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Arctic epishelf lakes as sentinel ecosystems: Past, present and future

Julie Veillette,[1] Derek R. Mueller,[2] Dermot Antoniades,[1] and Warwick F. Vincent[1]

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[1] Ice shelves are a prominent but diminishing feature of the northern coastline of Ellesmere Island in the Canadian High Arctic (latitude 82–83°N). By blocking embayments and fiords, this thick coastal ice can create epishelf lakes, which are characterized by a perennially ice-capped water column of freshwater overlying seawater. The goal of this study was to synthesize new, archived, and published data on Arctic epishelf lakes in the context of climate change. Long-term changes along this coastline were evaluated using historical reports, cartographic analysis, RADARSAT imagery, and field measurements. These data, including salinity-temperature profiling records from Disraeli Fiord spanning 54 years, show the rapid decline and near disappearance of this lake type in the Arctic. Salinity-temperature profiling of Milne Fiord, currently blocked by the Milne Ice Shelf, confirmed that it contained an epishelf lake composed of a 16-m thick freshwater layer overlying seawater. A profiling survey along the coast showed that there was a continuum of ice-dammed lakes from shallow systems dammed by multiyear landfast sea ice to deep epishelf lakes behind ice shelves. The climate warming recently observed in this region likely contributed to the decline of epishelf lakes over the last century, and the air temperature trend predicted for the Arctic over the next several decades implies the imminent loss of this ecosystem type. Our results underscore the distinctive properties of coastal ice-dammed lakes and their value as sentinel ecosystems for the monitoring of regional and global climate change.

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1. Introduction

[2] Arctic landscapes harbor a great diversity and abundance of freshwater ecosystems, and these are likely to vary in their sensitivity to climate change [*White et al.*, 2007]. Polar aquatic ecosystems that depend upon ice cover and ice dams for their water column structure and integrity may be especially prone to the impacts of future warming. These include stamukhi lagoons that form along the coastal Arctic Ocean each winter [*Galand et al.*, 2008], meltwater lakes on ice shelves [*Mueller et al.*, 2006], perennially ice-covered lakes that are found in Greenland and the Canadian High Arctic [*Van Hove et al.*, 2006], and epishelf lakes that occur behind ice shelves.

[3] Epishelf lakes are highly stratified systems in which a layer of freshwater, derived from ice and snow melt, is dammed behind an ice shelf, defined as thick (>10 m), landfast (attached to the coastline) ice floating on the sea. In the Canadian Arctic, ice shelves are formed mostly by *in situ* accretion of basal and meteoric ice while in Greenland, Franz Josef Land, Severnaya Zemlya and Antarctica, they are derived mainly from the floating extensions of glaciers flowing off the continent [*Williams and Dowdeswell*, 2001]. Mixing of the freshwater and marine layers in epishelf lakes is precluded by strong density stratification and the lack of wind-induced turbulence due to perennial ice cover. The saline bottom waters of Arctic epishelf lakes have a hydraulic connection with the Arctic Ocean, and therefore experience some tidal exchange. The lakes are unique ecosystem types in that they contain freshwater and marine biota within the same water column [*Vincent and Laybourn-Parry*, 2008, and references therein].

[4] Epishelf lakes were first described in Antarctica where there are many known examples: Moutonnée and Ablation lakes adjacent to the George VI Ice Shelf and Alexander Island on the western side of the Antarctic Peninsula [*Heywood*, 1977; *Hodgson et al.*, 2004; *Smith et al.*, 2006], 12 lakes near the Shackleton Ice Shelf in the Bunger Hills Oasis in East Antarctica [*Doran et al.*, 2000; *Gibson and Andersen*, 2002], several in the Schirmacher Oasis [*Richter and Bormann*, 1995] and Beaver Lake, next to the Amery Ice Shelf, also in East Antarctica but located more than 200 km from the open ocean [*Laybourn-Parry et al.*, 2001]. In the Arctic, an epishelf lake existed until recently in Disraeli Fiord, Ellesmere Island, Canada [*Vincent et al.*, 2001]; however this freshwater ecosystem drained as a result of fracturing of the Ward Hunt Ice Shelf between 1999 and 2002 [*Mueller et al.*, 2003].

[1]Département de Biologie et Centre d'Études Nordiques, Université Laval, Québec City, Quebec, Canada.
[2]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska, USA.

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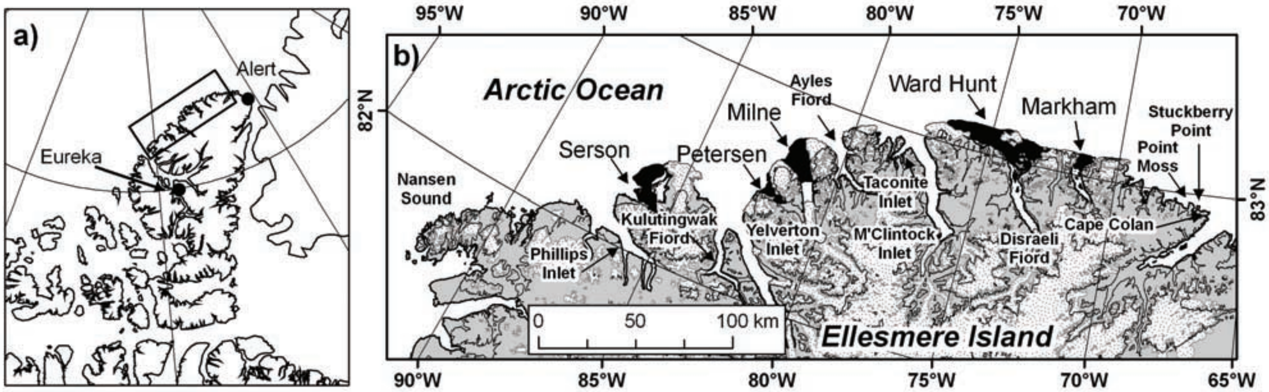

Figure 1. (a) Location map of the study area; (b) map of the northern coastline region, Ellesmere Island, showing the five ice shelves as of June. Labeled ice shelves are indicated in solid black, glaciers are marked in stipple and the contours lines correspond to 200, 1000, and 1800 m.

[5] The rate of climate warming over the last four decades has been up to three times greater in the Arctic than the global average, and climate change will likely continue to be amplified in the polar regions [*ACIA*, 2005; *Anisimov et al.*, 2007; *Serreze et al.*, 2000; *Turner et al.*, 2007]. This recent warming trend, along with a warming phase during the 1930s and 1940s, has resulted in the demise of Northern Hemisphere ice shelves [*Copland et al.*, 2007; *Mueller et al.*, 2003; *Vincent et al.*, 2001]. At the turn of the last century, there was a continuous ice shelf along the northern coastline of Ellesmere Island, from Point Moss to Nansen Sound [*Peary*, 1907]. Radiocarbon dating of driftwood found behind the present-day ice shelves indicate that they formed 3500–5000 years BP [*Evans and England*, 1992], during the period of climatic cooling that followed the mid-Holocene thermal maximum [*Bradley*, 1990]. However, over the course of the 20th century, this vast expanse of ice disintegrated, leaving ice shelf remnants isolated in fiords, inlets and embayments [*Hattersley-Smith*, 1963, 1967; *Jeffries*, 1986, 2002; *Jeffries and Serson*, 1983; *Koenig et al.*, 1952; *Vincent et al.*, 2001]. Ice shelf disintegration has continued during the last decade, leaving in 2007 five main ice shelves totaling ~950 km^2 in area [*Copland et al.*, 2007; *Mueller et al.*, 2003]. These ice shelf losses are likely irreversible, since no signs of regrowth have been observed [*Copland et al.*, 2007].

[6] Ice shelves are known to be sensitive indicators of climate change [*Jeffries*, 2002; *Mercer*, 1978; *Vaughan and Doake*, 1996]. By extension, epishelf lakes may also be indicative of climate conditions, given that their existence is intimately linked to ice shelf integrity, and their depth is representative of the minimal thickness of the ice that restrains them [*Keys*, 1977]. Similarly, shallow ice-dammed lakes, which may remain following ice shelf loss, are sensitive to changes in the thickness and integrity of multiyear landfast sea ice. The objectives of the present study were to evaluate the structure of ice-dammed lake ecosystems of the northern coastline of Ellesmere Island and their potential as indicators of climate change. We evaluated the questions: how many ice-dammed lakes existed during the 20th century, how many currently occur along the northern coastline of Ellesmere Island, how have they changed over this period, and do these changes correspond to variations in air temperature? To address these questions we analyzed maps, aerial photographs, satellite imagery and climate station records, and we retrieved and analyzed all available hydrographic data from expeditions dating back to 1954, including previously unpublished records. We then determined the extent of recent changes in the extant ice-dammed lakes by analyzing profiling data, synthetic aperture radar (SAR) scenes and field observations. Finally, we explored remote-sensing as a complementary method to in situ profiling of the lakes in order to evaluate its effectiveness for monitoring future environmental change in the coastal High Arctic environment.

[7] The study area encompassed the northern coastline of Ellesmere Island (~83°N), between Cape Colan (66°20′W) and Nansen Sound (92°W), Nunavut, at the northern limit of Canada (Figure 1). Ward Hunt Island air temperature data were collected by meteorological stations of the Centre d'études nordiques/ArcticNet (2005–2007) and Parks Canada (1995–2005). Air temperature data from 1950 to 2006 were obtained for Alert, located 84 km from the eastern boundary of the study area, from the Meteorological Service of Canada website (www.weatheroffice.gc.ca, last accessed December 2007). There was no overall trend in mean annual temperatures at Alert for the period 1951 to 2005 (Figure 2a), with the early part of this record showing an initial phase of cooling (1951 to 1975). However, when only the last three decades were considered (1976 to 2005), mean annual temperatures have risen at an average rate of 0.46°C decade^{-1} ($p = 0.02$). A more detailed seasonal analysis of this 30 year period showed that there was large and significant warming in autumn (+1.00 °C decade^{-1}, $p = 0.004$), but that the warming trends were not significant in summer (+0.26°C decade^{-1}, $p = 0.14$), winter (+0.25°C decade^{-1}, $p = 0.35$) or spring (+0.56°C decade^{-1}, $p = 0.16$). Seasonal mean air temperatures at Ward Hunt Island (1995 to 2007) adjacent to Disraeli Fiord (see Figure 2b for the annual cycle of mean annual temperature 2006 to 2007) were highly correlated with temperature values at Alert (p <

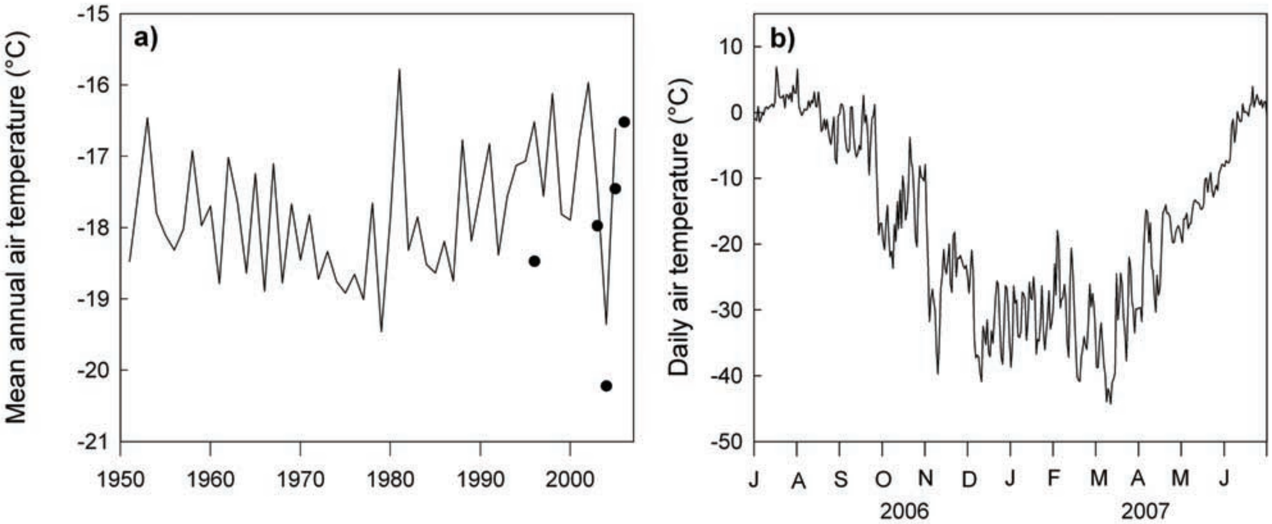

Figure 2. (a) Air temperature trends for Alert (1951 to 2005) (solid line) and Ward Hunt Island (several years between 1994 and 2006) (solid dots); (b) the annual cycle of mean daily air temperature 2006 and 2007 at Ward Hunt Island.

0.0001) and were significantly lower by an average of 1.19°C ($p < 0.0001$).

2. Methods

[8] For our assessment of past potential epishelf lakes over the last century, we considered the 450 km stretch of coastline corresponding to the extent of the Ellesmere Ice Shelf (glacial fringe) described by the Peary expedition at the beginning of the 20th century [*Peary*, 1907]. Within this region, all fiords, embayments and inlets of more than 10 km in length were identified as potential epishelf sites. Data from 1960 were obtained from Canadian National Topographic System map sheets 560D, 340F&560E, 340E&H, 120F&G, and data from 2007 and 2008 were collected using satellite images and field measurements. We considered the probable existence of an epishelf lake at each fiord, embayment or inlet where the ice shelf was clearly blocking its mouth or when a salinity profile indicated its presence. Profiles of temperature and salinity were taken with an XR-420 CTD (conductivity-temperature-depth profiler; RBR Ltd., Ottawa, Canada), which was lowered through drilled holes or natural openings in the ice cover, with the exception of profiles from Milne Fiord in 1983 and Ayles Fiord in 1986 that were measured using a 1 L Knutsen bottle, an Endeco refracting salinometer (YSI Inc., Marion, MA, USA) and reversing thermometers (M. O. Jeffries, unpublished data, 1983, 1986). RADARSAT-1 SAR data were converted to normalized radar cross section (σ^0), terrain-corrected, georeferenced and mosaicked. Our data set consisted of three standard beam images from January 2005 to April 2006 and 16 fine beam images from mid-January to early February 2007. Areas with ice-dammed lakes confirmed by profiling, and blocked by an ice shelf or multiyear landfast sea ice, were examined with mid-winter fine beam SAR scenes. Histograms of backscatter in these regions indicated that ice-dammed lakes had radar returns that typically exceeded −6.0 dB whereas sea and ice shelf ice had lower backscatter. SAR images were gamma filtered with a 3 × 3 kernel to remove speckle and then were segmented to delineate contiguous regions with a backscatter coefficient exceeding −6.0 dB. Only the surface areas of ice-dammed lake segments greater than 1 km^2 were assessed. MODIS imagery was obtained from NASA.

3. Results

3.1. Past and Present Status of Arctic Epishelf Lakes

[9] A continuous ice shelf fringe existed on Ellesmere Island's northern coast in 1906 [*Peary*, 1907], and cartographic inspection and identification of bays and fiords suggests that this may have retained up to 17 epishelf lakes. By 1960, this number had been reduced to nine due to the disintegration of the "Ellesmere Ice Shelf". Five major ice

Table 1. The Surface Area of Ice-Dammed Lakes Along the Northern Coast of Ellesmere Island as Detected Using RADARSAT-1 SAR Imagery[a]

Ice-Dammed Lake	Area (km^2)	Depth (m)	Volume (km^3)
Stuckberry	2.4	–	–
Moss	2.0	–	–
Disraeli (1999)	143.0	28	4.00
M'Clintock	291.8	–	–
Taconite	27.9	3.7	0.10
Ayles	118.9	1.6	0.19
Milne	39.8	16.0	0.64
Kulutingwak	10.3	–	–
Serson	35.0[b]	4.1	0.31
Phillips	9.5	–	–

[a]The depth of the 3 ppt isohaline is indicated when profile data were available (Taconite: 2005; Ayles: 2007; Milne: 2007; Serson: 2004). For comparison, data are given for Disraeli Fiord in 1999 before the break-up event. The volume of low salinity water was then calculated, assuming the walls of ice-dammed lakes to be vertical and including the ice cover volume. – : not known.

[b]The total area is 76.0 km^2 including the 'suture' ice.

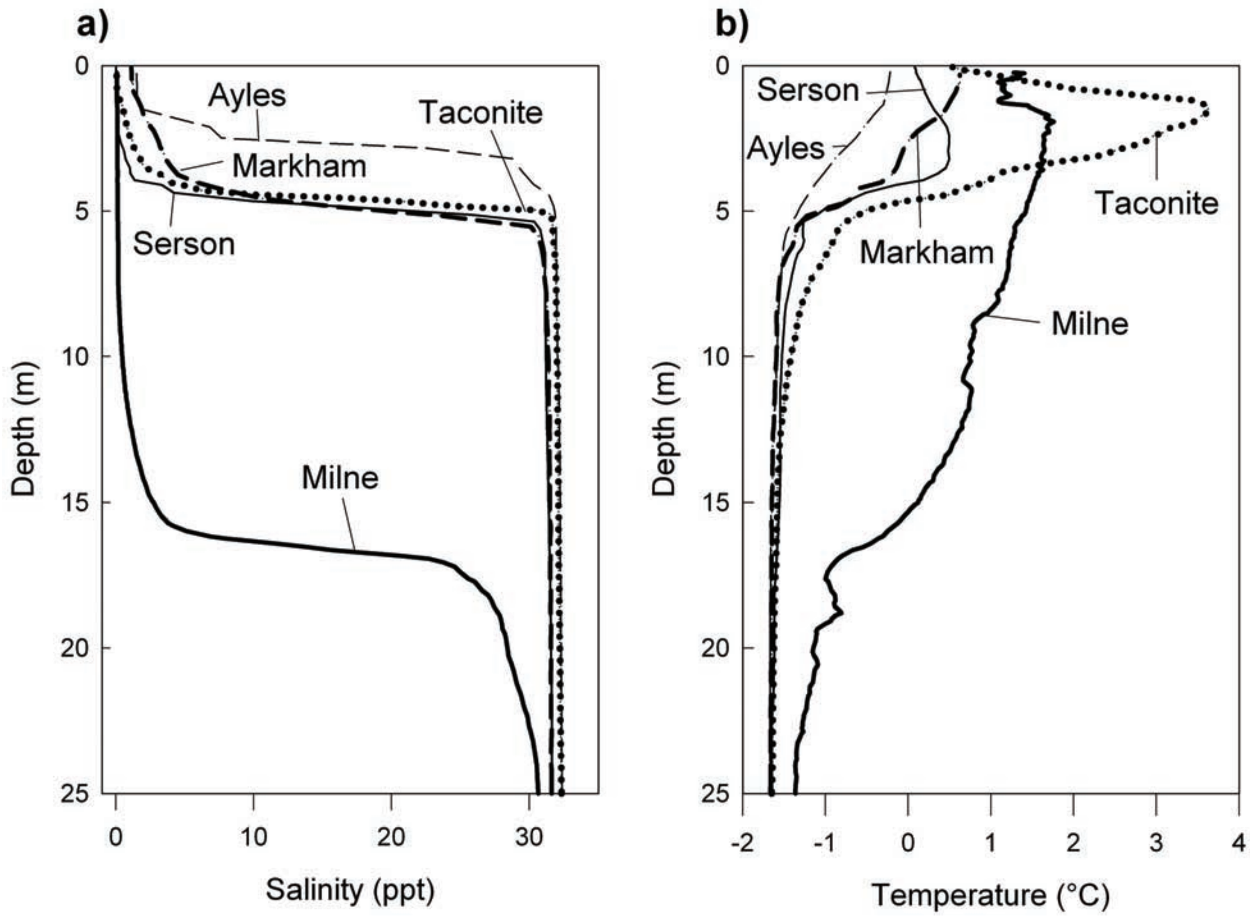

Figure 3. Stratification in Northern Ellesmere fiords and embayments. (a) Salinity profiles; (b) temperature profiles. Profiles were taken 6 August 2004 for Serson Bay, 3 August 2005 for Taconite Inlet, 30 May 2006 for Ayles Fiord, 12 July 2007 for Markham Fiord, and 13 July 2007 for Milne Fiord.

shelf remnants remained in June 2008 due to subsequent reduction and fragmentation, and Milne Fiord now appears to be the sole remaining deep epishelf lake in the Arctic. SAR imagery detected the presence of nine ice-dammed lakes from Cape Colan to Nansen Sound (Table 1).

3.2. Profiles of Temperature and Salinity

[10] Our field measurements (2004 to 2007) along the northern coast of Ellesmere Island showed that five fiords or embayments contained ice-dammed lakes. Their patterns of salinity and temperature stratification can be seen in Figure 3. The salinity gradient across the halocline of these systems was sharp, reaching, for example, a maximum difference of 11 ppt per meter in Milne Fiord. This fiord had the thickest freshwater layer in 2007, with a halocline at 16 m and a freshwater volume of 0.64 km^3 (Table 1). Milne Fiord was first profiled in 1983 (M. O. Jeffries, unpublished data, 1983) at which time the freshwater layer was 17.5 m thick (Figure 4a). The halocline depth appears to have remained relatively stable over the subsequent 24 years, with a recorded depth of 16 m in 2007 (Figure 4a). Serson Bay, Taconite Inlet, Ayles and Markham Fiord had very similar salinity profiles, with haloclines at depths of 2 to 5 m, indicating much thinner freshwater layers relative to Milne Fiord (Figure 3 and Table 1). Previous studies reported a 7 m thick freshwater layer behind Serson (formerly known as Alfred Ernest) Ice Shelf in May 1986 [*Jeffries*, 2002], a 5.5 m thick layer in Taconite Inlet in 1992 [*Ludlam*, 1996], and a 4 m thick layer in Ayles Fiord in 1986 (M. O. Jeffries, unpublished data, 1986) (Figure 4b). Our profiles (Figures 3 and 4c) are the first data showing the presence of a freshwater layer in Markham Fiord. The surface water salinities of these fiords or embayments were fresh to slightly brackish (<1.5 ppt). In all systems, water temperatures ranged from −1.5 to 0.3°C in the saltwater layers and from near zero to 3.6 °C in the freshwater layers.

[11] The recent dynamics of Milne, Markham and Ayles fiords suggest that there is interannual variation in their freshwater layers (Figure 4), with slight differences in thickness between 1983 and 2007 in Milne Fiord, between 2004 and 2007 in Markham Fiord and between 1986 and 2007 in Ayles Fiord. These profiles also emphasized the quasi-stability on decadal timescales of Milne and Ayles fiord stratification. Surface salinity varied by a factor of three (1 to 3 ppt) in Markham Fiord from 2004 to 2007 and by a factor of two (0.65 to 1.5 ppt) in Ayles Fiord between 2006 and 2007.

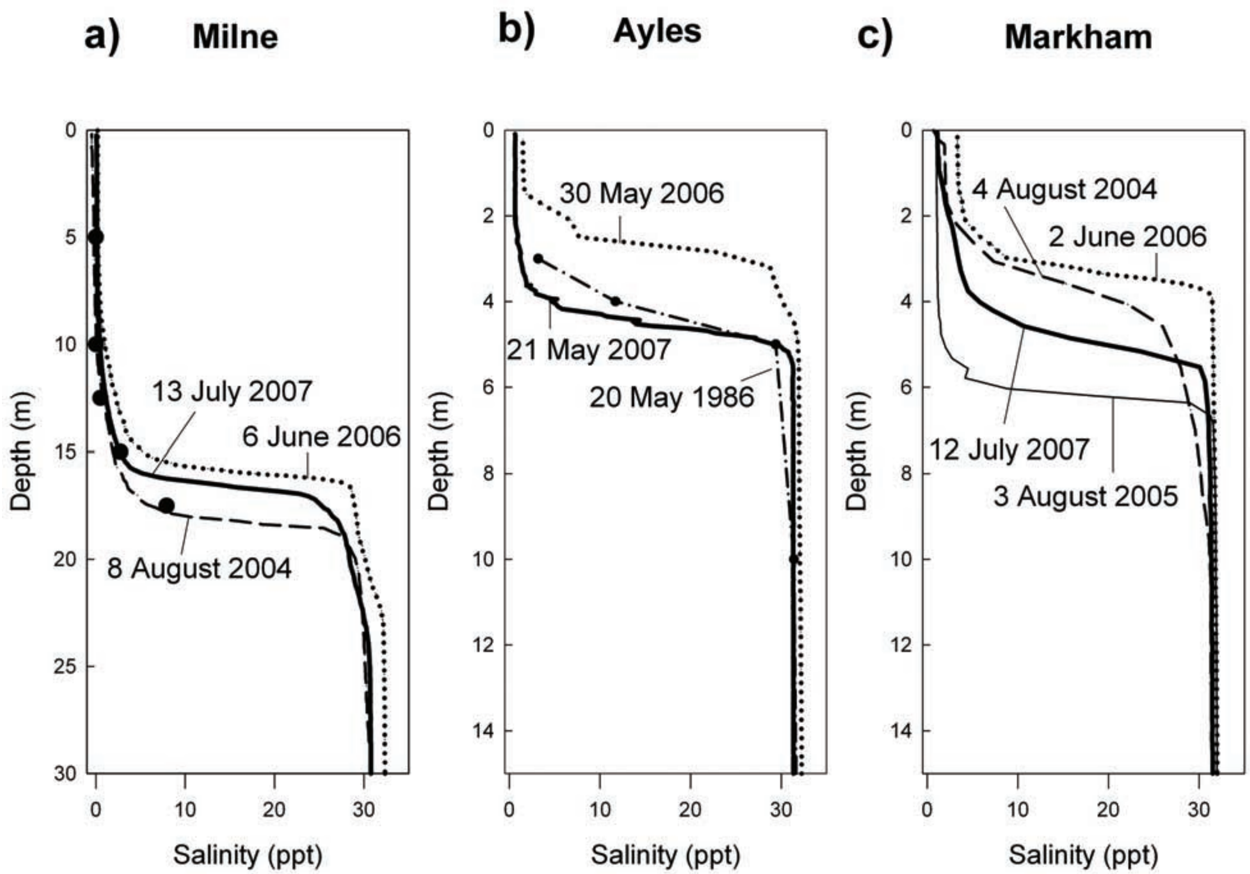

Figure 4. Interannual variation in stratification for: (a) Milne Fiord, (b) Ayles Fiord, and (c) Markham Fiord. Note the different depth scales for the three panes. Solid dots in the Milne Fiord pane correspond to data from May 1983.

[12] The first measurements of water column stratification in Disraeli Fiord were taken in 1954, at which time the freshwater layer was observed to be 63 m thick [*Crary*, 1956] (Figure 5a). The ten subsequent salinity profiles from this fiord illustrate a dramatic change in water column stratification since that time (Figure 5a). Profiles indicate that the freshwater layer gradually diminished between 1960 and 1999, by which time it had been reduced to 33 m in thickness (Figure 5b). However a fracture running the full north-south extent of Ward Hunt Ice Shelf appeared in 2001 and 2002 which resulted in the complete drainage of freshwater from this large epishelf lake [*Mueller et al.*, 2003]. All five profiles taken between 2002 and 2008 show a complete absence of freshwater (Figure 5a), and no indication of a return to ice-dammed epishelf conditions.

3.3. Ayles Ice Shelf and Fiord After Break-up

[13] In August 2005 almost the entire Ayles Ice Shelf broke off and created an ice island in the Arctic Ocean (Figure 6a; details in *Copland et al.* [2007]). We estimated the freeboard of the resultant Ayles Ice Island several months after the break out to be about 6 m (Figure 6b), indicating a total ice thickness of about 40 m. Ground penetrating radar subsequently gave measurements of ice thickness of 42 to 45 m [*Copland et al.*, 2007]. SAR imagery shows the presence of freshwater at the bottom of the ice cover in Ayles Fiord before and after the calving event (Figure 7). A change in the extent of freshwater was indicated in April 2006 (Figure 7c). At this time, the backscatter coefficient decreased at the mouth of the fiord and to the eastern side of the fiord, consistent with the infiltration of brine into the bottom of this ice cover [*Jeffries*, 2002]. However an examination of mid-winter SAR imagery from 2007 (Figure 7d) indicates that these changes were temporary and that the fiord ice returned to normal in the intervening months.

4. Discussion

4.1. Past and Present Status of Arctic Epishelf Lakes

[14] Our cartographic analysis of the northern coastline of Ellesmere Island revealed that many epishelf lakes were likely to have been present in this region 100 years ago. Multiyear landfast sea ice is still extensive along Ellesmere Island's northern coast. It currently replaces areas previously occupied by ice shelves [*Jeffries*, 2002], and has formed several draft ice-dammed lakes (e.g., M'Clintock Inlet). Profiles measured in our study indicated the existence of ice-dammed lakes in Serson Bay (2004), Markham Fiord (2007), Taconite Inlet (2005), Ayles Fiord (2007) and Milne Fiord (2007) while satellite imagery analyses from *Jeffries* [2002] suggested the presence of a freshwater layer in Kulutingwak Fiord, Ayles Fiord, Taconite Inlet and M'Clintock Inlet. Several of the nine ice-dammed lakes

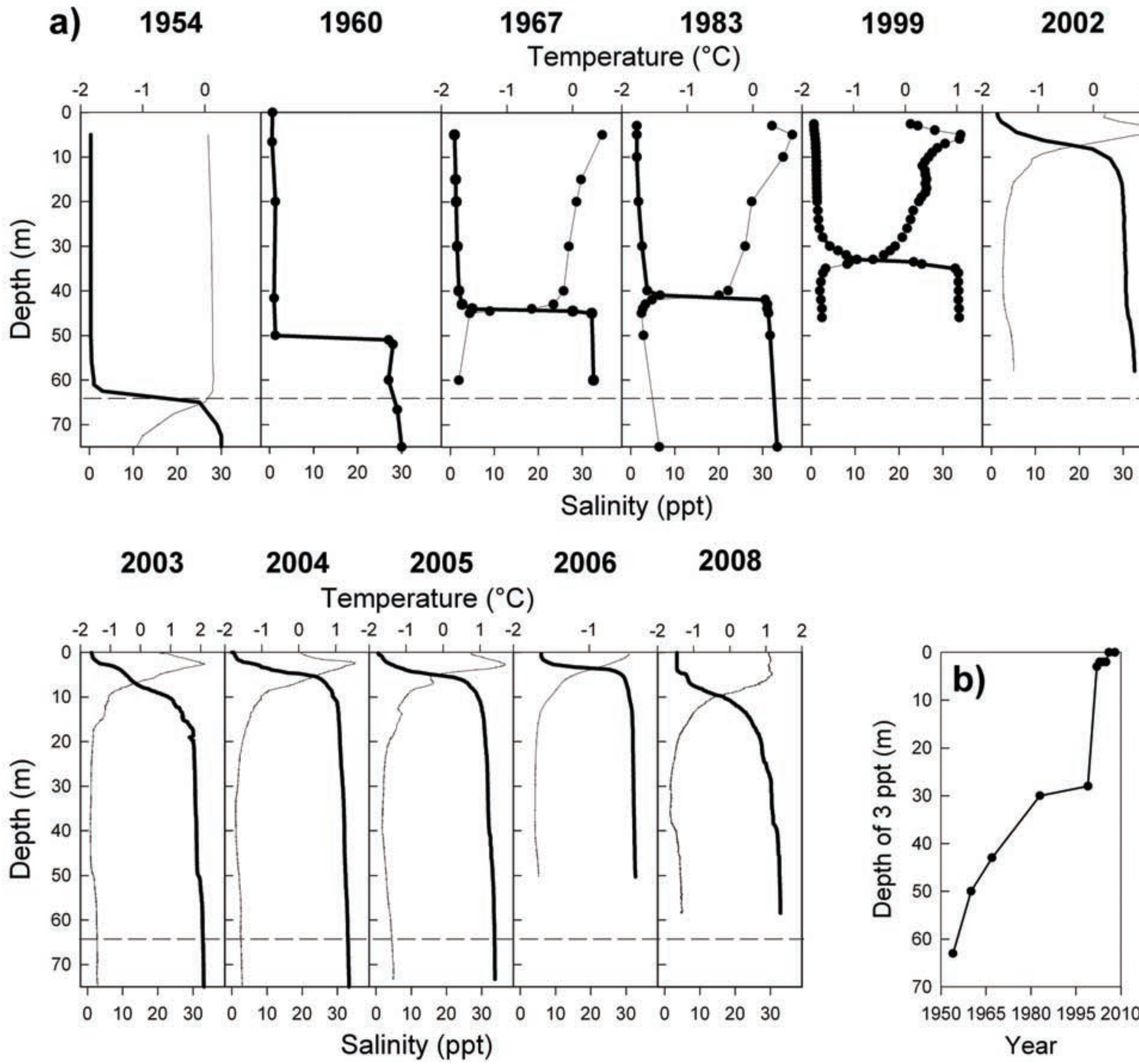

Figure 5. (a) Time series of salinity (dark line) and temperature (pale line) profiles of Disraeli Fiord, from 1954 to 2008. The dashed line indicates the depth of the halocline in 1954. Profile data are from 18 September 1954 [*Crary*, 1956]; September 1960 [*Lyons and Leavitt*, 1961]; June 1967 [*Keys et al.*, 1968]; May 1983 [*Jeffries and Krouse*, 1984]; 9 June 1999 [*Vincent et al.*, 2001]; 28 July 2002 [*Mueller et al.*, 2003]; 1 August 2003, 5 August 2004, 3 August 2005, 27 May 2006 and 19 August 2008 (present study); (b) epishelf lake depth as measured by depth of the 3 ppt isohaline, from 1954 to 2008.

that were detected using SAR imagery (Moss, Stuckberry, and Phillips Inlet) have not been profiled, therefore their surface freshwater status is unconfirmed. Our SAR methodology failed to detect a freshwater layer in Markham Fiord. This is likely due to salt intrusion into the ice which absorbs radar. Either this system is periodically mixed or its freshwater layer is so new that salts have not yet been flushed from the ice cover. A 41 km^2 portion of the Serson ice-dammed lake was also not detected using SAR, likely due to the texture of this unique ice type known as "suture ice" [*Jeffries*, 2002]. There are likely to be several small ice-dammed lakes (<1 km^2) that were not detected with our SAR methodology.

[15] This survey shows that profiling and SAR imagery provide complementary information for the monitoring of ice-dammed lakes. However direct profiling is the only method that can detect with certainty the presence of an epishelf lake, as SAR imagery analysis is limited to the detection of freshwater below the ice cover, and does not indicate its thickness. Moreover, there may be a time lag before a freshwater layer can be detected by the SAR methodology, while profiling provides immediate data. On the other hand, the advantage of SAR imagery is that it provides integrative observations, since this methodology will only detect ice-dammed lakes that have been stable for several years, and it allows a degree of spatial coverage and

Figure 6. Imagery of the Ayles Ice Shelf after the break-up event. (a) MODIS image showing Ayles Ice Island moving away from Ayles Fiord (13 August 2005, 19:05 UTC); (b) Ayles Ice Island, 30 May 2006; the freeboard was estimated as 6 m, giving a total ice thickness of ca. 40 m.

sampling that is logistically impossible in this vast, far northern region.

4.2. Physical Structure of Extant Arctic Ice-Dammed Coastal Lakes

[16] Following the demise of the Disraeli Fiord epishelf lake in 2002, Milne Fiord represents the only known deep Arctic epishelf lake (Figure 3). The northwest section of the Milne Ice Shelf calved between 1959 and 1974 [*Jeffries*, 1986]. This area refilled with multiyear ice, which calved in 1988 [*Jeffries*, 1992] and again in 2005 [*Copland et al.*, 2007]. However these events were relatively minor and do not appear to have disrupted the stratification in Milne Fiord. Given its status as the deepest and most stable of northern epishelf lakes, it is an attractive site for future monitoring of climate effects. At present, Milne Fiord is completely dammed by the Milne Ice Shelf, the second largest of the Ellesmere ice shelves. This ice shelf is currently 20 km in length and extends from the mouth of the fiord to the edge of the epishelf lake. *Jeffries* [1984] suggested that a large portion of the Milne Ice Shelf is composed of relict glacial tongues. The central unit of this ice shelf is influenced by glacial ice and is estimated to be up to 100 m thick [*Narod et al.*, 1988]. This is unusually thick relative to the neighboring Ayles Ice Shelf, which was 42 to 45 m in May 2007, almost 2 years after calving [*Copland et al.*, 2007] and the Ward Hunt Ice Shelf, which reached thicknesses up to 63 m [*Crary*, 1956]. However our profiles suggest that the Milne Ice Shelf has a minimum thickness of 16 m as indicated by the depth of the freshwater layer. The persistence of the Milne Ice Shelf and its adjacent epishelf lake is likely influenced by several geomorphological factors. The Milne Ice Shelf is glacially thickened by inflowing ice from both sides, which keeps the ice shelf pinned in place. It is also located in a long fiord with very little of its perimeter exposed to calving, and is strongly influenced by the presence of the Milne Glacier at the fiord's head, which was shown to be surging as recently as 1983 [*Jeffries*, 1984].

[17] The large variations in the surface salinity of Markham and Ayles fiords between profiling dates were likely due to seasonal effects, reflecting ice melt and runoff during the summer [*Ludlam*, 1996]. The Markham, Taconite, Ayles and Serson sites cannot accumulate a thick freshwater layer because they are impounded by multiyear landfast sea ice, which may be accompanied by an incomplete ice shelf dam. These shallow ice-dammed lakes are intermediate systems between epishelf lakes that are dammed completely by an ice shelf and open fiords with no ice dam. Given the sensitivity of landfast sea ice to climate warming [*Flato and Brown*, 1996], these fiords and embayments are likely to be sensitive to further changes in the High Arctic climate regime. In theory, these systems may be incipient deep epishelf lakes if the multiyear landfast ice thickens; however this is highly unlikely given current and projected climate warming. Similarly, *Copland et al.* [2007] suggest that ice shelves are not currently viable in the Arctic since they are unable to regenerate under actual climate conditions. In the past, Arctic ice shelves and their associated epishelf lakes may have repeatedly formed and dispersed due to changes in climatic variables such as air temperature, which controls ice melt and can influence the magnitude and temperature of meltwater runoff from land, or offshore winds, which act to move fractured shelf ice away from the coast. Oceanographic factors may also accelerate ice shelf break-up, including changes in currents or water temperature, mechanical effects associated with tides, low sea ice conditions or reduced pack-ice pressure. The latter sea ice effects are increasingly favored by the ongoing decreases in total Arctic sea ice extent [*Holland et al.*, 2006; *Serreze et al.*, 2007]. Major changes have also been observed in circulation and temperature of the Arctic Ocean over the second half of the 20th century [*Carmack et al.*, 1998], and these may have contributed to the ice shelf thinning and resultant loss of epishelf lake volume in Disraeli Fiord. At Alexander Island in the Antarctic Peninsula region, sedimentary records from an epishelf lake indicate that there were periods of ice shelf absence during the Holocene [*Bentley et al.*, 2005; *Roberts et al.*, 2007; *Smith et al.*, 2007]. These aspects emphasize the dynamic nature of epishelf lakes and thus their value as indicators of change.

[18] The correspondence between halocline and thermocline depths in Milne Fiord, as well as in Serson Bay, Taconite Inlet, Ayles and Markham Fiord (Figure 3), is related to the presence of cooler sea water [*Keys*, 1977], which acts as a heat sink and prevents the freshwater layer

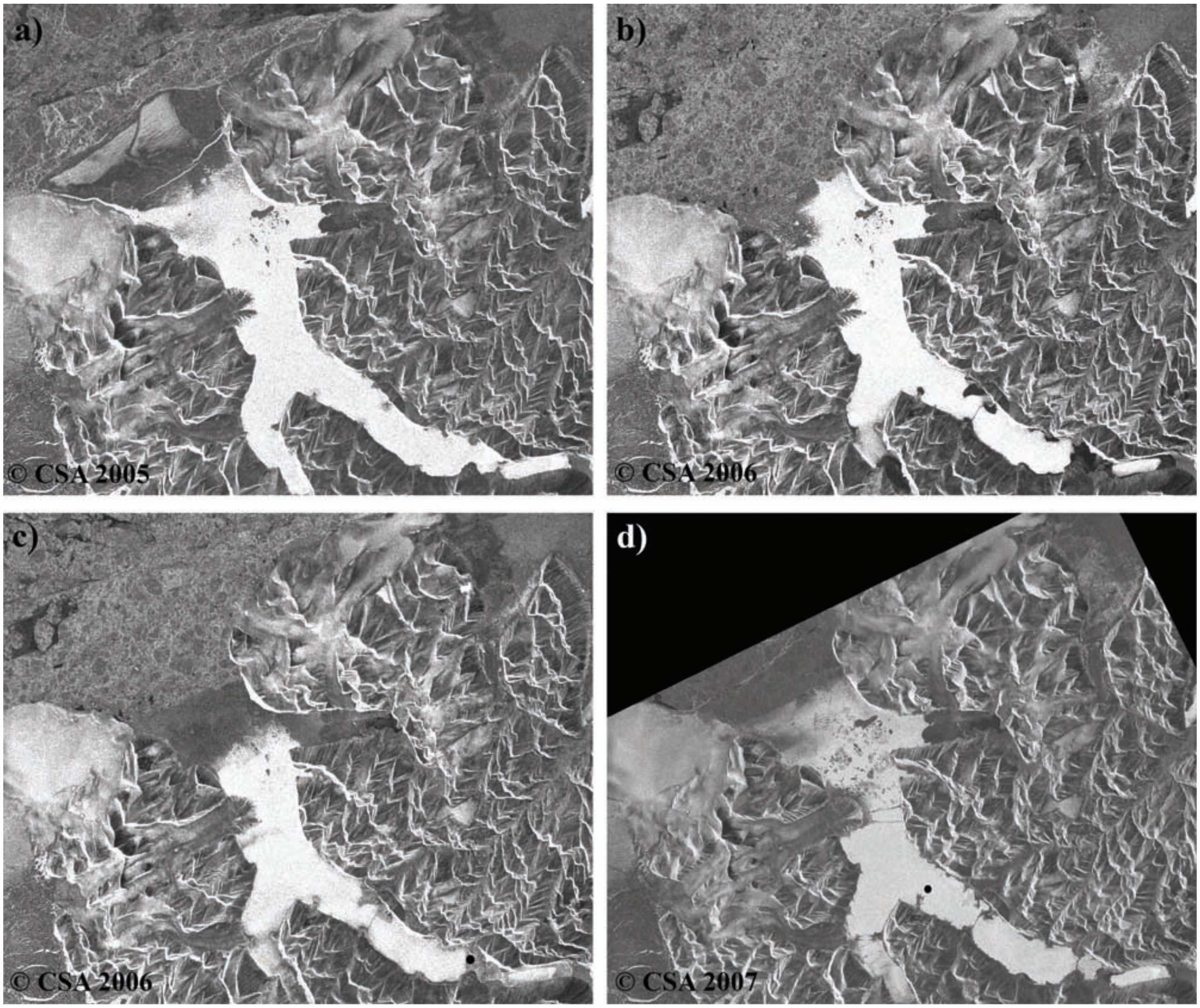

Figure 7. Standard and fine beam RADARSAT-1 images of Ayles Fiord, Nunavut, Canada in (a) January 2005 prior to the Ayles Ice Shelf calving; (b) in January 2006, 5 months after the calving; (c) April 2006; and (d) January 2007. The dots on (c) and (d) indicate the positions of the profiles. The backscatter throughout most of the fiord remained high after the break-up event which suggests that the ice-dammed lake in Ayles Fiord was not lost. However, the darkening at the northern margin and the northeastern arm of the fiord in April 2006 indicates a change in the fiord ice which subsequently recovered (d).

from attaining higher temperatures. Temperature profiles were typically complex, with two temperature maxima. The first maximum, just below the ice cover, results from heating by solar radiation. The second, smaller temperature peak, located just above the thermocline, may result from heat released during the formation of frazil ice which then floats up and contributes to the ice cover [*Keys*, 1977].

4.3. Recent Dynamics of Arctic Ice-Dammed Lakes

[19] Some of the interannual variation in the freshwater layers of Milne, Markham and Ayles fiords is likely the result of tidal cycles, although the tidal range is of low amplitude in this region (0.1 m to 0.2 m at Disraeli Fiord, Fisheries and Oceans Canada; www.tides.gc.ca, last accessed June 2008). Tides have also been suggested to influence halocline depth in Ablation Lake on the Antarctic Peninsula [*Smith et al.*, 2006] and to create turbulent mixing at the halocline in epishelf lakes of the Bunger Hills, where the tidal range is ~1.3 m [*Gibson and Andersen*, 2002]. *Keys* [1977] suggested that a tidally-driven internal wave influenced the depth of the halocline in Disraeli Fiord in 1967, and this effect may have contributed to the profiles we observed in other fiords as well. Circulation of water masses in these fiords could also contribute to these variations. A shoulder was present at the end of the halocline in several of our profiles (16 to 23 m in Milne Fiord in 2006 and 2007, Figure 4a; 3 to 5 m in Ayles Fiord in 2006, Figure 4b), and was also noted in measurements of Disraeli Fiord in 1967 [*Keys*, 1977]. This anomaly could be caused by an inflow of "warmer" freshwater that sinks as an interflow to the halocline due to its greater density [*Retelle and Child*, 1996], and pushes the halocline down-

ward [*Keys*, 1977]. Shear friction of freshwater flowing to the Arctic Ocean underneath the ice shelf could also further deepen the halocline.

[20] Disraeli Fiord has been visited by scientific expeditions for half a century, and our compilation of all available records provides a remarkably long-term picture of the decline, final collapse and lack of recovery of this epishelf lake system. We interpret the higher rate of decrease in depth of the epishelf lake contained in Disraeli Fiord between 1999 and 2002 as evidence of the formation of a narrow, river-like fissure in the ice shelf that developed into a complete fracture, which drained the freshwater layer into the sea. Since 2002, Disraeli Fiord has essentially functioned as an estuarine system, and no longer contains freshwater at its surface.

4.4. History and Status of the Ayles Epishelf Lake

[21] In the 1950s, the Ayles Ice Shelf spanned the mouth of Ayles Fiord and was approximately 100 km^2 in area [*Jeffries*, 1986]. In the early 1960s this ice shelf broke up and drifted 4 km to the northwest, where it froze in for four decades [*Copland et al.*, 2007; *Jeffries*, 1986]. This break-up event [*Jeffries*, 1986] would likely have destroyed any stratification in the Ayles Fiord epishelf lake had it existed prior to that point. Multiyear landfast sea ice grew at the mouth of the fiord during the 1970s, at which point stratification was likely re-established in the ice-dammed fiord. However no profile data are available prior to 1986, when a thin freshwater layer of $\sim$4 m was present (Figure 4b). Remotely-sensed SAR data from 1992 to 2005 suggest that the water directly underneath the fiord ice cover was fresh during this period (D. R. Mueller, unpublished data, 2007). Profile data collected in May 2006 and May 2007 suggest that the thin freshwater layer that was present in Ayles Fiord since the 1980s remained in place after the 2005 break-up event (Figure 4b and 7). This suggests that a plug of multiyear landfast sea ice ($\geq$5m in thickness) still remains across the mouth of Ayles Fiord and was unaffected by the break-up event of 2005. The thickness of the epishelf lake in 1986 was similar to that currently dammed by multiyear sea ice, but was far less than that of the Ayles Ice Shelf itself. This implies that the multiyear ice which reformed in the mouth of Ayles Fiord following the detachment of the ice shelf in the 1960s was approximately the same thickness as that observed today. Evidence from SAR imagery supports the profile results, showing the presence of freshwater at the bottom of the ice cover before and after the 2005 calving event (Figure 7).

4.5. Epishelf Lakes in Other Regions

[22] The existence of epishelf lakes in areas of the Arctic other than the coast of Ellesmere Island is unlikely. In Greenland, satellite images show glaciers that feed into fiords rather than blocking them [*Higgins*, 1989], leaving no space for the accumulation of freshwater. In Svalbard, ice shelves do not exist because all glacier fronts terminating at the sea are grounded [*Liestøl*, 1993]. A few glacier-fed ice shelves have been reported from the Russian archipelagos of Franz Josef Land and Severnaya Zemlya [*Dowdeswell et al.*, 1994; *Williams and Dowdeswell*, 2001], but no epishelf lakes have been reported from these areas.

[23] Ice shelves are extensive along the coasts of Antarctica, and some retain much deeper epishelf lakes than those in the Arctic. Among them, Beaver Lake is characterized by a freshwater layer estimated to be between 170 to 270 m deep [*Laybourn-Parry et al.*, 2001], and the largest and deepest of the epishelf lakes of the southern Bunger Hills, Transkriptsii Gulf, had a freshwater layer of $\sim$85 m in 1992 and 2000 [*Gibson and Andersen*, 2002]. In the Antarctic Peninsula region, some ice shelves have undergone substantial disintegration in the last decades [*Vaughan and Doake*, 1996], but there has been no clear effect on epishelf lakes to date. Moutonnée Lake had a freshwater layer of 36 m in 2001 but was $\sim$10 m deeper in 1973 [*Smith et al.*, 2006]. Ablation Lake, 5 km away, did not show this trend with a stable halocline at $\sim$65 m between 1973 and 2001 [*Smith et al.*, 2006]. The authors argue that seasonal variation might explain these observed changes and a thinning of the ice shelf may not be responsible. Long-term monitoring of epishelf lakes located on the Antarctic Peninsula is crucial since they are vulnerable to future ice shelf disintegration. For example, the George VI Ice Shelf, 100 to 500 m in thickness, is predicted to be close to its theoretical limit of stability [*Vaughan and Doake*, 1996]. The rapid warming trend recorded on the Antarctic Peninsula has not been observed on the remainder of the continent [*Turner et al.*, 2007] and therefore most Antarctic epishelf lakes are not presently threatened.

4.6. Prospects of Extant Arctic Ice-Dammed Lakes in Relation to Climate Change

[24] The substantial warming observed at Alert during the thirty year period 1976 to 2005 forewarns the much greater changes that are projected for the northern coast of Ellesmere Island in the future: the Fourth IPCC report predicts a surface air temperature increase in this region of 6 to 7°C for the period 2090 to 2099 relative to the period 1980 to 1999 [*Solomon et al.*, 2007]. The high correlation between seasonal mean air temperatures at Ward Hunt Island and Alert suggests that, although microclimates may be moderated by local environmental factors, temperature trends are consistent throughout our study area. The recent loss of epishelf lakes is likely related to the increase in temperature over the last three decades. An earlier warming phase during the 1930s and 1940s [*Vincent et al.*, 2008] would have resulted in the loss of many epishelf lakes at that time. The current warming trend has wide ranging implications for the Arctic including the reduction in sea ice area and thickness [*Holland et al.*, 2006; *Serreze et al.*, 2007], and changes in oceanic circulation patterns [*Carmack et al.*, 1998]. These changes might expose ice shelves to additional stresses and contribute to their break-up. Multiyear landfast sea ice is also sensitive to climate warming [*Flato and Brown*, 1996] and large losses of this ice type have been recently observed along the northern coastline of Ellesmere Island [*Copland et al.*, 2007], implying that shallow ice-dammed lakes may be prone to future loss. Numerous impacts of recent warming have been detected in the Ellesmere Island region. For example, ponds have dried up, perhaps for the first time in millennia [*Smol and Douglas*, 2007], lake diatom communities and sedimentary pigment concentrations have changed dramatically during the last two centuries

[*Antoniades et al.*, 2007, and references therein], and lake ice cover duration and extent are diminishing (D. R. Mueller et al., unpublished data, 2007).

5. Conclusions

[25] Epishelf lakes are effective integrators of change since their presence depends on ice shelf integrity and their depth is a proxy measure of the minimum thickness of their ice dam. Milne Fiord may contain the last remaining deep epishelf lake in the Arctic, and is now a key site for environmental monitoring. The numerous existing deep epishelf lakes in the Southern Hemisphere may also provide important insights into the magnitude, rate and regional variations of climate change. Similarly, the status of lakes dammed by multiyear landfast sea ice can indicate changes in sea ice extent and, as shown here, SAR imagery provides an excellent option for ongoing monitoring. This ecosystem type, represented today by the epishelf lake contained in Milne Fiord and by shallower ice-dammed lakes along the northern coastline of Ellesmere Island, is vulnerable to complete disappearance as a result of ongoing climate change.

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D. Antoniades, J. Veillette, and W. F. Vincent, Département de Biologie et Centre d'Études Nordiques, Université Laval, 1045 avenue de la Médecine, Québec City, QC, Canada G1V 0A6. (julie.veillette.2@ulaval.ca)

D. R. Mueller, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks, AK 99775-7320, USA.