Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake

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[1] Field observations and RADARSAT imagery of the Ward Hunt Ice Shelf (lat. 83°N, long. 74°W), Nunavut, Canada, show that it broke in two over the period 2000 to 2002, with additional fissuring and further ice island calving. The fracturing caused the drainage of an ice-dammed epishelf lake (Disraeli Fiord), a rare ecosystem type. Reductions in the freshwater volume of Disraeli Fiord occurred from 1967 to the present and accompanied a significant rise in mean annual air temperature over the same period in this far northern region. The recent collapse of ice shelves in West Antarctica has been interpreted as evidence of accelerated climate change in that region. Similarly, the inferred thinning and observed fragmentation of the ice shelf, plus the drainage of the epishelf lake, are additional evidence for climate change in the High Arctic. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 9315 Information Related to Geographic Region: Arctic region; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 1620 Global Change: Climate dynamics (3309); 1640 Global Change: Remote sensing. **Citation:** Mueller, D. R., W. F. Vincent, and M. O. Jeffries, Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake, *Geophys. Res. Lett.*, *30*(20), 2031, doi:10.1029/2003GL017931, 2003.

1. Introduction

[2] The abrupt collapse of glacially fed ice shelves in West Antarctica during the last two decades has been attributed to regional climate change [*Vaughan and Doake*, 1996]. It is less widely known that ice shelves occur in the High Arctic, and that these are also undergoing substantial contraction [*Jeffries*, 2002; *Vincent et al.*, 2001]. With a few exceptions, Arctic ice shelves are not glacially fed, relying instead on the basal accretion of sea ice and surface accumulation of precipitation to achieve a maximum thickness of a few tens of meters [*Jeffries*, 1992]. These northern systems may therefore be particularly responsive to climate warming and oceanographic change. Polar amplification of current global warming trends [*Moritz et al.*, 2002] may further threaten Arctic ice shelves. These ice shelves have undergone a marked decline during the past century [*Vincent et al.*, 2001] and, because of scant regional precipitation and the lack of significant glacial input, will not likely recover. Apart from their potential value as sentinels of climate change, Arctic ice shelves are also ecologically important. They provide cryo-habitats for well-developed communities of extremophilic microbes [*Vincent and Howard-Williams*, 2000]. In some cases, they also retain low-salinity water floating on the sea (epishelf lakes) with unusual mixed communities of marine and freshwater biota [*Laybourn-Parry et al.*, 2001; *Van Hove et al.*, 2001].

[3] The Ward Hunt Ice Shelf (latitude 83°N, longitude 74°W, Figure 1a), Nunavut, Canada, is a 443 km^2 remnant of a much larger feature that extended along the northern coast of Ellesmere Island at the beginning of the last century [*Peary*, 1907]. The original ice shelf contracted 90% during the period 1906–1982 by calving from its northern edge [*Vincent et al.*, 2001]. Since then, the remnant ice shelves, including the ~3000 year old Ward Hunt Ice Shelf [*Crary*, 1960], have remained relatively stable.

[4] The surface of the Ward Hunt Ice Shelf is characterized by a ridge and trough topography (observable by RADARSAT, Figure 1) with a wavelength of roughly 235 m, an amplitude of 3.5 m and an east-west trend [*Holdsworth*, 1987]. Long melt pools (up to 20 km) form in the troughs each summer. The ice shelf dams the mouth of Disraeli Fiord, where the topmost 43 m was, until recently, filled with freshwater derived from terrestrial snow and ice meltwater. Disraeli Fiord is 30 km long by approximately 5 km wide and has a drainage basin of 2100 km^2 [*Keys*, 1978]. The low salinity water overlying ocean water in the 400 m deep fiord has a hydraulic residence time of decades (according to *Keys* [1978]) to centuries (according to *Shpaikher* [1969]). Lakes of this type are rare and are referred to as epishelf lakes in Antarctica [*Laybourn-Parry et al.*, 2001]. Disraeli Fiord was the largest remaining such lake in the Northern Hemisphere [*Jeffries*, 2002].

[5] In this paper we describe and evaluate recent changes that have taken place in the Ward Hunt Ice Shelf—Disraeli Fiord region. We undertook observations at this remote site, the northern limit of North America, by satellite-borne synthetic aperture radar, by helicopter overflight transects and by *in situ* profiling measurements. These show that the ice shelf has entered a period of accelerated break-up resulting in the complete drainage and loss of an epishelf lake ecosystem.

2. Results

[6] RADARSAT observations show that in 1998 and 1999 the surface of the Ward Hunt Ice Shelf resembled aerial images acquired occasionally since 1954, with no

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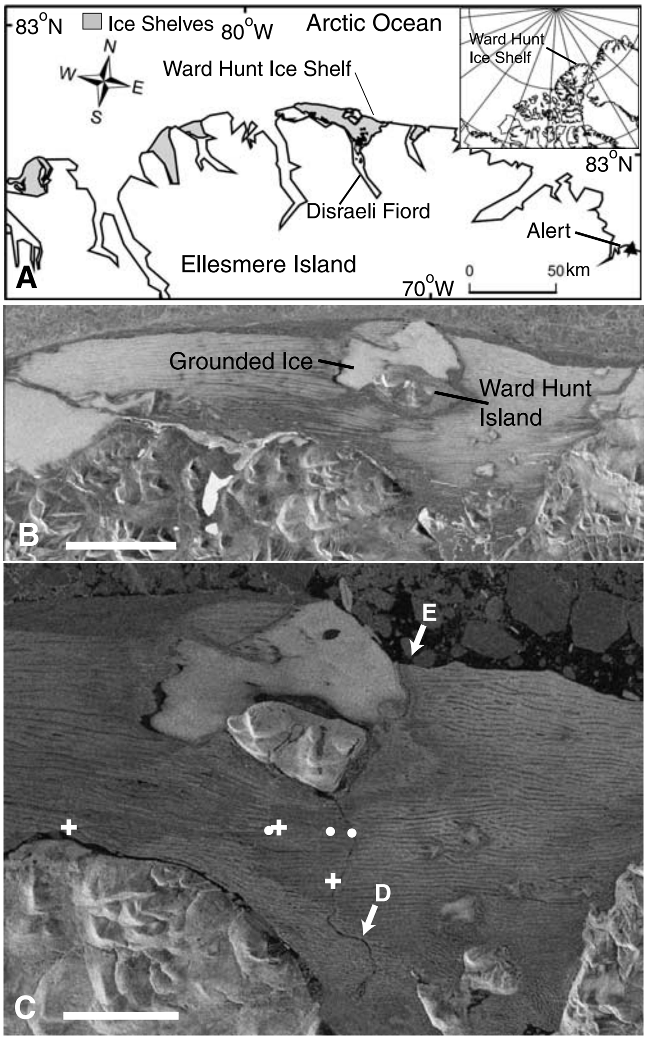

Figure 1. The development of cracks and calving on the Ward Hunt Ice Shelf. (A), Location map of the Ward Hunt Ice Shelf. (B), The ice shelf prior to crack development - October 29, 1999, RADARSAT-1, orbit 20756, standard beam mode 5, resolution 12.5 m, scale bar indicates 10 km. (C), The ice shelf after crack development - August 30, 2002, RADARSAT-1, orbit 35605, fine beam mode 1, resolution 6.5 m, scale bar indicates 5 km. D, The main north-south crack is apparent in the center of the image. E, Indentation resulting from the loss of 6 km^2 of ice shelf and 20 km^2 of multi year landfast ice from the northern end of the ice shelf can be seen following the calving event in August 2002. The profile locations confirming complete fracturing through the ice shelf are indicated by white crosses. The triangular region of free-floating ice blocks is outlined by GPS waypoints (white dots) and the southernmost ice crack profile. Both images were spatially and radiometrically corrected.

evidence of fracturing other than peripheral tidecracks (Figure 1b). By contrast, observations made from a helicopter in 2001 revealed a north-south fracture that extended from the southern margin of Ward Hunt Island to Disraeli Fiord, not only cleaving the ice shelf in two, but destroying its overall integrity and consequently draining the epishelf lake in Disraeli Fiord. RADARSAT imagery in early April 2000 was the first to clearly show the beginning of this feature and subsequent images show evidence of its further extension (Figure 1c). By September 2002, the southern third of this fracture had a maximum width of 80 m and, near Disraeli Fiord, it had bifurcated several times, producing many small icebergs.

[7] Our direct measurements on the ice shelf in July–August 2002 revealed extensive cracking with the separation of a 4 km^2 central portion into discrete, free-floating ice blocks. CTD profiling to depths of 37 to 58 m within these cracks confirmed that they extended right through the ice shelf to underlying seawater (Figure 1c). The resultant independent ice masses were retained within large expanses of intact shelf ice, and additional fissures extended eastwards from the shore towards this central area. RADARSAT images revealed only some of these cracks, since many occur at the bottom of and parallel to the direction of the troughs, where they are masked by the signal from the undulating topography. In these cases, ponded water drained through the cracks, and considerable drainage also occurred when cracks ran perpendicular to the undulations. In addition to the fracturing south of Ward Hunt Island, a calving event occurred (Figure 1e) between August 6th and 11th, 2002 resulting in a loss of shelf ice (6 km^2 of ice islands) plus multiyear landfast sea ice (20 km^2). A comparison of RADARSAT images from 1998 and 2002 also showed recent calving from the southern edge of the ice shelf into Disraeli Fiord.

[8] A number of authors reported on the strong density stratification in ice-dammed Disraeli Fiord and interpreted the depth of the freshwater layer as being equivalent to the draft of the ice shelf [*Hattersley-Smith*, 1973; *Jeffries and Krouse*, 1984; *Keys et al.*, 1968; *Vincent et al.*, 2001]. A steady decrease in the thickness of the freshwater layer since

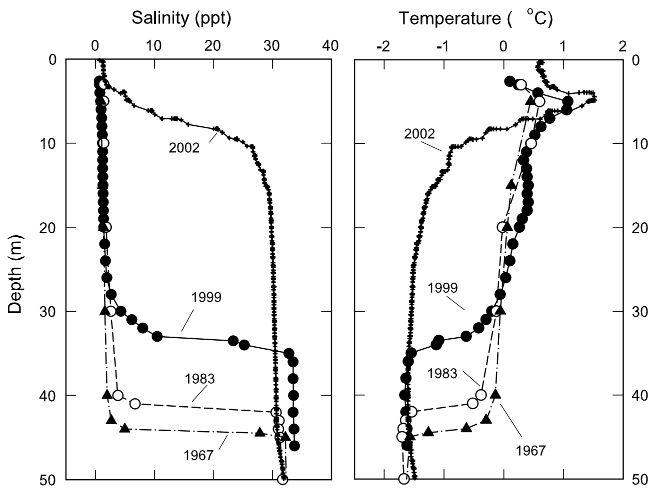

Figure 2. CTD profiles in Disraeli Fiord. Profile data are from June 1967 [*Keys et al.*, 1968], May 1983 [*Jeffries and Krouse*, 1984], June 1999 [*Vincent et al.*, 2001] and August 2002 (present study). Temperature data from 1999 were post-calibrated by adding 0.35°C to adjust bottom water (45 m) temperatures to the mean for 1967–2002. Slightly higher salinity at depth in the 1999 profile was likely due to a calibration offset. The 2002 profile was logged at 1 second intervals with a Brancker XR-420 CTD, which was lowered from an ice island into the fiord by hand.

Table 1. Disraeli Fiord Epishelf Lake Loss and Ward Hunt Ice Shelf Mean Seasonal Air Temperature Trends (1967–2002)

Year or Season	Depth of 3 ppt isohaline (m)[a]	Volume of low salinity water (km^3)[b]
1967	43	6.1
1983	30	4.3
1999	28	4.0
2002	3	0.5
	Months	Temperature trend (°C/decade)[c]
Winter	DJF	+0.18
Spring	MAM	+0.64[d]
Summer	JJA	+0.23
Fall	SON	+0.70[d]

[a]calculated using the data presented in Figure 2.
[b]we consider water <3 ppt to be low salinity, the fiord walls were assumed to be vertical and the surface area of Disraeli Fiord (143 km^2) was obtained from recent RADARSAT imagery. Also, note that Disraeli Fiord is perennially covered with 2 m of ice [*Keys*, 1978], thereby further reducing the available low salinity habitat by approximately 0.25 km^3.
[c]Ward Hunt proxy temperatures were transformed from the Alert, Nunavut meteorological record (Meteorological Service of Canada).
[d]significant ($p < 0.05$) trend.

the mid 1960s (Figure 2) suggests that there has been a general thinning of the Ward Hunt Ice Shelf or that freshwater has been preferentially draining via a localized conduit at the base of the ice shelf [*Vincent et al.*, 2001]. Our observations between the summers of 1999 and 2002 (Table 1) reveal a catastrophic drainage of the freshwater layer, probably through the fractures described above (Figure 3). Estimates of the freeboard observed at the cracks in the central area imply an ice thickness of no greater than 25 m for this particular area. This differs appreciably from past estimates of ice shelf thicknesses of 43 to 54 m by seismic methods [*Crary*, 1958], a maximum of 60 m by survey methods [*Crary*, 1958] and 42 m by coring [*Jeffries*, 1991].

[9] Several analyses point to atmospheric warming as a cause for ice shelf collapse on the Antarctic Peninsula [*Mercer*, 1978; *Scambos et al.*, 2000; *Vaughan and Doake*, 1996]. In that region, rates of warming of 0.056°C yr^{-1} from the 1940s to the present have been documented [*Vaughan and Doake*, 1996]. The longest meteorological record for Northern Ellesmere Island is at Alert, 175 km east of the Ward Hunt Ice Shelf (Figure 1a). A relatively small air temperature increase of 0.015°C yr^{-1}, $p = 0.056$ (p is the probability that the slope of the regression line is zero, assuming a linear association between the variables) has been observed at Alert since 1951. However, during the period of epishelf lake contraction and drainage (1967 to present), the air temperature increase (0.045°C yr^{-1}, $p = 0.001$) has been of a similar order to that observed on the Antarctic Peninsula. For the period August 2001 to July 2002, surface air temperature was measured at an automated meteorological station on the ice shelf. The mean monthly temperature at this site was highly correlated with air temperature values at Alert ($R^2 = 0.985$, $p < 0.0001$, RMSE = 1.8, n = 12), and this relationship was employed to generate historical proxy data for the Ward Hunt Ice Shelf. This yielded a mean July surface air temperature (1967–2002) of 1.3°C, well above the 0°C isotherm that has been identified as the critical threshold for ice shelf break-up in Antarctica [*Vaughan and Doake*, 1996, and references therein].

[10] No significant trend was observed in proxy summer air temperatures yet spring and fall warming trends were both significant (Table 1), as has been observed elsewhere in the Arctic [*Rigor et al.*, 2000]. The first observation of the ice crack (April 2000) and past ice island calving [*Hattersley-Smith*, 1963] from the Ward Hunt Ice Shelf show that major break-up events can occur in the spring and fall, indicating that warming trends in these seasons may play a significant role in ice shelf disintegration. The cumulative effects of a long-term warming trend since the Little Ice Age [*Overpeck et al.*, 1997] likely caused the ongoing changes in the Ward Hunt Ice Shelf. This includes the 20th century disintegration of the Ellesmere Ice Shelf [*Vincent et al.*, 2001] and the abrupt break-up and loss of integrity of the Ward Hunt Ice Shelf that we observed over the period 2000–2002. The precise timing and pattern of fracturing may involve a variety of mechanical stressors such as freeze-thaw, wind, and tidal events that act on the ice shelf already weakened by climatic warming.

3. Discussion

[11] Arctic ice shelf mass balance includes gains and losses at both the surface and underside. On the Ward Hunt Ice Shelf, the surface mass balance was negative (−0.96 m water equivalent) between 1965 and 1975 [*Serson*, 1979] plus there was no net accumulation between 1906 and 1954 [*Hattersley-Smith et al.*, 1955]. Surface ablation has been offset, at least in part, by the accretion of freshwater that flowed north-eastward under the ice shelf from Disraeli Fiord [*Jeffries and Krouse*, 1984; *Keys*, 1978]. The new fractures in the ice shelf now provide a direct conduit for freshwater transport from Disraeli Fiord to the open ocean (Figure 3). This will discontinue the sub-ice freshwater transport previously available for bottom accretion and may consequently amplify the thinning of the Ward Hunt Ice Shelf. However, the bottom mass balance of the ice shelf has not been quantified and therefore its role in recent events and relative importance remain unknown.

[12] A complete understanding of the observed and future changes requires the systematic study of ocean, atmosphere,

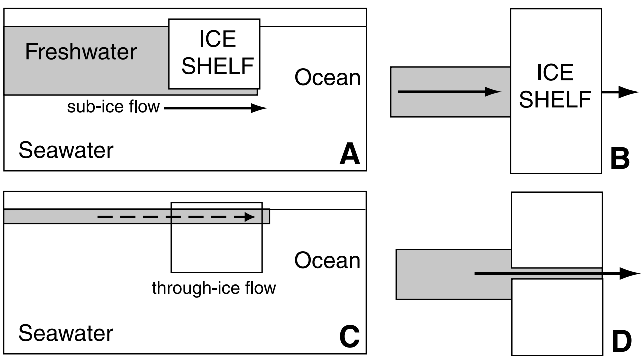

Figure 3. Schematic diagram showing the epishelf freshwater lake of Disraeli Fiord dammed behind the Ward Hunt Ice Shelf (A, side view; B, plan view) and its current draining at the surface via the fissure that now separates the two halves of the ice shelf (C, side view; D, plan view).

ice shelf and epishelf lake interactions. Apart from an increase in air temperature, other possible reasons for the recent events observed on the Ward Hunt Ice Shelf include changes in Arctic Ocean temperature, salinity and flow patterns [*Morison et al.*, 2000; *Newton and Sotirin*, 1997], changes in Disraeli Fiord hydrology and hydrography, or changes in the ice shelf surface heat budget. General or local thinning may have reduced the mechanical strength of the ice shelf, leaving it prone to the fracturing we observed.

[13] The pattern of disintegration of the Ward Hunt Ice Shelf differs radically from that observed in Antarctica. Antarctic ice shelves are glacially fed and extend northwards from a cold landmass. In contrast, Arctic ice shelves extend poleward from land and may be warmed on their landward side and bottom by hydrological input from the entire drainage basin (Figure 3). Epishelf lakes trapped behind these ice shelves provide a second front where calving may occur, as well as a reservoir for sub-ice flow.

[14] Recent fracturing on the Ward Hunt Ice Shelf may not only lead to additional shrinkage of the largest Arctic ice shelf, but is also a precursor to ice island production, which is of concern for ship operations and drilling platforms in the Arctic Ocean [*Jeffries*, 1992]. Furthermore, the fracturing of the Ward Hunt Ice Shelf has ecological implications since the observed change in the salinity profile of Disraeli Fiord shows a 96% loss (Table 1) of the fresh and brackish water habitats that were known to support a unique biological community [*Van Hove et al.*, 2001]. The ongoing loss of ice and drainage of surface meltwater lakes has also reduced the available habitat for ice shelf biota [*Vincent et al.*, 2000; *Vincent and Howard-Williams*, 2000]. These observations draw attention to the vulnerability of ice-dependent polar ecosystems to environmental change, and the accelerating loss of unique cryo-ecosystems in the Northern Hemisphere.

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