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Holocene sea-ice variations in Greenland: onshore evidence

Ole Bennike*

(Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark)

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Abstract: The oldest dated driftwood log from northern Greenland is *c.* 9300 cal. years old, which is about 2000 years younger than the beginning of the last deglaciation and 2000 years younger than the oldest driftwood on Svalbard. Driftwood entry to northern Greenland was rare until 7400 cal. years BP, indicating more severe summer sea-ice conditions than at present. More open water than at present probably characterized the period between 6800 and 5500 cal. years BP, during which time driftwood stranded on the beaches of Nioghalvfjerdsfjorden that is now covered by a floating glacier. In central East Greenland, the occurrence of the extralimital species *Mytilus edulis* in the time interval from *c.* 8500 to 6000 cal. years BP indicates more open water than at present, and in northwest Greenland studies of dinoflagellate cysts in a marine core indicate warmer surface waters, and hence less sea ice than at present from 7300 to 3700 cal. years BP.

Key words: Palaeoclimate, sea ice, driftwood, Greenland, Arctic, Holocene, climate optimum.

Introduction

There is growing concern that a marked decrease in the thickness and extent of sea ice in the Arctic region has occurred over the last decades (Johannesen *et al.*, 1999). Sea ice plays an important role in the climatic system, through its effect on albedo. A sea covered by ice reflects 80–90% of the incoming solar radiation, whereas an open sea only reflects about 10%. Thus, if global warming leads to shrinking sea ice, this would lead to increasing absorption of heat, and the extent of sea ice would be a powerful feedback mechanism. Therefore the extent of sea ice cover plays a major role in climate models, and information on past sea-ice variations is important for model validation (Miller *et al.*, 2001). However, obtaining information on past sea-ice variations has proved difficult. Data can be obtained from marine sediment cores raised from the sea bottom. Such cores can provide a continuous record, and skeletal or chemical remains of photosynthesizing organisms, such as dinoflagellates and diatoms, may provide a proxy for sea ice. However, so far only a single study has been conducted in Greenland waters (Levac *et al.*, 2001).

Another approach that will be explored here is to see what we can learn from the onshore record. In Greenland, where the glacio-isostatic uplift after the last deglaciation has surpassed the eustatic sea-level rise, raised beaches, deltas and marine deposits are fairly widespread. Driftwood or dead whales that stranded on the areas below the marine limit were lifted up together with the land and are now found above the shore. The same applies to remains of marine invertebrates, especially shells of molluscs that lived in the littoral or sublittoral zones.

This paper presents a compilation and discussion of radiocarbon dated driftwood from raised beaches in Greenland, mainly from the northern parts, and also discusses evidence from whale bones and invertebrates remains from raised marine deposits. Unfortunately the spatial and temporal coverage is rather uneven. In other parts of the Arctic, variations in the amount of driftwood and remains of the Greenland whale on raised beaches have been used as indicators of changes in sea-ice extent by, for example, Blake (1972), Häggblom (1982), Evans and England (1992) and Dyke *et al.* (1996; 1997), and shells of *Mytilus edulis* and other invertebrates have been used for reconstructions of past changes in climatic and oceanographic conditions (e.g., Andrews *et al.*, 1981; Salvigsen *et al.*, 1992; Hjort *et al.*, 1995).

In Greenland, driftwood on raised beaches was first reported from Hall Land in western North Greenland as a result of the United States North Polar Expedition (Bessels, 1879). Later reports on Holocene driftwood also come from North Greenland, as a result of Danish and US expeditions. Radiocarbon dates on sampled wood from North Greenland have been published in various dating lists (Preston *et al.*, 1955; Tauber, 1960; 1964; 1966; Ives *et al.*, 1964; Trautman and Willis, 1966; Weidick, 1972a; 1977), and the implication with respect to the sea-ice conditions that the former hunter cultures of the area faced and implications with respect to land uplift and glacial geology has been discussed by archaeologists and Quaternary geologists (e.g., Knuth, 1967; Weidick, 1972b).

*Author for correspondence (e-mail: obe@geus.dk)

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In addition, modern driftwood from Greenland beaches has received some attention. Studies have been performed on anatomical identification of wood, on growth ring measurements and the provenance of a few driftwood logs has been established from dendrochronological investigations (e.g., Ingvarson, 1903; Eggertsson, 1994b).

The first reports on whale bones from Holocene deposits in Greenland were published in the early part of the last century (Freuchen, 1915; Koch, 1916). At present, there are 21 radiocarbon dates on whale remains from non-archaeological contexts from Greenland (Bennike, 1997; Hjort, 1997; Bennike and Weidick, 2001). The first reports on southern extralimital molluscs also came from the early part of the last century (Nathorst, 1901; Engell, 1905; Jensen, 1905). The temporal range of thermophilous invertebrates and their palaeoclimatic implications in Greenland have been discussed most recently by Hjort and Funder (1974), Funder and Weidick (1991) and Bennike *et al.* (2000).

Modern currents and sea-ice distribution

The pattern of surface ocean currents plays an important role in the distribution of sea ice around Greenland (Figures 1 and 2). The West Greenland Current brings relatively warm water northwards along West Greenland, all the way up to Thule, although its effect decreases towards the north. Thus, in southern West Greenland the ports are open all year, whereas in the Thule area the ports are only navigable for a few months during the summer. The East Greenland Current brings cold water laden with sea ice from the Arctic Ocean southwards along East Greenland. In the far south, this current rounds the southern tip of Greenland and continues up along West Greenland, where its effect can be followed for some 100 km. The effect of the East Greenland Current diminishes within the fjords of East and South Greenland. In summer, once you have crossed the pack-ice belt, you will find more or less open fjords (Koch, 1945), and the fjords in central East Greenland are typically open for a few months each year.

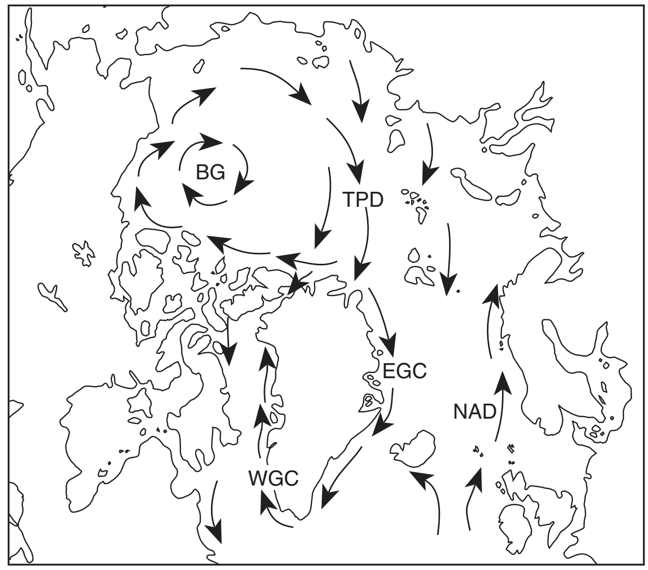

Figure 1 Map of the Earth's northern parts, showing generalized oceanographic surface currents. BG-Beaufort Gyre; TPD-Transpolar Drift; WGC-West Greenland Current; EGC-East Greenland Current; NAD-North Atlantic Drift.

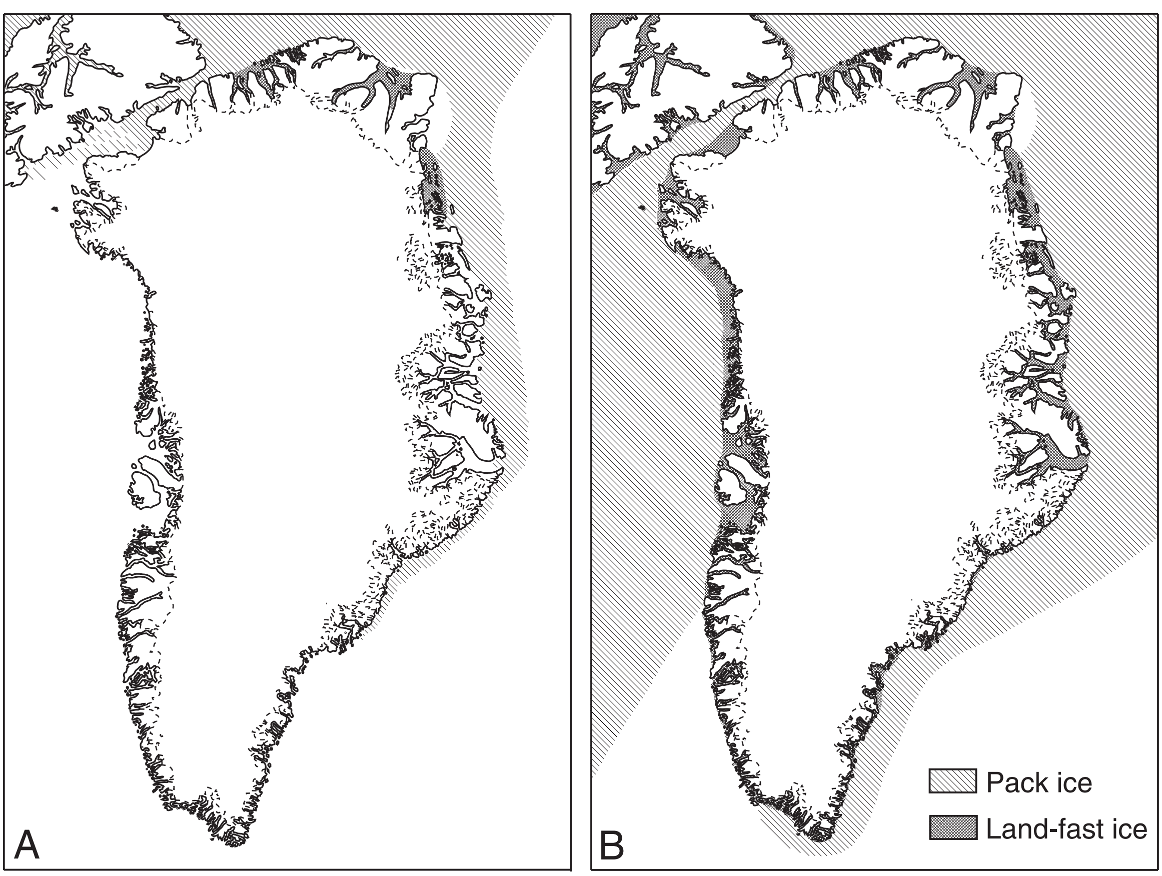

Figure 2 (A) Map of Greenland showing present-day minimum summer sea-ice extent, partly based on aerial photographs. (B) Winter maximum sea-ice distribution. These figures show generalized patterns; obviously there are large variations from year to year.

The upper, fresher and warmer water masses of the fjords are termed the fjord water, and the extent and thickness of this is controlled by the warmth of the summer.

In the Arctic Ocean, the Transpolar Drift carries sea ice from Siberia and the central parts of the Arctic Ocean towards Fram Strait, Svalbard and North Greenland. This leads to very thick, perennial pack ice in the area north of Greenland. In the Nares Strait between Ellesmere Island and Greenland, the surface currents normally go south. In central North Greenland, the fjords facing the Arctic Ocean are covered by perennial fast sea ice, and only a narrow lead develops between the land-fast fjord ice and the pack ice in the ocean. In eastern North Greenland, those fjords that receive large inputs of meltwater are open for about one month, at least in their inner parts. The lead between the fjord ice and the pack ice may become rather wide in this region, and in some years also the outer parts of the fjords become more or less ice-free (Koch, 1945).

The proxies

Driftwood

Driftwood can float on an open ocean for about one year before it becomes waterlogged and sinks. Since the journey across the Arctic Ocean to Greenland lasts about 4–5 years, driftwood depends on sea ice as a transporting agency (Häggblom, 1982). However, the coastal zone and the beach must be ice-free to allow the driftwood to strand on arrival in the coastal waters. There are marked regional differences in the distribution of driftwood on the beaches of North Greenland. In central North Greenland, where perennial sea ice is found at present, driftwood is extremely rare. Thus, during a two-month field season in this region only 10 driftwood pieces were spotted on modern and raised beaches (Kelly and Bennike, 1992). Driftwood is most common along fjords that are orientated towards the east or northeast, and which regularly become ice-free. This applies to Danmark Fjord, Jørgen Brønlund Fjord and Frederick E. Hyde Fjord (Figure 3), but the local distribution is also governed by local currents. Driftwood is nowhere in Greenland anywhere as common as on Svalbard, Jan Mayen or the Mackenzie Delta (e.g., Eggertsson, 1994a; Johansen, 1998).

Raised beaches

In areas with perennial sea ice, beaches rarely form. The presence of systems of raised beaches in some areas shows that open water was present in the past, at least for some time during the summer. Unfortunately, scarcity of datable material on these beaches often precludes that a good chronology can be established.

Marine mammals

The Greenland right whale *Balaena mysticetus* is the larger whale species best adapted to sea ice, but it cannot live in areas of perennial sea ice. This whale lives in the pack ice, and follows the sea ice margin as it changes during the year. After dying, the carcass can float for a long time before it sinks, which means that the probability that a dead whale will become stranded is rather large. Remains of other whales less adapted to sea ice have also been reported. Among the seals that occur in Greenland waters, the ringed seal *Phoca hispida* is best adapted to sea ice, and it even lives in areas of perennial sea ice, where it can maintain breathing holes in ice up to 2.5 m thick. This is the only marine mammal that is found in central North Greenland.

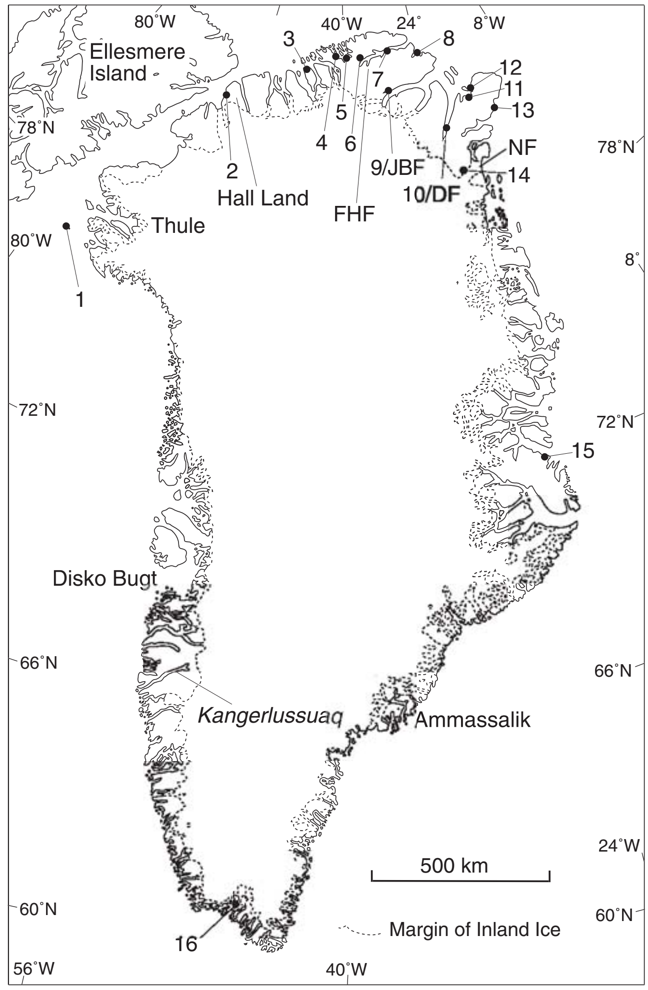

Figure 3 Map of Greenland showing localities with dated driftwood (Table 1), and the location of place names mentioned in the text. FHF-Frederick E. Hyde Fjord; JBF-Jørgen Brønlund Fjord; DF-Danmark Fjord; NF-Nioghalvfjerdsfjorden.

Marine invertebrates

Among the marine invertebrates the common blue mussel *Mytilus edulis* lives in shallow water, from the tidal zone and down to a few metres depth. Its modern geographical range in Greenland comprises the west coast up to Thule at *c.* 77°N, and the east coast up to Ammasalik at *c.* 66°N (Funder, 1989). This large latitudinal difference in the northern limit reflects the influence of the West Greenland Current that brings relatively warm water up along the west coast of Greenland, and the East Greenland Current that brings cold water down along the east coast of Greenland (Figure 1). The main factor that controls the northern limit is probably the length of the ice-free period.

Another intertidal invertebrate, the barnacle *Balanus balanoides*, has a northern range limit somewhat to the south of that of *M. edulis* (Funder, 1990), but this species is rarely found as a fossil (Bennike *et al.*, 2000).

The presence of the sublittoral barnacles *Balanus hammeri* and *Balanus crenatus* can also be used as an indication of warm water masses (Bennike *et al.*, 2000), and the same applies to some sublittoral molluscs (Funder and Weidick, 1991). However, two of the bivalve species that are known from raised marine Holocene deposits in West Greenland and which have long been considered extinct in Greenland waters appear to still live in West Greenland. *Zirphaea crispata* was first documented as a fossil from the Disko Bugt area (Engell, 1905; Jensen, 1905), but an extant population was found some years ago (Bennike, 2000). *Panopea norvegica*, which was first found as a fossil near Kangerlussuaq (Jensen, 1942), has also been considered extinct, but the presence of shells of the species in a Norse ruin shows that it lived in the region long after the Holocene thermal maximum, and indicates that it still lives in West Greenland (McGovern *et al.*, 1983). Both bivalve species live deep below the sediment/water interface, and are hence underrepresented by normal sampling of modern faunas.

Methods

Wood samples were identified from their anatomical structure as seen in tangential, radial and cross sections. *Larix* and *Picea* wood are very similar, and were distinguished by the features listed by Bennike (1990). No attempt at using dendrochronological methods was made, because the available chronologies from the far north only go back some centuries, which is not relevant for this study.

Radiocarbon dates on driftwood have been normalized for isotopic fractionation by normalizing to −25‰ on the PDB scale, or no normalization has been applied. Radiocarbon dates on marine shells and bones have been corrected for the seawater reservoir effect by subtracting 400 years (West Greenland) or 550 years (East and North Greenland). Further details are provided by Bennike *et al.* (1994) and Bennike (1997). The radiocarbon dates have been calibrated using the INTCAL98 data set (Stuiver *et al.*, 1998).

Results

Northern Greenland

About 70% of the driftwood found on raised beaches in northern Greenland belong to the genus *Larix*. This implies that Siberia is the main source for driftwood in North Greenland, since the northern forests in Siberia are dominated by *Larix*, in contrast to North America where *Picea* dominates. Wood from Siberia is transported to Greenland by the Transpolar Drift. Some Greenland driftwood come from North America (Eggertsson, 1994b), and this must have travelled in part via the Beaufort Gyre (Figure 1). In addition to *Larix* and *Picea*, a few specimens of *Populus* sp. and *Pinus sylvestris* type have been found on raised beaches in Greenland.

The oldest dated driftwood log from northern Greenland is *c*. 9300 cal. years old (S-2313, Table 1, England, 1985). Driftwood stranding in northern Greenland continued to be rare until 7400 cal. years BP. At around 7400 cal. years BP, an increase in the occurrence of driftwood is seen, which is followed by a peak from 7100 to 6500 cal. years BP (Figure 4). A new sudden spike is seen at 5700 to 5500 cal. years BP. Finally, the rarity of dates younger than 4500 cal. years BP probably reflects that only few driftwood pieces from low-lying raised beaches have been dated. Driftwood is not rare on such beaches in eastern North Greenland (Bennike, 1987).

Nioghalvfjerdsfjorden, which is presently covered by a floating glacier, was glacier-free between 7700 and 4500 cal. years BP (Bennike and Weidick, 2001). However, dated driftwood pieces from the fjord are confined to the period between 6800 and 5500 cal. years BP, which was presumably the time period with most open water during the summer in this region.

Central East Greenland

From central East Greenland, only four dates on driftwood pieces have been published (Washburn and Stuiver, 1962). The best onshore evidence for conditions with a longer ice-free period than at present are shells of *Mytilus edulis* in raised marine and littoral deposits. Assemblages with *M. edulis* are dated to the time interval from *c*. 8500 to 6000 cal. years BP (Hjort and Funder, 1974). Another bivalve species, *Chlamys islandica*, was apparently more widespread in East Greenland than at present, and it has been taken as an indication of warmer waters during the time from 9500 to 6300 cal. years BP (Hjort and Funder, 1974).

Western and southern Greenland

Driftwood is rather common on modern beaches in West Greenland, although large geographical variations are seen. However, driftwood pieces do not survive for long on the ground surface in the Subarctic, humid climate of West and South Greenland. Only if driftwood pieces become buried can they survive for millennia. Only a single radiocarbon date has been reported (Table 1, I-7664; Figure 4). This is also the oldest dated driftwood sample from Greenland, and it shows that local sea-ice conditions allowed driftwood to strand in southern Greenland already at around 10 600 cal. years BP.

During the earliest Holocene, when the margin of the Inland Ice was situated near the outer coast, cold, turbid rather fresh water and heavy sea ice may have characterized the near-shore waters. When the outer coastal areas had become deglaciated, Subarctic invertebrates could immigrate. The first influence of the West Greenland Current is registered in marine faunas around 1300 years after the beginning of the Holocene, at *c*. 10 200 cal. years BP, from which time the oldest radiocarbon dates on the Subarctic species *Mytilus edulis*, *Balanus crenatus* and *Balanus hammeri* have been obtained (Funder, 1990; Bennike *et al.*, 2000). The presence of *M. edulis* at Thule this early, near its present northern limit in West Greenland, would indicate that sea-ice conditions were similar to the present. Further strengthening of the West Greenland Current is indicated by the appearance of boreal molluscs, for which the oldest available dates are *c*. 9200 cal. years BP (Funder and Weidick, 1991). The northernmost influence of the West Greenland Current is seen in Washington Land, from where a single find of *Chlamys islandica* is dated to *c*. 7300 cal. years BP (Bennike, 2002). The youngest dates on boreal molluscs are around 5600 cal. years BP (Funder and Weidick, 1991), but this may reflect the age of the youngest raised marine deposits in West Greenland rather than the local disappearance of these species.

On the basis of studies of dinoflagellate cysts from a sediment core off northwest Greenland, Levac *et al.* (2001) concluded that warmer conditions than at present characterized the time period from 7300 to 3700 cal. years BP.

Discussion

The oldest dated driftwood log from northern Greenland is *c*. 9300 cal. years old, which is about 2000 years younger than the oldest driftwood on Svalbard (Figure 4). At several sites in northern Greenland, attempts have been made to locate older driftwood, but so far without success. The Svalbard record shows that driftwood was present in the Arctic Ocean, but apparently it was prohibited from reaching the coasts of northern Greenland. Large parts of the region had become deglaciated during the first millennia of the Holocene (Bennike and Björck, 2002), so this is not the reason for the lack of driftwood. However, deglaciation of the inner fjords was still going on, and it is possible that the production of calf ice was larger than at present. If so, more sea ice may also have been present in the summertime, which would prevent driftwood entry. No whale remains from northern Greenland have yielded earliest-Holocene ages, but whale remains are rare (Bennike,

Table 1 Radiocarbon dates of Holocene driftwood from Greenland[1]

Age (^{14}C years BP)	Calibrated age ± 1 stdv., BP[2]	Lab. no.	Loc. no.[3]	Material	Height (m a.s.l.)	N. lat.	W. long.	Reference
6220 ± 70	7000–7250	GSC-2446	1	*Picea* sp.	20	76°43′	73°11.5′	Blake, 1987
8295 ± 120	9030–9470	S-2313	2	wood	56	81°35′	60°55′	England, 1985
4470 ± 90	4880–5300	K-7089	3	*Larix* sp.	16	82°04.2′	47°34′	This study
7400 ± 100	8050–8340	K-7090	4	*Picea* sp.	44	82°04.2′	47°34′	This study
5470 ± 100	6130–6390	T-11775	5	?*Larix* sp.	13	82°59′	36°41′	Landvik *et al.*, 2001
5855 ± 50	6570–6730	T-11770	6	*Picea* sp.	24	82°54′	36°09′	Landvik *et al.*, 2001
1935 ± 90	1740–1990	I-5591	7	*Picea* sp.	4.2	83°05′	32°15′	Weidick, 1972a
4645 ± 115	5090–5580	I-5592	7	*Picea* sp.	15.1	83°05′	32°15′	Weidick, 1972a
4815 ± 115	5330–5650	I-5593	7	*Larix* sp.	18.5	83°05′	32°15′	Weidick, 1972a
2580 ± 150	2360–2840	I-307	8	wood	8	82°53′	24°05′	Trautman and Willis, 1966
3450 ± 90	3590–3830	I-9119	9	wood	11–12	82°08′	31°21′	Weidick, 1977
3585 ± 100	3720–4070	I-9129	9	wood	11–12	82°08′	31°21′	Weidick, 1977
4790 ± 75	5470–5600	K-7085	9	*Picea* sp.	22	82°09.6′	29°45′	This study
4810 ± 95	5470–5610	K-7083	9	*Populus* sp.	21	82°09′	29°46′	This study
4970 ± 260	5330–6000	W-1073	9	wood	11	82°10′	29°50′	Ives *et al.*, 1964
5350 ± 100	5950–6280	K-7086	9	*Larix* sp.	19.7	82°10.8′	30°07′	This study
5870 ± 100	6550–6790	Y-19	9	wood	?	82°10′	30°30′	Preston *et al.*, 1955
6500 ± 105	7310–7550	K-7084	9	*Larix* sp.	38	82°09.6′	29°45′	This study
3375 ± 150	3450–3830	I-313	10	wood	*c.* 8	80°31′	23°30′	Trautman and Willis, 1966
4860 ± 150	5330–5740	I-306	10	wood	*c.* 30	80°45′	23°45′	Trautman and Willis, 1966
4975 ± 150	5590–5910	I-312	10	wood	*c.* 40	80°55′	23°30′	Trautman and Willis, 1966
5510 ± 75	6210–6400	K-7088	11	*Larix* sp.	27	81°20.5′	17°23′	This study
6880 ± 110	7590–7820	K-7087	11	*Larix* sp.	27	81°20.5′	17°23′	This study
4200 ± 320	4300–5290	W-1066	12	wood	6	81°36′	16°41′	Ives *et al.*, 1964
3400 ± 70	3570–3720	Lu-3781	13	wood	10	*c.* 80°55′	*c.* 15°	Hjort, 1997
4730 ± 95	5320–5590	K-6893	14	*Picea* sp.	10	79°39.0′	21°07.2′	Bennike and Weidick, 2001
6160 ± 75	6910–7210	Ua-11481	14	*Populus* sp.	?	79°39.7′	21°05.2′	Bennike and Weidick, 2001
5080 ± 55	5745–5910	AAR-3834	14	*Larix* sp.	5	79°37.6′	22°23.0′	Bennike and Weidick, 2001
5440 ± 55	6200–6290	AAR-4129	14	?*Larix* sp.	1	79°40′	22°30′	Bennike and Weidick, 2001
5955 ± 55	6680–6850	AAR-3837	14	*Larix* sp.	1	79°37.2′	22°35.0′	Bennike and Weidick, 2001
5995 ± 55	6750–6890	AAR-3836	14	*Larix* sp.	1	79°36.8′	22°30.9′	Bennike and Weidick, 2001
6035 ± 55	6760–6950	AAR-3835	14	?*Larix* sp.	24	79°37.6′	22°23.0′	Bennike and Weidick, 2001
6040 ± 55	6760–6950	AAR-4128	14	*Larix* sp.	0.5	79°36.8′	22°30.9′	Bennike and Weidick, 2001
6080 ± 55	6810–7000	AAR-4121	14	*Larix* sp.	27	79°37.6′	21°55.5′	Bennike and Weidick, 2001
735 ± 110	560–740	Y-702	15	wood	3	72°13.1′	23°53.5′	Washburn and Stuiver, 1962
2980 ± 120	2960–3340	Y-703	15	wood	4	72°13.1′	23°53.5′	Washburn and Stuiver, 1962
5590 ± 140	6210–6500	Y-882	15	wood	4	72°07.3′	23°51.5′	Washburn and Stuiver, 1962
7460 ± 130	8070–8390	Y-879	15	wood	20	72°14.9′	24°0.9′	Washburn and Stuiver, 1962
9410 ± 125	10430–11040	I-7664	16	wood	17	60°55.5′	46°3′	Weidick, 1975

[1]Charred driftwood and driftwood from archaeological sites are not included.
[2]Calibrated according to CALIB 4.0, using the INTCAL98 dataset (Stuiver et al. 1998).
[3]See Fig. 3

1997; Hjort, 1997). However, in eastern North Greenland, early-Holocene raised beaches are seen at some sites, for example at Jørgen Brønlund Fjord (Bennike, 1987), in contrast to central North Greenland where raised beaches are not normally found. The presence of raised beaches without driftwood could indicate that only the inner parts of some fjords became ice-free, whereas the outer parts of the fjords were covered by perennial ice.

Meltwater outflow from the Canadian Arctic Archipelago may also explain why driftwood older than *c.* 10 000 cal. years BP has not been found here (Dyke *et al.*, 1997). Driftwood stranding in northern Greenland continued to be rare until 7400 cal. years BP, which is similar to the situation in large parts of the Canadian Arctic Archipelago.

In northern Greenland, the former, intermittent presence of hunting cultures has been taken as an indication of relatively warm periods with more open water than at present (Knuth, 1967). However, one must not forget that the Inuit cultures are adapted to sea ice, using sea ice as a platform for travel and hunting, and the former widespread presence of Palaeo-Eskimos even in northern Greenland would seem to indicate that they were adapted to extreme high-Arctic environments.

M. edulis was also more widespread around Svalbard and Baffin Island during the early to mid-Holocene than at present. On western Svalbard the species was continuously present between 11 000 and 4200 cal. years BP (Salvigsen *et al.*, 1992). On eastern Svalbard, dated *M. edulis* samples come from the time period from 9700 to 5700 cal. years BP (Hjort *et al.*, 1995). On Baffin Island the species was more widely distributed at around 9400 cal. years BP than at present (Andrews *et al.*, 1981).

A marked decrease in the abundance of driftwood in Arctic Canada between approximately 5000 and 500 cal. years BP was attributed to the onset of more severe sea-ice conditions by Blake (1972). However, this decrease is not seen in the much larger data set of Dyke *et al.* (1997). Along the north coast of Ellesmere Island in Canada, a number of ice shelves are found (Evans and England, 1992), and driftwood samples behind these have given dates between 10 000 and 3200 cal. years BP (Dyke *et al.*, 1997). It seems that more open water characterized this region than North Greenland in the early Holocene.

Spatial changes in driftwood abundance in the Canadian Arctic Archipelago after 9500 years BP have been explained as due to oscillations of the Transpolar Drift (Dyke *et al.*,

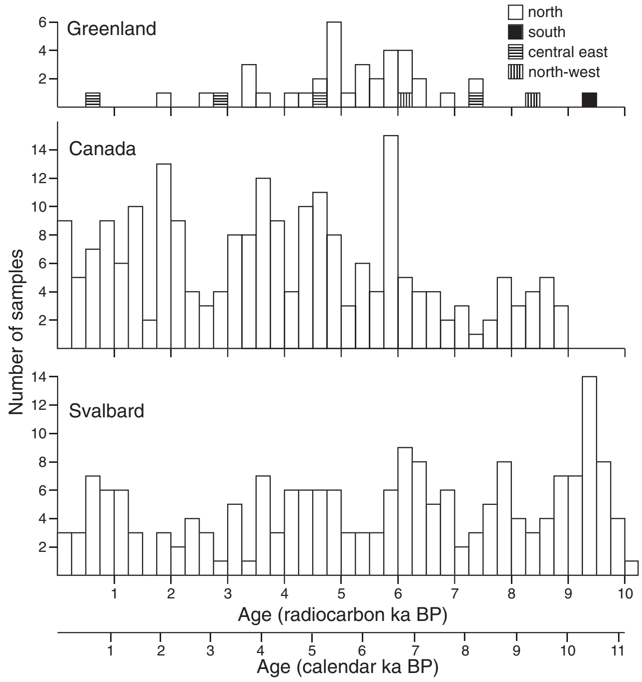

Figure 4 Frequency distribution of radiocarbon dates of non-archaeological driftwood from Greenland, the Canadian Arctic Archipelago (excluding the Baffin Bay region) and Svalbard. Canada and Svalbard data from Dyke *et al.* (1997).

1997). If so, a more clear difference between eastern North Greenland and northernmost Canada might be expected. However, the number of dated driftwood samples from Greenland is so small compared with Canada (more than 100 samples) and Svalbard (*c.* 200 samples) that comparisons are difficult.

It has been suggested that the Holocene in the Northern Hemisphere was characterized by peak warmth in the earliest part, followed by declining temperatures that culminated during the 'Little Ice Age' (Bradley, 2000). Studies of melt layers in one of the ice cores from the Greenland ice sheet show little melting for the first 2500 years of the Holocene, followed by peak melting between 8000 and 6000 years BP (Alley and Anandakrishnan, 1995). Oxygen isotope values from an ice core in East Greenland also point to a mid-Holocene rather than early-Holocene climate optimum (Johnsen *et al.*, 1992; Dahl-Jensen *et al.*, 1998).

Conclusions

The present compilation of data from Greenland seems to indicate that sea-ice conditions during the early Holocene were rather severe in northern Greenland (Figure 5). Thus driftwood entry was prohibited for the first two millennia of the Holocene, and rare for another two millennia, until around 7400 cal. years BP (Figure 5A). This is taken as an indication of widespread occurrence of perennial sea ice. In central North Greenland, perennial sea ice was present throughout the Holocene. In central East Greenland, the record of *Mytilus edulis* indicates that summer sea surface temperatures in the littoral zone were highest *c.* 8500 and 6000 cal. years BP (Figure 5C); this must also have been the period with most open water. Nioghalvfjerdsfjorden was glacier-free during the period from 7700 to 4500 cal. years BP (Figure 5B), and driftwood stranded between 6800 and 5500 cal. years BP. The record of dated driftwood in Greenland shows a decline in the late Holocene, but this may reflect that only few late-Holocene driftwood samples have been dated so far.

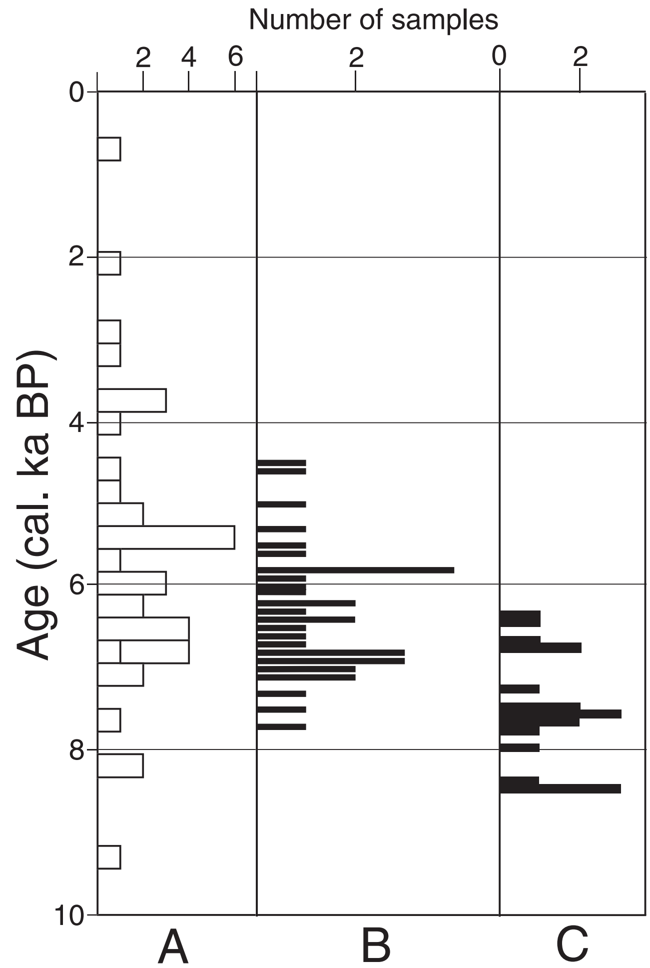

Figure 5 Summary of onshore sea-ice-related records from different parts of Greenland. (A) Distribution of dated non-archaeological driftwood from northern and eastern Greenland. (B) Distribution of dated shells, driftwood and bones of marine mammals from Nioghalvfjerdsfjorden. (C) Distribution of dated *Mytilus edulis* shells from East Greenland.

In western Greenland, the first indication for the onset of the West Greenland Current is seen 1300 years after the beginning of the Holocene, and sea-ice conditions may have been similar to present conditions at the outer coast. Warmer conditions than at present are seen in the middle Holocene.

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