*Polar Record 37 (201): 133-142 (2001). Printed in the United Kingdom.*

# Ice-shelf collapse, climate change, and habitat loss in the Canadian high Arctic

**W. F, Vincent**
Département de Biologie and Centre d'Études Nordiques,
Université Laval, Sainte-Foy, Québec G1K 7P4, Canada
**J.A.E. Gibson**
CSIRO Marine Research, GPO Box 1538, Hobart,
Tasmania 7001, Australia
**M.O. Jeffries**
Geophysical Institute, University of Alaska, PO Box 757320
Fairbanks, AK 99775-7320, USA

*Received July 2000*

ABSTRACT. Early explorers in the Canadian high Arctic described a fringe of thick, landfast ice along the 500-km northern coast of Ellesmere Island. This article shows from analyses of historical records, aerial photographs, and satellite imagery (ERS-1, SPOT, RADARSAT-1) that this ancient ice feature ('Ellesmere Ice Shelf') underwent a 90% reduction in area during the course of the twentieth century. In addition, hydrographic profiles in Disraeli Fiord (83°N, 74°W) suggest that the ice-shelf remnant that presently dams the fiord (Ward Hunt Ice Shelf) decreased in thickness by 13 m (27%) from 1967 to 1999. Mean annual air temperatures at nearby Alert station showed a significant warming trend during the last two decades of this period, and a significant decline in the number of freezing degree days per annum. The ice-dammed fiord provides a stratified physical and biological environment (epishelf lake) of a type that is otherwise restricted to Antarctica. Extensive meltwater lakes occur on the surface of the ice shelf and support a unique microbial food web. The major contraction of these ice–water habitats foreshadows a much broader loss of marine cryo-ecosystems that will accompany future warming in the high Arctic.

### Contents

## Introduction

Ice shelves are a major feature of Antarctica, where they account for approximately 40% of the coastline and cover > $10^6$ km$^2$ (Drewry and others 1982). These floating sheets of landfast ice are mostly derived from the ice streams and glaciers flowing off the continent, with additional inputs from snow and basal freezing. Antarctic ice shelves have been the subject of considerable study during the last decade because of their vast extent, their role in global processes, and their potential sensitivity to climate change. Over the period 1966 to 1989, the Wordie Ice Shelf in the region of the Antarctic Peninsula contracted from 2000 to 700 km$^2$ (Doake and Vaughan 1991), and, in 1992, 4200 km$^2$ of the northern Larsen Ice Shelf on the eastern side of the Peninsula fractured and disintegrated in a period of a few days (Rott and others 1996). These massive calving events have been interpreted as a response to regional warming, with the abrupt retreats triggered by shifts across a critical threshold in mean annual temperature (Vaughan and Doake 1996).

The Arctic coastline lacks ice shelves of the size found in Antarctica, but smaller features derived from multiyear landfast sea ice, basal freezing, snow accumulation, and sometimes glacial input occur at several Arctic locations, specifically northern Ellesmere Island, northern Greenland (Higgins 1989), and possibly Severnaya Zemlya and Zemlya Frantsa-Iosifa (Dowdeswell and others 1994). A much larger northern ice shelf, however, existed in the Arctic until well into the 1900s. Explorers in the nineteenth century and at the beginning of the twentieth century observed a band of thick floating ice along the northern margins of Ellesmere Island in the Canadian high Arctic (Fig. 1), with a total length of 500 km. During the course of the twentieth century, this apparently continuous fringe of ice-the `Ellesmere Ice Shelf' this and other commonly used but unofficial place-names are in quotations when they first appear in this paper) -has largely disintegrated, releasing icebergs or ice islands into the Arctic Ocean and leaving behind disconnected residual ice shelves along the Ellesmere Island coastline (Koenig and others 1952). The largest of these is the Ward Hunt Ice Shelf (Fig. 2), which appears to be experiencing further reductions in area and thickness.

The causes of the collapse of Ellesmere Ice Shelf have been debated since the mid-1950s. Koenig and others (1952) suggested that the combination of wind action, tidal action, and pressure exerted by the pack ice caused fracturing and subsequent disintegration of the ice. Subsequent authors identified other potential mechanisms,

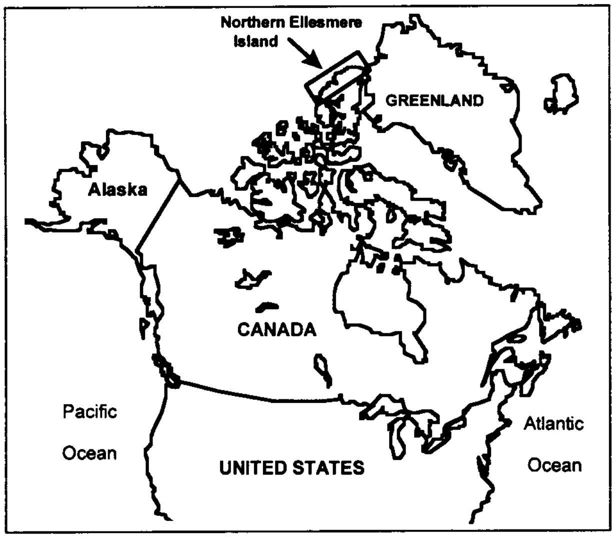

**Fig. 1. Location of northern Ellesmere Island in the Canadian high Arctic. The framed sector is as shown in the top panel of Figure 3.**

including persistent offshore winds (Ahlnès and Sackinger 1988), seismic activity and abnormal tides (Holdsworth 1970), and resonant vibrations in the ice sheet (Holdsworth and Glynn 1978). The original extent and age of Ellesmere Ice Shelf are also subjects of conjecture, although on the basis of driftwood analyses it appears that ice shelves along this coastline began to develop during a period of cooling in the mid-Holocene about 4000 years ago (Evans and England 1992). Given that the ice shelves owe their origin to sustained cold temperatures, they are also likely to be sensitive indicators of a return to warmer conditions.

The aim of the present paper is to evaluate the twentieth-century collapse of Ellesmere Ice Shelf within the context of climate change. The authors first summarise the direct observations from the early explorers and then compile data from aerial and ground surveys describing the evolution of the ice shelf from the 1940s to the present. The most recent data from the region is presented, based on RADARSAT and other satellite observations and from salinity and temperature measurements in a strongly density-stratified fiord where fresh water is impounded behind the Ward Hunt Ice Shelf. Both the fiord and the ice shelf provide unusual habitats for aquatic life, and the studies to date on the nature of these cryo-ecosystems are summarised. Finally, other data sets concerning environmental change in the Canadian high Arctic are examined, including the climate record at Alert, Canada's northernmost weather station (82.50°N, 62.37°W) in the vicinity of the ice shelf.

## The nineteenth century `glacial fringe'

Ellesmere Ice Shelf was first discovered during the British Arctic Expedition of 1875-76. Lieutenant Pelham Aldrich led a party during this expedition from Cape Sheridan (82.47°N, 61.50°W) westwards to Cape Alert (82.27°N, 85.55°W), including a traverse across the region now referred to as the Ward Hunt Ice Shelf. He recorded several observations about the `undulating surface' of the snow and ice along this region, noting the `long fringe of large and troublesome hummocks' (Nares 1878: 356) that are characteristic of the ice shelf (Fig. 2).

In 1906 Robert E. Peary led an expedition in northern Ellesmere Island, from Cape Sheridan along the coast to the western side of Nansen Sound (93°W). In the course of this journey he made many observations about the distinctive undulating topography of the ice, and noted that the troughs between the parallel ridges were often filled with meltwater lakes and streams: `From the summit of the tumulus I saw the ice ahead of us in the same condition; a gigantic potato field with a long blue lake or a rushing stream in every furrow' (Peary 1907: 220). These ice-shelf meltwaters are now known to be the habitat for a remarkable community of extremophilic micro-organisms, but for Peary they constituted a `watery hell' (Peary 1907: 225) and a major impediment to dog sledging. On several occasions he therefore traversed the ice shelf to its seaward limit to find a better route, and was surprised by the distances involved, for example in Yelverton Bay (83.00°N, 82.42°W): `After travelling some 4 hours about due west, and not reaching the ice foot, I got a little irritated and made up my mind to go to it no matter how far out it was. We were all night (8112 hours) reaching it' (Peary 1907:189).

Peary's work drew attention to the vast extent of the Ellesmere Ice Shelf, and his records seem to imply that it formed a continuous fringe of ice from Cape Hecla (82.9°N, 64.8°W) to Axel Heiberg Island (81.3°N, 92.5°W). In his concluding remarks on the journey, Peary noted that one of the major accomplishments was the exploration of `one of the most unique and interesting features of this region to the glacialist, namely the broad glacial fringe of the Grant Land coast from Hecla westward' (Peary 1907: 242-243). The approximate extent of the ice shelf in 1906 based on his observations is given in Figure 3.

There is no certainty about the ice-shelf coverage in Nansen Sound (`Nansen ice plug') at that time. However, Peary noted: `The ice in the Strait was to all appearance a continuation of the glacial fringe of the Grant Land Coast' (Peary 1907: 203). It is also possible that the Ellesmere Ice Shelf extended beyond Peary's western limit along the northwest coastline of Axel Heiberg Island. Assuming the extent of the ice shelf to be as shown in Figure 3, the authors estimate its total area in 1906 as 8900 km$^2$.

A more detailed survey of one section of the Ellesmere Ice Shelf was undertaken in June-July 1906 by Ross Marvin, a civil engineer whom Peary had appointed as a scientist on the expedition. Marvin ran a line of openwater soundings at the edge of the ice shelf between longitudes 67 and 79°W, and his observations allow a more accurate estimate of the extent of the ice shelf in this sector (Bushnell 1956), which can be used as a reference for subsequent changes (Table 1, Fig. 3).

## Mid twentieth-century observations

Subsequent to Peary's expedition there was little further information about the Canadian high Arctic until aerial mapping flights began in the late 1940s. However, in the

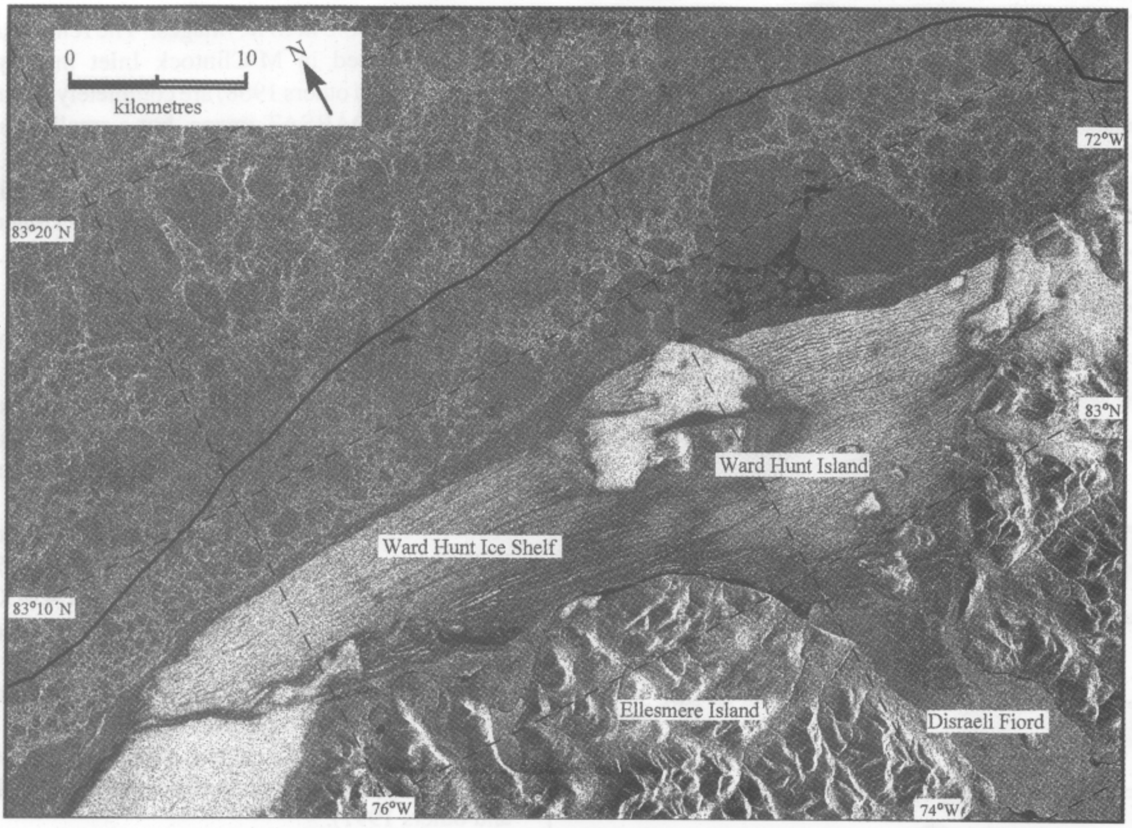

Fig. 2. RADARSAT-1 image of the Ward Hunt Ice Shelf, 12 h 47 min (GMT), 30 August 1998. The data were obtained in SAR wide 3-beam mode during descending orbit 14720. The line marks the outer limit of the ice shelf as surveyed by Marvin in 1906 (from Bushnell 1956). The ice-shelf surface shows the parallel elongate lakes as first described by Peary (1907) and that are now known to be the habitat for complex ice-mat communities.

intervening period there are reports of large icebergs or `ice islands,' with the undulating surface topography characteristic of the Ellesmere Ice Shelf drifting in the Arctic Ocean as far west as Alaska (Jeffries 1992). In 1947 a large section of ice island was photographed close to the northern Ellesmere coastline with a shape and location that indicated it had calved from a section of the Ellesmere Ice Shelf as mapped by Marvin in 1906 (Bushnell 1956), and three years later some 60 ice islands were counted in the Queen Elizabeth Islands (Koenig and others 1952). The aerial photographs taken in the 1950s showed that there had been major attrition of the ice shelf by this time (Fig. 3, Table 1). The ice was substantially lost between Cape Colan (82.93°N, 66.13°W) and the eastern side of Markham Fiord (83.08°N, 71.47°W), leaving a few small ice shelves associated with protected bays and nearshore islands. `Markham Ice Shelf' remained connected to the Ward Hunt Ice Shelf by a narrow strip of ice, while north of Ward Hunt Island the ice edge remained largely as mapped by Marvin in 1906 (Bushnell 1956; Crary 1956). Ice island ARLIS-II calved from the `Alfred Ernest Ice Shelf' n 1955 (Jeffries 1992) and was used as a research station by the US Navy. Similarly, T-3, thought to have broken out of Yelverton Bay, was used as a research station by the US Air Force from 1952 to the 1970s.

A major calving event took place at the front of the Ward Hunt Ice Shelf in 1961 or 1962, resulting in the formation of major ice islands (Koenig and others 1952; Hattersley-Smith 1963) and a seaward edge that was now defined in part by the `Ward Hunt Ice Rise' (Fig. 2). Tenuous connections remained with the Markham and the M'Clintock ice shelves, and small shelves near Bromley Island and to the east of Cape Aldrich were still present. The `M'Clintock Ice Shelf' s thought to have broken out sometime between 1962 and 1966 (Hattersley-Smith 1966).

An ice island calved from the northwest corner of `Milne Ice Shelf' between 1959 and 1974, and in its place grew the `Milne Re-entrant' (multiyear landfast sea ice: MLSI) (Jeffries 1986). The Milne Re-entrant itself calved in February 1988 (Jeffries and Sackinger 1990) and in its place grew more MLSI (see figure 5 in Jeffries 1992). Between 1959 and 1974, a 1.5 x 10 km strip of ice broke off from `Ayles Ice Shelf,' and the remaining ice shelf was dislodged about 5 km seaward out of the fiord. MLSI then grew in the gap between the ice shelf and the eastern shore (Jeffries 1986). A comparison of aerial photographs taken in 1974, an airborne SAR image of Ayles Ice Shelf in February 1988 (Jeffries 1992), and a 1998 RADARSAT image (Fig. 4) shows that the position and area of Ayles Ice Shelf has remained largely unchanged since 1974.

## Late twentieth-century observations

Small areas of ice shelf were lost from the far west of the Ward Hunt Ice Shelf to the north of the `Discovery Ice Rise' between 1980 and 1982 and then in 1982 from the eastern end of the shelf (Jeffries and Serson 1983). By

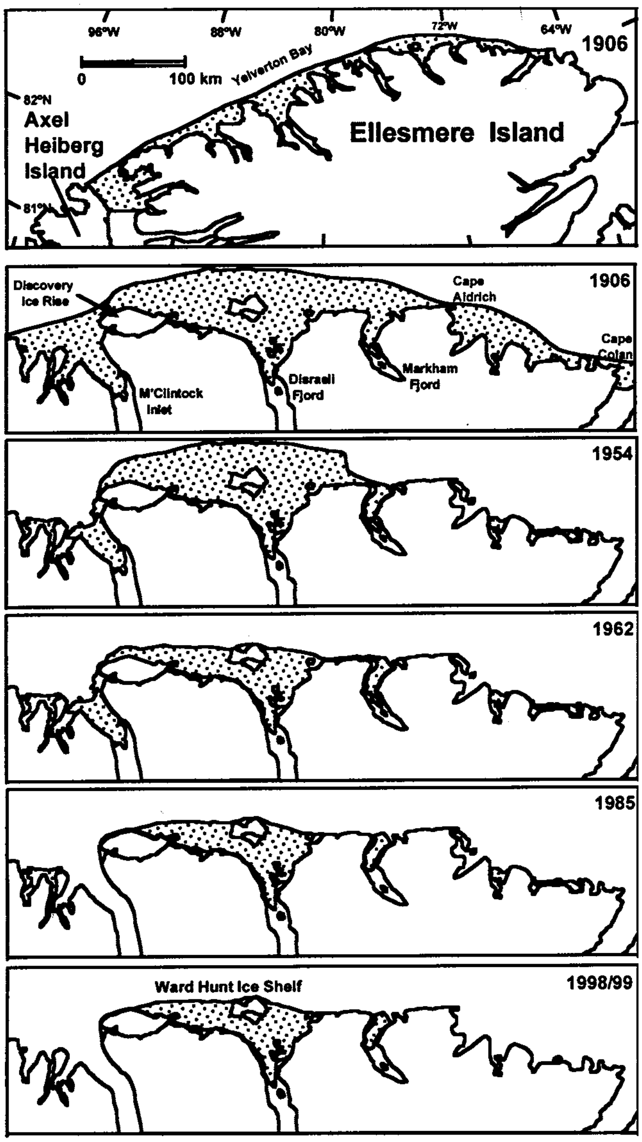

Fig. 3. The Ellesmere Ice Shelf in 1906 (top panel; stipple indicates thick, landfast ice) and changes in the sector surveyed by Marvin in 1906. The estimates are from digital analysis of the maps or images as in Table 1, and the 1998/99 estimates are from RADARSAT-1 images.

1982 the ice shelf in this region had broken back to a small ice rise located to the west of Cape Albert Edward. An ice island that calved from the Ward Hunt Ice Shelf in 198283 - `Hobson's Choice' - was subsequently used as a research platform by Canadian scientists.

Comparisons of RADARSAT images recorded in July 1999 (W.F. Vincent, unpublished) and August 1998 (Fig. 2) with an ERS-1 synthetic aperture radar (SAR) image from 21 February 1992 (M.O. Jeffries, unpublished), a SPOT image in August 1988 (King 1989), and aerial survey records from 1985 (Jeffries 1987) show that the edge of the Ward Hunt and Markham ice shelves have remained relatively stable throughout this most recent, 14year period. The small shelves to the east of Cape Aldrich appear to have been lost, although more detailed aerial inspections are required to check for small remnants that are not detectable in SAR images. The remnants of ice shelf embedded in M'Clintock Inlet in July 1984 (Sackinger and others 1988) are completely absent from the 1998 RADARSAT image, but a small area to the south of the Discovery Ice Rise is still present. Large fissures that were observed in the Ayles and Milne ice shelves in 1984 and 1988 (Jeffries and Sackinger 1990) were also conspicuous features in 1998 (Fig. 4).

## Ice-shelf thickness

The first measurements of the thickness of Ellesmere Ice Shelf were recorded in the 1950s, specifically for the remnant Ward Hunt Ice Shelf. Initial seismic surveys and measurements of above-sea-level elevations gave a thickness of the Ward Hunt Ice Shelf of 43-54 m, with a possible maximum thickness of 60 m (Crary 1956). Airborne radio echo-sounding east of Ward Hunt Island in 1966 gave thickness estimates in the range 25-80 m (Hattersley-Smith and others 1969) and 45-50 m in 1981 (Narod and others 1988). The latter survey also included the Milne Ice Shelf, which was up to 100 m thick at that time. A further measurement was made in 1985 by drilling through Hobson's Choice Ice Island, which had recently calved from the eastern side of Ward Hunt Ice Shelf; this gave a thickness of 42.06 m (Jeffries and others 1991).

Streams and glacial meltwaters enter Disraeli Fiord on the landward side of this ice shelf (Figs 2, 3) and result in a surface fresh-water layer that is dammed behind the ice. Physical oceanographic measurements in the fiord in May-July 1967 (Keys and others 1968) indicated that the depth of the outflowing fresh-water layer could be used as a surrogate measure of thickness of the Ward Hunt Ice Shelf, which was thereby estimated as 48 m. Subsequent profiling of temperature and salinity in May 1983 (Jeffries and Krouse 1984) and June 1999 (the present study) showed pronounced reductions in the thickness of the fresh-water layer (Fig. 5). The 1999 profiles implied an ice-shelf thickness of 35 m, which is 22% thinner than in 1983 and 27% thinner than the 1967 estimate.

## Ice-shelf cryo-ecosystems

Recent ecological surveys of the northern Ellesmere Island region have revealed that the Ward Hunt Ice Shelf provides two types of unique habitat for aquatic life. Firstly, the waters dammed behind the ice shelf in Disraeli Fiord are characterised by sharp vertical gradients in their physical and chemical properties and contain stratified populations of picocyanobacteria, other photosynthetic organisms, protists and four species of zooplankton (Van Hove and others, in press). A small number of analogous ecosystems are known from Antarctica, where they are referred to as epishelf lakes (Bayly and Burton 1993).

The second type of habitat is provided by the elongate meltwater lakes on the Ward Hunt Ice Shelf (Vincent and others 2000). These acidic waters contain sparsely distributed patches of microbial mats growing in cylindrical

Table 1. Areal changes in the sector of the Ellesmere Ice Shelf between longitudes 66 and 79°W that was initially surveyed by Marvin in 1906 (Fig. 3). The estimates are from digital analysis of the maps or images given in each reference.

| Year | Area | | Source |
|---|---|---|---|
| | km² | % 1906 | |
| 1906 | 2327 | 100.0 | Bushnell (1956) |
| 1954 | 1422 | 61.1 | Crary (1956) |
| 1962 | 906 | 38.9 | Hattersley-Smith (1963) |
| 1985 | 644 | 27.7 | Jeffries and Serson (1983) |
| 1998 | 490 | 21.1 | present study |

holes sunk into the ice at the base of the lakes. The ice-mats are often brightly pigmented with a carotenoid-rich surface layer, and although they are dominated by filamentous cyanobacteria, they also contain viruses, heterotrophic bacteria, flagellates, ciliates, algae, and microscopic animals, specifically nematodes, rotifers, tardigrades, and palyhelminthes (flatworms). These complex communities are analogous to the microbial mats found on the McMurdo Ice Shelf, Antarctica, and are providing insights into the potential for survival and growth during periods of extensive glaciation, for example, during the early evolution of life in the Proterozoic (Vincent and Howard-Williams 2000).

### Northern Ellesmere climate

The three decades of shallowing of the fresh-water layer in Disraeli Fiord (May 1967-May 1999) correspond to a period of significant change in climate of the Canadian high Arctic. For this analysis the authors examined the meteorological records from Alert (latitude 82.5°N, longitude 62.3°W), Canada's northernmost climate station, located 150 km east of Disraeli Fiord. There was a significant difference in mean daily air temperatures between the periods 1967-82 and 1983-98 (means =-18.2 and-17.6°C, respectively; $t = 2.0$; $p = 0.01$; $df = 30$). For the full 32-year record, there was a significant warming trend in mean annual temperatures (0.043°C $a^{-1}$, $r=+0.46$; $p < 0.01$) and a significant decline in the number of freezing degree days per annum ($r = -0.47$, $p < 0.01$). However, it should be noted that most of the warming took place in the last two decades, and the measurements at the beginning of the record suggest an initial cooling phase (Fig. 6).

An additional index of climate change, the number of thawing degree days (days with a mean air temperature above 0°C), showed no significant trend (Fig. 6). The variations in this latter index underscore the very large inter-annual variability in the Alert climate record, with two-fold differences between consecutive years. Such variability is likely to obscure any long-term trends. However, there is evidence that the frequency of warm years increased substantially in the 1980s and 1990s relative to the 1960s and 1970s. For example, the number of freezing degree days fell below 6600 per annum in only two years over the period 1967-82, but in eight years over the period 1983-98. The number of thawing degree days rose above 200 at a slightly greater frequency in the second versus the first half of the record (11 versus 8 years). There was no significant change in precipitation during this 32year period (Fig. 6; mean ± SD = 160 ±38 mm $a^{-1}$),

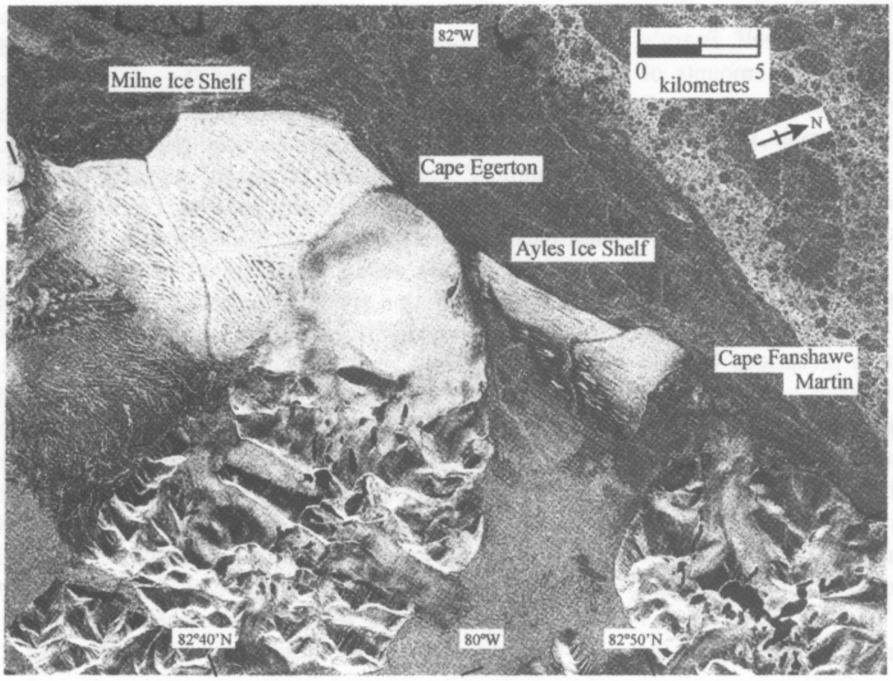

Fig. 4. RADARSAT-1 image of northern Ellesmere Island, 30 August 1998 (details as in Fig. 2) showing the Milne and Ayles ice shelves.

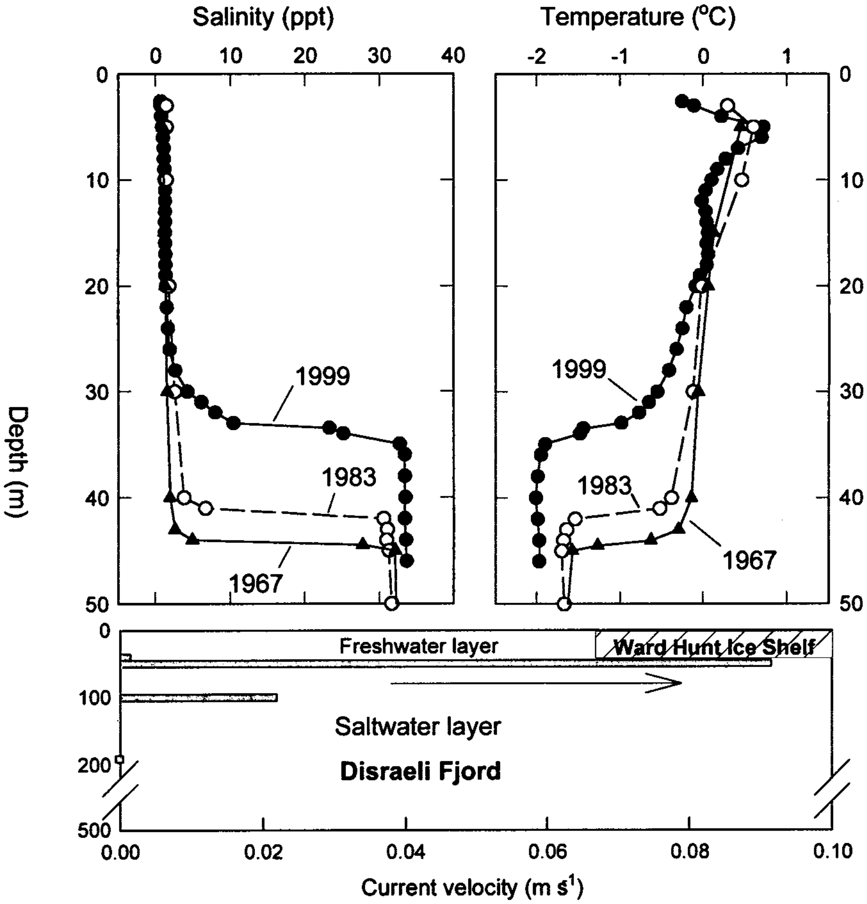

Fig. 5. Profiles of salinity (left) and temperature (right) in Disraeli Fiord in June 1967 (Keys and others 1968), May 1983 (Jeffries and Krouse 1984) and June 1999 (present study). Also shown are the current velocity data in July 1967, which indicate a strong outflowing current at a depth coinciding with the estimated base of the ice shelf (replotted from Keys and others 1968).

implying that the reduction in depth of the fresh-water layer of Disraeli Fiord could not be explained by decreased snowfall in the region.

## Discussion

The records of the early explorers in high Arctic Canada provide clear evidence that a fringe of thick, undulating ice existed along the northern Ellesmere Island coastline, forming a large and possibly continuous ice shelf. Peary's records also draw attention to substantial amounts of surface meltwater that formed in mid-summer at almost all sites on the Ellesmere Ice Shelf. For example, in his notes on Milne Bay (Fig. 4) on 11 July 1906, Peary referred to `the devil-inspired labyrinth of lakes and rivers set in a morass of knee-deep slush which fills this bay' (1907: 225), while in Nansen Sound he recorded a `continuous sheet of water' that would eventually drain from the ice (1907: 213). These observations suggest that even in the early twentieth century there was a precarious balance between ice accretion and ablation. Large-scale disintegration of the ice shelf took place between the time of Peary's expedition and aerial surveys in the late 1940s, with additional changes over the latter half of the century. The RADARSAT observations from 1998 and 1999 indicate that the present-day remnants of the ice shelf now amount to 9.6% of the estimated total extent of the Ellesmere Ice Shelf in 1906.

The most recent observations on the northern ice shelves show that these remnants of Peary's original `glacial fringe' entered a new phase of attrition in the latter half of the twentieth century. Ayles and Milne ice shelves underwent major change between the 1950s and 1970s, and large sections of Ward Hunt Ice Shelf were lost in the 1960s and again in 1982-83. There has also been a pronounced shallowing of the fresh-water layer dammed behind the Ward Hunt Ice Shelf. These latter changes in the salinity and temperature profiles of Disraeli Fiord imply that at least part of the Ward Hunt Ice Shelf has substantially thinned through increased melting during the late twentieth century and/or reduced rates of accretion. The authors' compilation of results suggests that this process was already underway between 1963 and 1987, but that the greatest change took place in the second period, 1987-99. These observations cannot be explained by reduced precipitation, for the meteorological records from Alert indicate no significant change in snowfall during this period. Similarly, the thinning of this fresh-water layer cannot be attributed to cool air temperatures and reduced meltwater input to the fiord because the measurements are within a period of significantly increasing temperature (Fig. 6). An important question for future studies in the region is to what extent these changes in the thinnest part of the ice shelf, as indicated by the depth of the dammed fresh-water layer, are representative of changes in mean thickness of the entire Ward Hunt Ice Shelf.

Although many hypotheses have been advanced to

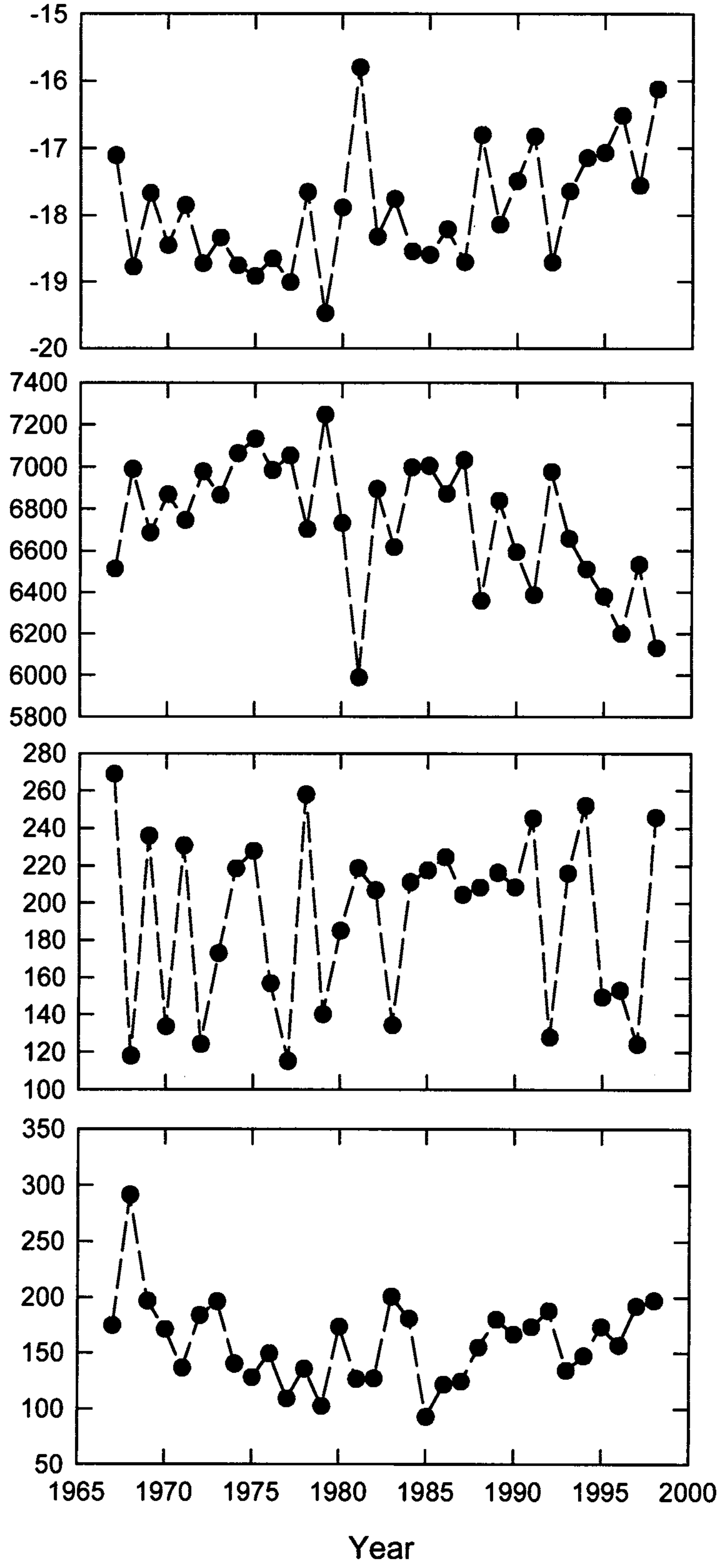

Fig. 6. Annual figures for Alert station during the period 1967 to 1998: top, mean air temperatures in degrees C; second, freezing degree days; third, thawing degree days; and bottom, total precipitation in mm (water equivalent).

account for the major phase of loss of the Ellesmere Ice Shelf in the period 1906-63, the evidence from the more recent disintegration of Antarctic ice shelves, in combination with the meteorological records from northern Ellesmere, suggests that climate change is likely to be the primary cause of collapse. In the Antarctic ice-shelf systems, initial weakening by temperature change leads to an abrupt decline to a new equilibrium position underpinned by islands and ice rises (Vaughan and Doake 1996). The current Ward Hunt Ice Shelf is now similarly held in by Ward Hunt Island, Ward Hunt Ice Rise, the Discovery Ice Rise, the Marvin Islands, and five ice rises to the north of these islands.

The lack of significant change in precipitation at Alert contrasts markedly with the western Arctic region, where there has been a significant decline over the period 1949-88, for example, at a mean rate of 12 mm per decade at Barrow, Alaska (71.28°N; 156.78°W; Curtis and others 1998). The Alert data also contrast with measurements at Spitsbergen (78.00°N, 20.00°E), which show a significant rise in annual mean temperatures from the 1960s to 1996 accompanied by a significant overall increase in precipitation (Hanssenbauer and Forland 1998). Precipitation measurements are notoriously difficult at high latitudes, where snowfall is the dominant form of precipitation, often accompanied by high winds. However, the qualitative differences indicate large regional variations in direction as well as magnitude of climate change.

The recent warming trend in the northern Ellesmere Island region is consistent with climate and oceanographic data from elsewhere in the Arctic, although the overall rate of increase in mean annual air temperatures is much lower than that observed for the same three decades in northern Alaska and the Eurasian Arctic (Weller 1998). The inferred changes in thickness of the Ward Hunt Ice Shelf parallel the substantial contraction (Johannessen and others 1999) and thinning (Rothrock and others 1999) of the Arctic Ocean pack ice and major changes in the circulation of the Arctic Ocean. Specifically, there has been an eastward redistribution of the surface fresh-water layer from the Eurasian Basin (Dickson 1999) between 1979 and the 1990s, and this has been accompanied by thinning sea ice and record extents of open water. These trends appear to be related to the Arctic Oscillation, which is currently in a phase that favours a lengthening of the melt season in the eastern Arctic (Rigor and others 2000).

Large-scale calving of the ice shelf earlier in the twentieth century is likely be the result of general warming trends in the Arctic during the late Holocene (Overpeck and others 1997), in combination with periods of accelerated melting, and intrinsic thresholds of mechanical instability of the ice shelf. Ice-core records from high Arctic glaciers (Koerner and Fisher 1990) and the increasingly negative mass balances for most Arctic glaciers (Dowdeswell and others 1997) indicate that the Arctic region experienced a step-like warming in the early twentieth century. Disintegration of the Ellesmere Ice Shelf prior to 1950 may have been triggered by especially high global temperatures in the 1930s and 1940s, which were accompanied by a pronounced decrease in the extent of sea ice off Eurasia (Kelly and others 1982). Although the most recent warming and melting trend appears to be associated with a naturally occurring source of variability in the atmosphere (the Arctic Oscillation), it may be currently amplified by radiative forcing caused by greenhouse gas emissions (Shindell and others 1999) that will continue to increase through human activities over the course of the twentyfirst century.

Summer 1998 was a globally warm season that saw a record reduction in sea-ice cover in the Beaufort and Chukchi seas (Maslanik and others 1999) and within the Queen Elizabeth Islands in the Canadian high Arctic (Jeffers and other, in press). The retreat of the ice cover in the Queen Elizabeth Islands included the disintegration of the Nansen and Sverdrup ice plugs, which last broke up in 1962 when the summer weather and ice conditions were as extreme as those in 1998 (Jeffers and others, in press). The ice plugs are multiyear landfast sea-ice features that are considered to be incipient ice shelves analogous to the early formation of sea-ice-derived ice shelves such as the Ward Hunt Ice Shelf (Jeffries 1992). The disintegration of the ice plugs and the evidence for recent changes at Ward Hunt Ice Shelf suggest that these features maybe considered bellwethers of climate change. Ongoing shifts in climate have the potential to cause further glaciological and oceanographic changes in the Ellesmere Ice Shelf region.

The reduction of ice extent and thickness in the high Arctic has been previously considered in terms of the physical effects; however, the north polar cryosphere also provides a set of environments for unique microbial-based ecosystems. The elongate meltwater lakes on the Ward Hunt Ice Shelf are the habitat for a complex food web of micro-invertebrates, algae, bacteria, and viruses (Vincent and others 2000). These communities are likely to have been more widespread in the meltwater lakes that were described by Peary (1907) throughout his traverse across the Ellesmere Ice Shelf. Similarly, the current Ward Hunt Ice Shelf retains an epishelf lake of a type that is likely to have been more widespread in the past along the Ellesmere coastline, for example in M'Clintock Inlet and Yelverton Bay (Fig. 3). The Arctic ice-shelf and ice-dammed meltwater systems have both undergone a major decline in volume over the course of the twentieth century. Such changes foreshadow a potentially much broader loss of biological ice-water habitats (annual sea ice, multiyear pack ice, perennial lake ice) and biodiversity in the high Arctic region over the coming decades.

The undulating ice along the northern Ellesmere Island coastline today amounts to only a small area relative to the vast northern ice shelf that existed at the onset of the twentieth century. However these remnant sections are still conspicuous features of the region and their distinctive surface ice properties can be readily detected from space. Synthetic aperture radar such as RADARSAT offers an attractive remote-sensing option for measurements of ice and surface meltwaters (Jeffries, in press) and can be used to produce high-resolution images of the Ayles, Markham, Milne and Ward Hunt ice shelves (Figs 2, 4). Continued monitoring of these ancient ice features by satellite imagery and ground observations will provide a valuable ongoing measure of climate and cryo-habitat change in the high Arctic ecosystem.

## Acknowledgements

This research was funded by the Natural Sciences and Engineering Research Council of Canada. Participation of M.O. Jeffries was made possible by NASA grant NAGW 4966 and support from the Geophysical Institute, University of Alaska Fairbanks. The RADARSAT imagery was obtained under a grant to W.F. Vincent from the Earth Observation Data Sets Program (Canada); the air temperature and precipitation data for Alert were provided by Environment Canada. The authors thank Polar Continental Shelf Project for logistic support in the Arctic (this is PCSP publication no. 02400); Dr Robert Gauthier and staff at the Canadian Center for Remote Sensing for their help in the acquisition of RADARSAT imagery; Dr Lorenz King (University of Giessen) for providing the SPOT image; and Drs M. Allard, E.C. Carmack, R.M. Koerner, and two anonymous referees for their insightful comments on the manuscript.

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