Extreme ecosystems and geosystems in the Canadian High Arctic: Ward Hunt Island and vicinity[1]

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Abstract: Global circulation models predict that the strongest and most rapid effects of global warming will take place at the highest latitudes of the Northern Hemisphere. Consistent with this prediction, the Ward Hunt Island region at the northern terrestrial limit of Arctic Canada is experiencing the onset of major environmental changes. This article provides a synthesis of research including new observations on the diverse geosystems/ecosystems of this coastal region of northern Ellesmere Island that extends to latitude 83.11° N (Cape Aldrich). The climate is extreme, with an average annual air temperature of –17.2 °C, similar to Antarctic regions such as the McMurdo Dry Valleys. The region is geologically distinct (the Pearya Terrane) and contains steep mountainous terrain intersected by deep fiords and fluvial valleys. Numerous glaciers flow into the valleys, fiords, and bays, and thick multi-year sea ice and ice shelves occur along the coast. These extreme ice features are currently undergoing rapid attrition. The polar desert landscape contains sparse, discontinuous patches of vegetation, including dense stands of the prostrate shrub *Salix arctica* (Artic willow) at some sites, and 37 species of vascular plants on Ward Hunt Island. Diverse aquatic ecosystems occur throughout the area, including meromictic, epishelf, and perennially ice-covered lakes. Many of these have responded strongly to climate shifts in the past and like other geosystems/ecosystems of the region are now sentinels of ongoing global climate change.
Keywords: climate change, cryosphere, Holocene, ice shelves, lakes, landscapes, periglacial, polar deserts, vegetation.

Résumé : Les modèles climatiques globaux prévoient que le réchauffement du climat aura des effets plus prononcés et plus rapides aux latitudes les plus élevées de l'Hémisphère Nord. En accord avec cette prédiction, la région de l'île de Ward Hunt à la limite septentrionale terrestre de l'Arctique canadien subit en ce moment le début de changements environnementaux majeurs. Cet article est une synthèse des recherches incluant de nouvelles observations sur les différents géosystèmes/écosystèmes de cette région côtière du nord de l'île d'Ellesmere qui atteint la latitude de 83,11° N (cap Aldrich). Le climat y est extrême avec une température moyenne annuelle de l'air de –17,2 °C, similaire à celle de régions antarctiques comme les vallées sèches de McMurdo. La région est distincte du point de vue de la géologie (le terrane Pearya), elle est constituée de montagnes escarpées entrecoupées de profonds fjords et vallées fluviales. De nombreux glaciers s'écoulent vers les vallées, les fjords et les baies et l'on retrouve le long des côtes d'épaisses couches multiannuelles de glace de mer et de plateformes de glace. Ces éléments glaciaires extrêmes sont actuellement en réduction rapide. Ces déserts polaires ont une végétation généralement dispersée et discontinue avec sur certains sites un couvert dense de *Salix arctica* (saule arctique), un arbuste décidu au port prostré. Sur l'île de Ward Hunt, on dénombre 37 espèces de plantes vasculaires. La région comprend des écosystèmes aquatiques diversifiés dont des lacs méromictiques, épiplateformes et d'autres couverts de glace permanents. Plusieurs d'entre eux ont réagi fortement aux changements climatiques dans le passé et comme d'autres géosystèmes/écosystèmes de la région constituent maintenant des sentinelles des changements climatiques en cours.
Mots-clés : changement climatique, cryosphère, Holocène, plateforme de glace, lacs, paysages, déserts polaires, périglaciaire, végétation.

Nomenclature: Flora of North America Editorial Committee (eds), 1993+; see also Appendix I.

Introduction

Although global circulation models vary in their estimates of the magnitude and rate of climate change, most converge on the prediction that the fastest and most severe changes will occur at the highest northern latitudes (IPCC, 2007). Consistent with this prediction, analyses of recent warming trends indicate that some of the greatest temperature increases over the last 3 decades have been in the High Arctic. These changes have been especially pronounced at the base of the High Arctic troposphere, implying feedback

effects of sea-ice loss that will continue to accelerate over the course of this century (Screen & Simmonds, 2010).

The unique geosystems and ecosystems at the far northern coastline of Arctic Canada are especially prone to ongoing climate change. These coupled physical–biotic systems are critically dependent on ice for their structural integrity and seasonal dynamics, and small changes in temperature across the melting point can therefore have pronounced impacts on geophysical and ecological processes.

Ward Hunt Island lies at the northern tip of Canada, 6 km off the northern coast of Ellesmere Island in High Arctic Nunavut (Figure 1). It was first visited by Europeans in 1876 during the British Arctic Expedition, and was named after George Ward Hunt, who at the time was the First Lord of the British Admiralty. During the 20th century, this island and the adjacent northern coastline of Ellesmere Island became preferred launching off points for expeditions to the North Pole, which is 766 km north of the northern terrestrial limit of Canada (Cape Aldrich on Ellesmere Island, at 83° 07' 00" N, 69° 35' 00" W; 61 km east of Ward Hunt Island). Much of this area is now within Quttinirpaaq ("top of the world" in Inuktitut) National Park, Canada's vast northernmost park, created in 2000. From the 1950s onwards, this region has been the focus of many environmental studies, and in the late 1990s a set of research sites in the area was incorporated into the Centre for Northern Studies (CEN: Centre d'études nordiques) Network for northern research and monitoring. The CEN Network is composed of research stations (Qaujisarvik) and climate stations (SILA) throughout eastern Canada (details at www.cen.ulaval.ca), and in 2009 these were integrated into the SCANNET circumpolar network of terrestrial observatories (www.scannet.nu).

Ward Hunt Island and vicinity is a region of diverse landscapes, coastal environments, and ecosystems. This review article provides an introduction to this geosystem–ecosystem diversity and summarizes the wide range of studies conducted to date in this area, as a background to ongoing research and for comparisons with other long-term research sites. Each section first describes general features of the region and then focuses on specific sites where detailed research has been undertaken, including new observations. After a brief introduction to the regional and local climate regime, this review begins offshore in the coastal marine cryosphere and then describes the ice and freshwater dynamics of the fiord systems, followed by a geomorphological survey of coastal landforms, lakes and catchments. We briefly summarize the limnology and microbial ecology of the lakes and paleolimnological studies on them that have provided insights into climate change and landscape processes during the Holocene. We complete this review with introductions to the plant and animal ecology, including updated species lists from our own field records combined with those available from other expeditions, as baselines for evaluating future change in this fast-evolving region.

Climate

The northern Ellesmere Island region is subject to an extreme polar desert climate. The nearest Environment Canada climate station is at Alert, 170 km to the east of Ward Hunt Island (Figure 1). For the 3 y spanning
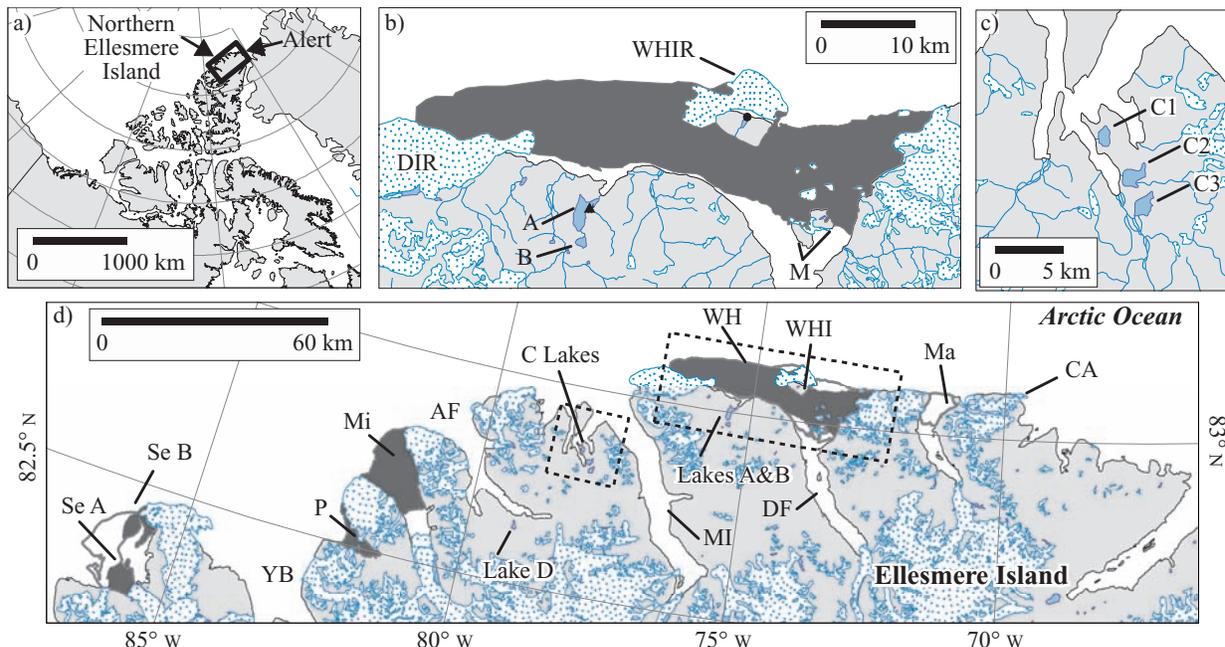

FIGURE 1. Map of northern Ellesmere Island. The dark grey shading shows the extent of the ice shelves at the end of summer 2008. A, B, C1, C2 and C3: lakes; DIR: Discovery Ice Rise; WHIR: Ward Hunt Ice Rise; M: Marvin Islands; Se A/B: Serson Ice Shelf remnants; YB: Yelverton Bay; P: Petersen Ice Shelf; Mi: Milne Ice Shelf; AF: Ayles Fiord; MI: M'Clintock Fiord; WH: Ward Hunt Ice Shelf; WHI: Ward Hunt Island; DF: Disraeli Fiord; Ma: Markham Ice Shelf; CA: Cape Aldrich. Symbols in panel b) mark the position of SILA stations. Light grey line in panel d) indicates the ice shelf extent at the beginning of summer 2008.

the Fourth International Polar Year (2007-2009), the mean annual temperature at Alert was –15.9 °C (range –15.8 to –16.2 °C), and the mean annual precipitation was 154 mm (range 116 to 217 mm). The Alert record shows that the northern Ellesmere Island region has mean annual temperatures that are amongst the lowest relative to other sites in the CEN Network sector of eastern Canada (Figure 2). However, temperatures at Alert are slightly warmer, and precipitation much higher, relative to Eureka, which lies on the Fosheim Peninsula, central Ellesmere Island, in the rain shadow of Axel Heiberg Island. The long-term record at Alert indicates rising temperatures over the last decade; for 2010, the temperature anomaly (deviation from mean recorded 20th century values) was 4.7 times the global anomaly (Figure 2 inset).

Our temperature measurements from the 10-m-high CEN-SILA climate station at Ward Hunt Island and a 3-m-high SILA station at Lake A on the northern Ellesmere Island coast (see the "Geomorphological features" section below for site descriptions) show a close correspondence between these 2 sites, but with frequently warmer and sometimes cooler conditions at Lake A (Figure 3). Warm summers with temperatures in excess of 10 °C were recorded in 2006, 2008, and 2010, and the latter two corresponded to years of major changes in the Ellesmere ice shelves (loss of the Markham Ice Shelf and much of the

FIGURE 3. Hourly air temperature data from the SILA climate stations at Ward Hunt Island (black) and Lake A delta site (grey) for the period 10 August 2005 to 11 July 2010. A reference line is drawn at 10 °C to identify extreme warming events.

Serson Ice Shelf in 2008, and massive break-up and attrition of the Ward Hunt Ice Shelf in 2010). Air temperatures are on average cooler at Ward Hunt Island than Alert (Figure 2); for example, the mean annual temperature was –17.2 °C for the 3 y 2007-2009, which is 1.3 °C below the Alert mean for the same period.

Given its extreme northern latitude, Ward Hunt Island experiences large fluctuations in incident radiation, from continuous daylight in summer to continuous darkness in winter (Figure 4). Irradiance (PAR; phosynthetically active radiation) falls below detection from late October to late February (Figure 4a), while during clear skies at the summer solstice, irradiance varies by a factor of three between solar midnight and noon (Figure 4b). There can be considerable diurnal and day-to-day fluctuations in temperature, including multiple freeze–thaw transitions throughout the day during summer (Figure 4b). Most of the snowfall along the coast occurs in autumn (September-November), and the snow pack remains relatively steady for the following 6-7 months, with rapid melting and exposure of bare ground during July-August (Vincent et al., 2009; Harding et al., 2011).

Coastal ice and cryo-ecosystems

The Arctic pack ice off the northern coast of Ellesmere Island is in constant motion under the influence of the clockwise Beaufort Gyre. This current pushes sea ice up against the coast and creates a flaw lead (region of open water) where flow diverges beyond the rubble fields (Hattersley-Smith, 1962). In the less dynamic bays and fiords sheltered behind headlands, several other ice types are present. Some of this ice has become extremely thick, not from ridging as seen offshore, but from decades to millennia of *in situ* growth (Jeffries, 2011).

In contrast to seasonal landfast ice, which grows out from the shore every fall, the coast of Ellesmere Island supports multi-year landfast sea ice (MLSI), which has survived for at least 2 y and, more typically, up to several decades (Jeffries, 1992a). This ice thickens over
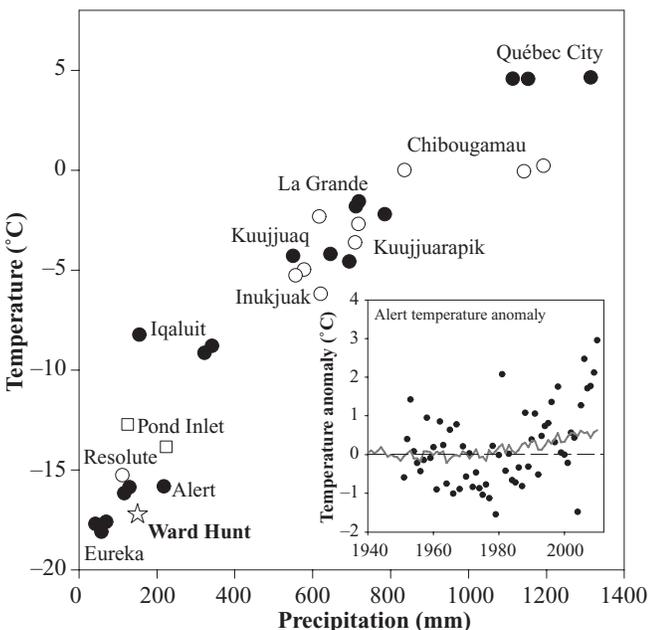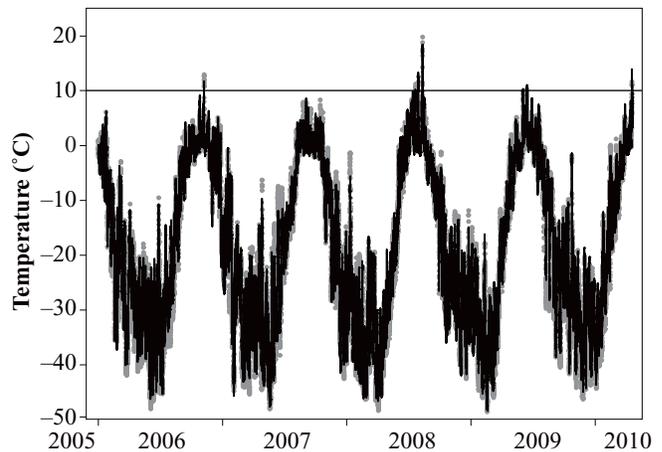

FIGURE 2. Climate of northern Ellesmere Island relative to other sites in the CEN Network sector, which extends over a north–south gradient of eastern Canada from Ward Hunt Island through Nunavut and Nunavik to southern Québec (details at www.cen.ulaval.ca). The data are for the 3 y (2007-2009) encompassing International Polar Year activities (only 2007 available for Resolute). Different symbols are used to differentiate the stations. Ward Hunt Island (star) is the mean measured temperature at the SILA station for the 3 y, with precipitation estimated as the mean for Alert. INSET: Temperature anomalies for Alert from 1950 to 2010, relative to the average values for the period 1950-2000. Also plotted is the NASA global mean anomaly (grey line): http://data.giss.nasa.gov/gistemp/graphs/Fig. A2.txt. All other data are from Environment Canada's National Climate Archive (http://climate.weatheroffice.gc.ca/).

time when melt is exceeded by the mass gained through freezing of water to the bottom of the ice or by snow accumulation. Some 3000 to 5500 y ago, in a cooling climate, Ellesmere Island MLSI became thick enough (> 20 m) to be considered ice shelves (Jeffries, 1992a; England *et al*., 2008).

The Ellesmere ice shelves differ from their Antarctic counterparts because they are formed primarily from MLSI that in some cases is augmented by floating glacier tongues (Jeffries, 2011). Currently, there are 4 main ice shelves in Canada (Figure 1), with a total combined area of less than 675 km^2 (Mueller *et al*., 2008; this study). The Serson Ice Shelf is composed of a floating glacier tongue ("Serson A" Ice Shelf) and a sea-ice ice shelf a few kilometres to the north ("Serson B" Ice Shelf). The Petersen Ice Shelf fills most of a small triangular bay and has some input from 2 small glaciers on its northern margin. The Milne Ice Shelf has had significant glacial contribution from both sides of the narrow fiord in which it floats (Jeffries, 1986a). Consequently, this ice shelf is the thickest in Canada, attaining ice thicknesses of 90 m in places (Narod, Clarke & Prager, 1988; Mortimer, 2011). The Ward Hunt Ice Shelf is a sea-ice ice shelf that fills a broad embayment at the mouth of Disraeli Fiord and is the largest of the 4 in

extent, although it is now fractured substantially (Figure 5; Mueller, Vincent & Jeffries, 2006; Mueller *et al*., 2008; and see below in this section). This ice shelf surrounds several ice rises, sections of ice shelves that are grounded on the ocean floor and are therefore points of stability (Jeffries, 1992a). The grounding of the ice rises and their accumulation to substantial ice thicknesses (estimated by radio echo sounding in the 1960s to be 46-125 m) have been attributed to local topography (*e.g*., the sloping sea floor around Ward Hunt Island, from a maximum depth of 860 m between Ward Hunt and Ellesmere Islands; Crowley, 1961) and localized accumulations of massive snowdrifts; glacio-isostatic uplift was thought to be too slow to be a major factor accounting for their grounding (Lyons, Ragle & Tamburi, 1972).

FIGURE 5. Landscape and lake features at Ward Hunt Island and vicinity. Upper panel: Ward Hunt Island, 19 August 2008. This view towards the north shows the Ward Hunt Ice Shelf in the foreground, with its characteristic ridge and trough topography and substantial fracturing; Ward Hunt Lake on the island with a central pan of perennial ice; and Quttinirpaaq Lagoon, the narrow band of open water between the northern shoreline of the island and the Ward Hunt Ice Rise. Middle panel: Neige Bay (unofficial name), part of the Milne Fiord epishelf lake, which is bounded by the Milne Glacier (right-hand side of the photograph) and Milne Ice Shelf (not shown); this bay receives meltwater inflow from the Neige Glacier (unofficial name), seen on the left-hand side of the photograph; 13 July 2007. Lower panel: Lake A (foreground) and Lake B during full ice-out conditions, Ellesmere Island; 20 August 2008. Photo credits: W. F. Vincent, D. Antoniades, D. Sarrazin.
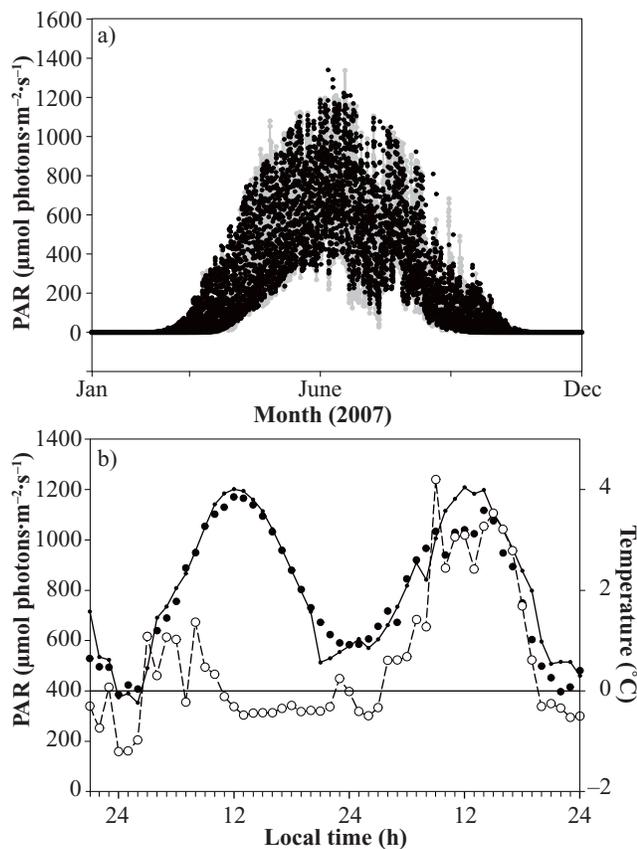

FIGURE 4. Hourly radiation data (PAR) at the SILA climate stations. a) Annual irradiance cycle at Ward Hunt Island (black circles) and Lake A (grey) in 2007. b) Daily irradiance cycles at Ward Hunt Island (closed circles) and Lake A (solid line), 17/18 June 2007, and mean hourly air temperatures (open circles). Over this 48-h period, temperatures crossed the 0 °C line 9 times.

The surface morphology of the ice shelves is typically marked with undulations that are parallel to the coast (Hattersley-Smith, 1957; Holdsworth, 1987) and that likely result from the alongshore winds. The troughs of these "rolls" fill with meltwater in the summer (Figure 5), which can occasionally erode through ridges, resulting in lakes that bifurcate. This easily recognizable pattern helps identify free-drifting pieces of ice shelf, tabular icebergs known as ice islands (Koenig *et al.*, 1952), among the pack ice of the Arctic Ocean. Ice islands have been used as drifting research stations in the past and are also considered a hazard to navigation (Althoff, 2007; Belkin & Kessel, forthcoming; Fuglem & Jordaan, forthcoming) and to offshore drilling in the Beaufort Sea (Sackinger, 1988).

Over the course of the 20th century there have been marked changes in the ice fringing the northern coast of Ellesmere Island. The current extent of ice shelves is in striking contrast to the 8900 km^2 that was estimated to be present in 1906 from anecdotal evidence reported by Peary (Vincent, Gibson & Jeffries, 2001). In the intervening century the single "Ellesmere Ice Shelf" (unofficial name) deteriorated into several individual ice shelves and calved numerous ice islands (28 were reported in 1950; Koenig *et al.*, 1952), including T-1, T-2, and T-3, which were thought to have originated in Yelverton Bay between 1935 and 1946 (Jeffries, 1992a). A portion of the Serson (formerly known as Alfred Ernest) Ice Shelf calved in 1955 to form the ARLIS-II ice island (Jeffries, 1992b). In the early 1960s, 596 km^2 of the Ward Hunt Ice Shelf calved, forming 5 large ice islands (Hattersley-Smith, 1963). In subsequent years, the M'Clintock Ice Shelf was lost and the Ayles Ice Shelf detached and moved north within its fiord by approximately 5 km (Hattersley-Smith, 1967; Jeffries, 1986b). The Milne Ice Shelf lost 33 km^2 from its northwest corner by the end of the 1970s, and in the early 1980s the Ward Hunt Ice Shelf was reduced by a total of 40 km^2 on its western, and by a similar amount on its eastern, calving front (Jeffries & Serson, 1983; Jeffries, 1986b). By the end of the 20th century, a total of 1043 km^2 of ice shelf remained along the coast (Mueller, Vincent & Jeffries, 2006).

Between 2000 and 2002, after 2 decades of relative stability, fractures developed across the Ward Hunt Ice Shelf (Mueller, Vincent & Jeffries, 2003). One went north–south and connected the Arctic Ocean to Disraeli Fiord, which contained the epishelf lake to the landward side of the ice shelf (Figure 5; see Fiord section below). In addition, numerous fractures went westward up to 12 km, and a calving of MLSI (20 km^2) and ice shelf (6 km^2) occurred along the eastern calving front. On August 13, 2005, the Ayles Ice Shelf calved completely, moving out of Ayles Fiord and into the open ocean in a span of 1 h under the influence of alongshore winds of up to 25 m·s^{-1} (Copland, Mueller & Weir, 2007). The MLSI in Yelverton Bay, which had been in place since the calving of ice islands T-1, T-2, and T-3, broke up, allowing a 12.6-km^2 portion of the Petersen Ice Shelf to calve. In 2007, the Petersen Ice Shelf calved again (a loss of 8 km^2) following another break-up of Yelverton Bay sea ice (D. Mueller, unpubl. data). In 2008, a total of 214 km^2 (23%) of ice shelf was lost

from the northern Ellesmere coast (Mueller *et al.*, 2008; Vincent *et al.*, 2009). These events began in late July with the calving of 2 large ice islands from just to the west and east of the Ward Hunt Ice Rise. Following that, the Serson Ice Shelf lost 122 km^2 (60%) of its area over a period of a week (Mueller *et al.*, 2008). The Markham Ice Shelf disintegrated into several large pieces and drifted away at the beginning of August, resulting in the complete loss of this 50 km^2 ice shelf (Vincent *et al.*, 2009). The following summer brought no significant calving events; however, the Ward Hunt Ice Shelf continued to disintegrate in 2010 (see below). In concert with the recent ice shelf attrition, hundreds of square kilometres of MLSI have also been lost (Copland, Mueller & Weir, 2007; Vincent *et al.*, 2009). In the 1980s, MLSI was considered to be thickening, and it seemed likely that it would eventually replace ice shelves that had calved in the mid-20th century (Jeffries & Serson, 1986; Evans, 1989). Now that very little MLSI remains along this coast, the changes in ice shelf extent appear to be irreversible in the foreseeable future, especially given the current and projected climate (Copland, Mueller & Weir, 2007; Vincent *et al.*, 2009).

Although the surface of the Ellesmere ice shelves appears inhospitable from a human perspective, it provides cryo-habitats for diverse communities of cold-tolerant microbiota, which are now threatened by rapid climate change (Vincent *et al.*, 2000; Vincent, Mueller & Bonilla, 2004; Vincent, 2010). These consortia are found in snow, in the water columns of the meltwater lakes, and associated with sediment on the ice surface (Jungblut, Mueller & Vincent, forthcoming). In the last case, microbial consortia form loosely cohesive microbial mats that are bound together chiefly by filamentous cyanobacteria. The cyanobacterial taxa that dominate the microbial mat consortia are found in tundra ponds, in lakes, and on glaciers in Arctic, alpine, and Antarctic habitats (Jungblut, Lovejoy & Vincent, 2010). However, the particular microbial mat macro-characteristics appear to be unique to the ice shelves, especially in areas of the ice shelves that have a high abundance of surface sediment (Mueller, Vincent & Jeffries, 2006). In these regions, net ice ablation at the surface brought marine sediment (that became frozen to the underside of the ice) up through the ice shelf over decades (Mueller & Vincent, 2006). The high electrical conductivity of meltwater in these areas also confirms a marine influence, which is in contrast to the very low conductivity meltwater in areas where ice is derived from surface accumulation of snow, *i.e.*, meteoric ice (Mueller, Vincent & Jeffries, 2006). The marine ice areas also tend to have relatively high accumulations of microbiota compared to meteoric ice, where benthic consortia are restricted to cryoconite holes (round melt holes caused by absorption of solar radiation) in the ice surface.

Ward Hunt Ice Shelf is the largest and best-known ice shelf in the Northern Hemisphere. Until recently it surrounded the eastern and southern side of Ward Hunt Island, while the Ward Hunt Ice Rise remains adjacent to the island to the north and west (Figure 5). Aerial photographs from the late 1940s and 1950s (published in

Hattersley-Smith, 1974) clearly show the undulating ice shelf extending more than 5 km to the north of the ice rise and contiguous with the Markham Ice Shelf to the east, as well as extending into Disraeli Fiord to the south. The ice shelf in 2008 was approximately 55 km wide, ranging from the Discovery Ice Rise in the west to Cape Albert Edward in the east. The eastern half of the ice shelf is pinned on several unnamed ice rises as well as the Marvin Islands near the southern edge of the ice shelf. Microbial mats were especially luxuriant and common in the marine ice areas to the south of Ward Hunt Island and adjacent to the Marvin Islands (Figure 1). A 2001 helicopter survey indicated that 9.7% of the (then) 448 km^2 Ward Hunt Ice Shelf had significant sediment cover, and by extrapolating pigment and organic content of sediment samples, a standing stock estimate was derived of 16 Gg of biomass or 7.6 Mg of chlorophyll a across the entire ice shelf (Mueller, Vincent & Jeffries, 2006). Molecular clone library analyses (Bottos *et al.*, 2008) and metagenomic (full DNA) analyses (Varin *et al.*, 2010) of the ice shelf microbial mats have shown that they are functionally as well as taxonomically diverse consortia with representatives from each of the 3 domains of life (mostly Bacteria and Eukarya, with a small contribution by Archaea) plus numerous types of viruses. Although cyanobacteria likely dominate total biomass, the most abundant DNA sequences are diverse Proteobacteria (Varin *et al.*, 2010). The eukaryotes include green algae, diatoms, heterotrophic protists, and microfauna such as nematodes, rotifers, tardigrades, and flatworms (Vincent, Gibson & Jeffries, 2001; Jungblut, Mueller & Vincent, forthcoming). This biodiversity is surprising given the extreme nature of the ice shelf environment: temperatures below 0 °C for up to 80% of the year, temperatures as low as –18 °C under snow and ice, variable conductivity during freeze-up and melt, and alternation of extremely low and high irradiances (Mueller & Vincent, 2006). From assays and pigment analysis, it appears that the phototrophic community is composed of generalist taxa that have broad tolerances to these fluctuating conditions and that use a variety of pigment strategies to reduce the physiological impacts of these combined stressors (Mueller *et al.*, 2005). In contrast, the heterotrophic bacterial community appears to be more adapted to specialized conditions found on the ice shelf, such as active growth in extreme cold (Mueller *et al.*, 2005; Bottos *et al.*, 2008).

The Ward Hunt Ice Shelf and Ice Rise have been studied by glaciologists since the 1950s, and consequently a record of surface mass balance exists for these ice masses. The data clearly indicate a long-term trend of surface mass wasting on the order of 6.3 m water equivalent from 1952 to 2007 for the ice shelf and 1.8 m water equivalent for the ice rise from 1959 to 2005 (Braun, forthcoming). Aside from a few years of substantial mass wasting in the 1950s, and some years of accumulation in the 1960s, the ice shelf record shows a steady decline over the latter half of the 20th century, with increased ablation over the last decade (Braun *et al.*, 2004; Braun, forthcoming). It is not known whether the overall thickness of the ice shelf is also changing; however, it seems likely that there is little freeze-on of ice to the bottom of the ice shelf. This is especially the case following the demise of
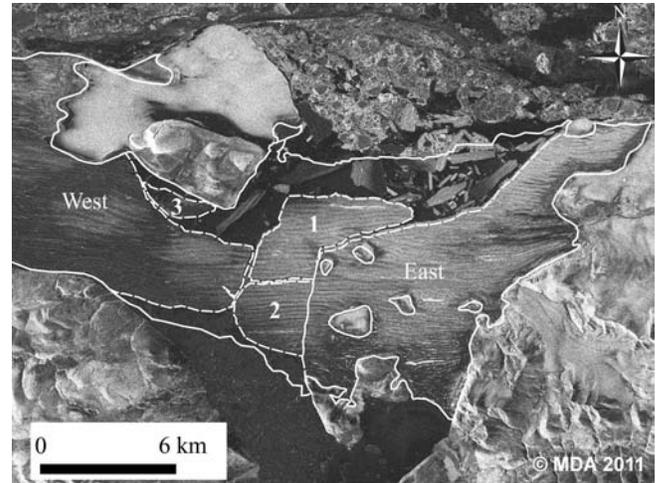

FIGURE 6. Radarsat-2 imagery showing the August 2010 break-up of the Ward Hunt Ice Shelf. The 2008 extent is denoted by a solid white line, and the 2010 extent of the ice shelf and proximal fragments is shown with a dashed line. The western portion of the ice shelf at the time of this image totalled 240 km^2, the eastern portion was 74 km^2, and the 3 labelled ice shelf fragments were 15, 9, and 2.3 km^2, respectively. This high-resolution fine beam image was acquired on 23 March 2011 at 21:42 UTC. RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. - All Rights Reserved.

the epishelf lake in Disraeli Fiord, which at times delivered supercooled freshwater under the eastern portion of the ice shelf, where it accreted (Jeffries *et al.*, 1988).

Following the events of 2008, the Ward Hunt Ice Shelf had an extent of 385 km^2, but by 13 September 2010 several changes had occurred, resulting in the calving of approximately 45 km^2 of ice shelf (Figure 6). In early August 2010, the northeastern portion of the ice shelf calved away, which allowed a previously fragmented section of ice shelf to the south of Ward Hunt Island to move around the island and out to the open ocean. There was further calving from the southern edge of the ice shelf into Disraeli Fiord, and many pre-existing fractures expanded to reach widths of several hundred metres. This created 2 central fragments that are currently held in place by first-year sea ice (1 and 2 in Figure 6). These fragments will almost certainly drift further from the ice shelf during open water conditions, given favourable wind and currents. The 2010 break-up events removed sections of the ice shelf that harboured abundant microbial mats to the south of Ward Hunt Island and at the southern edge of the ice shelf. These marine ice areas together with the former Markham Ice Shelf contained 85-95% of the biomass in the entire Ellesmere ice shelf cryo-ecosystem (Mueller, Vincent & Jeffries, 2006). These vulnerable Arctic ecosystems are now exceedingly rare and will likely become extinct in the coming decades.

Fiords and paleoclimate

The coast of northern Ellesmere Island is characterized by deeply incised fiords formed by glaciers outflowing from the Grant Land Mountains. Glacial retreat in the region occurred around 9500 calibrated y before present (y BP)

(Dyke, 2004), although Disraeli and adjacent fiords are not thought to have been filled with glacial ice during the last ice age (Lemmen, 1989). During the summer months, freshwater input from snowmelt and from streams enters the fiords from their catchments. This freshwater is less dense than the marine water into which it flows due to lower solute concentrations; as a result it floats over the salt water. Depending on the morphology and climate of a given fiord, this stratification may be ephemeral or seasonal (Cottier *et al*., 2010; Skardhamar & Svendsen, 2010); however, when ice completely dams the mouths of fiords stratification becomes entrenched, thus forming a system known as an epishelf lake. The depth of the freshwater layer is equivalent to the draft of the ice shelf damming the fiord, and it can therefore provide information about changes in the thickness of the ice shelf (Veillette *et al*., 2008). These ecosystems are stratified biologically as well as physically, and can contain an unusual mix of freshwater and marine organisms in the same water column (Van Hove *et al*., 2001; 2008; Veillette *et al*., 2011b). It has been estimated that the Ellesmere Ice Shelf retained up to 17 epishelf lakes at the beginning of the 20th century (Crary, 1960; Veillette *et al*., 2008). However, due to the disintegration of ice shelves since that time it is thought that Milne Fiord (Figure 5) now contains the only remaining epishelf lake on Ellesmere Island's northern coast (Veillette *et al*., 2008).

The age and history of the ice shelves of Ellesmere Island has been the subject of conjecture for over half a century, and is highly relevant to understanding the structure and dynamics of the adjacent fiord ecosystems as well as past fluctuations in climate. In 1946, the discovery of several large ice islands in the Arctic Ocean and suggestions of their possible strategic use (see above) led to a concerted effort to determine their characteristics and origins. With the major calving of the Ward Hunt Ice Shelf (WHIS) that occurred in 1961/62, the stability of the ice shelves on long time scales became an increasingly important question (Hattersley-Smith, 1963), and more so with the accelerated decline of northern ice shelves over the last decade (see "Coastal ice and cryo-ecosystems" above). Paleoclimate studies along the coastline, including in the fiords, have helped place these recent ice dynamics in a much longer term context.

Research to determine the age of Arctic ice shelves has largely focused on the Ward Hunt Ice Shelf and Disraeli Fiord (Figure 1). Several approaches have been applied to age determinations; the most common has been radiocarbon dating of driftwood samples. Crary (1960) pioneered this approach, using the assumption that ice shelves act as a barrier to the entry of sea ice and the deposition of material from the ocean, and therefore that driftwood located inland of ice shelves was deposited during periods of ice shelf absence. He suggested that these samples could provide only a maximum age for the ice shelves: an ice shelf could not be older than the driftwood ages, but it could be younger, given that later lack of deposition may have been affected by other processes. Subsequent research has suggested that changes in ocean currents, ice conditions, driftwood supply, and disturbance after deposition may affect driftwood deposition (Blake, 1972; Bradley, 1990; Dyke *et al*., 1997).

Driftwood records from Disraeli Fiord show deposition beginning 9900 calibrated years before present (y BP) until 3300 y BP (Crary, 1960; Blake, 1972; Lemmen, 1989; England *et al*., 2008), suggesting that the maximum age for the WHIS is 3300 y BP. The shores of Clements Markham Inlet, situated roughly 90 km to the east, also appear to have continuously received driftwood between 9900 and 3500 y BP, with some deposition between 2300 and 2200 y BP (Crary, 1960; Stewart & England, 1983; England *et al*., 2008). Lyons and Mielke (1973) also observed an extirpation of marine biota beneath the WHIS at 3400 y BP, and hypothesized that it may have resulted from freshwater poisoning due to ice shelf formation. Taken collectively, these data suggest the absence of ice shelves from the early Holocene until roughly 3300-3500 y BP, and are in accord with available data from the Arctic Ocean and ice core records. Maximum solar insolation during the Holocene occurred between 8000 and 10 000 y BP (Berger & Loutre, 1991), during which time temperatures were up to 3 °C higher than at present (Fisher *et al*., 2006) and low-ice conditions prevailed in the Arctic Ocean (Polyak *et al*., 2010).

Not all ice shelves were observed to change in synchrony. In Phillips Inlet, some 220 km to the west, driftwood was absent after 5500 y BP, implying earlier ice shelf formation (England *et al*., 2008). Given the ontogenetic differences between sea-ice ice shelves and those of glacial origins, it is expected that the chronology of their formation and disintegration may differ (Jeffries, 1992a). Changes during the 20th century also appear to indicate that the mechanisms involved in calving events differ between the remaining ice shelves along the Ellesmere Island coast (Holdsworth, 1971). Regardless, all available data indicate that on longer time scales, the ice shelves of northern Ellesmere Island respond together to changes in regional climate. They formed in the middle Holocene in response to general climatic cooling, and they continue to deteriorate rapidly in the face of recent climate warming. In the absence of ice shelves, the fiords are now open to direct surface water exchange with the Lincoln Sea, thereby creating new and rapidly evolving coastal ecosystems in the High Arctic.

Geomorphological features

Located north of the glaciarized Grant Land Mountains and bounded by the Arctic Ocean, the serrated coastline of northern Ellesmere Island is a region of diverse landforms, including mountains, deep fiords and inlets, lowland and fluvial plains, lake basins, and a variety of periglacial landscape features (Figure 7). The geology of the region (including a volume of maps) is described in Trettin (1991). The area of Ward Hunt Island and vicinity as described in this review corresponds to the geological province called the Pearya terrane (a block of the Earth's crust with different geological provenance, now attached to the North American tectonic plate) and is composed of 4 major units that range from middle Proterozoic to upper Silurian in age. Here we briefly describe the main landscape features from our coastal survey in 2010 from Milne Fiord in the west to Ward Hunt Island and Disraeli Fiord in the east.

FIGURE 7. Coastal and periglacial features of Ward Hunt Island and vicinity. Clockwise from top left: Coastal cliffs and scree slopes at Cape Discovery, at the entry to M'Clintock Fiord; talus-derived rock glacier flowing into the northeast side of Lake A at the outlet of the lake; solifluction lobes at Ward Hunt Lake; large well-developed sorted circle on one of the rounded, eastern summits of Ward Hunt Island; vegetated sorted stripes, which are common on the lower concave part of slopes and transfer nutrients and medium-grained sediments towards Ward Hunt Lake and Quttinirpaaq Lagoon; perennially ice-capped Ward Hunt Lake, with Ward Hunt Ice Shelf in the background. Photo credits: D. Fortier and D. Antoniades.

Milne Fiord is sealed by the Milne Ice Shelf and bounded to the southwest by Cape Evans and to the northeast by Cape Egerton. Landscape dynamics in this sector of the coastline are strongly influenced by the structural control exerted by coastal and inland ice features. The Cape Evans area and the northwestern tip of the Ferbrache Peninsula support local, low-altitude, ice caps flowing towards the coast and the fiord, which lock in the southwestern and northeastern end of Milne Ice Shelf. Inland, Milne Glacier and other valley glaciers originating from the northern British Empire Range and the western Challenger Mountains flow into Milne Fiord and contribute to the mass balance of the Milne Ice Shelf. Recessional moraines of Milne Glacier can be observed on the Milne Ice Shelf at the fiord head (Jeffries, 1986a). The fiord is well-defined by steep rock walls ending in scree slopes.

The Milne Fiord epishelf lake is formed in the fiord where glacier and snow meltwaters are dammed by the ice shelf (Figure 5; see also "Fiords and paleoclimate" above; a full description and satellite image of this fiord system is given in Veillette *et al.*, 2011b). Along the steep southeast valley walls facing the lake margin at Neige Bay (Figure 5), scree slopes with coalescent colluvial fans and 2 poorly developed talus-derived rock glaciers transfer significant amounts of rock debris to the lake. Large sediment inputs also occur at the valley head, where glacier and snow meltwater discharge forms 2 coalescent deltas in the lake. Higher, undated deltaic terraces at 95, 60, 51, 30, and 18 m asl mark pauses in the glacio-isostatic uplift and indicate the position of ice-contact deltas in the fiord prior to the inception of the ice shelf (Figure 5). The landscape on the northern and the southwestern sides of the lake consists of glacially rounded bedrock covered by a veneer of glacial and marine deposits that are intensively reworked by periglacial processes. Well-developed, sorted polygons supporting patches of tundra vegetation are conspicuous on flat surfaces, whereas on low-angle slopes sorted stripes and solifluction sheet flow convey rock debris, finer sediments, and solutes to the epishelf lake.

East of Milne Fiord, the coastline of the Ferbrache Peninsula is dominated by radially flowing glaciers with recently deglaciated peaks, ridges, and plateaus protruding from the ice and covered by frost-shattered rock debris. Ayles Fiord is bounded to the southwest by Cape Bicknor and to the northeast by a glacier flowing west towards the coast near Cape Fanshawe Martin. The Ayles Ice Shelf calved completely in 2005 (see "Coastal ice and cryo-ecosystems" above), and Ayles Fiord is now characterized by rock walls with long scree slopes ending on the sea ice. The coastline between Cape Fanshawe Martin and Cape Richards shows limited exposures of frost-shattered, glacially rounded bedrock and is essentially dominated by a large network of glaciers flowing into the sea and bounded by frontal and lateral moraines.

The coastline of the sector between Cape Richards and Cape Discovery is indented by large embayments, which are frequently bounded by coastal cliffs and scree slopes. The entrance of M'Clintock Inlet is marked to the southwest by Borup Point and to the northeast by Cape Discovery. Inland, higher summits of the eastern Challenger Mountains support glaciers, some of them flowing into U-shaped valleys towards M'Clintock Inlet. Taconite Inlet is located south of Bromley Island and is fed by the Taconite River. The southwestern side of Taconite Inlet is steep and has coastal cliffs with long scree slopes and a number of alluvial fans. Discontinuous remnants of marine coastlines attached to the walls along with deltaic and ice-contact sediments can be observed near the mouth of the inlet. The northeastern side of Taconite Inlet has a rolling and undulating glacially eroded bedrock topography (tens of metres) covered by a thin veneer of marine and glacial deposits or frost-shattered bedrock. Glacial deepening has created depressions to several tens of metres depth in the bedrock. Following the marine transgression, glacio-isostatic uplift isolated 3 of these depressions, which now form the basins of lakes C1, C2, and C3 (Figure 1; see "Aquatic ecosystems and paleolimnology" below).

Lake C1 (82° 51' N, 78° 12' W) is 1.1 km^2, 65 m deep, and 4 m asl (Bradley *et al.*, 1996). The lake catchment is limited to 3.3 km^2, and the landscape is characterized by low-relief, undulating bedrock covered by a veneer of glacial and marine deposits dissected by ice wedges. Lake C1 is fed entirely by snowmelt run-off, and its outlet drains into Taconite Inlet via a gully that is incised more than 10 m into coastal and glacial sediments. On low angle slopes of the catchment, the deposits are extensively reworked into vegetated sorted stripes flowing into the lake. The eastern shore of the lake rests directly on rock outcrops with low angle slopes where the veneer of frost-shattered rocks is moved downslope towards the lake in the form of block streams and gelifluction lobes.

Lake C2 (82° 50' N, 78° 05' W) is 1.8 km^2, 84 m deep, and 1.2 m asl (Douglas, Ludlam & Feeney, 1996). The high relief (to > 1000 m asl) watershed encompasses 23.5 km^2 of mountainous terrain, and Lake C2 is fed by meltwater from inland glaciers and the snow from local slopes. It drains into Taconite Inlet via a gully incised more than 10 m into the surficial deposits (diamicton). A stream flowing in a deeply incised, abandoned, glacial meltwater channel and carrying large sediment loads is forming a delta in the southeast corner of the lake (Hardy, 1996). Higher undated deltaic terraces at 79, 44, 40, 35, 32, and 15 m asl indicate the elevation of the sea in Taconite Inlet as a response to glacio-isostatic uplift during the Holocene (Bradley *et al.*, 1996). The northeast shore of the lake is bounded by steep rock walls with frost-shattered slopes, coalescent scree fans, and poorly developed, talus-derived rock glaciers delivering debris to the lake. The western portion of the catchment is characterized by low-relief undulating bedrock covered by a veneer of glacial and marine deposits that is sparsely colonized by tundra plants and mosses and dissected by ice-wedge polygons. On low angle slopes of the catchment, the deposits form a few alluvial fans or are extensively reworked into sorted stripes discharging fine-grained sediments into the lake.

Lake C3 (82° 48' N, 78° 05' W) is 1.7 km^2, 51 m deep, and 10 m asl (Van Hove *et al.*, 2006). The lake is partially fed by outwash sediments discharged by the Taconite River, which drains an extensive (260 km^2) inland watershed

(Bradley *et al.*, 1996). The southwestern margin of Lake C3 is contained by glaciofluvial sediments deposited during higher stages of the paleo-Taconite river. The lake drains by way of its outlet in the southwest corner into the Taconite River. The total sediment and water input from the Taconite River remains poorly known (Van Hove *et al.*, 2006) but appears to be significant based on the extensive fine-grained sediment plume and the progressing outwash delta at the southern end of the lake. The northeastern portion of the lake faces glacially eroded and frost-shattered bedrock exposures with scree slopes feeding coalescent colluvial fans and poorly developed talus-derived rock glaciers flowing into the lake. Two alluvial deltas discharge sediments on the eastern shore of the lake, and higher undated deltaic terraces measured on one delta at 48 and 32 m asl indicate the contact between these sediments and the paleo-glaciofluvial outwash of the Taconite River during the Holocene. The western portion of the catchment is characterized by low-relief undulating bedrock covered by a veneer of frost-shattered rock debris, glacial, and glaciofluvial deposits remobilized towards the lake by sorted stripes and solifluction sheet flows.

The sector between Cape Discovery and Cape Alexandra is characterized by peaks and ridges with unstable coastal rock cliffs. Scree slopes form large coalescent colluvial fans in the sea, and reworking of the colluvium by ice-pushing explains the serrated appearance of the coast (Figure 7). The northwestern tip of the Marvin Peninsula is largely dominated by the Discovery Ice Rise extending for kilometres along its coast. Recently deglaciated peaks and ridges have a discontinuous cover of frost-shattered rock debris and rounded summits that are reshaped by felsenmeer, blockstreams, and gelifluction lobes. Inland, cirque glaciers and valley glaciers have poorly developed medial and lateral moraines, which suggests limited glacial erosion today. These glaciers are either stagnant or retreating, and burial of ice by glaciofluvial sediment along the pro-glacial margins and at the glacier front is common. East of the Discovery Ice Rise, the coast is fringed by sea ice and the fractured Ward Hunt Ice Shelf. The inland landscape is characterized by the Sentinel River valley extending southward and other low-lying interconnected valleys (central valleys) extending inland eastward to Cape Alexandra. West of Rambow Hill, glacial overdeepening has created depressions tens to hundreds of metres deep that were isolated from the sea by glacio-isostatic uplift to form the basins of Lakes A and B (Figures 1 and 5c; also see the "Aquatic ecosystems" section below). East of Rambow Hill, 3 deltas ranging from 73 to 75 m asl in elevation mark the position of the marine limit (around 8600 y BP) in this sector (Crary, 1960; Lyons & Mielke, 1973; Lemmen, 1989). The exposed, raised coastal spit, outwash, and delta sediments observed along the coast are commonly incised by large epigenetic ice-wedge polygons and deformed by gelifluction and solifluction processes.

Lake A (83° 00' N, 75° 30' W) is 4.9 km^2, 128 m deep, and 3.3 m asl (Hattersley-Smith *et al.*, 1970; Tomkins *et al.*, 2009a, b). The 37-km^2 watershed is rocky (Figures 5, 7 and 8) and extends inland, but is not glaciarized; Lake A is therefore fed by snowmelt run-off only. To the

north, the lake is isolated from the sea by a rock sill and dammed by undulating marine deposits dissected by ice-wedge polygons. Lake A drains into the sea to the northeast by a sinuous gully incised in marine and glacial deposits (diamicton). The western side of the lake is contained by a well-defined rock ridge. The steep rock-walls facing the lake have scree slopes with coalescent colluvial fans, and the rock face is incised by several streams forming small alluvial fans in the lake. To the northwest of the lake a well-developed multi-ridge talus-derived rock-glacier flows down the rock face and onto the marine deposits. Another talus-derived rock-glacier flows into the northeast corner of the lake (Figure 7). Block streams and sorted stripes follow the sloping topography and flow into the northwest corner of the lake. The eastern side of the lake is circumscribed by low angle glacially eroded and frost-shattered rock slopes on which gelifluction lobes, blockstreams, and streams move coarse debris downslope and which are overlain by sorted stripes conveying finer sediments to the lake shore. A stream flowing in a deeply incised, abandoned, glacial meltwater channel drains the large inland catchment, delivering large sediment loads and forming an alluvial delta on the eastern shore of the lake. We measured higher undated deltaic terraces at about 73, 59, 45, 42, 23, and 20 m asl, and discontinuous remnants of marine coastline were also observed attached to the western wall of the Lake A basin. These ice-contact deltaic deposits mark the limit of the Holocene sea level and its subsequent regression during glacio-isostatic uplifting of the area. Large networks of epigenetic polygons have developed in the deposits following exposure to periglacial conditions.

Lake B (82° 58' N, 75° 26' W) is 0.9 km^2, 51 m deep, and 23 m asl (Hattersley-Smith *et al.*, 1970; Veillette *et al.*, 2011a). The rocky catchment (Figure 5) is limited to 5.2 km^2, and the lake is fed by snowmelt run-off from the surrounding slope only. Lake B drains into Lake A to the north via shallow, braided alluvial channels (Figure 8). The southern side of the lake is contained by a well-defined glacially eroded rock ridge. The steep north-facing rock walls have scree slopes with coalescent colluvial fans, and a well-developed, talus-derived rock glacier flows into the lake. The rest of the watershed is characterized by low-relief, undulating, glacially eroded bedrock covered by a veneer of marine and coastal sediments remobilized towards the lake by rills, blockstreams, and sorted stripes.

Ward Hunt Island (83° 05' N, 74° 10' W) is located north of Disraeli Fiord and locked between the Ward Hunt Ice Rise to the north and the recently fractured Ward Hunt Ice Shelf and sea ice to the south and east (Figure 5). The landscape of the island is characterized by a central depression bounded by Walker Hill (412 m asl) to the west and lower rounded summits (155 m and 240 m asl) to the east. Ward Hunt Lake occupies this central depression and is fed by snowmelt from the surrounding slopes (Figure 7). The lake is 0.37 km^2, 8 m deep, and covered in the centre by perennial ice up to 4 m thick (recorded as 14 feet [4.24 m] thick in mid-July of 1953; Hattersley-Smith, Crary & Christie, 1955), but the western shore is ice-free for up to a few weeks in the summer (Bonilla, Villeneuve & Vincent, 2005). The lake is contained to the north by
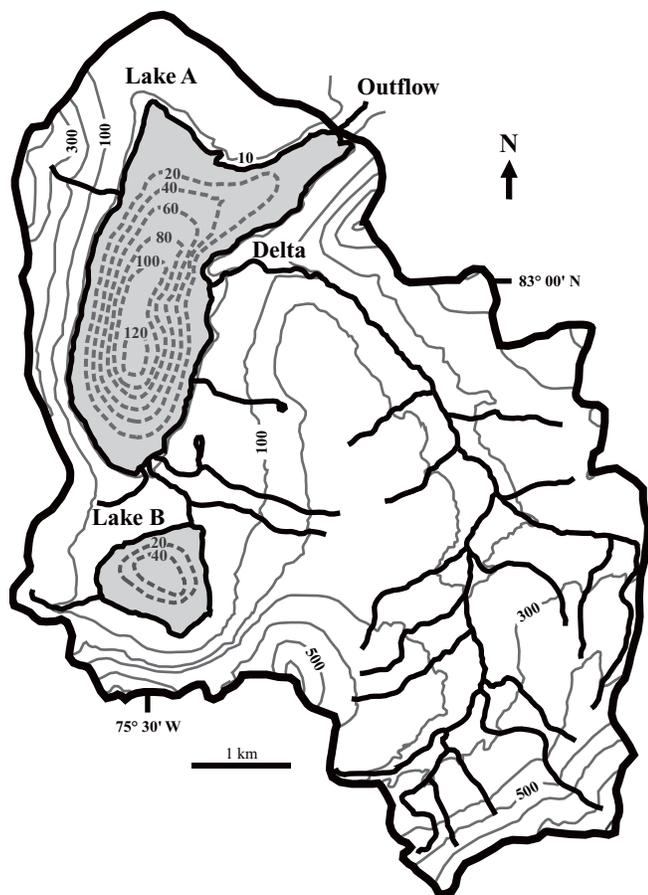
Figure 8. The drainage basin of Lake A and Lake B on northern Ellesmere Island. Modified from Tomkins *et al.* (2009a).

raised-beach ridges, and it drains to the south towards Disraeli Fiord via shallow braided alluvial channels incised in silty marine sediments. The Holocene limit of sea level on Ward Hunt Island is about 62 m, and shells collected on a 40 m asl raised beach were dated at 7200 to 7800 y BP (Lemmen, 1989).

On the rounded summits of Ward Hunt Island, frost-shattering and sorting of volcanic, intrusive, and sedimentary rock has created well-developed felsenmeers, sorted polygons, and sorted circles on 1-4° slopes. Sparse colonization of these landforms by mosses occurs around late-lying snowbanks. Cryoplanation terraces, differential erosion along dykes, and tors up to 3 m high occur on the eastern summit's crest. Two hill-slope tors a few metres high were also observed in the volcanic rocks northeast of Ward Hunt Lake. Glacial erratics were observed at the toe of some summit tors and among the frost-shattered bedrock. Glacial erratics can be found at high elevation on all summits of the island. Lemmen (1989) reported that there was no clear geomorphic evidence such as ice-contact deposits to suggest that glaciers rode over the island during the last glacial maximum. Therefore, the glacial erratics observed could predate the last glacial maximum, and this could explain the advanced state of cryogenic weathering of the felsenmeers, tors, and cryoplanation terraces observed on the crest and summits. On the

hillsides, the frost-shattered debris is reworked into various periglacial landforms according to the local slope. On slope shoulders, cryogenic steps, bench-like features with a downslope border of rock rubble, gelifluction lobes (3-12°), and blockstreams (10-20°) connect to the upper portions of slopes (20-30°), which are partially to completely covered with rock screes. Silty sediments deposited during the marine transgression and sand/gravel raised-beach deposits at lower elevation are extremely deformed by gelifluction processes and masked by rock debris from upslope. At the bottom of slopes, vegetated and mineral sorted stripes (5-10°) and solifluction sheet flows (2-7°) move a mixture of rock debris, marine sediments, and dead organic matter into the lake (Figure 7). Considering the small volume of Ward Hunt Lake, these sediment and nutrient fluxes may have a considerable influence on the biogeochemistry of the lake.

Our soil pit analysis in mid-July 2010 of the sand and gravel beach deposits between the northern side of the island and Ward Hunt Lake revealed that the active layer was about 80 cm thick. This site was situated at 45 m asl and was dissected by ice-wedge polygons. The sand and gravel deposits at the bottom of the active layer were saturated with clear ice. Over the top of the ice-wedges, we observed a 2- to 5-cm discontinuous layer of clear ice with vertically aligned, sub-centimetric, hexagonal ice crystals. The crystallography of this ice was in marked contrast with the underlying foliated wedge ice. Ground temperatures measured by a thermistor cable installed in similar raised-beach deposits several hundred metres away at the CEN SILA site indicate that the active layer was about 65 cm deep from 2005 to 2007 and abruptly increased to 80 cm in 2008 and 2009 (Vincent *et al.*, 2009). Air temperatures at the SILA station (Figure 2) indicate that 2005 was a cold summer with only 52 atmospheric thawing degree-days and a maximum air temperature of 7.4 °C. The summers of 2006 and 2007 were warmer, with 91 atmospheric thawing degree-days in both years and 239 and 268 ground surface thawing degree-days, respectively. The summers of 2008 and 2009 were exceptionally warm, with 167 and 143 atmospheric thawing degree-days and 378 and 404 ground surface thawing degree-days, respectively. This implies that the observed clear ice layer resulted from the refreezing of water released during melting of interstitial ground ice and wedge ice associated with a deepening of the active layer during the warm summers of 2008 and 2009. Epigenetic ice wedges formed in coarse grain deposits of fluvial, glaciofluvial, beach, or deltaic landforms are widespread along the coast of northern Ellesmere Island. Our observations suggest that ice-wedge polygons in coarse deposits and devoid of vegetation are highly sensitive to thermokarst processes during short-term summer warming.

Aquatic ecosystems and paleolimnology

One of the outstanding features of the Ward Hunt Island region is its diversity of lakes, streams, rivers, and wetlands as habitats for aquatic life. Many of these ecosystems are critically dependent upon ice and perennial snow packs and are therefore vulnerable to the ongoing

effects of climate change. The lakes that form on the surface of ice shelves (meltwater lakes and ponds, see "Coastal ice and cryo-ecosystems" above) or are retained by ice shelves blocking the seaward end of fiords (epishelf lakes; see "Fiords and paleoclimate" above) have been especially prone to climate warming in the region and to the attrition of this thick ancient ice. Many of the lakes and ponds of the region have ice covers that remain in place through most of the year, in some cases throughout the year, but this is likely to change markedly as the High Arctic continues to warm. The aquatic microbial ecosystems of the Ward Hunt region are already showing evidence of the onset of major change (Vincent *et al.*, 2009).

Ward Hunt Island itself contains 2 water bodies that have been the subject of limnological study. The first of these is a lagoon (unofficially named Quttinirpaaq Lagoon) at the northern end of the island, bounded by the Ward Hunt Ice Rise (Figure 5). This lagoon is hydraulically connected to the sea, rising and falling with the tides. Although it has been freshwater in the past, the collapse of a section of Ward Hunt Ice Shelf in the warm 2008 season resulted in the entrance of seawater directly into the lagoon, and salinities have been measured up to 15 mS·cm^{-1} (Vincent *et al.*, 2009). The second water body, Ward Hunt Lake (Figures 5, 7, 9 and 10), is freshwater (conductivity around 200 μS·cm^{-1}) derived from melting snowbanks, mostly via diffuse overland flows and small runnels. This lake has never been known to become completely ice free, and the thickness of its ice cover has been measured in excess of 4 m (see "Geomorphological features" above). The plankton contains picocyanobacteria and chrysophytes in low concentrations (chlorophyll *a* values less than 0.5 μg·L^{-1}; Villeneuve, Vincent & Komarek, 2001), with the littoral region coated by mats of pink and black cyanobacteria. The dominant cyanobacterial genera are *Tolypothrix*, *Leptolyngbya*, *Pseudanabaena*, *Tychonema*, and *Nostoc*, with a blue-green pigmented underlayer composed of diverse oscillatorian filaments (Villeneuve, Vincent & Komarek, 2001; Bonilla, Villeneuve & Vincent, 2005). The mats contain associated populations of green algae, chrysophytes, and diatoms.

Benthic "cyanomats" are well known features of polar aquatic ecosystems in general, and in shallow waters they often contribute most of the total ecosystem biomass and productivity (Vincent, 2000; Singh & Elster, 2007). Typically the surface layers are rich in UV sunscreens such as scytonemin (as in the black colonies on the Ward Hunt Lake mats) and photoprotective carotenoids that may colour the surface layer orange (see Figure 11 below) or pink, as in Ward Hunt Lake (Bonilla, Villeneuve & Vincent, 2005; Bonilla, Rautio & Vincent, 2009). Molecular analysis of the mat cyanobacteria at Ward Hunt Lake and on the Ellesmere ice shelves has shown that several taxa are genetically similar to those reported from other polar and alpine environments, including to taxa previously thought to be endemic to Antarctica. These observations imply the global dispersal of low-temperature–adapted microbes throughout the cold biosphere (Jungblut, Lovejoy & Vincent, 2010). Molecular analyses of the snowpack at Ward Hunt Island and vicinity has revealed the presence of cyanobacteria

with a 100% match to sequences of the same gene in the High Arctic mat cyanobacteria, likely indicating dispersal by the wind from local sources (Harding *et al.*, 2011). This latter study also found a surprising abundance of cold-adapted but obligate marine bacteria in the snowpack and in the air blowing onto Ward Hunt Island from across the sea ice. These findings suggest that wind plays a role in the dispersal of marine microbiota across the Arctic.

Initial analyses of the Ward Hunt cyanomats showed that they contained inorganic nitrogen and phosphorus in their interstitial waters that were well above concentrations in the overlying lake water (Villeneuve, Vincent & Komarek, 2001). In a set of experiments during 2 seasons, the response of the cyanomats to nutrient enrichment was assayed and compared with the nutrient responsiveness of the phytoplankton. The results showed a strong nutrient stimulation of chlorophyll biomass in the latter but no significant effect on photosynthesis or biomass of the cyanobacterial mats, even after 15 d of enrichment (Bonilla, Villeneuve & Vincent, 2005). These results are consistent with studies of cyanomats on the nearby Ward Hunt and Markham ice shelves using advanced high-throughput DNA analysis. These metagenomic analyses showed that the cyanomats are complex, species-rich communities adapted towards nutrient scavenging and recycling (Varin *et al.*, 2010).

A contrasting set of lakes occurs along the northern coastline of Ellesmere Island, within helicopter range of Ward Hunt Island (see "Geomorphological features" above). These were discovered by the Defence Research Board of Canada expedition to the region in 1969 and were provisionally named Lakes A to G (Hattersley-Smith *et al.*, 1970). Some were found to be meromictic, with a surface layer of freshwater overlying old seawater that had been trapped by isostatic uplift of the northern coastline (later studied by isotopic analysis, Jeffries *et al.*, 1984). Subsequent visits to the Taconite Inlet region revealed the presence of 2 additional lakes, and this series is now referred to as Lakes C1 (closest to the coast, and called Lake C by Hattersley-Smith *et al.*, 1970), C2, and C3. Lake C2 is similarly meromictic, while Lake C3 is freshwater, with conductivities rising from around 200 μS·cm^{-1} at the surface to around 300 μS·cm^{-1} at the base of the water column (Ludlam, 1996). Our profiling of an additional lake in the Ayles Fiord region, Lake D in the Hattersley-Smith *et al.* (1970) expedition, showed slight increases in salinity and temperature with depth (Figure 9) that were not recorded earlier, probably because of shallower profiles and less sensitive methods.

One of the remarkable features of the northern Ellesmere Island meromictic lakes is their unusual thermal regime, with a mid-water column maximum that remains throughout the year at values up to 30 °C above the mean annual air temperature (Figure 9). This unusual thermal pattern is also found in Antarctic meromictic lakes; for example, the temperature profile of Lake A is strikingly similar to that of Lake Bonney, a perennially ice-capped lake in the McMurdo Dry Valleys. The development and application of a one-dimensional heat flux model for Lake A (Vincent, Mueller & Vincent, 2008) using SILA

climate station data and radiometric measurements of PAR through the snow, clear lake ice, and water column (Belzile *et al.*, 2001; Belzile, Gibson & Vincent, 2002) has shown that the thermal profile of the lake can be accurately reproduced and that it depends on solar heating over a period of many decades. The modelling results suggested that Lake A last lost its ice cover during the 1930s-1940s, a period known to correspond to substantial warming elsewhere in the north polar region, and that with prolonged ice-free periods in the future it will gradually lose this large amount of excess heat stored in its mid-water column (Vincent, Mueller & Vincent, 2008). Changes in these thermal profiles over the last few decades, along with shifts in their ice cover, have revealed cascading regime shifts that indicate the value of these lakes as sentinels of climate change (Mueller *et al.*, 2009).

The northern Ellesmere Island meromictic lakes have also attracted considerable interest as highly stratified microbial ecosystems, with pronounced changes in species composition, biomass, and biogeochemistry down through their water columns. The lakes have strong vertical gradients in oxygen, nutrient, sulphide, and metal concentrations (Ludlam, 1996; Gibson *et al.*, 2002). Their oxygenated surface waters contain abundant populations of picocyanobacteria (Van Hove *et al.*, 2008) as well as chrysophytes and green algae (Veillette *et al.*, 2011a; Charvet, Vincent & Lovejoy, 2012). Molecular analyses have shown the presence of diverse Archaea down the water columns, with the stratified occurrence of different taxa, including ammonium oxidizers (nitrifiers) across the oxycline (Pouliot *et al.*, 2009). Ice-out and mixing are now beginning to disrupt and modify these stratified populations (Veillette *et al.*, 2011a).
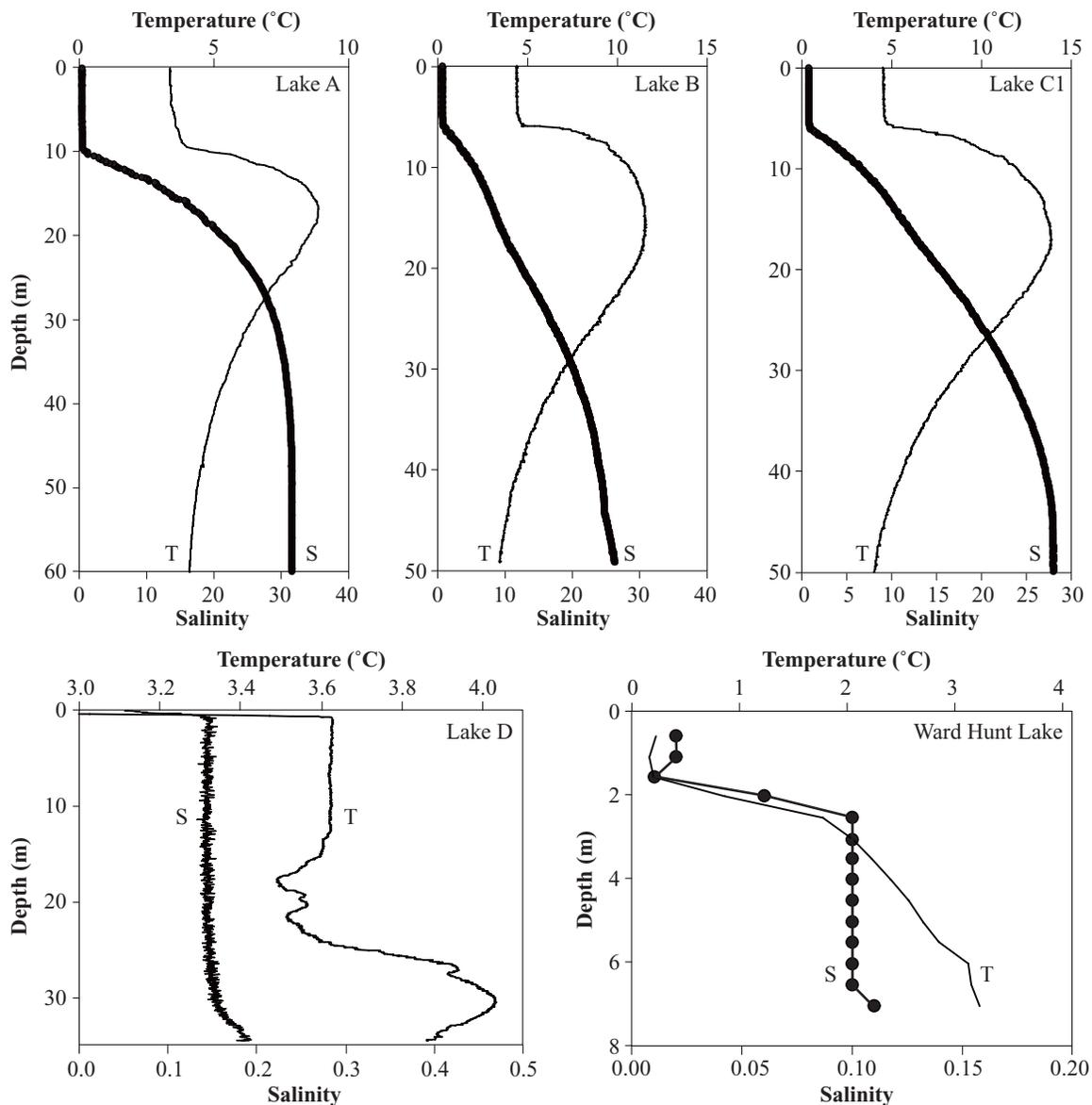

FIGURE 9. Water column profiles from lakes in the Ward Hunt Island region, showing the diversity of limnological conditions. S: salinity. T: temperature. From Veillette *et al.* (2011a) and unpublished data. Dates of profiling were 20 August 2008 (Lake A), 24 August 2008 (Lakes B and C1), 4 July 2009 (Lake D), and 27 June 2010 (Ward Hunt Lake).

In contrast to Antarctic lakes, the Ellesmere Island meromictic lakes contain a food web that extends all the way to fish and birds: benthic invertebrates, including chironomids and the freshwater amphipod *Gammarus lacustris*, calanoid copepods (notably the glacial relicts *Limnocalanus macrurus* and *Drepanopus bungei*; Van Hove *et al.*, 2001), the opossum shrimp *Mysis relicta*, and Arctic char (*Salvelinus alpinus*). Fairy shrimps (*Artemiopsis stefanssoni*) also occur in some of the shallow ponds on northern Ellesmere Island and derive at least part of their nutrition and pigmentation from feeding on the benthic cyanobacterial mats (Rautio, Bonilla & Vincent, 2009). The meromictic lakes and their biota have proved useful as latitudinal end members for contaminant studies, which have shown the presence of anthropogenic mercury in the sediments (Muir *et al.*, 2009) and perfluorinated acid contaminants in all components of the food web (J. Veillette, unpubl. data), but at extremely low concentrations relative to more southerly sites.

The lakes of the Ward Hunt Island region have also been of great interest to paleolimnologists for determining past changes in climate. Speculation that the meromictic lakes might contain high resolution paleoclimatic records, due to a lack of bioturbation in their anoxic bottom waters, was the inspiration for the Taconite Inlet Lakes Project (Bradley *et al.*, 1996). This project concentrated on the C-series lakes, with a particular focus on Lake C2 and its catchment, and was a process-based study that included studies of physical limnology, meteorology, sediment flux from the catchment, and climate and environmental records from lake sediments (summarized in Bradley *et al.*, 1996). These studies concluded that sediment flux was strongly related to summer temperatures and that varve thickness could therefore be used as a proxy of climate change (Hardy, 1996). Lamoureux and Bradley (1996) studied the 3300-y varved record from Lake C2 and from varve characteristics inferred relatively cold periods 3000-2400, 900-700, and 250-100 y BP and above-average temperatures 2500-1200 and 700-250 y BP as well as during the last century. Ludlam *et al*. (1996) also analyzed the abundance of stream diatoms in Lake C2 sediments and used the results to infer variations in runoff over the last 2 centuries. These data suggested a general decline in runoff through the 19th century, followed by an increasing trend during the 20th century, with the exception of the 1970s, and showed strong agreement with the varve record. Douglas, Ludlam, and Feeney (1996), in a longer-term diatom study from Lake C2, used changing diatom communities to infer increased open water conditions (and therefore warmer temperatures) during the last 2 centuries.

More recent research has focused on the sedimentary record of Lake A. Tomkins *et al.* (2009a) examined Lake A sedimentation, including features such as grain size, organic content, and varve formation. They determined that varves had been characteristic of sediment deposition in Lake A for the last ~1000 y. Agglomerated pellets deposited in the sediments over this time were used as a proxy for ice-rafting, and by analyzing changes in the abundance of these pellets over time, Tomkins *et al*. (2009b) determined that

ice cover in Lake A has fluctuated over the last millennium, with the period of greatest ice cover reductions having occurred since ~1891 AD. Tomkins *et al*. (2010) linked varve characteristics to autumn snowfall and temperatures. They determined that sediment delivery to Lake A was highly variable over time and that the highest autumn snowfall of the last millennium occurred during the early 20th century.

An examination of photosynthetic pigments in the water column of Lake A indicated that primary productivity is dominated by photosynthetic green sulfur bacteria that occur in large populations in the anoxic region of the water column (Antoniades *et al*., 2009). The 2 y of data in the study suggested a correlation between biomass and the penetration of solar radiation into the water column. Given the control of the ice and snow cover on light attenuation (Belzile *et al*., 2001), the authors hypothesized that bacterial pigments in Lake A sediment could be used to reconstruct past changes in ice cover. Sedimentary concentrations of bacterial pigments suggest highly variable productivity in the past and therefore potentially highly variable ice cover extent (D. Antoniades *et al*., 2011).

Ward Hunt Lake has also proved to contain a valuable sedimentary record of environmental change (Figure 10). Paleolimnological analysis of a sediment core from this lake showed the appearance of diatom communities and striking increases in photosynthetic pigment concentrations during the last 2 centuries (Antoniades *et al*., 2007). Diatoms, almost exclusively from the species *Staurosirella pinnata*, were detected only in the upper part of the sedimentary record, and pigment concentrations also grew by 2 orders of magnitude in these recent sediments. This record is consistent with other sequences from the circumpolar Arctic (Smol *et al.,* 2005) and implies that recent climate warming has strongly affected the Ward Hunt Lake ecosystem.

Collectively, these studies of environmental change in the lakes of northern Ellesmere Island suggest considerable environmental variability during the mid- to late Holocene. Climate-mediated fluctuations are evident in sedimentary microfossils as well as in biogeochemical and inorganic proxy indicators. During the last 2 centuries notable changes in all proxy indicators occurred in lakes along the coast of northern Ellesmere Island; these changes suggest that this period has been marked by the most pronounced environmental change of the last several millennia.

Plant ecology

Given the cold, short growing season for plant communities on northern Ellesmere Island, the sparse High Arctic vegetation of the area generally falls within the categories "polar desert" (vascular plant cover < 5% and low lichen and bryophyte cover) and "semi-desert" (vascular plant cover from 5 to 20% and lichen and bryophytes up to 50%; Bliss & Matveyeva, 1992). Comparable polar desert areas are found in northern Greenland (Bay, 1992; 1997) and to a lesser extent in northern Eurasia (Aleksandrova, 1988).

Broad-scale generalizations have been used to classify High Arctic vegetation based on soil and temperature
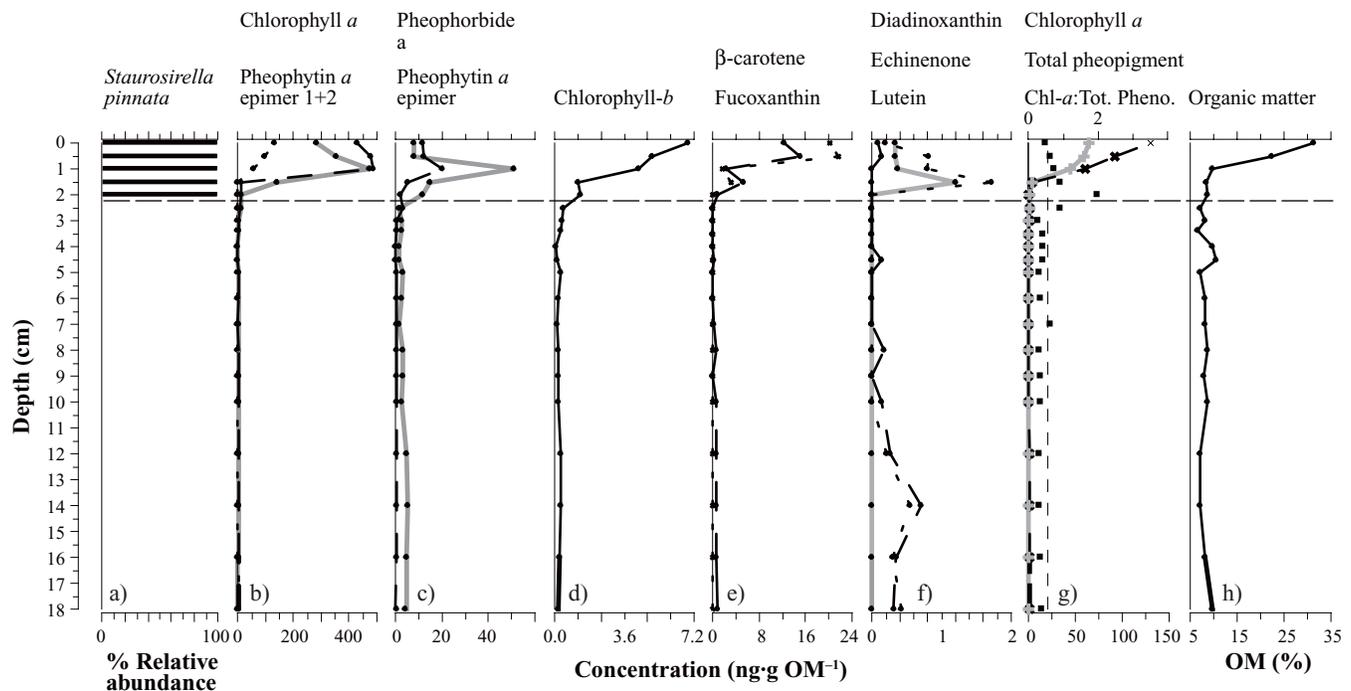
FIGURE 10. Paleolimnological record from Ward Hunt Lake, showing the recent appearance of a diatom (*Staurosirella pinnata*) and large increases in pigments and organic carbon, implying increased algal production associated with climate warming. (a) Relative abundance of *S. pinnata.* (b) Chlorophyll *a*, solid grey line; Pheophytin *a* epimer 1, dashed line; Pheophytin *a* epimer 2, dotted line. (c) Pheophorbide *a*, solid grey line; Pheophytin *a* epimer 3, dashed line. (d) Chlorophyll *b*. (e) β,β-carotene, dashed line; Fucoxanthin, dotted line. (f) Diadinoxanthin, solid grey line; lutein, dashed line; echinenone, dotted line. (g) Total chlorophyll *a* (solid grey line) and total pheopigments (dashed black line and crosses) expressed as molar concentrations and not corrected for organic matter content; black squares represent the molar ratio of chlorophyll *a* to total pheopigment, and the dashed vertical line is the mean ratio. (h) Percent organic matter determined by loss on ignition. Modified from Antoniades *et al.* (2007).

information (Edlund & Alt, 1989) as well as on NDVI analyses of satellite images (AVHRR; CAVM Team, 2003). Edlund and Alt (1989) proposed a northern limit of shrubs and suggested that woody plants (Arctic willow [*Salix arctica*] and Arctic avens [*Dryas integrifolia*]) and sedges would be absent from the northernmost part of Ellesmere Island. The CAVM project (2003) described this region as cryptogam-herbs barrens with very sparse and low-growing plant cover, with the exception of a small region near Alert that was described as rush/grass, forb, cryptogam tundra. Although these broad-scale synopses allow for comparisons across regions, they do not reflect the heterogeneous nature of High Arctic vegetation, especially in such a diverse landscape, where topography and substrate strongly affect the microclimate (Lévesque, Henry & Svoboda, 1997).

Accounting for part of this landscape complexity, Edlund (1994) proposed a map of Quttinirpaaq National Park in which purple saxifrage barrens dominate in the Ward Hunt Island region and vicinity. Long-lived cushions of *Saxifraga oppositifolia* are found throughout the area on well-drained soils reaching 5-20% cover (Figure 11). They grow with a range of herb and grass species as well as with a sparse but frequent occurrence of 2 low-growing shrubs, *Dryas integrifolia* and, more frequently, *Salix arctica*. Polunin (1940) summarized findings from early botanical records (late 1800s to early 1900s), and for northernmost Ellesmere Island sites there are numerous records of *Salix arctica* from almost all localities. In 1954, approximately 50 willows were collected from the western slope of Ward

Hunt Island during the first expedition of the Geological Survey of Canada to the region (Hattersley-Smith, Crary & Christie, 1955; Polunin, 1958).

Here we present an updated species list for the Ward Hunt Island region (Table I; Appendix I) based on information in Polunin (1940), our survey of the botanical collections from Northern Ellesmere and Ward Hunt Island in 2 major herbaria (Canadian Museum of Nature [CAN] and Agriculture Canada [DAO]), and our own collections made in 2001 and 2009. The vascular flora of the study area (from Floeberg Beach [82° 27' 00" N] north to Cape Columbia [83° 06' 41" N] and from Floeberg Beach [61° 25' 00" W] west to Taconite Inlet [78° 08' 00" W]) consists of 64 taxa (species, subspecies, and varieties) distributed in 15 families and 33 genera. All are herbaceous taxa except for 3 woody species: 2 creeping shrubs (*Dryas integrifolia* and *Salix arctica*) and 1 ericaceous dwarf shrub (*Cassiope tetragona*). The species richness of Ward Hunt Island is considerably less, with only 37 taxa. The 5 most diversified families of vascular plants in the study area comprise more than 70% (45 taxa) of the total flora: *Brassicaceae* (11 taxa, 17.2% of the flora), *Poaceae* (11 taxa, 17.2%), *Caryophyllaceae* (9 taxa, 14.1%), *Saxifragaceae* (9 taxa, 14.1%), and *Cyperaceae* (5 taxa, 7.8%). The regional flora belongs essentially to the Arctic *sensu lato* phytogeographical domain (62 taxa [96.9% of the flora]; Arctic-alpine: 38 taxa [59.4%], Arctic *sensu stricto*: 24 taxa [37.5%]) and is predominantly of circumpolar distribution with 51 taxa (79.7% of the flora).
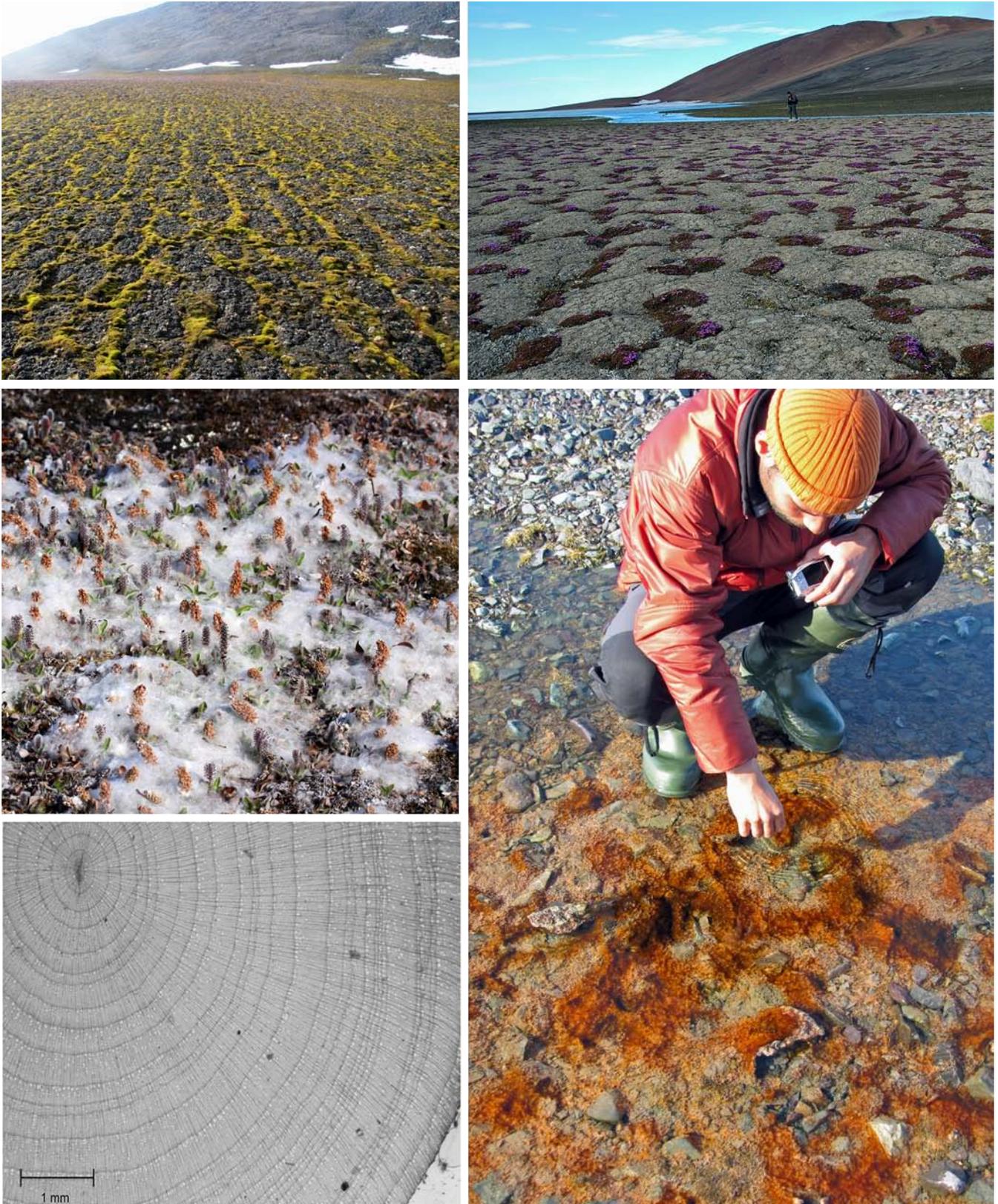
FIGURE 11. Photosynthetic communities at Ward Hunt Island and vicinity. Clockwise from top left: moss communities in sorted polygons on moist ground near Ward Hunt Lake; flowering *Saxifraga oppositifolia* in drier sorted polygons near Ward Hunt Lake; cyanobacterial mat in a shallow pond at Cape Discovery; cross-section of an Arctic willow root collar collected at the margin of Lake A showing the large interannual variability in growth rates (Boulanger-Lapointe, 2011); abundant Arctic willows in bloom (numerous catkins visible) at the Lake A margin, with seeds from the warm preceding year forming a white down (3 July 2009). Photo credits: D. Fortier, W. F. Vincent, and N. Boulanger-Lapointe.

Tᴀʙʟᴇ I. List of vascular plants currently known from Ward Hunt Island (*) and surrounding areas (extreme northern Ellesmere Island, Nunavut, Canada). Taxa are listed by family, and the most commonly used synonyms are given. Taxonomy follows published volumes of Flora of North America (FNA) or recent taxonomic papers. See Appendix I for further details.

	Taxa	Synonyms
Woodsiaceae		
	Cystopteris fragilis (L.) Bernh.	
Poaceae		
*	*Alopecurus borealis* Trin.	*A. alpinus* Sm.
	Arctagrostis latifolia (R. Br.) Griseb subsp. *latifolia*	
	Festuca baffinensis Polunin	
	Festuca brachyphylla Schult. & Schult. f. subsp. *brachyphylla*	
*	*Phippsia algida* (Sol.) R. Br.	
*	*Poa abbreviata* R. Br. subsp. *abbreviate*	
*	*Poa arctica* R. Br. subsp. *arctica*	
	Poa glauca Vahl subsp. *glauca*	
	Poa hartzii Gand subsp. *hartzii*	
	Puccinellia angustata (R. Br.) Rand & Redfield	
	Puccinellia vahliana (Liebm.) Scribn. & Merr.	*Colpodium vahlianum* (Liebm.) Nevski
Cyperaceae		
	Carex aquatilis Wahlenb. var. *minor* Boott	*C. aquatilis* var. *stans* (Drej.) Boott
*	*Carex fuliginosa* Schkuhr	*C. misandra* R. Br.
*	*Carex nardina* Fries *s. lat.*	incl. var. *atriceps* Kük.; var. *hepburnii* (Boott) Kük.
	Eriophorum angustifolium Honck. subsp. *angustifolium*	
	Eriophorum angustifolium Honck. subsp. *triste* (Fr.) Hult.	*E. triste* (Th. Fries) Hadac & Á. Löve
Juncaceae		
*	*Juncus biglumis* L.	
*	*Luzula arctica* Blytt	*L. nivalis* (Laest.) Beurling
*	*Luzula confusa* Lindeb.	
Salicaceae		
*	*Salix arctica* Pallas	
Polygonaceae		
*	*Bistorta vivipara* (L.) Delarbre	*Persicaria vivipara* (L.) Ronse Decr.; *Polygonum viviparum* L.
*	*Oxyria digyna* (L.) Hill.	
Caryophyllaceae		
*	*Cerastium arcticum* Lange	
*	*Cerastium beeringianum* Cham. & Schlecht.	
*	*Cerastium regelii* Ostenf.	
*	*Minuartia rossii* (R. Br. ex Richards.) Graebn.	*Arenaria rossii* R. Br. ex Richards.
*	*Minuartia rubella* (Wahlenb.) Hiern	*Arenaria rubella* (Wahlenb.) Sm.
	Silene acaulis (L.) Jacq.	*S. acaulis* subsp. *exscapa* (All.) DC.
	Silene involucrata (Cham. & Schlecht.) Bocquet subsp. *involucrate*	*Lychnis affinis* J. Vahl ex Fries; *Melandrium affine* (J. Vahl ex Fries) J. Vahl
	Silene uralensis (Rupr.) Bocquet subsp. *uralensis* subsp. *arcticum* (Fries) Hult.	*Lychnis apetala* L. subsp. *arctica* Hult.; *Melandrium apetalum* (L.) Fenzl
*	*Stellaria longipes* Goldie subsp. *longipes*	*S. crassipes* Hult.; *S. edwardsii* R. Br.; *S. laeta* Richards.; *S. monantha* Hult.; *S. subvestita* Greene
Ranunculaceae		
	Ranunculus nivalis L.	
	Ranunculus sabinei R. Br.	
	Ranunculus sulphureus Sol.	
Papaveraceae		
*	*Papaver cornwallisense* D. Löve	*P. radicatum* Rottb. subsp. *polare* auct., non Tolm.
*	*Papaver dahlianum* Nordh subsp. *polare* (Tolm.) Elven & Ö. Nilsson	*P. radicatum* Rottb. subsp. *polare* Tolm.
Brassicaceae		
	Braya glabella Richards. subsp. *purpurascens* (R. Br.) Cody	*B. purpurascens* (R. Br.) Bunge ex Ledeb.
*	*Cardamine bellidifolia* L.	
*	*Cochlearia groenlandica* L.	*C. arctica* Schlecht. ex Dc.; *C. officinalis* L. subsp. *arctica* (Schlecht. ex DC.) Hult.
	Draba alpina L.	
*	*Draba cinerea* Adams	
*	*Draba corymbosa* R. Br. ex DC.	*D. bellii* Holm
*	*Draba lactea* Adams	
*	*Draba micropetala* Hook.	*D. alpina* L. var. *micropetala* Durand
	Draba nivalis Liljebl.	
*	*Draba subcapitata* Simm.	
	Erysimum pallasii (Pursh) Fern.	

TABLE I. Continued.

Taxa	Synonyms
Saxifragaceae	
* _Micranthes foliolosa_ (R. Br.) Gornall	_Saxifraga foliolosa_ R. Br.
* _Micranthes nivalis_ (L.) J. K. Small	_Saxifraga nivalis_ L.
Micranthes tenuis (Wahlenb.) Sm.	_Saxifraga tenuis_ (Wahlenb.) Sm. ex Lindm.;
	S. nivalis L. var. _tenuis_ Wahlenb.
* _Saxifraga cernua_ L.	
* _Saxifraga cespitosa_ L.	
* _Saxifraga flagellaris_ Willd. subsp. _platysepala_ (Trautv.) Tolm.	_S. platysepala_ (Trautv.) Tolm.
Saxifraga oppositifolia L. _s. lat._	
* _Saxifraga oppositifolia_ L. cf.	
subsp. _smalliana_ (Engl. & Irmsch.) Hult.	_S. oppositifolia_ subsp. _glandulisepala_ Hult.
* _Saxifraga rivularis_ L. subsp. _rivularis_	
* _Saxifraga tricuspidata_ Rottb.	
Rosaceae	
* _Dryas integrifolia_ Vahl. subsp. _integrifolia_	
* _Potentilla hyparctica_ Malte subsp. _hyparctica_	
Potentilla pulchella R. Br.	
Ericaceae	
Cassiope tetragona (L.) D. Don subsp. _tetragona_	
Orobanchaceae	
Pedicularis hirsuta L.	
Asteraceae	
Erigeron uniflorus L. var. _eriocephalus_ (J. Vahl) Boivin	_E. eriocephalus_ J. Vahl
Taraxacum phymatocarpum J. Vahl _s. lat._	

The dominant vegetation type of Ward Hunt Island beach ridges is _Saxifraga_ barrens (Edlund & Alt, 1989); at a beach ridge site on the northern side of the island we measured nearly 10% cover for _Saxifraga oppositifolia_ but less than 1% for all other vascular plant species, including _Minuartia rubella, Draba subcapitata_, and _Papaver_ sp. Moss and lichen cover was also low, < 1% and < 2%, respectively. These well-drained sites did not have visible black cryptogamic crust. Both densely clumped cushions and trailing forms of _S. oppositifolia_ were observed. The cushion plants had a structuring impact on the semi-desert ecosystem, with improved soil conditions under the clumps, as measured by increased organic matter and the presence of other vascular species within or adjacent to _S. oppositifolia_ clumps (E. Lévesque, unpubl. data).

The vegetation on the hills of the eastern side of Ward Hunt Island (from 180 m to 250 m asl) had a similar diversity but sparser vascular plant cover (< 2%) relative to the beach ridge vegetation, with diverse lichens as well as extensive cryptogamic crusts (8%) and moss cover (5%). The hilly top offers micro-habitats that capture snow and provide wind protection. The main vegetation is characteristic of the _Saxifraga_ barrens (Edlund & Alt, 1989). Adjacent to Ward Hunt Lake, late-lying snow patches provide an inflow of water throughout the growing season and allow the extensive development of cryptogamic crusts (up to 30% cover). On the lake margin, the cover is almost continuous, while it divides into stripes in the periphery (Figure 11). This snowflush community contains mosses (1.4%), _Phippsia algida_ (0.6%), and _S. oppositifolia_ (0.3%). Mosses dominate in the furrows around moist polygons, while _S. oppositifolia_ occupies this habitat in drier environments (Figure 11). More than half of the lake margin

remains covered with snow until late in the season, which may currently restrict the recruitment of vascular plants.

During our vegetation surveys in 2001 and 2009, approximately 20 _Salix arctica_ individuals were recorded between the camp (next to Quttinirpaaq Lagoon) and Ward Hunt Lake, most of them female plants. Three _Dryas_ clumps and 2 clumps of _Carex nardina_ were recorded in the same area. In late July - early August 2001 most of the few willow catkins observed were still at stigma-out stage, whereas further south in the park at Tanquary Fiord (81° 24' N, 76° 52' W) we observed that the willows were in early fruiting stages. This suggests poor success at producing seeds in 2001, a cold summer with approximately 500 thawing degree days (TDD; sum of positive mean daily temperatures) in Tanquary Fiord and < 90 TDD at Ward Hunt Island. The temperature sums at Ward Hunt Island are comparable to cold, higher-elevation sites in central Ellesmere Island (Lévesque, Henry & Svoboda, 1997), where dolomitic sites at 600-700 m asl had TDD from 60 to 200 between 1989 and 1993 and low-elevation granitic sites (330 m asl) had TDD ranging from 400 to 600 over the same period. _Salix arctica_ reproduced at those lower sites, whereas only purple saxifrage, poppies, and _Draba subcapitata_ grew and periodically reproduced at the most extreme sites (Lévesque, 2001).

The Lake A/B catchment has an oasis-like, richer development of vegetation, with the communities similarly dominated by _Salix arctica_, _Dryas integrifolia_, and _Saxifraga oppositifolia_. Arctic willow cover at the lake margin averaged 7% but was over 80% in places. There was a high production of willow seeds in the warm 2008 season (Figure 11). Our dendrochronological analyses indicate that _Salix arctica_ was established at least 120 y ago and

that there has been consistent growth each season, but with large interannual variability in growth rates (Figure 11, Boulanger-Lapointe *et al.*, 2011). This builds on the study by Woodcock and Bradley (1994), who showed the value of dendrochronological analysis of *Salix arctica* in this region of the High Arctic. Their work on specimens from the Lake C2 catchment showed that growth was extremely slow (average of < 0.1 mm·y^{-1}), with establishment dates suggesting that warm summers occurred in the mid-1930s and mid-1950s.

Animal ecology

The Park Resource Inventory (Parks Canada, 1994) for the establishment of Quttinirpaaq National Park notes that wildlife is not common along this northern coastline (classified as Ecoregion CM01) but that ringed and bearded seals were observed on the ice, wolves, Arctic foxes, and seabirds occurred, and Peary caribou (*Rangifer tarandus pearyi*) were relatively common on the Marvin Peninsula. Muskox (*Ovibos moschatus*) are also regularly observed in this region. Despite more than 10 000 visitor days to the region since the 1950s, there have been no records of polar bear sightings, although the field logbook at Ward Hunt Island records that polar bear tracks were observed in M'Clintock Inlet. Given the ongoing and predicted deterioration of sea ice habitats further south in the Arctic (Durner *et al.*, 2009) and the increase in open water conditions along this region of the coast, this northern coastal region may become an important refuge for polar bears and other marine mammals in the future. Some 14 bird species have been recorded on Ward Hunt Island (Table II) in addition to Arctic foxes (*Alopex lagopus*), Arctic hares (*Lepus arcticus*), lemmings (*Lemmus lemmus*), and ermine (*Mustela erminea*). We have observed Brant geese (*Branta bernicla*) and Red throated loons (*Gavia stellata*) in the Lake A/B catchment, including the latter with juveniles on Lakes A and B during ice-out in August 2008 (Vincent *et al.*, 2009). Little is known about the insect ecology of this region (apart from the well-known presence of bumblebees, *Megabombus hyperboreus*; Milliron & Oliver, 1966), and it would be useful to establish collections of what is now likely to be a shifting baseline in community

structure. With ongoing warming, increased vegetation, and increasingly ice-free conditions in the lakes, fiords, and coastal seas, the animal ecology of Ward Hunt Island and vicinity is likely to undergo substantial change over the next few decades.

Conclusion

Despite its extreme High Arctic climate regime at the northern limit of North America, the Ward Hunt Island region has a remarkable diversity of landforms, snow and ice features, and ecosystems. The latter includes coastal seas with different ice types, deep stratified fiords, polar desert, and semi-desert terrestrial ecosystems, wetlands, flowing waters, and a variety of freshwater and saline lake ecosystems. These geosystems and ecosystems have proven to be productive sites for environmental research and valuable places to seek deep insights into broader questions such as variations in climate during the Holocene, the long-range dispersal of contaminants, the ecology of polar desert plant communities, and the structure and functioning of microbial ecosystems under extreme conditions for life. Many of these systems have begun to show striking changes in their physical and ecological properties. Ice shelf ecosystems that have been present for millennia are collapsing towards extinction, the active layer of permafrost soils is deepening, and the lakes of the region are losing their thick perennial ice covers or becoming ice free for a longer duration each year. These landscapes and ecosystems are now rapidly evolving towards new states, and these will require ongoing close attention by researchers from diverse disciplines to track the pace and impacts of global change.

Acknowledgements

TABLE II. Bird observations at Ward Hunt Island, as recorded in the station log books: 11 September 1969 - 23 July 2007 and 29 March 2008 - 11 July 2010.

Species	Common name (French name)	Dates of sighting (month/year)
Arenaria interpres	Ruddy turnstone (tournepierre à collier)	8/2002; 6/2008
Branta bernicla	Brant (bernache cravant)	8/2002; 8/2004; 6/2006; 6/2008; 8/2008
Bubo scandiacus	Snowy owl (harfang des neiges)	7/2008 (abandoned nest)
Calidris bairdii	Baird's sandpiper (bécasseau de Baird)	7/2009
Calidris canutus	Red knot (bécasseau maubèche)	8/2002; 7/2007; 6/2008; 7/2009; 7/2010
Charadrius hiaticula	Ringed plover (pluvier grand-gravelot)	07/2010
Clangula hyemalis	Long-tailed duck (cacaoui)	06/1972
Falco rusticolus	Gyrfalcon (faucon gerfaut)	06/2008
Lagopus mutus	Rock ptarmigan (lagopède alpin)	4/1989; 4/2008 (tracks); 7/2009
Larus hyperboreus	Glaucous gull (goéland bourgmestre)	7/2004; 6/2008
Plectrophenax nivalis	Snow bunting (bruant des neiges)	4/1991; 7/2004; 6/2006; 7/2007; 6/2008; 7/2008; 7/2009; 7/2010
Pluvialis squatarola	Black-bellied plover (pluvier argenté)	7/2002
Stercorarius longicaudus	Long-tailed jaeger (labbe à longue queue)	8/2002; 7/2004; 6/2008; 7/2008; 7/2009
Stercorarius parasiticus	Arctic skua (labbe parasite)	8/2008; 7/2010

Literature cited

Aleksandrova, V. D., 1988. Vegetation of the Soviet Polar Deserts. Cambridge University Press, Cambridge.

Althoff, W. F., 2007. Drift Stations: Arctic Outposts of Superpower Science. Potomac Books, Washington, DC.

Antoniades, D., C. Crawley, M. S. V. Douglas, R. Pienitz, D. Andersen, P. T. Doran, I. Hawes, W. Pollard & W. F. Vincent, 2007. Abrupt environmental change in Canada's northernmost lake inferred from fossil diatom and pigment stratigraphy. Geophysical Research Letters, 34: L18708.

Antoniades, D., J. Veillette, M.-J. Martineau, C. Belzile, J. Tomkins, R. Pienitz, S. Lamoureux & W. F. Vincent, 2009. Bacterial dominance of phototrophic communities in a High Arctic lake and its implications for paleoclimate analysis. Polar Science, 3: 147–161.

Antoniades, D., P. Francus, R. Pienitz, G. St-Onge & W. F. Vincent, forthcoming. Holocene dynamics of the Arctic's largest ice shelf. Proceedings of the National Academy of Sciences, USA.

Bay, C., 1992. A phytogeographical study of the vascular plants of northern Greenland: North of 74° northern latitude. Meddelelser om Grönland, Bioscience, 36: 102.

Bay, C., 1997. Floristical and ecological characterization of the polar desert zone of Greenland. Journal of Vegetation Science, 8: 685–696.

Belkin, I. & S. Kessel, forthcoming. Russian drifting stations on Arctic ice islands. In L. Copland & D. R. Mueller (eds). Arctic Ice Shelves and Ice Islands. Springer SBM, Dordrecht.

Belzile, C., J. A. E. Gibson & W. F. Vincent, 2002. Colored dissolved organic matter and dissolved organic carbon exclusion from lake ice: Implications for irradiance transmission and carbon cycling. Limnology and Oceanography, 47: 1283–1293.

Belzile, C., W. F. Vincent, J. A. E. Gibson & P. Van Hove, 2001. Bio-optical characteristics of the snow, ice, and water column of a perennially ice-covered lake in the High Arctic. Canadian Journal of Fisheries and Aquatic Sciences, 58: 2405–2418.

Berger, A. & M. F. Loutre, 1991. Insolation values for the climate of the last 10 million years. Quaternary Science Reviews, 10: 297–317.

Blake, W. J., 1972. Climatic implications of radiocarbon-dated driftwood in the Queen Elizabeth Islands. Pages 77–104 in Y. Vasari, H. Hyvärinen & S. Hicks (eds). Climatic Changes in Arctic Areas During the Last Ten Thousand Years. University of Oulu, Oulu.

Bliss, L. & N. Matveyeva, 1992. Circumpolar arctic vegetation. Pages 59–89 in F. Chapin III, R. Jefferies, J. Reynolds, G. Shaver, J. Svoboda & E. Chu (eds). Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective. Academic Press, San Diego, California.

Bonilla, S., V. Villeneuve & W. F. Vincent, 2005. Benthic and planktonic algal communities in a High Arctic Lake: Pigment structure and contrasting responses to nutrient enrichment. Journal of Phycology, 41: 1120–1130.

Bonilla, S., M. Rautio & W. F. Vincent, 2009. Phytoplankton and phytobenthos pigment strategies: Implications for algal survival in the changing Arctic. Polar Biology, 32: 1293–1303.

Bottos, E. M., W. F. Vincent, C. W. Greer & L. G. Whyte, 2008. Prokaryotic diversity of arctic ice shelf microbial mats. Environmental Microbiology, 10: 950–966.

Boulanger-Lapointe, N., 2011. Étude de populations de saules artiques dans le haut-Artique canadien et groenlandais. M.Sc thesis, Université du Québec à Trois-Rivières, Trois-Rivières, Québec, Canada.

Bradley, R. S., 1990. Holocene paleoclimatology of the Queen Elizabeth Islands, Canadian High Arctic. Quaternary Science Reviews, 9: 365–384.

Bradley, R. S., M. J. Retelle, S. D. Ludlam, D. R. Hardy, B. Zolitschka, S. F. Lamoureux & M. S. V. Douglas, 1996. The Taconite Inlet lakes project: A systems approach to paleoclimatic reconstruction. Journal of Paleolimnology, 16: 97–110.

Braun, C., forthcoming. The surface mass balance of the Ward Hunt Ice Shelf and Ward Hunt Ice Rise, Ellesmere Island, Nunavut, Canada. In L. Copland & D. R. Mueller (eds). Arctic Ice Shelves and Ice Islands. Springer SBM, Dordrecht.

Braun, C., D. R. Hardy, R. S. Bradley & V. Sahanatien, 2004. Surface mass balance of the Ward Hunt Ice Rise and Ward Hunt Ice Shelf, Ellesmere Island, Nunavut, Canada. Journal of Geophysical Research-Atmospheres, 109: D22110.

Brouillet, L. & P. E. Elvander, 2009. Saxifraga Linnaeus. Pages 132–147 in Flora of North America Editorial Committee (ed.). Flora of North America, Volume 8: Magnoliophyta: Paeoniaceae to Ericaceae. Oxford University Press, New York, New York.

CAVM Team, 2003. Circumpolar Arctic Vegetation Map. Scale 1:7 500 000. Conservation of Arctic Flora and Fauna (CAFF). Map No. 1. US Fish and Wildlife Service, Anchorage, Alaska.

Charvet, S., W. F. Vincent & C. Lovejoy, 2012. Chrysophytes and other protists in High Arctic lakes: molecular gene surveys, pigment signatures and microscopy. Polar Biology, doi: 10.1007/s00300-011-1118-7

Copland, L., D. R. Mueller & L. Weir, 2007. Rapid loss of the Ayles Ice Shelf, Ellesmere Island, Canada. Geophysical Research Letters, 34: L21501.

Cottier, F. R., F. Nilsen, R. Skogseth, V. Tverberg, J. Skardhamar & H. Svendsen, 2010. Arctic fjords: A review of the oceanographic environment and dominant physical processes. Geological Society, London, Special Publications, 344: 35–50.

Crary, A. P., 1960. Arctic ice island and ice shelf studies. Part II. Arctic, 13: 32–50.

Crowley, F. A., 1961. Gravity Observations Along the Northern Coast of Ellesmere Island. Air Force Cambridge Research Laboratories, GRD Research Notes, 53. Hanscom Field, Massachusetts.

Douglas, M. S. V., S. Ludlam & S. Feeney, 1996. Changes in diatom assemblages in Lake C2 (Ellesmere Island, Arctic Canada): Response to basin isolation from the sea and to other environmental changes. Journal of Paleolimnology, 16: 217–226.

Durner, G. M., D. C. Douglas, R. M. Nielson, S. C. Amstrup, T. L. McDonald, I. Stirling, M. Mauritzen, E. W. Born, O. Wiig, E. DeWeaver, M. C. Serreze, S. E. Belikov, M. M. Holland, J. Maslanik, J. Aars, D. A. Bailey & A. E. Derocher, 2009. Predicting 21st-century polar bear habitat distribution from global climate models. Ecological Monographs, 79: 25–58.

Dyke, A. S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. Pages 373–424 *in* J. Ehlers & P. L. Gibbard (eds). Quaternary Glaciations: Extent and Chronology, Part II. Elsevier, Amsterdam.

Dyke, A. S., J. England, E. Reimnitz & H. Jette, 1997. Changes in driftwood delivery to the Canadian Arctic Archipelago: The hypothesis of postglacial oscillations of the transpolar drift. Arctic, 50: 1–16.

Edlund, S., 1994. Chapter 8: Vegetation. *In* D. R. Gary & S. E. Gray (eds). Parks Canada Resource Description and Analysis: Ellesmere Island National Park Reserve. Natural Resource Conservation Section, Parks Canada, Department of Canadian Heritage, Winnipeg, Manitoba.

Edlund, S. A. & B. T. Alt, 1989. Regional congruence of vegetation and summer climate patterns in the Queen Elizabeth Islands, Northwest Territories, Canada. Arctic, 42: 3–23.

England, J. H., T. R. Lakeman, D. S. Lemmen, J. M. Bednarski, T. G. Stewart & D. J. A. Evans, 2008. A millennial-scale record of Arctic Ocean sea ice variability and the demise of the Ellesmere Island ice shelves. Geophysical Research Letters, 35: L19502.

Evans, D. J. A., 1989. An early Holocene narwhal tusk from the Canadian High Arctic. Boreas, 18: 43–50.

Fisher, D., A. Dyke, R. Koerner, J. Bourgeois, C. Kinnard, C. Zdanowicz, A. de Vernal, C. Hillaire-Marcel, J. Savelle & A. Rochon, 2006. Natural variability of Arctic sea ice over the Holocene. EOS Transactions, 87: 273–275.

Flora of North America Editorial Committee (eds.), 1993+. Flora of North America North of Mexico. 16+ volumes. Oxford University Press, New York and Oxford.

Fuglem, M. & I. Jordaan, forthcoming. Risk analysis and hazards of ice islands. *In* L. Copland & D. R. Mueller (eds). Arctic Ice Shelves and Ice Islands. Springer SBM, Dordrecht.

Gibson, J. A. E., W. F. Vincent, P. Van Hove, C. Belzile, X. W. Wang & D. Muir, 2002. Geochemistry of ice-covered, meromictic Lake A in the Canadian High Arctic. Aquatic Geochemistry, 8: 97–119.

Harding, T., A. D. Jungblut, C. Lovejoy & W. F. Vincent, 2011. Microbes in High Arctic snow and implications for the cold biosphere. Applied and Environmental Microbiology, 77: 3234–3243.

Hardy, D. R., 1996. Climatic influences on streamflow and sediment flux into Lake C2, northern Ellesmere Island, Canada. Journal of Paleolimnology, 16: 133–149.

Hattersley-Smith, G., 1957. The rolls on the Ellesmere Ice Shelf. Arctic, 10: 32–44.

Hattersley-Smith, G., 1962. Ice Conditions Off the North Coast of Ellesmere Island. Defence Research Board, Ottawa, Ontario.

Hattersley-Smith, G., 1963. The Ward Hunt Ice Shelf: Recent changes of the ice front. Journal of Glaciology, 4: 415–424.

Hattersley-Smith, G., 1967. Note on ice shelves off the north coast of Ellesmere Island. Arctic Circular, 17: 13–14.

Hattersley-Smith, G., 1974. North of Latitude Eighty. Defence Research Board of Canada, Ottawa, Ontario.

Hattersley-Smith, G., A. P. Crary & R. L. Christie, 1955. Northern Ellesmere Island, 1953 and 1954. Arctic, 8: 1–36.

Hattersley-Smith, G., J. E. Keys, H. Serson & J. E. Mielke, 1970. Density stratified lakes in northern Ellesmere Island. Nature, 225: 55–56.

Holdsworth, G., 1971. Calving from Ward Hunt Ice Shelf, 1961–1962. Canadian Journal of Earth Sciences, 8: 299–305.

Holdsworth, G., 1987. The surface waveforms on the Ellesmere Island ice shelves and ice islands. Pages 385–403 *in* G. R. Pilkington & B. W. Danielewicz (eds). Workshop on Extreme Ice Features. National Research Council of Canada, Banff, Alberta.

Holmgren, P. K., N. H. Holmgren & L. C. Burnett, 1990. Index Herbariorum, Part I: The Herbaria of the World. New York Botanical Garden, New York, New York.

IPCC, 2007. Climate Change 2007, the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change. Geneva.

Jeffries, M. O., 1986a. Glaciers and the morphology and structure of Milne Ice Shelf, Ellesmere Island, NWT, Canada. Arctic and Alpine Research, 18: 397–405.

Jeffries, M. O., 1986b. Ice island calvings and ice shelf changes, Milne Ice Shelf and Ayles Ice Shelf, Ellesmere Island, NWT. Arctic, 39: 15–19.

Jeffries, M. O., 1992a. Arctic ice shelves and ice islands: Origin, growth and disintegration, physical characteristics, structural-stratigraphic variability, and dynamics. Reviews of Geophysics, 30: 245–267.

Jeffries, M. O., 1992b. The source and calving of ice island ARLIS-II. Polar Record, 28: 137–144.

Jeffries, M. O., forthcoming. The ice shelves of northernmost Ellesmere Island, Nunavut, Canada. *In* L. Copland & D. R. Mueller (eds). Arctic Ice Shelves and Ice Islands. Springer SBM, Dordrecht.

Jeffries, M. O. & H. Serson, 1983. Recent changes at the front of Ward Hunt Ice Shelf, Ellesmere Island, NWT. Arctic, 36: 289–290.

Jeffries, M. O. & H. Serson, 1986. Survey and mapping of recent ice shelf changes and landfast sea ice growth along the north coast of Ellesmere Island. Annals of Glaciology, 8: 96–99.

Jeffries, M. O., H. R. Krouse, M. A. Shakur & S. A. Harris, 1984. Isotope geochemistry of stratified lake "A", Ellesmere Island, N.W.T., Canada. Canadian Journal of Earth Sciences, 21: 1008–1017.

Jeffries, M. O., W. M. Sackinger, H. R. Krouse & H. V. Serson, 1988. Water circulation and ice accretion beneath Ward Hunt Ice Shelf (Northern Ellesmere Island, Canada), deduced from salinity and isotope analysis of ice cores. Annals of Glaciology, 10: 68–72.

Jungblut, A. D., C. Lovejoy & W. F. Vincent, 2010. Global distribution of cyanobacterial ecotypes in the cold biosphere. ISME Journal, 4: 191–202.

Jungblut, A. D., D. R. Mueller & W. F. Vincent, forthcoming. Arctic ice shelf ecosystems. *In* L. Copland & D. R. Mueller (eds). Arctic Ice Shelves and Ice Islands. Springer SBM, Dordrecht.

Koenig, L. S., K. R. Greenaway, M. Dunbar & G. Hattersley-Smith, 1952. Arctic ice islands. Arctic, 5: 66–103.

Lamoureux, S. F. & R. S. Bradley, 1996. A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. Journal of Paleolimnology, 16: 239–255.

Lemmen, D. S., 1989. The last glaciation of Marvin Peninsula, northern Ellesmere Island, High Arctic, Canada. Canadian Journal of Earth Sciences, 26: 2578–2590.

Lévesque, E., 2001. Small scale plant distribution within a polar desert plateau, central Ellesmere Island, Canada. Écoscience, 8: 350–358.

Lévesque, E., G. H. R. Henry & J. Svoboda, 1997. Phenological and growth responses of *Papaver radicatum* along altitudinal gradients in the Canadian High Arctic. Global Change Biology, 3: 125–145.

Ludlam, S. D., 1996. The comparative limnology of High Arctic, coastal, meromictic lakes. Journal of Paleolimnology, 16: 111–131.

Lyons, J. B. & J. E. Mielke, 1973. Holocene history of a portion of northernmost Ellesmere Island. Arctic, 26: 314–323.

Lyons, J. B., R. H. Ragle & A. J. Tamburi, 1972. Growth and grounding of the Ellesmere Island ice rises. Journal of Glaciology 11: 3–52.

Milliron, H. E. & D. R. Oliver, 1966. Bumblebees from northern Ellesmere Island, with observations on usurpation by *Megabombus hyperboreus* (Schönh.). Canadian Entomologist, 98: 207–213.

Mortimer, C., 2011. Quantification of changes for the Milne Ice Shelf, Nunavut, Canada, 1950–2009. M.Sc. thesis. University of Ottawa, Ottawa, Ontario.

Morton, J. K., 2005. *Cerastium* Linnaeus. Pages 74–93 *in* Flora of North America Editorial Committee (ed.). Flora of North America, volume 5: Magnoliophyta: Caryophyllidae, Part 2. Oxford University Press, New York, New York.

Mueller, D. R. & W. F. Vincent, 2006. Microbial habitat dynamics and ablation control on the Ward Hunt Ice Shelf. Hydrological Processes, 20: 857–876.

Mueller, D. R., W. F. Vincent & M. O. Jeffries, 2003. Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. Geophysical Research Letters, 30: 2031.

Mueller, D. R., W. F. Vincent & M. O. Jeffries, 2006. Environmental gradients, fragmented habitats, and microbiota of a northern ice shelf cryoecosystem, Ellesmere Island, Canada. Arctic, Antarctic, and Alpine Research, 38: 593–607.

Mueller, D. R., W. F. Vincent, S. Bonilla & I. Laurion, 2005. Extremotrophs, extremophiles and broadband pigmentation strategies in a High Arctic ice shelf ecosystem. FEMS Microbiology Ecology, 53: 73–87.

Mueller, D. R., L. Copland, A. Hamilton & D. R. Stern, 2008. Examining Arctic ice shelves prior to the 2008 breakup. Eos, 89: 502–503.

Mueller, D. R., P. Van Hove, D. Antoniades, M. O. Jeffries & W. F. Vincent, 2009. High Arctic lakes as sentinel ecosystems: Cascading regime shifts in climate, ice cover, and mixing. Limnology and Oceanography, 54: 2371–2385.

Muir, D. C. G., X. Wang, F. Yang, N. Nguyen, T. A. Jackson, M. S. Evans, M. Douglas, G. Kock, S. Lamoureux, R. Pienitz, J. P. Smol, W. F. Vincent & A. Dastoor, 2009. Spatial trends and historical deposition of mercury in eastern and northern Canada inferred from lake sediment cores. Environmental Science & Technology, 43: 4802–4809.

Narod, B. B., G. K. C. Clarke & B. T. Prager, 1988. Airborne UHF radar sounding of glaciers and ice shelves, northern Ellesmere Island, Arctic Canada. Canadian Journal of Earth Sciences, 25: 95–105.

Parks Canada, 1994. Ellesmere Island National Park Reserve. Park Resource Inventory. Parks Canada, Ottawa, Ontario.

Polunin, N., 1940. Botany of the Canadian Eastern Arctic, Part I. Pteridophyta and Spermatophyta. National Museum of Canada Bulletin, Ottawa, Ontario.

Polunin, N., 1958. The botany of Ice-Island T-3. Journal of Ecology, 46: 323–347.

Polyak, L., R. B. Alley, J. T. Andrews, J. Brigham-Grette, T. M. Cronin, D. A. Darby, A. S. Dyke, J. J. Fitzpatrick, S. Funder, M. Holland, A. E. Jennings, G. H. Miller, M. O'Regan, J. Savelle, M. Serreze, K. St John, J. W. C. White & E. Wolff, 2010. History of sea ice in the Arctic. Quaternary Science Reviews, 29: 1757–1778.

Pouliot, J., P. E. Galand, C. Lovejoy & W. F. Vincent, 2009. Vertical structure of Archaeal communities and the distribution of ammonia monooxygenase A gene variants in two meromictic High Arctic lakes. Environmental Microbiology, 11: 687–699.

Rautio, M., S. Bonilla & W. F. Vincent, 2009. UV photoprotectants in Arctic zooplankton. Aquatic Biology, 7: 93–105.

Sackinger, W. M., 1988. Coastal ice dynamics. Pages 63–84 *in* A. T. Chen & C. B. Leidersdoff (eds). Arctic Coastal Processes and Slope Protection Design. American Society of Civil Engineers, New York, New York.

Screen, J. A. & I. Simmonds, 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. Nature, 464: 1334–1337.

Singh, S. M. & J. Elster, 2007. Cyanobacteria in Antarctic lake environments: A mini-review. Pages 303–320 *in* J. Seckbach (ed.). Algae and Cyanobacteria in Extreme Environments. Springer, Dordrecht.

Skardhamar, J. & H. Svendsen, 2010. Short-term hydrographic variability in a stratified Arctic fjord. Geological Society, London, Special Publications, 344: 51–60.

Smol, J. P., A. P. Wolfe, H. J. B. Birks, M. S. V. Douglas, V. J. Jones, A. Korhola, R. Pienitz, K. Ruhland, S. Sorvari, D. Antoniades, S. J. Brooks, M. A. Fallu, M. Hughes, B. E. Keatley, T. E. Laing, N. Michelutti, L. Nazarova, M. Nyman, A. M. Paterson, B. Perren, R. Quinlan, M. Rautio, E. Saulnier-Talbot, S. Siitoneni, N. Solovieva & J. Weckstrom, 2005. Climate-driven regime shifts in the biological communities of arctic lakes. Proceedings of the National Academy of Sciences of the United States of America, 102: 4397–4402.

Stewart, T. & J. England, 1983. Holocene sea-ice variations and paleoenvironmental change, northernmost Ellesmere Island, NWT, Canada. Arctic and Alpine Research, 15: 1–17.

Tomkins, J. D., S. F. Lamoureux, D. Antoniades & W. F. Vincent, 2009a. Sedimentology of perennial ice-covered, meromictic Lake A, Ellesmere Island, at the northern extreme of Canada. Canadian Journal of Earth Sciences, 46: 83–100.

Tomkins, J. D., S. F. Lamoureux, D. Antoniades & W. F. Vincent, 2009b. Sedimentary pellets as an ice-cover proxy in a High Arctic ice-covered lake. Journal of Paleolimnology, 41: 225–242.

Tomkins, J. D., S. F. Lamoureux, D. Antoniades & W. F. Vincent, 2010. Autumn snowfall and hydroclimatic variability during the past millennium inferred from the varved sediments of meromictic Lake A, northern Ellesmere Island, Canada. Quaternary Research, 74: 188–198.

Trettin, H., (ed.), 1991. Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland. Geological Survey of Canada, Ottawa, Ontario.

Van Hove, P., K. M. Swadling, J. A. E. Gibson, C. Belzile & W. F. Vincent, 2001. Farthest north lake and fjord populations of calanoid copepods *Limnocalanus macrurus* and *Drepanopus bungei* in the Canadian High Arctic. Polar Biology, 24: 303–307.

Van Hove, P., C. Belzile, J. A. E. Gibson & W. F. Vincent, 2006. Coupled landscape–lake evolution in High Arctic Canada. Canadian Journal of Earth Sciences, 43: 533–546.

Van Hove, P., W. F. Vincent, P. E. Galand & A. Wilmotte, 2008. Abundance and diversity of picocyanobacteria in High Arctic lakes and fjords. Algological Studies, 126: 209–227.

Varin, T., C. Lovejoy, A. D. Jungblut, W. F. Vincent & J. Corbeil, 2010. Metagenomic profiling of Arctic microbial mat communities as nutrient scavenging and recycling systems. Limnology and Oceanography, 55: 1901–1911.

Veillette, J., D. R. Mueller, D. Antoniades & W. F. Vincent, 2008. Arctic epishelf lakes as sentinel ecosystems: Past, present and future. Journal of Geophysical Research-Biogeosciences, 113: 1–11.

Veillette, J., M.-J. Martineau, D. Antoniades, D. Sarrazin & W. F. Vincent, 2011a. Effects of loss of perennial lake ice on mixing and phytoplankton dynamics: Insights from High Arctic Canada. Annals of Glaciology, 51: 56–70.

Veillette, J., C. Lovejoy, M. Potvin, T. Harding, A. D. Jungblut, D. Antoniades, C. Chénard, C. A. Suttle & W. F. Vincent, 2011b. Milne Fiord epishelf lake: A coastal Arctic ecosystem vulnerable to climate change. Écoscience, 18: 304–316.

Villeneuve, V., W. F. Vincent & J. Komarek, 2001. Community structure and microhabitat characteristics of cyanobacterial mats in an extreme High Arctic environment: Ward Hunt Lake. Pages 199–223 *in* J. Elster, J. Seckbach, W. F. Vincent & O. Lhotsky (eds). Algae and Extreme Environments: Ecology and Physiology. Nova Hedwigia, Beiheft.

Vincent, A. C., D. R. Mueller & W. F. Vincent, 2008. Simulated heat storage in a perennially ice-covered High Arctic lake: Sensitivity to climate change. Journal of Geophysical Research-Oceans, 113: C04036.

Vincent, W. F., 2000. Cyanobacterial dominance in the polar regions. Pages 321–340 *in* B. A. Whitton & M. Potts (eds). Ecology of the Cyanobacteria: Their Diversity in Space and Time. Kluwers Academic Press, Dordrecht.

Vincent, W. F., 2010. Microbial ecosystem responses to rapid climate change in the Arctic. ISME Journal, 4: 1089–1091.

Vincent, W. F., J. A. E. Gibson & M. O. Jeffries, 2001. Ice-shelf collapse, climate change, and habitat loss in the Canadian High Arctic. Polar Record, 37: 133–142.

Vincent, W. F., D. R. Mueller & S. Bonilla, 2004. Ecosystems on ice: The microbial ecology of Markham Ice Shelf in the High Arctic. Cryobiology, 48: 103–112.

Vincent, W. F., J. A. E. Gibson, R. Pienitz, V. Villeneuve, P. A. Broady, P. B. Hamilton & C. Howard-Williams, 2000. Ice shelf microbial ecosystems in the High Arctic and implications for life on snowball earth. Naturwissenschaften, 87: 137–141.

Vincent, W. F., L. G. Whyte, C. Lovejoy, C. W. Greer, I. Laurion, C. A. Suttle, J. Corbeil & D. R. Mueller, 2009. Arctic microbial ecosystems and impacts of extreme warming during the International Polar Year. Polar Science, 3: 171–180.

Woodcock, H. & R. S. Bradley, 1994. *Salix arctica* (Pall.): Its potential for dendroclimatological studies in the High Arctic. Dendrochronology, 12: 11–22.

APPENDIX I. Vascular plants currently known from Ward Hunt Island (*) and surrounding areas (extreme northern Ellesmere Island, Nunavut, Canada). Taxa are listed by family. Under the Collections column are given name of collectors followed by collection number (w.n. = without number) as well as acronym of herbarium where voucher is kept (herbaria acronyms follow Holmgren, Holmgren & Burnett, 1990): BM: The Natural History Museum Herbarium, London (England); C: University of Copenhagen Herbarium, Copenhagen (Denmark); CAN: Canadian Museum of Nature Herbarium, Ottawa (Canada); K: Royal Botanic Gardens Herbarium, Kew (England); NY: New York Botanical Garden Herbarium, Bronx (United States); S: Swedish Museum of Natural History Herbarium, Stockholm (Sweden); UQTR: Université du Québec à Trois-Rivières Herbarium, Trois-Rivières (Canada). Taxonomy follows published volumes of 'Flora of North America' (FNA) or recent taxonomic papers.

Taxa	Collections	Comments
Woodsiaceae		
Cystopteris fragilis (L.) Bernh.	*Bartlett w.n.* (C, K, NY); *Hattersley-Smith 44, 45* (CAN)	#44 (*sub Woodsia glabella* R. Br.) is a very small and compact specimen of *C. fragilis*, easily mistaken for a *Woodsia* species.
Poaceae		
* *Alopecurus borealis* Trin.	*Christie 34, 35* (CAN); *Hattersley-Smith 52* (CAN); *Kingston 23* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Arctagrostis latifolia (R. Br.) Griseb subsp. *latifolia*		*Fide* Polunin (1940), numerous collections from the general area.
Festuca baffinensis Polunin	*Fielden w.n.* (BM, K)	*Fide* Polunin 1940.
Festuca brachyphylla Schult. & Schult. f. subsp. *brachyphylla*		*Fide* Polunin 1940.
* *Phippsia algida* (Sol.) R. Br.	*Lévesque w.n.* (UQTR)	
* *Poa abbreviata* R. Br. subsp. *abbreviata*	*Lévesque w.n.* (UQTR)	According to Polunin (1940), numerous other collections exist from the general area.
* *Poa arctica* R. Br. subsp. *arctica*		*Fide* Polunin (1940), numerous collections from the general area.
Poa glauca Vahl subsp. *glauca*	*Bartlett w.n.* (BM, K, S)	
Poa hartzii Gand subsp. *hartzii*	*Bartlett w.n.* (NY)	
Puccinellia angustata (R. Br.) Rand & Redfield	*Wolf w.n.* (NY)	
Puccinellia vahliana (Liebm.) Scribn. & Merr.	*Feilden w.n.* (K)	
Cyperaceae		
Carex aquatilis Wahlenb. var. *minor* Boott		*Fide* Polunin (1940), numerous collections from the general area.
* *Carex fuliginosa* Schkuhr	*Christie 37* (CAN); *Lévesque w.n.* (UQTR)	According to Polunin (1940), numerous other collections exist from the general area.
* *Carex nardina* Fries *s. lat.*	*Christie 38* (CAN); *Lévesque w.n.* (UQTR)	
Eriophorum angustifolium Honck. subsp. *angustifolium*		*Fide* Polunin 1940.
Eriophorum angustifolium Honck. subsp. *triste* (Fr.) Hult.		According to Polunin (1940), most collections from the general area belong to this subspecies.
Juncaceae		
* *Juncus biglumis* L.	*Christie 39* (CAN); *Lévesque w.n.* (UQTR)	According to Polunin (1940), numerous other collections exist from the general area.
* *Luzula arctica* Blytt	*Christie 36* (CAN); *Feilden w.n.* (BM); *Hansen w.n.* (C)	According to Simmons (1906), numerous other collections exist from the general area.
* *Luzula confusa* Lindeb.	*Kingston 22* (CAN); *Lévesque w.n.* (UQTR)	According to Polunin (1940), numerous other collections exist from the general area.
Salicaceae		
* *Salix arctica* Pallas	*Christie 40* (CAN); *Hattersley-Smith 27, 28, 29* (CAN); *Kingston 11* (CAN); *Wolf w.n.* (NY)	According to Polunin (1940), numerous other collections exist from the general area.
Polygonaceae		
* *Bistorta vivipara* (L.) Delarbre	*Christie 41* (CAN); *Lévesque w.n.* (UQTR)	According to Polunin (1940), numerous other collections exist from the general area.
* *Oxyria digyna* (L.) Hill.	*Kingston 18* (CAN); *Hattersley-Smith 30* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Caryophyllaceae		
* *Cerastium arcticum* Lange	*Beschel w.n.* (CAN); *Christie 42, 43* (CAN); *Serson w.n.* (CAN)	
Cerastium beeringianum Cham. & Schlecht.	*Lévesque w.n.* (UQTR); *Hattersley-Smith 31* (CAN); *Kingston 10* (CAN); *Moore w.n.* (CAN)	Specimens belong to the "Arctic Dwarf" taxon (*C. bialynickii* Tolm. *sensu* Morton, 2005), still without a proper name and for the time being put under *C. beeringianum*.

Appendix I. Continued.

Taxa	Collections	Comments
* *Cerastium regelii* Ostenf.	*Lévesque w.n.* (UQTR); *Christie 44* (CAN); *Hattersley-Smith 32* (CAN); *Kingston 12* (CAN); *Serson w.n.* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
* *Minuartia rossii* (R. Br. ex Richards.) Graebn.	*Lévesque w.n.* (UQTR); *Christie 50* (CAN)	
* *Minuartia rubella* (Wahlenb.) Hiern	*Lévesque w.n.* (UQTR); *Christie 49* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Silene acaulis (L.) Jacq.	*Hattersley-Smith 53* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Silene involucrata (Cham. & Schlecht.) Bocquet subsp. *involucrata*		*Fide* Polunin (1940), numerous collections from the general area.
Silene uralensis (Rupr.) Bocquet subsp. *uralensis*		*Fide* Polunin (1940), numerous collections from the general area.
* *Stellaria longipes* Goldie subsp. *longipes*	*Kingston 5* (CAN); *Christie 45, 47, 48* (CAN); *Hattersley-Smith 33* (CAN); *Feilden w.n.* (K); *Wolf w.n.* (NY)	According to Polunin (1940), numerous other collections exist from the general area.
Ranunculaceae		
Ranunculus nivalis L.		*Fide* Polunin (1940), numerous collections from the general area.
Ranunculus sabinei R. Br.	*Bartlett w.n.* (K); *Feilden w.n.* (K)	
Ranunculus sulphureus Sol.	*Bartlett w.n.* (C, K, NY); *Feilden w.n.* (K); *Goodsell w.n.* (NY)	*Fide* Polunin (1940), numerous collections from the general area.
Papaveraceae		
* *Papaver cornwallisense* D. Löve	*Christie 51, 52, 55* (CAN); *Hattersley-Smith 35* (CAN); *Kingston 2* (CAN); *Lévesque w.n.* (UQTR); *Moore w.n.* (CAN); *Serson w.n.* (CAN)	
* *Papaver dahlianum* Nordh subsp. *polare* (Tolm.) Elven & Ö. Nilsson	*Christie 56* (CAN); *Hattersley-Smith 34* (CAN); *Lévesque w.n.* (UQTR);	Collections from CAN were identified by H. Solstad & R. Elven as *P. cf. dahlianum* and the identification of Lévesque's collection to this taxa remains tentative.
Brassicaceae		
Braya glabella Richards. subsp. *purpurascens* (R. Br.) Cody	*Wolf w.n.* (NY)	According to Polunin (1940), numerous other collections exist from the general area.
* *Cardamine bellidifolia* L.	*Kingston 9* (CAN)	
* *Cochlearia groenlandica* L.	*Bartlett w.n.* (BM, C, K, NY); *Christie 60, 62* (CAN); *Feilden w.n.* (BM, K); *Hattersley-Smith 36* (CAN); *Kingston 17* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Draba alpina L.	*Bartlett w.n.* (C, K); *Feilden w.n.* (BM, K)	According to Polunin (1940), numerous other collections exist from the general area.
* *Draba cinerea* Adams	*Hattersley-Smith 59* (CAN)	According to Polunin (1940), several collections exist from the general area.
* *Draba corymbosa* R. Br. ex DC.	*Christie 57, 58* (CAN); *Hattersley-Smith 37* (CAN); *Lévesque w.n.* (UQTR); *Serson w.n.* (CAN)	
* *Draba lactea* Adams*	*Hattersley-Smith 62* (CAN)	
* *Draba micropetala* Hook.	*Kingston 13A* (CAN)	
Draba nivalis Liljebl.	*Feilden w.n.* (BM)	
* *Draba subcapitata* Simm.	*Christie 59* (CAN); *Feilden w.n.* (BM, K); *Hansen w.n.* (C); *Hattersley-Smith 38, 60, 61* (CAN); *Kingston 13B* (CAN); *Lévesque w.n.* (UQTR)	

APPENDIX I. Concluded.

Taxa	Collections	Comments
Erysimum pallasii (Pursh) Fern.		*Fide* Polunin (1940).
Saxifragaceae		
* *Micranthes foliolosa* (R. Br.) Gornall	*Kingston 20A* (CAN)	
* *Micranthes nivalis* (L.) J. K. Small	*Christie 70* (CAN); *Hattersley-Smith 65* (CAN); *Kingston 20, 21* (CAN); *Lévesque w.n.* (UQTR)	*Fide* Polunin (1940), numerous collections from the general area. We were unable to verify the collections and no mention of subspecies.
Micranthes tenuis (Wahlenb.) Sm.		*Fide* Polunin (1940), numerous collections from the general area. We were unable to verify the collections and no mention of subspecies.
* *Saxifraga cernua* L.	*Bartlett w.n.* (K); *Christie 66A* (CAN); *Feilden w.n.* (K); *Hattersley-Smith 40* (CAN); *Kingston 7* (CAN); *Lévesque w.n.* (UQTR);	According to Polunin (1940), numerous other collections exist from the general area.
* *Saxifraga cespitosa* L.	*Christie 68* (CAN); *Hattersley-Smith 39* (CAN); *Kingston 8* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
* *Saxifraga flagellaris* Willd. subsp. *platysepala* (Trautv.) Tolm.	*Hattersley-Smith 41* (CAN); *Kingston 15* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Saxifraga oppositifolia L. *s. lat.*		*Fide* Polunin (1940), numerous collections from the general area. We were unable to verify the collections and no mention of subspecies.
* *Saxifraga oppositifolia* L. cf. subsp. *smalliana* (Engl. & Irmsch.) Hult.	*Lévesque w.n.* (UQTR; two plates)	According to Brouillet & Elvander (2009), subsp. *smalliana* is restricted to Yukon and Alaska. However, these specimens have glandular-ciliate sepal margins and were thus placed tentatively in this subspecies.
* *Saxifraga rivularis* L. subsp. *rivularis*	*Christie 65, 66, 67* (CAN)	
* *Saxifraga tricuspidata* Rottb.	*Hattersley-Smith 64* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Rosaceae		
* *Dryas integrifolia* Vahl. subsp. *integrifolia*	*Feilden w.n.* (BM, K); *Hattersley-Smith 43* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
* *Potentilla hyparctica* Malte subsp. *hyparctica*	*Feilden w.n.* (BM, K); *Hattersley-Smith 67* (CAN); *Kingston 19* (CAN)	According to Polunin (1940), numerous other collections exist from the general area.
Potentilla pulchella R. Br.	*Bartlett w.n.* (BM, C); *Feilden w.n.* (BM, K); *Lévesque w.n.* (UQTR)	
Ericaceae		
Cassiope tetragona (L.) D. Don subsp. *tetragona*	*Hattersley-Smith 69* (CAN)	
Orobanchaceae		
Pedicularis hirsuta L.	*Bartlett w.n.* (C, K)	
Asteraceae		
Erigeron uniflorus L. var. *eriocephalus* (J. Vahl) Boivin	*Hattersley-Smith 70* (CAN)	
Taraxacum phymatocarpum J. Vahl *s. lat.*	*Fielden w.n.* (BM, K); *Wolf w.n.* (NY)	*Fide* Polunin (1940). We were uable to verify these collections. In some earlier treatments of arctic dandelions *T. phymatocarpum* included other species now recognized: *T. hyparcticum* Dahlst., *T. holmenianum* Sahlin (syn. *T. pumilum* Dahlst.) and even *T. ceratophorum* (Ledeb.) DC. (syn. *T. lacerum* Greene, *T. hyperboreum* Dahlst.). As such, collections mentioned here may be any of these species.