshwater groups. (*C*): Diatom profile showing the relative abundances of the most common taxa from a short (7.5 cm) gravity sediment core from control lake C-28. Background levels of ^{210}Pb activity were estimated based on the activity of ^{214}Bi (Fig. S2). In all three sediment cores, constrained incremental sum of squares cluster analysis (CONISS) results are included.

delta floodplain lakes (20) (Fig. 3*B*). Nonetheless, the diatom assemblage continues to be composed exclusively of freshwater taxa. Although the sedimentary sequence obtained from the combined high-resolution gravity and piston cores from impacted DZO-29 likely encompasses the entire period since the lake's inception, the only significant occurrence of saline taxa in the diatom assemblages occurred in the most recent sediments of the surface core (depth of 2.5 cm and ^{210}Pb-dated to between ~1998 and 2002) (Fig. 3*A*, Fig. S2), marked by a dramatic and synchronous shift from once dominant freshwater taxa to an assemblage now dominated by brackish water taxa. The nature and timing of this major change is consistent with the 1999 storm surge and shows that marine inundation had an immediate and striking ecological impact. Elevated lake water salinity and continued abundance of brackish water diatom taxa in DZO-29 indicates that closed-basin lakes on the outer alluvial plain have not yet recovered from the 1999 storm surge. In contrast, the diatom assemblages from our control location, C-28, remains unchanged during the 1999 storm surge event (Fig. 3*C*), and are composed of a diverse group of freshwater taxa similar to those found in other Arctic lakes with no known history of saline influence (19, 21, 22), including other inland floodplain lakes from this region (20). These freshwater taxa changes reflect recent warming in this region and across the Arctic (19, 21, 23).

Dynamics of the outer Mackenzie Delta front reflect a balance between sediment supply and deposition, augmented by deltaic compaction, eustatics, and permafrost aggradation (24). Variability in the relative importance of these processes through time could alter the position of our study sites relative to the Delta front and make them more/less susceptible to the impacts of marine storm surges. Permafrost at the Mackenzie Delta front is aggrading upward due to sediment deposition and alluvial vegetation succession (24), despite recent warming. This process is expected to continue and outpace deepening of the active layer for at least the next several decades. The majority of alluvial terrain at the Delta front is underlain by permafrost which remains two to three degrees below zero (25). Therefore, we cannot attribute the 1999 event to active layer deepening and surface subsidence. While permafrost is aggrading at the Delta front, the Delta front is also undergoing a period of transgression and has experienced an estimated 2 m/y of coastal retreat over the past ~40 y (26), while relative sea level rise in the Beaufort Sea is estimated at 1–3 mm/y during the past 3,000 y (27). In this dynamic environment, the position of DZO-29 and C-28 with respect to the contemporary coastline may have decreased by 1–3 km over the past 1,000 y; a change that would not alter the sensitivity of the lakes to inundation, given that recent storm surges often flood alluvial surfaces within 20 km of the coast.

When assessing why the ecological impacts of the 1999 marine storm surge were so dramatic, it is also important to consider the role of tidal flooding near the Mackenzie Delta front. Hurricane-driven storm surges, combined with high tides, can lead to significant physical and ecological damage in low-lying, hurricane-prone regions. One possibility is that the 1999 marine storm surge was the combination of a very strong storm and an exceptionally high tide. However, instrumental gauge data indicate that tidal ranges at the Mackenzie Delta front are quite small, normally <0.50 m (27). The data does not support the hypothesis that the 1999 storm surge was the result of an anomalously high tide combined with a powerful storm surge. In fact, many storm surges recorded by water level stations throughout the outer Mackenzie Delta exceed the normal tidal range by a factor of 3–4 times.

As the Arctic warms, sea levels rise, ice cover declines, and the length of the open water season increases, the likelihood and potential impacts of storm surges will be exacerbated in low-lying Arctic coastal environments (3). These changes will impact not only the ecological integrity of Arctic coastal systems, but also the infrastructure and economies of many Arctic coastal communities. In the Mackenzie Delta, increasing exposure to autumn storms and associated surges as sea ice duration decreases may lead to more frequent saltwater intrusions in an ecosystem adapted to freshwater flooding. The ecological impacts of the 1999 storm surge were not matched over the past millennium. The profound and persistent impact to the terrestrial and aquatic systems suggests that an ecological threshold may have been crossed. Ecological trajectories may now favor saline-tolerant vegetation communities, which are currently rare in the outer Mackenzie Delta (28). The changing ecosystem dynamics in the outer Mackenzie Delta represent complex responses to an emerging stressor. As sea levels rise, storm variability increases, and sea ice extent declines during the 21st century, there exists potential for wide-ranging impacts to sensitive coastal environments throughout the circumpolar Arctic. These marine intrusions will also have significant social impacts, as nearly all Arctic indigenous communities are coastal. These communities will need to be prepared as sea ice cover, sea levels, and the frequency and intensity of storms and marine storm surges become more variable in the 21st century.

Materials and Methods

Cross sections were obtained from green alder shrubs in 2006 and 2007. Samples were prepared using standard dendrochronological methods (29), including visual cross-dating and measuring using a Velmex tree-ring measuring system attached to an Accurite digital encoder. Cross-dating was verified using the computer program COFECHA (29) and age-related trends were removed from raw ring-width series using the program ARSTAN (29) prior to aggregating them into the three mean chronologies which were developed based on the apparent health status of the individual alder shrubs when they were sampled.

High-resolution surface sediment cores (30) were obtained from lakes DZO-29 (22.5 cm) and C-28 (7.5 cm) in August of 2009. In May 2010 an additional 1.4 m of sediment was recovered from Lake DZO-29 using a modified Livingstone piston corer (30). Sediment age determination for the last ~150 y was determined using ^{210}Pb and ^{137}Cs radiometric dating techniques (31) (Fig. S2). Two accelerator mass spectrometry radiocarbon dates were obtained from plant and wood fragments recovered from the piston core (Table S2). The surface cores were sampled contiguously at 0.25-cm intervals for the top 15 cm, and 0.5-cm intervals below 15 cm. The piston core was sectioned at 0.5-cm intervals and sampling was contiguous, with every sediment sample analyzed. Integrated samples from each contiguous sediment interval (i.e., every sediment sample was analyzed so there are no gaps in the record) were analyzed for sedimentary diatoms following standard methods (32). A minimum of 300 (surface cores) or 100 (piston core) diatom valves were identified and enumerated for each sample. Fewer diatoms were counted in the piston core due to the large number of samples, as every sediment sample was enumerated, a strategy employed in other studies (33). Standard methods were followed (32) to ensure taxa were not under-represented by this counting strategy.

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