ARCTIC
VOL. 62, NO. 1 (MARCH 2009) P. 38–44

A 10 400-Year-Old Bowhead Whale (*Balaena mysticetus*) Skull from Ellef Ringnes Island, Nunavut: Implications for Sea-Ice Conditions in High Arctic Canada at the End of the Last Glaciation

NIGEL ATKINSON[1]

(Received 8 April 2008; accepted in revised form 9 July 2008)

ABSTRACT. Variations in the distribution and radiocarbon ages of postglacial bowhead whale (*Balaena mysticetus*) remains throughout the Canadian Arctic Archipelago indicate that the range of this whale expanded and contracted several times during the Holocene. Since the annual bowhead migration reflects the preference of this species for an ice-edge habitat, fossil bowheads have been used to infer that significant variations in summer sea-ice extent occurred throughout the archipelago during the last 10.5 thousand years. Previous studies have demonstrated that climatic amelioration, concomitant with enhanced meltwater flux from the retreating Laurentide Ice Sheet, cleared sea ice from the inter-island channels of the central archipelago, enabling early Holocene bowhead whales to extend beyond the range of contemporary populations. A 10.4 ka BP bowhead whale skull was discovered on Ellef Ringnes Island in the northern Canadian Arctic Archipelago, 700 km north of its previously reported early Holocene range. Consequently, sea ice along the polar margin of the Canadian Arctic Archipelago is inferred to have been less extensive than previously recognized. Both biological evidence and glaciological evidence suggest that this reduction in sea-ice extent was the result of climate forcing, amplified by meltwater-driven outflows from the rapidly retreating marine-based sector of the Innuitian Ice Sheet. Following a reduction of these outflows at ~9 ka BP, sea-ice conditions worsened, despite ongoing climatic amelioration, preventing additional bowhead whale incursions until ~4 ka BP.

Key words: bowhead whale, sea ice, deglaciation, ocean currents, paleoclimate

RÉSUMÉ. Des variations en matière de répartitions et d'âges déterminés par la méthode du carbone 14 relativement aux restes de baleines boréales (*Balaena mysticetus*) postglaciaires trouvés dans l'archipel arctique canadien laissent croire que le parcours de cette baleine s'est agrandi et s'est rétréci à maintes reprises pendant la période de l'Holocène. Puisque la migration annuelle de la baleine boréale tient compte de la préférence de cette espèce pour un habitat de lisières de glace, les fossiles de baleines boréales ont permis de déduire qu'il y a eu d'importantes variations en matière d'étendue de la glace de mer à la grandeur de l'archipel en été au cours des derniers 10,5 milliers d'années. Des études antérieures ont permis de démontrer que l'amélioration climatique, alliée au plus grand débit de l'eau de fusion provenant de la calotte glaciaire reculante des Laurentides, ont eu pour effet d'enlever la glace des canaux interinsulaires de l'archipel central, ce qui a permis aux baleines boréales de l'Holocène inférieur de se rendre au-delà du parcours des populations contemporaines. Le crâne d'une baleine boréale de 10,4 ka avant le présent qui a été découvert sur l'île Ellef Ringnes dans le nord de l'archipel arctique canadien se trouvait à 700 km au nord du parcours de l'Holocène inférieur signalé auparavant. Par conséquent, on en déduit que la glace de mer le long de la marge polaire de l'archipel arctique canadien aurait été moins étendue qu'on ne le croyait avant. Les preuves biologiques et les preuves glaciologiques laissent croire que cette réduction de l'étendue de glace de mer découlait du forçage climatique, ce qui était amplifié par les écoulements d'eau de fusion provenant du secteur marin de la calotte glaciaire inuitienne reculant rapidement. Suivant la réduction de ces écoulements à ~9 ka avant le présent, les conditions entourant la glace de mer se sont empirées malgré l'amélioration climatique constante, ce qui a empêché d'autres incursions de la part des baleines boréales et ce, jusque vers ~4 ka avant le présent.

Mots clés : baleine boréale, glace de mer, déglaciation, courants océaniques, paléoclimat

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

A variety of environmental proxies document a significant amelioration in Arctic climate at the end of the last glaciation, culminating in a peak in postglacial warming associated with increased summer insolation between 12 000 and 10 000 calendar years BP (Berger, 1988; Berger and Loutre, 1991; Kaufman et al., 2004). The Holocene

[1] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada; present address: Alberta Geological Survey, Energy Resources Conservation Board, 4th Floor Twin Atria Building, 4999–98 Avenue, Edmonton, Alberta T6B 2X3, Canada; nigel.atkinson@ercb.ca

FIG. 1. Map of bowhead whale stocks (adapted from Dyke et al., 1996), showing place names referred to in the text.

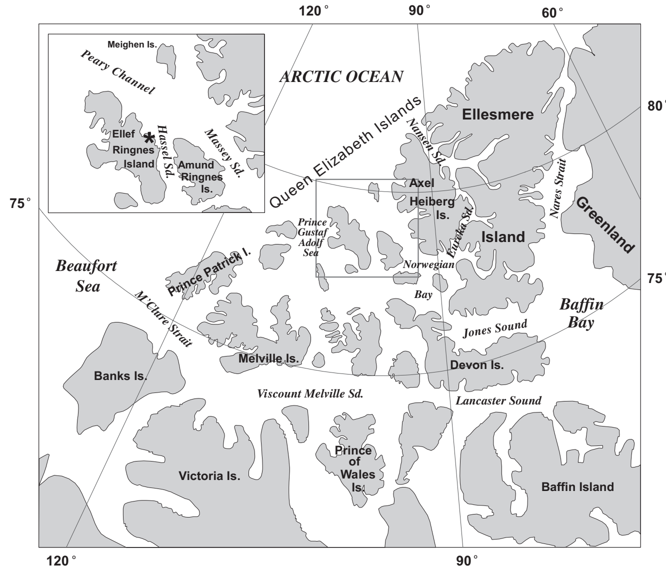

FIG. 2. Map of the Canadian Arctic Archipelago, showing place names referred to in the text. Inset map shows the area discussed in this paper and the bowhead skull location (*).

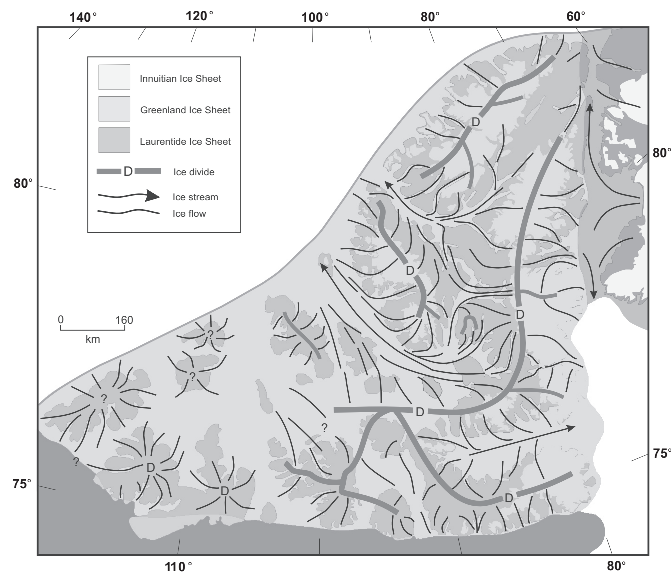

FIG. 3. Map of the Innuitian Ice Sheet during the last glaciation (modified from England et al., 2006).

thermal maximum was followed by climatic deterioration that began in the mid-Holocene, and persisted to the 19th century (Bradley, 1990; Fisher et al., 2006). However, spatial variations in the timing and magnitude of the response of proxy records to early Holocene warming demonstrate that significant local-scale factors modulated or amplified the effects of radative forcing across the western Arctic (Kaufman et al., 2004).

Sea ice is an important component of the climate system, modulating albedo and ocean stratification, including deep-water formation, as well as the exchange of latent heat and moisture between the ocean and atmosphere (Barry, 1989; Greatbatch et al., 1991; Charles and Fairbanks, 1992; Broecker, 1994; Smith et al., 2003). Dyke et al. (1996) demonstrated that fossils of the bowhead whale (*Balaena mysticetus*) provide the best available proxy of sea-ice history in the Canadian Arctic Archipelago (CAA), since the bowheads' annual migration reflects their preference for an ice-edge habitat. Previous studies have shown that reduced summer sea-ice conditions in the central CAA enabled bowhead whales to migrate well beyond their current range several times during the Holocene, with peak abundance occurring between 11 000 and 8500 ^{14}C years BP (12 800 to 9500 calendar years BP; Dyke and Morris, 1990; Dyke et al., 1996; Figs. 1 and 2). However, in the absence of early Holocene bowhead whale fossils from the northern CAA, it was inferred that pervasive summer sea ice persisted in the northern channels and adjacent Arctic Ocean throughout the interval of maximum postglacial warming.

This paper reports a bowhead whale from the northwest Queen Elizabeth Islands (QEI) and discusses its implications for early Holocene sea-ice conditions in the northern CAA (Fig. 2). Determining how sea ice responds to external forcing, particularly during intervals involving dramatically different forcing mechanisms (e.g., the Holocene thermal maximum), provides data to constrain general circulation model simulations of climatic conditions in the recent geological past. Although these simulations are not an analogue for present or near-future climate change, they do provide insight into long-term natural climate variability, and place observed trends of decreased Arctic Ocean sea-ice cover into a pre-anthropogenic context (de Vernal and Hillaire-Marcel, 2000; de Vernal et al., 2000; Miller et al., 2001; Meier et al., 2005, 2006; Fisher et al., 2006).

The culmination of the last glaciation in the northern CAA was characterized by the growth of the Innuitian Ice Sheet at ~19 000 ^{14}C years BP (Blake, 1992; Dyke et al., 2002; England et al., 2004, 2006; Fig. 3). During this time, ice divides spanning the central and eastern QEI supplied trunk glaciers that extended along the fiords and inter-island channels, terminating on the polar continental shelf. Deglaciation commenced ~11600 ^{14}C years BP, and by 10000 ^{14}C years BP, prominent marine embayments extending from the Arctic Ocean had evacuated the Innuitian Ice Sheet from the inter-island channels of the western QEI (Hodgson et al., 1994; Atkinson, 2003; England et al., 2006). After 9000 ^{14}C years BP, only island-based ice caps remained in the central and western QEI, although the Innuitian Ice Sheet remained contiguous between western Axel Heiberg Island and northwest Greenland (Lamoureux and England, 2000; Atkinson, 2003; England et al., 2004, 2006; Fig. 2). By 8500 ^{14}C years BP, the sea had penetrated the length of Nansen and Eureka sounds, culminating with ice-free conditions at the heads of tributary fiords at ~8000 ^{14}C years BP (Hodgson, 1985; Bednarski, 1998; Ó Cofaigh et al., 2000; England et al., 2004; Fig. 2).

SITE DESCRIPTION AND STRATIGRAPHIC SIGNIFICANCE

Atkinson and England (2004) radiocarbon dated a partial bowhead whale skull at 41 m above sea level (asl) along Hassel Sound, eastern Ellef Ringnes Island (78˚44′ N 100˚10′ W; Fig. 2). The original purpose of dating this sample was to determine the age of deglaciation and history of postglacial emergence of eastern Ellef Ringnes Island.

Using marine mammal remains to constrain emergence (relative sea level) curves assumes that the animal either died at the beach, or floated ashore after dying, beaching on a contemporaneous shoreline. However, the bowhead whale bones described by Atkinson and England (2004) are anomalously old compared with dated driftwood and marine shells collected from the same shoreline, suggesting that the animal either sank prior to being exposed by falling sea level, or experienced post-stranding redeposition, likely due to solifluction. The usefulness of this bowhead whale in reconstructing the postglacial emergence history of Ellef Ringnes Island was therefore limited, and Atkinson and England (2004) did not discuss these remains further.

The remains consist of a mandible and skull base, which enabled positive identification of the animal as *Balaena mysticetus*, since it is the only large Arctic whale. The bowhead exceeds the length of the other two Arctic whales, the narwhal (*Monodon monoceros*) and the beluga (*Delphinapterus leucas*), by more than 60%. The skull was disintegrated, and the mandible and skull base protruded from the surface of the low angle coastal slope (Fig. 4). Both bones extended below the active layer (~50 cm thick) and were embedded within ground ice. Because of the frozen substrate, it was not possible to excavate either bone completely, or to estimate the total number of bones present at the site. Samples were collected from the skull base, and after careful pretreatment by sectioning, a cube of dense subsurface bone was submitted for AMS radiocarbon dating. The radiocarbon age of this bowhead whale, reported without a marine reservoir correction, is 10370 ± 60 BP (11680 cal. BP; Atkinson and England, 2004). All ages subsequently cited in this paper are reported in radiocarbon years.

FIG. 4. Photograph of the partially excavated, disintegrated bowhead skull protruding from the coastal slope adjacent to Hassel Sound, east-central Ellef Ringnes Island. A hand tool is circled for scale.

PALAEOCLIMATIC SIGNIFICANCE AND DISCUSSION

Bowhead whales are adapted to an ice-edge habitat and range through open waters and areas of loose sea ice (30–50% cover; Dyke et al., 1996), so their migrations approximate the seasonal oscillation of the floe edge. The distribution and radiocarbon ages of bowhead whale fossils throughout the CAA demonstrate that between 11 and 8.5 ka BP, reduced summer sea-ice conditions enabled Davis Strait bowheads to range into the eastern and central channels bordering Baffin Bay, and Bering Sea bowheads to reach the western channels adjoining the Beaufort Sea (Figs. 1 and 5). Dyke et al. (1996) attributed these summer sea-ice minima to meltwater-driven outflows from the retreating Laurentide Ice Sheet, which may have cleared the inter-island channels of sea ice. Alternatively, Kaufman et al. (2004) suggested that increased early Holocene warming alone may have been responsible for reducing sea-ice cover in the central CAA.

The occurrence of a 10.4 ka BP bowhead whale in Hassel Sound (Fig. 2) suggests that the contemporaneous bowhead population ranged ~700 km farther north than previously reported (c.f., Dyke et al., 1996; Dyke and Savelle, 2001) and has direct implications for summer sea-ice conditions in the Arctic Ocean at the end of the last glaciation. Because of the configuration of the Innuitian Ice Sheet at 10 ka BP, Hassel Sound would not have been accessible to Davis Strait bowhead stocks via Baffin Bay (Fig. 5a). Therefore, if this whale originated from the Bering Sea stock, the most likely migration route into Hassel Sound would have been northward through Prince Gustaf Adolf Sea, or eastward from the Arctic Ocean (Figs. 2 and 5a). Alternatively, this whale may have migrated from a Spitsbergen stock via the

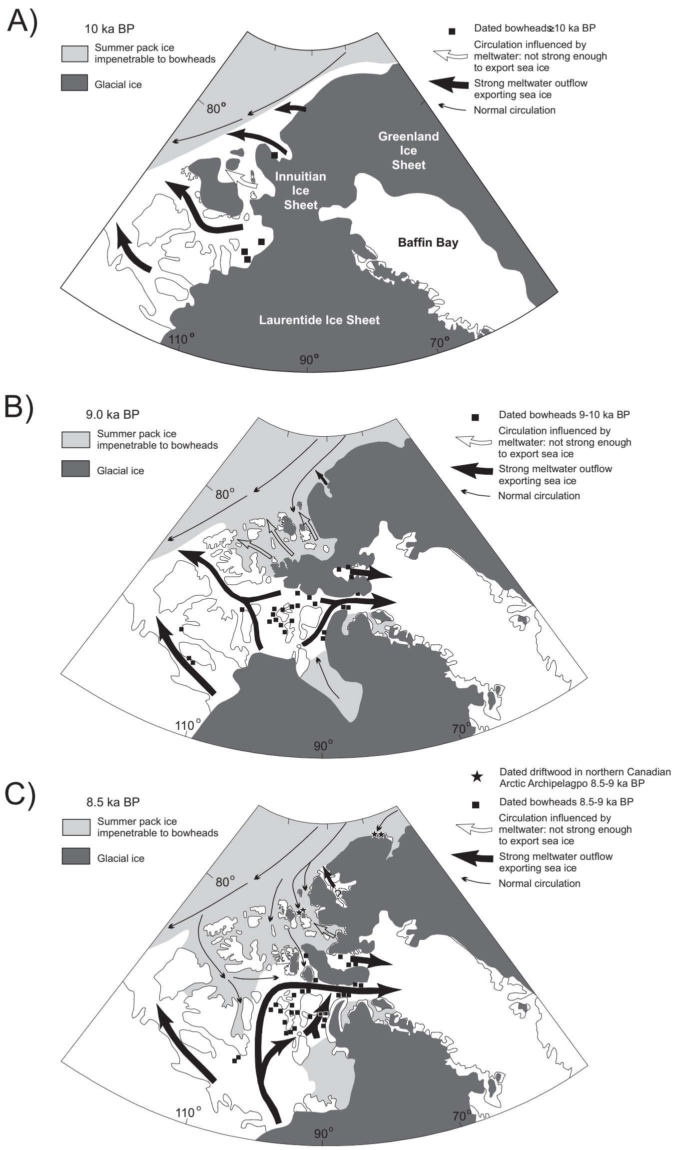

FIG. 5. Early Holocene paleogeographic reconstruction of the Canadian Arctic Archipelago, showing summer sea-ice distribution and ocean circulation patterns (modified from Dyke et al., 1996). Distribution of glacial ice is adapted from Dyke et al. (2002) and England et al. (2006).

Arctic Ocean, although the oldest whale skeleton currently reported on northern Greenland is 1.2 ka younger than the bowhead whale described in this paper (Vibe, 1967; Bennike, 1987; Bennike and Weidick, 2001). Nevertheless, glaciological evidence from northern Greenland suggests that prior to the inception of a local ice cap at ~7.2 ka BP, the Hans Tausen Plateau was ice-free during the early Holocene (Landvik et al., 2001; Fig. 1). Therefore, sea-ice extent north of Greenland may have been sufficiently diminished prior to 9.1 ka BP to enable Spitsbergen bowheads to migrate towards the QEI (c.f., Vibe, 1967). The occurrence of a bowhead whale in Hassel Sound, assuming the whale was alive when it entered the archipelago and regardless of the route it used, suggests that summer sea-ice conditions along the polar margin of the northern CAA may have been more open at the end of the last glaciation than previously recognized (cf., Dyke et al., 1996; Dyke and Savelle, 2001; Smith et al., 2003). Moreover, the likelihood that this migration occurred during an interval of reduced Arctic Ocean sea ice, rather than simply during one abnormally favorable year, is consistent with the stratigraphy of ice cores from the Agassiz Ice Cap, which contain melt-layers recording considerable warming between 10 and 9 ka BP (Koerner and Fisher, 1990; Fisher and Koerner, 2003).

Collectively, data presented in this paper suggest that following the incursion of bowhead whales into the northwest QEI before 10 ka BP, increased summer sea ice probably precluded their entry into the northern CAA (Figs. 5b and c). The archipelago remained beyond their range until ~4 ka BP, when stray whales occasionally reached polynyas from Baffin Bay, and foraged along coastal leads before being trapped during freeze-up (Dyke and England, 2003). To date, the only other early Holocene bowhead whale reported in the northern CAA occurs on northeast Axel Heiberg Island, adjacent to Nansen Sound, and dates to 7.5 ka BP (Bednarski, 1990; Fig. 2). However, Dyke et al. (1996) cautioned against any paleoenvironmental significance of this skeleton, since an incursion at this time would have coincided with an interval of widespread bowhead exclusion from the central CAA, concomitant with the regional climatic deterioration (Bradley, 1990; Fisher and Koerner, 2003). Instead, Dyke et al. (1996) suggested that the presence of the skeleton may have been the result of a brief interval of exceptional sea-ice clearance, or possibly the stranding of a far-drifted corpse frozen in sea ice.

Variations in Arctic Ocean sea-ice conditions have also been inferred from changes in the abundance of driftwood entering the Canadian Arctic Archipelago, with intervals of abundant driftwood being attributed to more open water (Häggblom, 1982; Stewart and England, 1983). However, Dyke and Morris (1990) remarked that spatial and temporal variations in the abundance and distribution of driftwood may not be a reliable paleoclimatic indicator, since driftwood penetration into the central Arctic reached a maximum during the Neoglacial (last 3000 years), when summers were colder and bowhead abundance declined. Dyke and Morris (1990) therefore suggested that long-distance transport of driftwood to the CAA depends on sea ice, as rafting prevents the wood from becoming saturated and sinking offshore.

Despite zoological evidence of open water in the Arctic Ocean at 10 ka BP, driftwood did not enter the northern CAA for another 1000 years, as indicated by the oldest dated samples collected along the northern coasts of Ellesmere Island and Amund Ringnes Island (Stewart and England, 1983; Bednarski, 1986; Atkinson and England, 2004; Fig. 5c). The lag between bowhead whale incursion into the northern CAA and driftwood delivery from the Arctic Ocean is significant, because it may have occurred during an interval when the Arctic Oscillation was in a positive phase (Kaufman et al., 2004). The Arctic Oscillation refers to opposing mid- to high-latitude atmospheric pressure patterns. The positive phase of this oscillation is characterized by decreased sea-level pressure over the pole and strengthened cyclonic circulation in the Arctic Ocean. These conditions result in fresh water and sea ice being forced through Fram Strait and the CAA (Rigor et al., 2002; Kaufman et al., 2004; Fig. 1). Nevertheless, it seems that the polar margin of the northern CAA was characterized by open water and restricted driftwood penetration between 10 and 9 ka BP, despite the potential for increased sea-ice severity associated with these circulation patterns.

Lags between bowhead whale and driftwood arrival have been described elsewhere in the region and have been used to infer that large-scale disruptions of sea ice were caused by changing meltwater flux as ocean circulation switched from a glacial to an interglacial mode in response to the retreat of the Laurentide Ice Sheet from the inter-island channels of the central and southern CAA (Dyke and Morris, 1990; Dyke et al., 1996; Fig. 5). Similarly, the lag between bowhead whale and driftwood arrival in the northwest QEI corresponds to the interval between the onset of rapid deglaciation of the marine-based sector of the Innuitian Ice Sheet at 10 ka BP or earlier, and its slower retreat along land-based margins after 9 ka BP (England et al., 2006; Fig. 5a and b). This asynchronicity suggests that from ~10 to 9 ka BP, meltwater from the Innuitian Ice Sheet provided an outflow from the northwest QEI that exported sea ice from the inter-island channels and enabled bowhead entry into Hassel Sound, while preventing the influx of driftwood to adjacent coastlines. However, there are currently no contemporaneous bowhead whale remains reported in the westernmost QEI, even though the southeastern Beaufort Sea contained a relatively large population of early Holocene bowhead whales (c.f., Dyke and Savelle, 2001). This absence of remains may reflect limited ground traversing in the western QEI, which to date has been mapped mostly at a reconnaissance scale (c.f., Hodgson, 1982). Alternatively, because this region may have been covered by relatively thin ice along the periphery of the Innuitian Ice Sheet, or by local, island-based ice caps at the end of the last glaciation (England et al., 2006; Fig. 3), meltwater outflows may have been insufficient to drive sea ice from the channels, preventing the entry of bowheads from the southeastern Beaufort Sea to the western QEI.

The arrival of driftwood into the northwest QEI at 9 ka BP coincides with the stabilization of residual ice caps, which may not have been able to sustain sufficient meltwater-driven outflows to keep the channels clear of sea ice. Consequently, the influx of driftwood into the northernmost channels at 9 ka BP may signal the arrival of loose sea ice from the Arctic Ocean due to the establishment of contemporary surface water circulation patterns (c.f., Dyke and Morris, 1990). This reconstruction supports the "meltwater drive" hypothesis proposed by Dyke and Morris (1990). Despite evidence that driftwood was received and transported by the Arctic Ocean during this interval, its near absence in the Norwegian Bay region between 8 and 7 ka BP indicates the presence of largely permanent and immobile landfast sea ice (Stewart and England, 1983; Dyke et al., 1996, 1997; Dyke and England, 2003; Atkinson and England, 2004; Figs. 2 and 5c).

CONCLUSIONS

Sea-ice conditions in the northern CAA inferred from bowhead whale remains in Hassel Sound suggest that an interval of reduced Arctic Ocean summer sea ice coincided with the initial retreat of the Innuitian Ice Sheet by approximately 10 ka BP. However, the congruity between the stabilization of residual ice masses and the arrival of driftwood at 9 ka BP suggests that diminished meltwater-driven outflows enabled the establishment of modern ocean circulation patterns that imported sea ice from the Arctic Ocean into the northern CAA. The subsequent exclusion of driftwood from the central channels signals worsening sea-ice conditions, which persisted into the mid Holocene. These data suggest that the reduction in summer sea-ice extent in the northern CAA was significantly amplified by outflows from the Innuitian Ice Sheet. Sea-ice severity evidently increased immediately after the widespread retreat of the Innuitian Ice Sheet, even though this was an interval of continued Holocene warmth elsewhere in the Canadian Arctic (Kaufman et al., 2004). Therefore, the influence of meltwater from the Innuitian Ice Sheet in reducing early Holocene sea-ice extent in the northern Canadian Arctic Archipelago and adjacent Arctic Ocean was more significant than previously recognized, and radiative warming alone is insufficient to explain these paleodata (Dyke and Morris, 1990; Kaufman et al., 2004). Moreover, within the context of the last 10 ka BP, the currently observed reduction in sea-ice extent is occurring without the amplifying effects of "meltwater drive" from the Canadian Arctic Archipelago, suggesting that current forcing mechanisms are exerting a greater influence than those that contributed to sea-ice reduction during the early Holocene.

ACKNOWLEDGEMENTS

Financial support for this research was generously provided by Dr. John England (University of Alberta), through Natural Sciences and Engineering Research Council of Canada funding, and the Circumpolar Institute, University of Alberta. Additional support by the Harington Paleoenvironmental Scholarship is gratefully acknowledged. Logistical support was provided by the Polar Continental Shelf Project, Natural Resources Canada. Particular thanks to Lachlan MacLean, whose keen eye helped relocate the whale bone during a snowstorm. I am grateful for the informal review of Dr. Gabriel Wolken (University of Alberta). The formal reviews of Dr. J. Bednarski (GSC, Pacific, Victoria, British Columbia), Dr. A.S. Dyke (GSC, Ottawa), and Dr. C.R. Harington (Canadian Museum of Nature, Ottawa) provided additional clarification and are much appreciated.

REFERENCES

Atkinson, N. 2003. Late Wisconsinan glaciation of Amund and Ellef Ringnes islands, Nunavut: Evidence for the configuration, dynamics and deglacial chronology of the northwest sector of the Innuitian Ice Sheet. Canadian Journal of Earth Sciences 40:351–363.

Atkinson, N., and England, J. 2004. Postglacial emergence of Amund and Ellef Ringnes islands, Nunavut: Implications for the northwest sector of the Innuitian Ice Sheet. Canadian Journal of Earth Sciences 41:271–283.

Barry, R.G. 1989. The present climate of the Arctic Ocean and possible past and future states. In: Herman, Y., ed. The Arctic seas: Climatology, oceanography, geology, and biology. New York: Van Nostrand Reinhold Company. 1–46.

Bednarski, J. 1986. Late Quaternary glacial and sea-level events, Clements Markham Inlet, northern Ellesmere Island, Arctic Canada. Canadian Journal of Earth Sciences 23:1343–1355.

———. 1990. An early Holocene bowhead whale (*Balaena mysticetus*) in Nansen Sound, Canadian Arctic Archipelago. Arctic 43:50–54.

———. 1998. Quaternary history of Axel Heiberg Island, bordering Nansen Sound, Northwest Territories, emphasizing the last glacial maximum. Canadian Journal of Earth Sciences 35:520–533.

Bennike, O. 1987. Quaternary geology and biology of the Jørgen Brønlund Fjord area, North Greenland. Meddelelser om Grønland, Geoscience 18. 23 p.

Bennike, O., and Weidick, A. 2001. Late Quaternary history around Nioghalvfjerdsfjorden and Jøkelbugten, North-East Greenland. Boreas 30:205–227.

Berger, A. 1988. Milankovitch theory and climate. Reviews of Geophysics 26:624–657.

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

Blake, W., Jr. 1992. Holocene emergence at Cape Herschel, east-central Ellesmere Island, Arctic Canada: Implications for ice sheet configuration. Canadian Journal of Earth Sciences 29:1958–1980.

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

Broecker, W.S. 1994. Massive iceberg discharge as triggers for global climate change. Nature 372:421–424.

Charles, C.D., and Fairbanks, R.G. 1992. Evidence from Southern Ocean sediments for the effect of North-Atlantic deep-water flux on climate. Nature 355:416–419.

De Vernal, A., and Hillaire-Marcel, C. 2000. Sea-ice cover, sea-surface salinity and halo- /thermocline structure of the northwest North Atlantic: Modern versus full glacial conditions. Quaternary Science Reviews 19:65–85, doi:10.1016/S0277-3791(99)00055-4.

De Vernal, A., Hillaire-Marcel, C., Turon, J.L., and Matthiessen, J. 2000. Reconstruction of sea-surface temperature, salinity, and sea-ice cover in the northern North Atlantic during the last glacial maximum based on dinocyst assemblages. Canadian Journal of Earth Sciences 37:725–750.

Dyke, A.S., and England, J. 2003. Canada's most northerly postglacial bowhead whales (*Balaena mysticetus*): Holocene sea-ice conditions and polynya development. Arctic 56:14–20.

Dyke, A.S., and Morris, T.F. 1990. Postglacial history of the bowhead whale and of driftwood penetration: Implications for paleoclimate, central Canadian Arctic. Geological Survey of Canada, Paper 89-24.

Dyke, A.S., and Savelle, J.M. 2001. Holocene history of the Bering Sea bowhead whale (*Balaena mysticetus*) in its Beaufort Sea summer grounds off southwestern Victoria Island, western Canadian Arctic. Quaternary Research 55:371–379.

Dyke, A.S., Hooper, J., and Savelle, J. 1996. A history of sea ice in the Canadian Arctic Archipelago based on postglacial remains of the bowhead whale (*Balaena mysticetus*). Arctic 49: 235–255.

Dyke, A.S., England, J., Reimnitz, E., and Jetté, H. 1997. Changes in driftwood delivery to the Canadian Arctic Archipelago: The hypothesis of postglacial oscillations of the Transpolar Drift. Arctic 50:1–16.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., and Veillette, J.J. 2002. The Laurentide and Innuitian ice sheets during the Last Glacial Maximum. Quaternary Science Reviews 21:9–31.

England, J., Atkinson, N., Dyke, A.S., Evans, D.J.A., and Zreda, M. 2004. Late Wisconsinan buildup and wastage of the Innuitian Ice Sheet across southern Ellesmere Island, Nunavut: Dominance of the Greenland Ice Sheet. Canadian Journal of Earth Sciences 41:39–61.

England, J., Atkinson, N., Bednarski, J., Dyke, A.S., Hodgson, D.A., and Ó Cofaigh, C. 2006. The Innuitian Ice Sheet: Configuration, dynamics and chronology. Quaternary Science Reviews 25:689–703, doi:10.1016/j.quascirev.2005.08.007.

Fisher, D.A., and Koerner, R.M. 2003. Holocene ice core climate history: A multivariable approach. In: Mackay, A., Batterbee, R., Birks, J., and Oldfield, F., eds. Global change in the Holocene. London: Arnold. 281–293.

Fisher, D.A., Dyke, A.S., Koerner, R.M., Bourgeois, J., Kinnard, C., Zdanowicz, C., De Vernal, A., Hillaire-Marcel, C., Savelle, J.M., and Rochon, A. 2006. Natural variability of Arctic sea ice over the Holocene. EOS 87:273–280.

Greatbatch, R.J., Fanning, A.F., Goulding, A.D., and Levitus, S. 1991. A diagnosis of interpentadal circulation changes in the North Atlantic. Journal of Geophysical Research 96(C12):22009–22023.

Häggblom, A. 1982. Driftwood in Svalbard as an indicator of sea ice conditions. Geografisker Annaler 64A:81–94.

Hodgson, D.A. 1982. Surficial materials and geomorphological processes, western Sverdrup and adjacent islands, District of Franklin. Geological Survey of Canada, Paper 81-9.

———. 1985. The last glaciation of west-central Ellesmere Island, Arctic Archipelago, Canada. Canadian Journal of Earth Sciences 22:347–368.

Hodgson, D.A., Taylor, R.B., and Fyles, J.G. 1994. Late Quaternary sea level changes on Brock and Prince Patrick islands, western

Canadian Arctic Archipelago. Géographie physique et Quaternaire 48:69–84.

Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., et al. 2004. Holocene thermal maximum in the western Arctic (0–180˚W). Quaternary Science Reviews 23:529–560, doi:10.1016/j.quascirev.2003.09.007.

Koerner, R.M., and Fisher, D.A. 1990. A record of Holocene summer climate from a Canadian High-Arctic ice core. Nature 343:630–631, doi:10.1038/343630a0.

Lamoureux, S.F., and England, J.H. 2000. Late Wisconsinan of the central sector of the Canadian High Arctic. Quaternary Research 54:182–188.

Landvik, J.Y., Weidick, A., and Hansen, A. 2001. The glacial history of the Hans Tausen Iskappe and the last glaciation of Peary Land, North Greenland. In: Hammer, C.U., ed. Hans Tausen Ice Cap. Glaciology and glacial geology. Meddelelser om Grønland, Geoscience 39:27–44.

Meier, W.N., Stroeve, J.C., Fetterer, F., and Knowles, K. 2005. Reductions in Arctic sea ice cover no longer limited to summer. EOS 86:326–327.

Meier, W.N., Stroeve, J.C., and Fetterer, F. 2006. Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record. Annals of Glaciology 46:428–434.

Miller, G.H., Geirsdottir, Á., and Koerner, R.M. 2001. Climate implications of changing Arctic Ocean Sea Ice. EOS 82: 97–103.

Ó Cofaigh, C., England, J., and Zreda, M. 2000. Late Wisconsinan glaciation of southern Eureka Sound: Evidence for extensive Innuitian ice in the Canadian High Arctic during the Last Glacial Maximum. Quaternary Science Reviews 19: 1319–1341, doi:10.1016/S0277-3791(99)00104-3.

Rigor, I.G., Wallace, J.M., and Colony, R.L. 2002. Response of sea-ice to the Arctic Oscillation. Journal of Climate 15: 2648–2663.

Smith, L.M., Miller, G.H., Otto-Bliesner, B., and Shin, S.-I. 2003. Sensitivity of the Northern Hemisphere climate system to extreme changes in Holocene Arctic sea ice. Quaternary Science Reviews 22:645–658, doi:10.1016/S0277-3791(02)00166-X.

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

Vibe, C. 1967. Arctic animals in relation to climatic fluctuations. Meddelelser om Grønland 170(5):1–227.