Environmental Archaeology **10**, 2005; pp. 113-126

Decadal-scale sea ice changes in the Canadian Arctic and their impacts on humans during the past 4,000 years

Peta J. Mudie, Andre Rochon and Elisabeth Levac

Abstract

Climate warming of >1.5°C over three decades has diminished Arctic sea ice and forced drastic changes on Inuit people of the Canadian Arctic. Discontinuities in archaeological records also suggest that climatic changes may have caused site abandonment and life style shifts in Paleo- and Neo-eskimo societies. We therefore examine the decadal-scale palaeoclimatic changes recorded by quantitative palynological data in marine records from Coburg Polynya, near Palaeo- and Neo-eskimo settlements on the North Devon Lowlands, and from the North Water Polynya between Canada and Northwest Greenland. Palaeotransfer functions from dinoflagellate cyst assemblages provide quantitative estimates of changes in sea surface temperature (SST) and sea ice cover (SIC) with the accuracy of historical measurements.

Both sites record temperature variations of 2–4°C corresponding to changes in hunting modes and occupation-abandonment cycles on Devon and Ellesmere Islands. Our data show that from ~6500 to 2600 BP, there were large oscillations in summer SST from 2–4°C cooler than present to 6°C warmer and SIC ranged from 2 months more sea ice to 4 months more open water. The warmer interval corresponds to the period of pre-Dorset cultures that hunted muskox and caribou. Subsequent marine-based Dorset and Neo-eskimo cultures correspond to progressively cooler intervals with expanded sea ice cover. The warming took ~50–100 years and lasted ~300 years before replacement by colder intervals lasting ~200–500 years. These climate oscillations are more rapid than the archaeological cultural changes, but are of similar length to successive Palaeoeskimo occupations in the Nares Strait region.

Key words: Arctic archaeology, Greenland, Palaeoclimate, Palaeoeskimo, Palynology, Sea ice

Introduction

In Canada, the continued rise of spring and summer temperatures and the reduction in sea ice associated with global warming over the past 25 years have led to grave concern about the disastrous consequences (Furgal *et al.* 2002) for the Inuit people of the CAA (Canadian Arctic Archipelago). Although interannual variations of 1–3°C and 6–15% in ice thickness can occur in Baffin Bay (Jacobs and Newell 1979), over the past forty years, there has been a sustained temperature increase of more than 0.5°C per decade over Alaska and western Canada (Chapman and Walsh 1993; Washington and Meehl 1996) and there has been a net decrease of 40% in sea ice thickness and 14% decrease in sea ice extent (Johannesson *et al*. 1995; 1999; Rothrock *et al*. 1999).

Inuit Elders from various parts of the CAA have reported (Krupnik and Jolly 2002) that during the past 10 years, the sun has begun to burn their skin, the weather has become too unpredictable to judge the correct conditions for hunting, and the sea ice is thinner and further offshore. These climate changes have led to a reduction in winter seal hunting, the death of hunters by drowning, a decline in the major food sources (ring seals and polar bear) that require spring sea ice for feeding or raising pups, the loss of fresh water sources from permanent snow banks, and the collapse of housing because of permafrost

Received June 2004, revised manuscript accepted October 2004.
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within a central core region of the CAA (from Hudson Bay north to Devon Island; Fig. 1) were periodically abandoned, then re-colonized in a nearby area after a few centuries, with slight modifications of housing styles and hunting tools (Helmer 1991). Examples include the Pre-Dorset Arnapik (~3150–2700 BP) and Early Dorset Tyara (~2680–2240 BP) settlements near the entrance to Hudson Bay (Taylor 1968), and the succession of 7 occupations from Early Palaeo-Eskimo (4500–3000 BP) to Historical Inuit (150 BP to present) on the North Devon Lowlands (Helmer 1991; 1992). In the Sisimiut area of West Greenland (Fig.1), there is an almost overlapping sequence of Saqqaq (~4500–2700 BP) and Early Dorset (~2500–2100 BP) cultures, then a total absence of occupation until the Mediaeval Warm Interval (MWI) at about 1100 A.D.. (Møbjerg 1998). During the long Saqqaq occupation, however, there was a sudden shift towards use of soapstone oil lamps for heating and increased reliance on marine mammals relative to caribou at about 3400–3300 BP. In general, most of the archaeological evidence from the Eastern Canadian Arctic indicates that occupation in peripheral High Arctic regions ceased abruptly, without clear evidence of transmittal of technology back to the central core area (Maxwell 1976). These abrupt changes have sometimes been interpreted as reflecting expansion followed by catastrophic decline in ecologically marginal regions in response to changes in climate and availability of critical animals, although more recent reviews (e.g. McGhee 1996; Schledermann 1996) emphasise that both Palaeo- and Neo-eskimo inhabitants probably had considerable skills in adapting to changing environments by relocation of settlements and flexibility in choice of hunting modes.

The purpose of the present paper is to examine high-resolution (decadal-scale) continuous palaeoceanographic records of past changes in summer and winter sea surface temperature (SST) and sea ice cover (SIC) in the northeastern CAA (Fig. 2) and

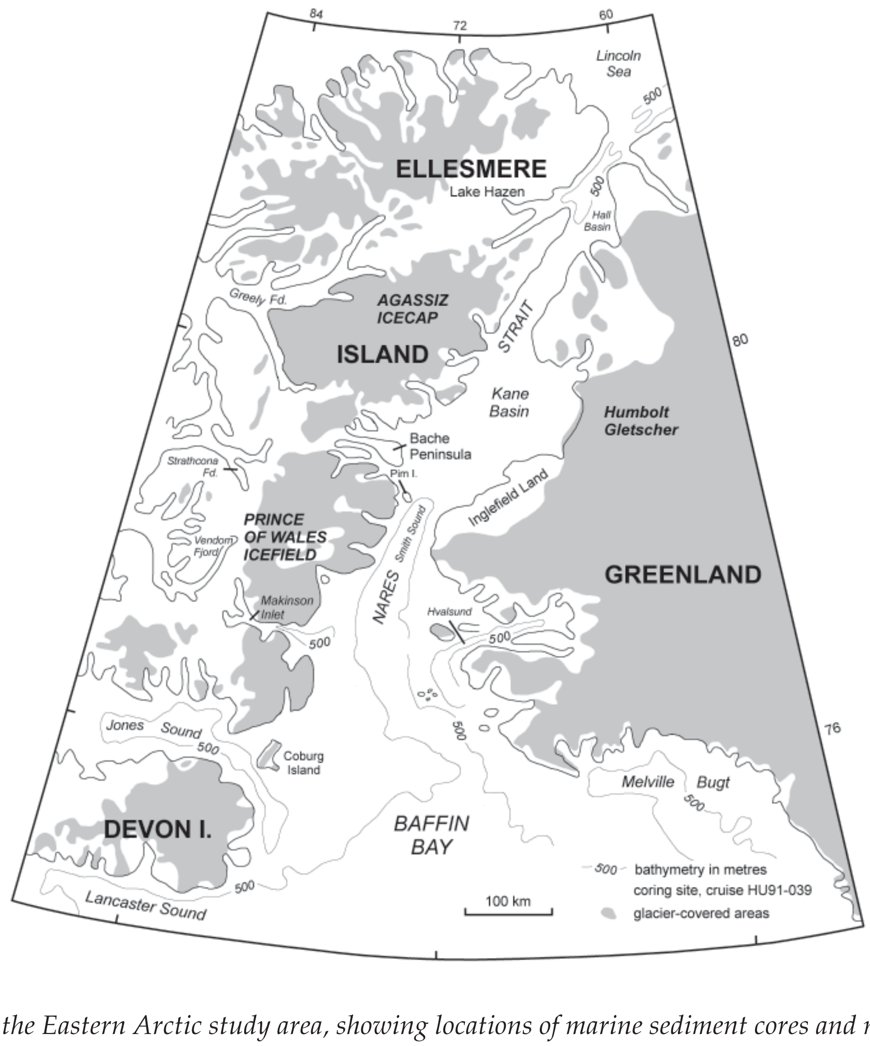

Figure 2. Map of the Eastern Arctic study area, showing locations of marine sediment cores and main archaeological sites on Devon Island. Dotted line marks the present extent of the North Water Polynya; lightly shaded area marks the Coburg Polynya. 1. Truelove Lowland; 2. Cape Sparbo-Hardy; 3. Sverdrup Lowland.

to compare these records to the long-term (~5,000 year) archaeological record of human occupation of the Eastern Arctic, and with shorter-term fluctuations in the occupations of the North Devon Lowlands, southeast Ellesmere Island and Inglefield Land around the North Water Polynya (NOW). Most of the archaeological records provide only fragmentary glimpses of possible human responses to rapid changes in climate and sea ice and the time resolution of these records is severely limited by three factors (Barry *et al*.1977; Taylor 1968; McGhee 1976; Schledermann 1990; 1996).

1) Radiocarbon dating is often based on driftwood that could have floated for several decades before its arrival at an occupied site, and dating of terrestrial and marine mammal bones involves large uncertainties about the corrections needed to account for degradation or marine reservoir effects.
2) There is often insufficient knowledge about the role of isostatic sea level oscillations in altering the site ecology and in the repositioning or preservation of artifacts. In the High Arctic regions north of Kane Basin, most molluscs are very small and the shells are extremely thin, making it difficult to obtain sufficient intact material for reliable AMS ages (Mudie *et al*. in press).
3) Preservation of organic remains is sometimes poor in the High Arctic regions of the eastern CAA proximal to polynyas, where repeated freezing and thawing of permafrost occurs, and where limestone bedrock is a source of old carbon contamination.

In contrast, cores of marine sediments from deep fiord (=fjord) or shelf basins near the archaeological sites provide continuous sections of Holocene sediments that can be accurately dated by radiocarbon ages on *in situ* mollusc shells and calcareous foraminifers (Mudie and Short 1985; Andrews *et a*l.1991; Levac *et al.* 2001; Mudie *et al.* in press). These marine sediments contain various sources of proxy-climatic and oceanographic data, including pollen and spores, dinoflagellate cysts (dinocysts), diatoms and foraminifers from which stable isotope records of oxygen and carbon can be obtained (e.g. Jennings *et al*. 2001; De Vernal *et al*. 2001; Mudie *et al.* in press). Previous studies of palynomorphs and foraminifers in cores from the North Water Polynya region of Smith Sound and southern Nares Strait (Figs. 1 and 2) have shown that the high sedimentation rates and excellent microfossil preservation allow resolution of past palaeoceanographic events with a precision of about 50 years for the past ~6,500 years (Levac *et al*. 2001; Mudie *et al*. in press). Quantitative palaeotransfer functions for dinocyst assemblages provide numerical estimates of past sea surface temperature (SST) in winter and in summer, and for reconstruction of the past duration of sea ice cover (SIC) with about the same accuracy as modern shipboard oceanographic measurements (Levac *et al*. 2001), as shown in the *Methods* section below

In the present paper, we first compare the decadal-scale palaeoceanographic reconstructions from Core LSSL2001–006 taken in the Coburg Polynya at the western edge of the NOW, about 30 km east of the North Devon Lowlands, with the records from Cores HU 91–039–007 and –008 taken in the northern part of the NOW, about 100–200 km south of the Palaeo- and Neo-eskimo archaeological sites in Northwest Greenland near Etah (see Appelt *et al*. 1998) and around the Bache Peninsula (Fig. 2). This detailed comparison will be followed by a discussion of the general patterns observed between climate change and archaeological records for the eastern CAA and adjacent Greenland regions. Finally, a comparison will be made between our marine proxy-data and other regional sea ice proxy-signals, such as sodium salt input to ice-cores.

Geographical Setting

The study area is at the south end of Nares Strait and in Smith Sound that are deep channels (~200–800 m) separating Greenland from Ellesmere and Devon islands and linking the surface waters of the Arctic Ocean with the relatively warm waters of eastern Baffin Bay (Fig. 2). Nares Strait is ~500 km long and includes two large basins, Kane and Hall Basins, linked by narrow channels ~50 km wide. Most of the area north of Smith Sound is covered by heavy sea ice (>1 m thick) for more than 10 months per year. The shorelines are deeply dissected by glaciated fiords, and there are glaciers descending to sea level from the Greenland, Agassiz and Devon Island icecaps, as well as the Prince of Wales Ice-field in southeastern Ellesmere Island (Fig. 2). The boundary between the arctic and subarctic surface waters in Baffin Bay corresponds to the position of the 8°C isotherm in summer and it slopes diagonally across the regions from southern Baffin Island to north of Disko Island (Mudie and Short 1985). This boundary also corresponds to the present-day northern limits of subarctic molluscan and benthic foraminiferan biogeographical distributions (Dyke *et al*. 1996a).

The North Water Polynya is an area of about 80,000 km2 that occupies Smith Sound and northern Baffin Bay, and periodically includes the Coburg Polynya west of Coburg Island (Fig. 2). Polynyas are polar marine ecosystems with seasonal or year-round ice-free or thin ice (<0.3 m) conditions and are all characterised by high primary productivity that provides important feeding grounds for zooplankton, fish and marine mammals (Pesant *et al*. 1996; Yao and Tang 2003). The North Water Polynya (NOW) is the largest in the Canadian Arctic and is sustained by a winter ice arch across southern Kane Basin, wind removal of locally formed ice and by upwelling and lateral advection of heat from deeper waters. Throughout the year, the NOW is an open water area with scattered ice floes or very thin ice but historical records show that the position of its margin varies considerably from year to year. The northern margin shifts between Pim Island and eastern Kane Basin, and the western margin may shrink to the east of Coburg Island (Appelt *et al*. 1998; Levac *et al*. 2001; Topham *et al*. 1983). The secondary polynyas in Jones Sound west of Coburg Island and around the Bache Peninsula are smaller, seasonally reoccurring open water areas within large glacial fiords. In winter, these areas are covered by land-fast ice dissected by leads, which is an important terrain for Inuit seal hunting (Tynan and DeMaster 1997). Early in spring, this ice breaks up and provides open water areas that are favoured by bearded seals, walrus and whales (Schledermann 1990; Helmer 1992; Tynan and DeMaster 1997). At present, the average sea surface temperature (SST) in NOW at the location of the core site HU91–039–008 (Core 8) at 77 ° 16.0′N, 74 ° 19.9′W is –1.1°C in winter and 2.8 to 2.9°C in summer. The SIC, expressed as number of months per year with more than 50% sea ice cover, is 8.1 months. At the location of Core LSSL2001–006 (Core 6) in Coburg Polynya at 75° 35′ N, 78 ° 41′W, the corresponding SSTs are –1.2°C and 4°C and the SIC is 9 months per year. Further details about the core sites and the sediment cores are given by Levac *et al*. (2001) and Mudie *et al*. (in press).

The study area lies at the southern end of the Canadian High Arctic climate zone. Average air temperature in this region is –15°C, ranging from about -30°C in winter to +5°C in summer (July and August). The High Arctic is a polar desert region with annual precipitation of 150–300 mm a-1. The North Devon Lowlands on the north-eastern edge of the Devon Ice Cap are four coastal lowland areas: from east to west, the Sverdrup, Sparbo-Hardy, Skogn and Truelove lowlands (Fig. 2), each separated by headlands of Precambrian metamorphic rocks projecting through the Palaeozoic limestone formations that characterize most of Devon Island (Helmer 1991; MacLean *et al*. 1984). The sheltered, wet lowlands support unusually lush tundra vegetation and large terrestrial mammal populations, including muskox, caribou and fox. The adjacent waters of Jones Sound support a wide range of large marine mammals, including narwhal, beluga whales, walrus, polar bear and bearded, harp and ring seals. There are 163 archaeological sites in these lowlands, spanning 4500 years of occupational history (Helmer 1991; 1992). The Bache Peninsular area is the largest glacier-free lowland in southeastern Ellesmere Island and is a fiord-dissected region carved out of the bedrock of Precambrian age (Schledermann 1990). The lowlands and fiords support rich habitats for terrestrial and marine mammals, and are accessible both from Jones Sound and from Strathcona Sound via the Sverdrup Pass. There are 115 archaeological sites along the coasts and on islands in Flagler and Buchanan Bays, and in Alexandra and Hayes Fiords. Alexandra Fiord is presently the northernmost community inhabited by the Inuit people.

Methods

Long piston and giant box cores of slightly bioturbated organic-rich mud were obtained from Canadian Coast Guard vessels during cruises of CSS Hudson in 1991 and CGS Louis S. St. Laurent in 2001. Methods of core recovery, X-radiography, sediment texture and storage are given elsewhere (Levac *et al*. 2001; Mudie *et al*. in press).

Palynomorphs were extracted from samples of 2–5 cm^3 volume, taken at intervals of 5 to 10 cm, and were processed using standard methods for Quaternary marine sediments (Rochon *et al*. 1999): sieving at 10 and 125 μm mesh sizes, digestion in hydrochloric and hydrofluoric acid, and adding exotic spores to obtain estimates of palynomorph concentration per cm^3. Quaternary palynomorph preservation is good in most sections of the cores, but all samples included common reworked pre-Quaternary (mainly Tertiary) triporate pollen and Mesozoic pollen and spores; reworked dinocysts are rarely present. The reworked palynomorphs were primarily recognized by their distinctive morphology and very dark color, but flattened and/or yellowish grains of extant pollen types were also scored as reworked.

One or two slides of each processed sample were counted at x25 magnification, until a minimum of 300 exotic spores was reached. This yielded counts of 100–200 for total dinocysts in the middle to upper Holocene samples. Nomenclature of the dinocysts follows that used by Rochon *et al*. (1999) and de Vernal *et al*. (2001).

Decadal-scale quantitative records of changes in SST summer and winter, and in SIC (as months a-1 with >50% sea ice) have been obtained using dinocyst assemblages as proxies. Dinocyst assemblages from the tops of box-core samples at 677 Arctic sites (de Vernal *et al*. 2001; Mudie and Rochon 2001) have been calibrated against the oceanographic data to develop palaeoclimatic transfer functions using the biogeographical closest analogue method (Rochon *et al*. 1999). For this study, log transformed data for 54 dinocyst species grouped into 40 taxa were used, and the reconstructed values are the weighted average of the 10 best analogues. The accuracy of the estimated SST is ± 1.3°C and 1.7°C for winter and summer, respectively, and ±1.1 months a-1 for the SIC.

Table 1 shows the radiocarbon ages of 9 molluscan and foraminiferan samples used for dating of the cores by accelerator mass spectrometry, and further validated by cross-correlation with shell ages in Core 83–023–52 from Jones Sound (MacLean *et al*. 1984) and with foraminiferan ages from Core HU93–034–015 from Hudson Strait (Fig. 3). The ^{14}C ages were normalized to a $\delta^{13}C$ of –25‰ and a marine reservoir correction of 400 years BP was applied to account for the air-sea reservoir difference. The calibrated ages were obtained using the 1998 version (4.0) of the Seattle CALIB program. The ages for Core 006 ages show that sedimentation rates in the Coburg Polynya range from about 22 cm/century in the sandy mud unit deposited between ~7 and 3.3 ka BP to ~14 cm/century during the late Holocene. Sedimentation rates for piston Core 008 average about 15 cm/century but appear to be slower in box Core 007 (6.8 cm/century) that is used to represent the youngest sediment at this site (see Levac *et al*. 2001). The interval from 2375–800 BP was not recovered in the NOW cores because the soft surface sediment was displaced by the impact of the piston corer.

Core	Depth (cm)	Material	Corrected age ^{14}C age (BP)	Calendar age cal BP
HU91-039-007C	14	forams	320+/-85	440-290
HU91-039-008PC	72	shell	2485+/-60	2730-2580
	461	shell	3665+/-50	4150-4000
	527	shell	3790+/-60	4360-4190
	704	shell	4710+/-55	5560-5430
	831	shell	6275+/-75	7370-7270
LSSL2001_006PC	518	shell	3405+/-55	3730-3690
	530	shell	3375+/-42	3684-3645
	1080	shell	6315+/-60	7355-7215
Baffin 83-023-52	175	shell	1530+/-50	1524-1328
HU93-034-015PC	80	forams	1180+/-50	1184-970
HU93-034-015PC	300	forams	1700+/-60	1737-1479
HU93-034-015PC	560	forams	2060+/-40	2122-1925
HU93-034-015PC	1300	forams	3340+/-60	3701-3442

Table 1. Radiocarbon ages of cores.

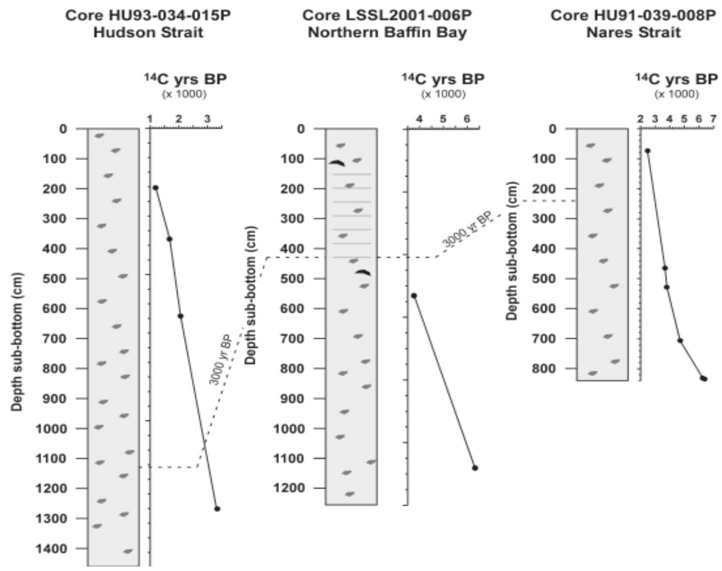

Figure 3. Time-depth data used for dating of the warm-cold events described in this study.

Results

Descriptions of the concentrations and relative abundances of the dinocyst species in Core 006 (Mudie *et al*. in press) and in Cores 007 and 008 (Levac *et al*. 2001) have been published previously and are not repeated here (data also available on request). Fig. 4 shows the paleoceanographic reconstructions from the dinocyst assemblages in Core 006 for winter and summer SST and for SIC. The records show little change in winter temperature over the past ~6500 years, but there is a gradual decrease in mean August SST from about 7 to 4°C and a corresponding increase in SIC from about 6 to 9 months per year. Superimposed on this general trend are nine large oscillations in summer SST that coincide with changes in SIC. The ages of the warm intervals with reduced SIC are shown in Table 2.

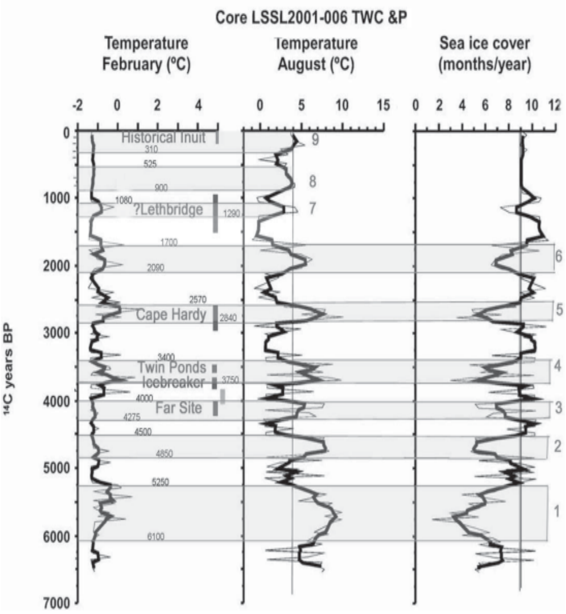

Figure 4. Core 006 from Coburg Polynya: palaeoceanographic reconstructions of SST winter and summer, and sea ice cover (bold lines = weighted averages; fine lines = possible ranges), and the ages of Devon Island site occupations (vertical bars). Shaded rectangles delineate warm intervals # 1–9 in Table 2.

The SST reconstructions for Core 6 indicate that from ~6100 to 2570 yr BP, there were large oscillations in summer SST from 3°C cooler than now to 6°C warmer, and these temperature changes correspond to annual variations in SIC ranging from 2 months more of heavy (>50%) ice to a 4–month extension of open water conditions compared to now. These temperature and SIC changes begin and end within about 50 to 100 years and re-occur at intervals of ~1000 years. This periodicity is close to the 1100–1500–year Bond Cycle. The oscillations in Core 6 probably correspond to the same forcing factor although the resolution of the response signals at the top of the core may be modified by the bioturbational mixing depth of about 15 cm (equal to 79–94 years), based on measured rates in Bylot Sound off eastern Smith Sound (Smith *et al*. 1994). The amplitude of the oscillations decreases over the last ~2500 years of declining temperature and the interannual ice variations recorded in more southerly regions for the past ~800 years (e.g. Ogalvie 1984 for Iceland; Grumet *et al*. 2001 for Penny Ice Cap) are not evident.

Fig. 4 and Table 2 also show the approximate age ranges of the Palaeoeskimo (4500–1000 BP) occupations on the North Devon Lowlands given by Helmer (1991) and shown in Table 2. The Early Palaeoeskimo (pre-Dorset) cultures that occupied the Eastern Arctic from ~4500–3000 BP are represented on Devon Island by the Far Site, Icebreaker and Twin Ponds archae-

N. Devon Lowland Complex		Event No.	Core 006	Core 008	Walrus	Bowhead Whale	Culture
		#1	6100 - 5250	6250 - 5500		6000-5700	
		#2	4850 - 4500	5000 - 4600			***Early***
Far Site	4160 - 4040	#3	4275 - 4000	4300 - 3750	4200-3400	5300-3700	***Palaeoeskimo***
Rocky Point	4060 - 3800						***(pre-Dorset)***
Icebreaker Beach	3850 - 3700	#4	3750 - 3400				
Twin Ponds	3680 - 3535	#4		3400 - 3200			
Cape Hardy	3100 - 2600	#5	2840 - 2570	2900-2375	2600-2300	2700-2500	***Late***
		#6	2090 - 1700	gap in record			***Palaeoeskimo***
Lethbridge	1500 - 1000	#7	1290 - 1080	gap in record	1500-400		***(Dorset)***
(Bache Thule)	800 - 300	#8	900 - 525	800 - 400			***Thule***
Historical Inuit	150 - 0	#9	310 - 0	150 - 0			***Historical Inuit***

Table 2. Radiocarbon ages (yr BP) of North Devon Lowlands occupations (Helmer 1991), warm events in Cores 006 and 008, and mammal bone occurrences reported by Dyke et al (1996b, 1999).

ological sites. These Palaeoeskimo sites are on the Truelove Lowland, furthest west of the 4 occupied areas (Helmer 1992). The Historic Inuit (150 BP – present) were at the most seaward location on the Sverdrup Lowland. Late Palaeoeskimo (Dorset) cultures (3000–1000 BP) are found at the Cape Hardy and Lethbridge sites in the intermediate Cape Sparbo-Hardy region. The Thule culture (1000–150 BP) also occupied this middle region on the North Devon Lowlands (Helmer 1991) but is not shown on Fig. 4 because there are no dated materials for these sites. On Bache Peninsula, the Thule occupations are dated ~850–300 BP (Schledermann 1990).

Fig. 5 shows the palaeoceanographic reconstructions from the dinocyst assemblages in Cores 008 and 007 for winter and summer SST and for SIC. The ages of the seven warm events are given in Table 2. The amplitude of the warm-cold oscillations and changes in SIC at this more northern offshore site are smaller than in the Coburg Polynya, but there are 3 major warm intervals with ages of 6250–4600, 4300–3750 and 2900–2375 BP and there are two minor intervals at the top of the core. The oldest event (6.25–4.6 ka) has two peaks around 6550–5500 and 5000–4600 BP that correspond to events 1 and 2 in Core 006. Other major warm intervals occur from 4300–3750, 4000–3200 and 2900–2375 BP, corresponding to the Far Site, Icebreaker and Cape Hardy Events 3 to 5 in Coburg Polynya. The youngest events at the NOW site correspond to the Bache Peninsula Thule and the Devon Island Historical Inuit occupations.

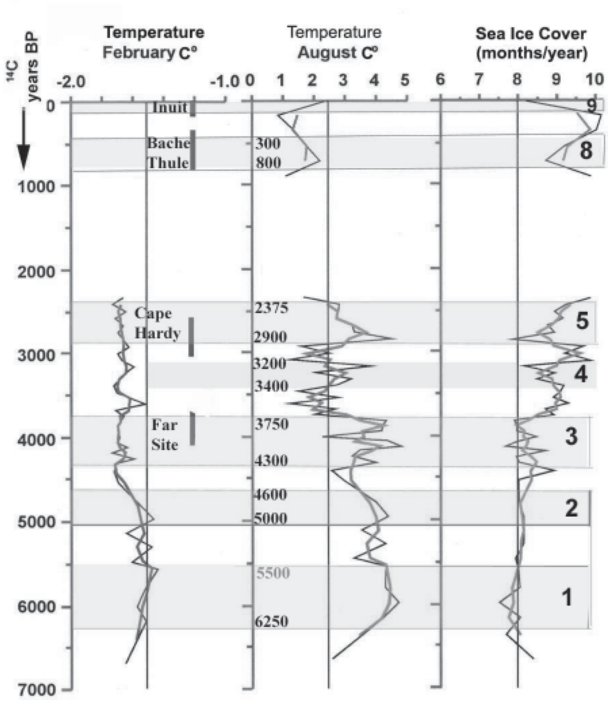

Figure 5. Core 007 (top) and 008 from the North Water Polynya: palaeoceanographic reconstructions of SST winter and summer, and sea ice cover cover (bold lines = weighted averages; fine lines = possible ranges), and the ages of Devon Island site occupations (vertical bars). Shaded rectangles delineate warm intervals # 1–5 and 8–9 in Table 2.

Discussion

Arctic marine records and cultural changes

Both marine cores show a major mid-Holocene warm interval from ~6,500 to 4,500 BP, the end of which coincides with the appearance of the earliest people in the Eastern Arctic (Fig. 6). These earliest human occupations are those of muskox hunters at Independence Fiord (northeast Greenland, ~4800–3700 BP) and at Lake Hazen (northern Ellesmere Island, ~4400–2700 BP), and the Saqqaq Palaeoeskimo (southwestern Greenland, 4500–2700 BP). Off Devon Island, the record in Core 006 shows that this interval was marked by an increase of up to 4°C in summer SST; further north, a smaller increase of 2.5°C is recorded in Core 008. These elevated temperatures are consistent with the archaeological evidence for warmer temperatures and reduced sea ice in the High Arctic. For example, the abundance of driftwood at the Independence I site on the northeast coast of Greenland (Fig. 1) shows that the shoreline was ice-free from about 6000–4000 BP (McGhee 1996; Dyke *et al*. 1997). The Greenland Independence Fiord and the Lake Hazen Independence 1 people depended heavily on muskox and caribou herds, indicating that the High Arctic vegetation formerly supported much bigger populations of large land mammals than nowadays. The earliest Palaeoeskimo on Bache Peninsula and the Early Saqqaq Palaeoeskimo of the Disko Island region, southwest Greenland, obtained roughly half of their food from land mammals and half from marine mammals.

Both of the marine cores show the periodic occurrence of warmer than present intervals from 4850 BP until at least 2500 BP, which marks the end of these pre-Dorset Palaeoeskimo cultures with their heavy reliance on land mammals for food. Core 006 shows a continuation of very warm intervals until 1700 BP when the Palaeoeskimo cultures abruptly disappeared. During this time in the North Devon Lowlands, there was a movement away from the Early Palaeoeskimo occupation of the fertile plains of Truelove Lowlands to the Late Palaeoeskimo occupation of the Cape Sparbo Headlands projecting into Jones Sound (Helmer 1992). This shift has been interpreted as reflecting an increased dependence on hunting of

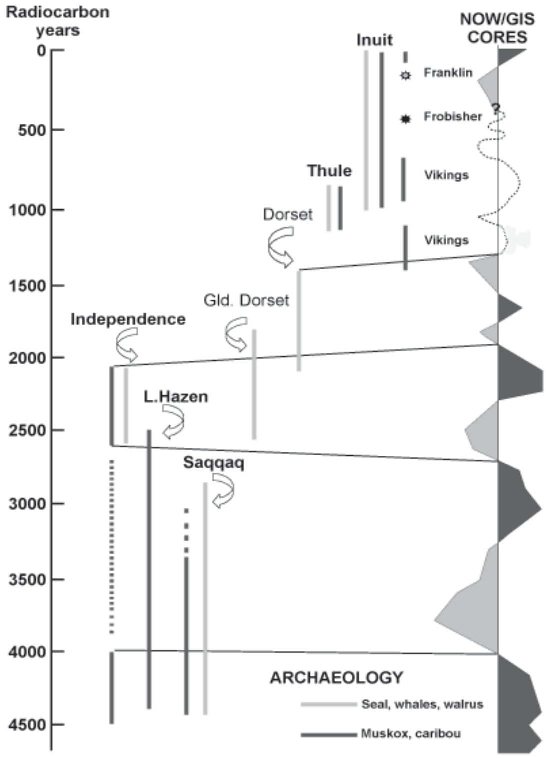

Figure 6. Summary diagram of cultural changes in the Eastern Canadian Arctic and Western Greenland (data from McGhee, 1996) and corresponding palaeotemperature changes estimated from marine core data, historical and ice-core (Barlow, 2001) records. Dark grey shading = warmer than now up to 4°C; light grey shading = colder down to -4°C; dark grey vertical bars = predominantly land-based economy; light grey bars = marine-based economy.

marine mammals from the sea ice (Helmer 1992). This interpretation is further supported by the increase of SIC by 1–2 months per year recorded in the marine cores.

The Thule and early Historical Inuit occupations (1000–150 BP) that utilized both marine and land mammal resources occur within a generally colder interval in which there appears to be no major, sustained reductions in SIC but some slightly warmer and colder intervals that roughly correspond to the Mediaeval Warm Interval and the Little Ice Ages, respectively (Fig. 6). The marine cores show increases in summer SST of ~1–2°C but only the offshore NOW polynya shows a corresponding ~1 month decrease in SIC.

Overall, the occupations of sites in the North Devon Lowlands mostly coincide closely with the marine warm intervals when there would have been more summer-open water than now, especially during the Far Site, Icebreaker and Twin Ponds occupations of the Truelove Lowlands from 4160–3700 BP when the Coburg Polynya may have extended far west into Jones Sound. The apparently anomalous Rocky Point occupation during a cold interval in Jones Sound may be related to the fact that the NOW remained warm and relatively ice-free at this time. The overall progressive cooling and decrease in duration of open water may explain the eastward shift in the relocation of the Late Dorset, Thule and Historical Inuit sites from Cape Sparbo-Hardy to the western edge of the NOW off eastern Devon Island. A comparable pattern of climate-related events has been used to explain abrupt shifts in the archaeological record from southwest Victoria Island in the western CAA (Fig. 1). Here the Palaeoeskimo arrived at ~4500 BP and attained their maximum numbers by 4000–3800 BP during which time >60% of their food was muskox (Savelle and Dyke 2002). This growth was terminated by a sudden decline within a few decades, followed by an apparent disappearance from 3200–3000 BP and a further decline during the last major warm event around 2800–2600 BP.

Our quantitative palaeotemperature and sea ice data for the Canadian High Arctic add new detail, precision and accuracy to previous conclusions drawn from comparison of palaeoenvironmental and archaeological data from the southern Canadian Arctic, Labrador and Greenland (Barry *et al*. 1977; Maxwell 1985). These authors concluded that in the Low and Middle Canadian Arctic, the expansion of the Arctic Small Tool Palaeoeskimo tradition was correlated with a warm climatic interval from 4500–3500 BP. In contrast, the later Pre-Dorset expansion coincided with a climatic deterioration (3400–3000 BP). They also considered that while the disappearance of the Dorset culture was probably the result of complex interactions between environmental factors, climate change also played an important role. They found that expansion of the Thule culture into the High Arctic coincided with warmer climatic conditions from 1100 to 800 BP, followed by a retreat during the onset of more severe cold and sea-ice conditions.

More recent reviews (Schledermann 1996; Rowley-Conwy 1999) of Arctic archaeological records, however, have suggested that although climate and sea ice oscillations are often associated with times of rapid cultural change, they do not necessarily result in elimination of hunting-gathering societies, but rather give rise to non-progressive flexibility in the face of new environmental opportunities and/or technological changes. For example, Tynan and DeMaster (1997) have clearly demonstrated the huge impact of decreases in Arctic sea-ice cover on marine mammal populations and the importance of changes in the location of the ice-edge ecosystem in determining the ability of the bowheads to find reliable food sources. However, their belief that the demise of the traditional Neo-eskimo Thule culture 500 years ago was related to climate-induced absence of bowheads on the ice margin of Canada Basin fails to consider the hunting flexibility demonstrated by the late Palaeoeskimo Dorset people in Foxe Basin (Murray 1999). The hunting adaptations shown by the Labrador Inuit living around Hamilton Inlet region east of Hudson Bay from 1600–1900 A.D.. also demonstrate that large changes in climate and sea-ice distribution of the Low Arctic region have been accommodated up until relatively recent times (Woollett 1999).

On the other hand, in the more peripheral regions of the CAA, one of the few very detailed zoo-archaeological studies for the High Arctic region (Dyke *et al*. 1996b, Savelle and Dyke 2002) shows that climate changes were the main factors contributing to one or more abandonment episodes of Palaeoeskimo settlements on Victoria Island, although over-hunting of musk ox populations may also have been involved. Woollett *et al*. (2000) further points out the limitations that Arctic zooarchaeological data can provide for quantitative palaeoclimatic or seasonal sea ice distributions because the marine mammal populations represent the degree of hunting activity and not the natural population sizes.

Other pre-historical proxy-data sources

Other sources of proxy-sea ice data that have been used to examine the linkage between Arctic climate change and archaeological data are driftwood and bowhead whale and walrus bones (Blake 1975; Dyke *et al*. 1996b; 1997; 1999). At Cape Storm, on the north shore of Jones Sound, driftwood was most abundant from 6000–4000 BP. The abundance then decreased and none was stranded there during the last 2000–250 years BP. Dyke *et al*. (1997) believe that the driftwood was delivered to Jones Sound from Baffin Bay rather than Nares Strait because of the preferential accumulation on east-facing beaches and presence of volcanic pumice probably from Iceland. These authors argue that changes in the delivery of driftwood throughout the Holocene were due to shifts in the trajectory of the Trans-Polar Drift (TPD). A similar model was proposed by Bischof (2000) to account for variations in ice-rafted detritus (IRD) in the Norwegian Sea. At present, however, the TPD oscillates on a time-scale of about 10–30 years (Mysak and Venegas 1998) and the century-scale resolution of the driftwood and IRD data are too coarse to validate this idea.

Palaeogeographic maps based on the distribution of bowhead whale bones show heavy sea ice in Jones Sound at 6 ka, followed by open water conditions at 5, 4, and 3 ka and a return to more sea ice during the past 2000 years (Dyke *et al*. 1996b). These results apparently disagree with our marine core data but the whale bone record for Devon Island shows peaks that broadly correspond to the warm events 1, 3 and 5 in our cores (Table 2). The few bones of Neoglacial age were interpreted as possibly indicating that bowhead whales moved northwards in open water along the Ellesmere coast but did not enter the ice-covered waters off the Devon Island coast. Savelle and Dyke (2002) also studied the whale bone record on Victoria Island, on the route of the possible eastward Thule migration in search of extended whale hunting grounds. They found few Thule sites on this island and concluded that if the Neo-eskimos did migrate because of the extended whale ranges, the increase in area of summer open water and reduction in SIC was of short duration.

Dyke *et al*. (1999) also examined the age distribution of walrus bones in the Canadian Arctic and attempted to link these to Palaeo- and Neo-eskimo occupation sites. They found that in the CAA, most of the Mid-Holocene walrus bones had the same age range (5000–3000 BP) as the bowhead whales and they concluded that this indicated a common control by sea ice conditions. Table 2 shows the ages of the intervals in which walrus bones are an important component of the archaeological sites. It is clear that these proxy-sea ice data do not provide a sensitive index compared to the marine palynological reconstructions.

Ice core records from Greenland and the eastern CAA have also been used to reconstruct past changes in air temperature and sea ice. Barlow (2001) found that the GISP2 and Central West Greenland ice cores record variable 50–100 yr long warm-cold oscillations from about 1400–1925 A.D.., but there is a surprisingly weak connection between the ice core proxy-temperature record and historical evidence for Arctic SIC fluctuations. Grumet *et al*. (2001) used sea salt Na+ fluctuations in a 700-year ice core record from the Penny Ice Cap (southeastern Baffin Island) as a proxy for Spring sea ice concentration and found that there was an apparent near-doubling in SIC over the past century, with the 10-yr mean sea ice variations being of the same magnitude as those found during the coldest intervals of the Little Ice Age from ~1810–1890 A.D..

Lamoureux and Gilbert (2004) have correlated the Penny ice core Na+ record with 5-yr mean changes in oxygen isotopes in the Devon Ice Cap and with varved sediments in Southern Baffin and Devon Island lakes, using varve thickness as a proxy for summer temperature. They conclude that all the records for the Baffin Bay region show similar trends for the past 150 years, with estimated summer temperature fluctuations of 2–3°C, but the Penny Ice Cap record shows less coherence for the preceding 550 years. Sediment, ice core and tree ring proxy air temperature records for the region from Arctic Europe to western Canada were also compared by Overpeck *et al*. (1997). These 400-year records indicate about 1–3°C of warming during the early 20th century and some records show a comparable warming between 1700 and 1820.

It is evident, therefore, that although the Canadian and Greenland ice core records may not provide a reliable long-term (more than two centuries) signal for changes in SIC, our Arctic marine sediment records provide a lower degree of resolution for both SST and SIC events during the same time interval. The main cause of this is may be the slower sedimentation rates (< 15 cm/century) at the tops of the cores. Bioturbation of stratigraphic signals in marine cores can displace stratigraphic signals and reduce their amplitude (Bard *et al.* 1987; Chapman and Shackleton 1998). Although in deep water, the effects should be minimal (~5% attenuation) as long as accumulation rates are above 10 cm/kyr., the bioturbational mixing down to about 15 cm (equal to 79–94 years) that was measured in the organic-rich surface sediments of the Bylot Sound fiord adjacent to our polynya study area (Smith *et al*. 1994) may in fact muffle the proxy-data signals more strongly than in pelagic open ocean cores, possibly reducing the resolution from the background decadal scale value of ~50 years to 79 (Core 6) or 94 years (Core 7). Therefore, although Chapman and Shackleton (1998) have shown that meaningful century-scale climate records can be recovered with sedimentation rates as low as 10 cm/kyr., i.e. almost an order of magnitude slower than for the tops of our core, it is important to take into consideration the level of activity of the burrowing organisms in different environmental settings.

Positioning of core sites in anoxic marine basins where annual varves may be present (e.g. at Saanich Inlet, Mudie *et al*. 2002) should also improve the quality of the marine proxy signals. The proxy SIC records may also be more sensitive in areas away from polynyas that are the most complacent Arctic marine environments with respect to ice coditions (Woollett *et al*. 2000). However, the summer open water areas of polynyas, particularly the larger primary polynyas like Jones Sound and NOW, are usually the focus of archaeological importance in the CAA (Schledermann 1980; 1990) and smaller nearshore polynya are subject to extinct by changes in sea level (Schledermann 1990). In addition to possibly strong bioturbational mixing of the signals at the tops of our cores, there is also need to increase the sensitivity of the winter temperature signal and the accuracy of the modern SIC calibration database (de Vernal *et al*. 2001).

Historical records of sea ice change

Detailed studies have been made of possible correlations between Viking and other early European excursions to the High Arctic and the historical or ice core records of climate change. The earliest evidence of Vikings in the High Arctic is in the twelfth century on Bache Peninsula (Schledermann 1980). Ogalvie (1984) compared a decadal sea-ice index for Iceland with that of earlier, less accurate work by Koch (1945) and showed that for the earliest interval of reliable historical records (1601–1780 A.D.), the amount of sea ice between Greenland and Iceland fluctuated from brief (10–30 years) lows of no or minimal ice at intervals of about 90 years (1651–1681 and in the 1740s). These low ice years alternated with ~20 year periods of considerable ice in 1610–1630, 1680–1710 and 1740–1760 (~50 year recurrence intervals). In a more detailed paper, Ogalvie and Jónsson (2001) have cautioned against use of the pre-sixteenth century data of various authors, including Koch (1945) who described a range from almost ice-free conditions for 400 years from 800–1200 A.D.., followed by 200-yr long oscillations of more or less SIC from 1200–1600 A.D..., heavy ice from 1600–1845 A.D..., then an interval of almost no ice from 1865–1884 A.D...

Correlatable summer temperature oscillations of about 2°C are evident in Core 006, but the SIC record shows little variation at this nearshore site after a brief interval of reduced ice corresponding to the Lethbridge occupation from ~700–910 A.D... In contrast, the NOW record does show a relatively warm summer interval (+1°C increase) and reduced SIC from ~1100–1400 A.D... and it shows the 1600–1845 heavy SIC event, with a corresponding summer temperature decrease of 0–5°C. These temperature changes are comparable with Bergthorsson's estimates (reported in Ogalvie and Jónsson 2001) of a 1.2°C decrease in 30-year means for Iceland over the interval from ~900–1300 and 1800–1900 A.D... More detailed comparison with the annual sea-ice index of Ogalvie and Jónsson (2001) for the interval of 1600–1990 is not valid because of our coarser time scale and the fact that the Iceland index seems to include all sea ice, whereas our data uses the standard oceanographic index that refers only to changes in ice cover *above* a background value of 50% SIC (Rochon *et al*. 1999; de Vernal *et al*. 2001). However, it is interesting to note that the detailed Icelandic record shows that the cold maximum from ~1775–1840 A.D..., took about 30 years to develop and less than 10 years to retreat, suggesting that the rapid pace of warming measured during the past 40 years had already commenced earlier in the last millennium, in contrast to the apparently slower 50–100 year rates of build-up and collapse seen in our older proxy-records.

Other historical sea ice records come from reports of British whaling ships crushed by sea ice in Davis Strait and northern Baffin Bay (e.g. Lubbock 1937 covers the time from 1585 to 1918). These events cannot be used quantitatively, however, for information about the Canadian Arctic and West Greenland because the numbers of ships depended on the number of whales harvested in the previous season, and because most ships chose to sail the shorter distance to the Greenland Sea as long as the whale harvest there was good. It is also notable that, despite the frequent shipwrecks (2–19 in many years), usually all or most of the crews were rescued and recovered safely (see records in Lubbock 1937). It appears that when severe losses of life did occur, e.g. about 220 men in the worst interval from 1830–1836, this was mostly associated with excessive alcohol use and severe scurvy (these factors are inter-related; alcohol also lowers body temperature, making it more prone to severe frost-bite). Likewise, the demise of ships attempting to sail the Northwest Passage through the CAA, such as the Franklin's Expedition in 1845–1848, just after the long Icelandic SIC event ending in 1840, was largely because of bureaucratic errors, lack of willingness to adapt to native subsistence foods, and dependence on tinned food with a high lead content (Beattie and Geiger 1988). It remains true, however, that SIC variations played an important role in the success or failure of attempts to explore the Northwest Passage (Alt et al. 1985) and in the length of time before shipwrecked seamen were rescued. For example, in the milder years from 1853 to 1881, the ships of Kane, Hayes, Nares and Young returned safely after almost reaching the Arctic Ocean via Nares Strait (Schledermann 1990; see Fig. 2) and Lieutenant Greely sailed into western Hall Basin to establish an American fort. In the following two years, however, heavy ice prevented transit of supply ships to the fort and Greely lost 19 of his 26 men from starvation by the spring of 1884 (Schley 1885).

Conclusions

Quantitative proxy-climatic data from continuous, decadal to centennial-scale records in marine cores from the North Water and Coburg polynyas provide a useful tool for examining possible connections between long-term climate/sea ice changes, the long (~5,000 year) archaeological record of human occupation of the Eastern Arctic, and the shorter (~200–300 year) occupations of the North Devon Lowlands, southeast Ellesmere Island and Inglefield Land around the North Water Polynya (NOW). In the North Devon Lowlands region, our marine records show that the periodic human abandonment and later recolonisation of neighbouring areas are closely related to changes in SST and SIC. These cultural changes can be interpreted in terms of expansion and contraction of the ice margins during the time of Palaeo- and Neo-eskimo occupation, up until ~1,000 years ago when the resolution of events in the marine sediments decreases to a quasi-centennial scale.

It appears that past cultures in peripheral Arctic regions were able to adapt to abrupt temperature increases of 2–4°C and a 4-month extension of the open water season and to colder summer events of 3°C lower than present, with a 2 month extension of annual SIC. Both the warming and cooling events began and ended within about 50 to 100 years and re-occurred at intervals of ~1000 years, possibly reflecting the 1100–1500-year Bond Cycle. There is a long-term overall cooling of about 3°C in summer that corresponds to the movement of Early Palaeoeskimos from the fertile plains of Truelove Lowlands to the Late Palaeoeskimo occupation of the Cape Sparbo Headlands projecting into Jones Sound. This shift is in accord with Helmer's (1992) interpretation of an increased dependence on hunting of marine mammals from the sea ice and is further supported by the increase of SIC by 1–2 months per year found in the marine cores.

The short-term climatic and sea ice changes were accommodated by modifications of housing styles and hunting tools as described by Helmer (1992) and Schledermann (1990; 1996). Unfortunately the resolution of our cores decreases to a centennial scale at the top of our cores (~ past millennium) and we are not able to resolve the apparently rapid SIC events recorded in ice cores and lake varves for the past 2 to 4 centuries.

Our quantitative palaeoceanographic reconstructions show that the GCM predictions of +4°C for continued global warming are represented in southern Nares Strait for several intervals during the mid-Holocene when solar insolation and ice sheet sizes were essentially the same as now. The most recent of these warming events, about ~2700 years ago, shows that SIC could become as low as 2 months per year in the Jones Sound region. However, our records indicate that in prehistoric times, these warmer intervals lasted only a few centuries and were replaced by intervals with summer temperatures 2–3°C colder than now and with 1–2 months more of heavy SIC. These climate oscillations are more rapid than some of cultural changes evident in the archaeological record of Palaeoeskimo populations in the Canadian Arctic and northern Greenland. As found in recent detailed archaeological studies, our data suggest that the natural sequence of climate changes in the Canadian High Arctic has not always been catastrophic to humans, and some of the changes may have stimulated new ways of coping with the environment and exploiting its food resources.

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