The Holocene 16,3 (2006) pp. 357–367

Mid- to late-Holocene hydrological and climatic variability in Disko Bugt, central West Greenland

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Received 12 August 2005; revised manuscript accepted 19 October 2005

A HOLOCENE RESEARCH PAPER

Abstract: Diatom and lithological analyses were carried out on two sediment cores from Disko Bugt and the adjacent Kangersuneq Fjord, West Greenland, in order to investigate mid- to late-Holocene (6.9–0.7 kyr BP) hydrographic and climatic variability. While the Disko Bugt record is found to reflect mainly West Greenland Current (WGC) fluctuations that can be linked to North Atlantic circulation variability, the fjord record appears to be more representative of local climate conditions. The records demonstrate that the period of investigation was marked by a late-Holocene Thermal Maximum beginning at *c*. 4.8 kyr and ending between 3.5 and 3.1 kyr BP, encompassing a colder period between *c*. 4.0 and 3.8 kyr BP. An episode of higher surface-water temperature is also indicated in Disko Bugt between 2.2 and 1.5 kyr BP. In contrast, the record from Kangersuneq Fjord suggests persisting cooler (summer) surface waters for this interval, interpreted to be attributable to increased meltwater outflow. The warming episode recognized in Disko Bugt corresponds to a reported interval of increased influence of Atlantic waters in the East Greenland Current, which suggests an active North Atlantic current system with enhanced Irminger Current transport also affecting the WGC. Within the later part of the Disko Bugt record ending at *c*. 0.7 kyr BP (*c*. AD 1300) no evidence could be found for a significant Mediaeval warming. When comparing the timing of various environmental changes with past shifts in human settlement in the Disko Bugt area, an apparent link exists between changes in hunting tradition and sea ice conditions.

Key words: Holocene, Disko Bugt, sea ice, fjord, hydrographic variability, climate variability, diatoms, Holocene Thermal Maximum, West Greenland.

Introduction

The Holocene climatic variability in West Greenland has been deduced mainly from terrestrial and limnological records (eg, Fredskild, 1973, 1983, 1988; Funder, 1989; Willemse and Törnquist, 1999; Kaplan *et al.*, 2002; McGowan *et al.*, 2003) with information on the marine environment limited to only a few studies (eg, Donner and Jungner, 1975; Funder and Weidick, 1991; Øhlenschlæger, 2000; Lloyd *et al.*, 2005). The hydrography of West Greenland coastal waters is linked to the large-scale North Atlantic current system by the combined influence of the East Greenland Current (EGC) and the Irminger Current (IC), which merge to form the West Greenland Current (WGC; Figure 1 inset). Hence, the hydrographic conditions off West Greenland are largely determined by the relative flow of Polar and Atlantic water masses within the WGC. Although the signature of the EGC may be suppressed by the IC, the hydrographic scenario off East Greenland can be assumed to be also transmitted to West Greenland coastal areas. Marine investigations performed in waters east of Greenland (eg, Jennings *et al.*, 2002; Jiang *et al.*, 2002) are therefore valuable references for comparative studies on spatial and temporal climate variability in West Greenland. Several palaeo-eskimo settlements are known in the Disko Bugt study area. Information on the different life style of the Saqqaq and Dorset cultures is known for the two settlement periods, 4.4–3.4 kyr BP and 2.8–2.1 kyr BP, respectively (Rasch and Jensen, 1997; Jensen *et al.*, 1999; Meldgaard, 2004). The cause of the 600 yr interruption of human settlement in the Disko Bugt area as well as in other areas of Greenland has been a matter of debate, though it is frequently ascribed to environmental change.

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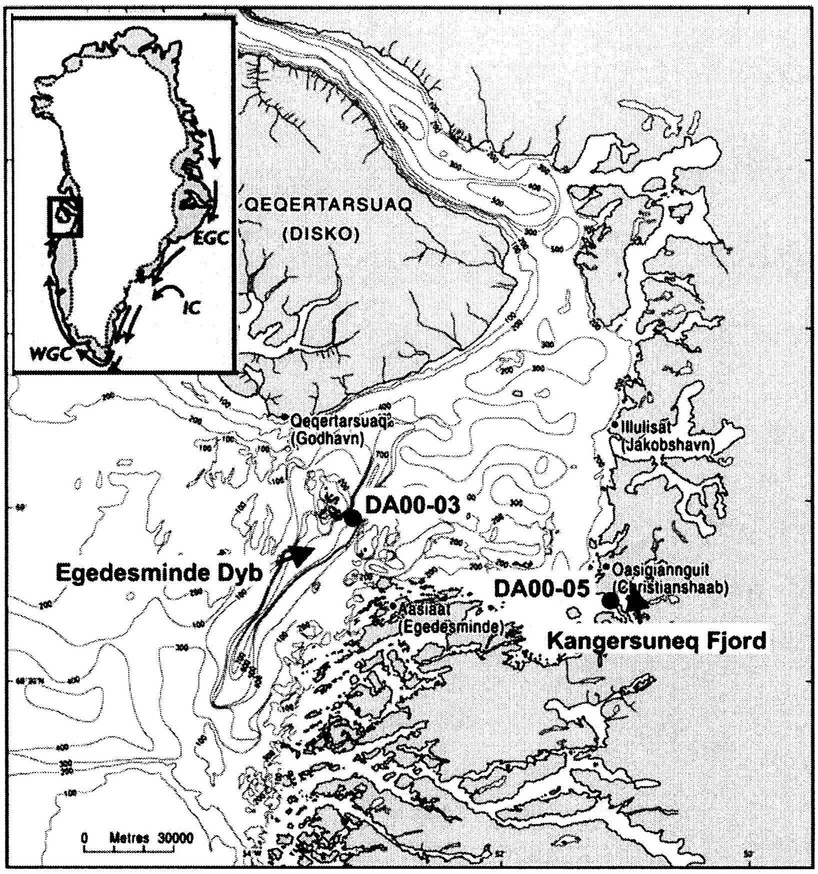

Figure 1 Bathymetry of Disko Bugt and coring sites DA00-03, Disko Bugt proper (Egedesminde Dyb) and core DA00-05, Kangersuneq Fjord. The inset shows the study area on West Greenland and major surface currents around Greenland (WGC, West Greenland Current; IC, warm Iceland Current; EGC, cold East Greenland Current)

The aim of the present investigation is to study Holocene environmental changes in the Disko Bugt area, central West Greenland and its relation to large-scale North Atlantic atmosphere and ocean circulation changes. Diatom and lithological analyses were carried out on two cores collected from western Disko Bugt and the Kangersuneq Fjord (Figure 1). The data confirm that large-scale climatic fluctuations recorded in the North Atlantic region also had an influence in the Disko Bugt area, but additionally show that the West Greenland climate also displayed marked regionally specific features. Our data demonstrate further that the timing of major environmental change coincided with the shifts in human settlement and hunting culture.

Physiographic setting

Disko Bugt is a large embayment in the west coast of Greenland between 68°30′ N and 69°15′ N, and 50°00′ W and 54°00′ W (Figure 1). The Disko region has a polar maritime climate with high precipitation rates and temperature variations (Humlum, 1985). Cyclone activity is most common during the summer season when maritime air masses from the south and southwest influence the area (Humlum, 1985), while continental polar air masses from the Inland Ice prevail during the winter months. Disko Bugt is covered by seasonal land fast sea ice with a mean thickness of *c.* 0.7 m (Buch, 2000). During the past 10 years the duration of sea ice cover of Disko Bugt has increased from 3 months in the beginning of the 1990s to about 5 months in later years (Nielsen *et al.*, 2001). Winter conditions of the surface waters are characterized by uniform salinities and low temperatures. In spring, solar heating and inflow of large amounts of fresh meltwater from land, and melting sea ice establish a pycnocline. Freshening of the surface layers starts in May but extensive freshening does not start until June or early July, maintaining a distinct stratification until September. Hereafter, reduced insolation and air temperatures, and enhanced autumn wind activity break down the stratification (Andersen, 1981b).

The topography of the Disko Bugt area is characterized by an extremely rugged sea bed with water depths typically varying between 200 and 400 m. A dendritic system of deeper transverse channels extends from central Disko Bugt westwards. Maximum water depths up to 990 m occur in the Egedesminde Dyb (Figure 1, location of core DA00-03), which is a deep channel between Kronprinsen Ejland and Hunde Ejland. The Egedesminde Dyb channel has a glacial origin and continues to the shelf edge where a large trough-mouth fan is found (Zarudzki, 1980). The sea bed of the outer part of Kangersuneq Fjord, location of core DA00-05 (Figure 1), is characterized by the presence of two sedimentary basins with a flat sea floor, separated by a moraine ridge. Water depths in this area are generally between 200 and 350 m (Lloyd *et al.*, 1999). DA00-05 was retrieved from the basin west of the moraine ridge. The complicated topography of Disko Bugt markedly influences the hydrography of the bay, which results in an oceanographic setting different from that of the coastal areas further south along the West Greenland coast. The bay with coring site DA00-03 is influenced by water masses of the WGC (Figure 1), by cold surface waters advected from Baffin Bay as well as fresh water derived from the adjacent land and Inland Ice (Andersen, 1981a; Buch, 2000). The WGC transports water masses of different origin. Proximal to the coast the surface waters mainly consist of low salinity water originally derived from the EGC and meltwater discharge along the WGC route. Between 200 and 500 m water depth more saline (> 34‰) Irminger Sea Water of Atlantic origin dominates the WGC (Cuny *et al.*, 2002). This implies that the relatively shallow fjords entering Disko Bugt, and particularly those strongly affected by meltwater outflow, like Kangersuneq Fjord, are relatively isolated from the WGC, which only influences the bottom part of the water column. Hence, the signals captured at the latter site may reflect mainly local environmental rather large-scale oceanic circulation.

Material and methods

The two piston cores (DA00-03, DA00-05, Figure 1) were collected by RV *Dana* in August 2000 (Kuijpers *et al.* 2001). Core DA00-03 was taken at 852 m water depth in Egedesminde Dyb at the southwestern entrance of Disko Bugt (69°00′00″ N, 53°08′00″ W), and core DA00-05 at 335 m water depth in Kangersuneq Fjord in the southeastern part of the bay (68°42′92″ N, 51°06′42″ W).

Core DA00-03 is 1008 cm long, and characterized by mottled and burrowed silty clays with 2–4 cm thick rhythmically alternating lighter and darker coloured intervals. The lithology showed a non-oxic sub-bottom environment below a 2–3 cm oxidized surface layer (Kuijpers *et al.*, 2001). While retrieving core DA00-03 intensive degassing led to disruption of the sediment core. Apart from this disruption at *c.* 700 cm core depth, the core appeared intact and undisturbed.

Core DA00-05 is 1048 cm long, and consists of olive-grey silty bioturbated mud. This suggests a depositional environment with continuous advection of well-ventilated, saline bottom water from Disko Bugt and the absence of permanent sea ice cover (Kuijpers *et al.*, 2001). On a larger scale, the interval from 300 to 450 cm core depth is characterized by increased sand content.

Age control is provided by accelerator mass spectometry (AMS) ^{14}C dates on shells, foraminifera and various plant remains of undefined marine flora (Table 1, Figure 2). All dates are given in calibrated years before present (kyr BP) with a standard marine reservoir correction of 400 years, and calibrated using the programme CALIB v. 4.0 (Stuiver and Reimer, 1998).

Processing and counting of diatom samples

Sediment samples were freeze dried, and 1.5 g of each subsample was boiled in 15 ml of 1% tetra-sodiumpyrophosphate solution for 10 min to disintegrate aggregates. Subsequently 5 ml of 30% hydrogen peroxide was added, and the samples boiled for further 10 min to oxidize organic material. Carbonates were dissolved by the addition of a few drops of HCl. The beakers were filled with distilled water and left to settle for a minimum of 12 h. In order to rinse the material, concentrate the diatoms, and remove silt and clasts, the supernatant was decanted every 8–14 h. This procedure was repeated until the water was almost clear. The sampling interval for DA00-03 was 8–12 cm and for core DA00-05 12–20 cm.

Relative abundance of diatom taxa was measured on the basis of counting a minimum of 400 planktonic valves (excluding unidentified *Chaetoceros* resting spores, r. sp.) with counts of unidentified *Chaetoceros* r. sp. noted. Relative abundance of individual plankton taxa and unidentified *Chaetoceros* r. sp. were calculated from the plankton sum. *Chaetoceros* is a planktonic genus that is problematic to identify below genus level when studied from fossil material. In the present investigation it comprised up to 90% of the total diatom valves, and was therefore excluded from the total plankton counts in order to improve the signal from other taxa.

The material was embedded in Naphrax®. Identifications and counting were made using an Olympus BX-60 light microscope equipped with phase contrast at a magnification of × 1000.

Lithological and mineral magnetic methods

Split halves of the cores DA00-05 and DA00-03 were subsampled continuously using 2 × 2 × 2 cm plastic boxes at *c.* 2.25 cm intervals. These subsamples were used for mineral magnetic measurements performed at Lund University (Sweden). The initial magnetic susceptibility (χ_{in}) of the samples was measured using a Geofyzica Brno KLY-2 Kappabridge. Anhysteretic remanent magnetization (ARM) was induced in each sample with a direct current (DC) bias field of 0.1 mT superimposed on a maximum peak AF of 100 mT, which was gradually reduced to zero. The ARM

Table 1 Chronological control of the sediment cores (see also Figure 2). Core DA00-05: various plant remains of undefined marine flora were dated

Core depth (cm)	Lab. code	Specimen	^{14}C age $\pm 1\sigma$ (yr BP)	Res. corr. ^{14}C age (400 yr)	Calibrated age (yr BP)	Age range 1σ (yr BP)
DA00-05						
43–50	AAR-7509	plant remains	1705±38	1305	1263	1286–1234
106	AAR-7510B	plant remains	2004±36	1604	1550	1518–1601
262	AAR-7511B	plant remains	3200±60	2800	2985	2913–3076
327	AAR-8283	plant remains	3600±120	3200	3520	3680–3410
592	AAR-6835	plant remains	4200±50	3800	4282	4218–4369
812	AAR-8297	plant remains	5350±100	4950	5760	5900–5650
1017	AAR-6836	plant remains	6300±75	5900	6738	6660–6844
DA00-03						
128	CAMS-91944	shell	1415±40	1015	947	920–983
239	AAR-7508	shell	1594±42	1194	1162	1209–1107
404	CAMS-91935	bivalve	1940±40	1540	1501	1435–1529
500	CAMS-86752	foraminifera	2065±40	1665	1623	1574–1689
738	AAR-6833	shell	2745±45	2345	2437	2348–2497
982	AAR-6834	shell	3265±45	2865	3078	3017–3159

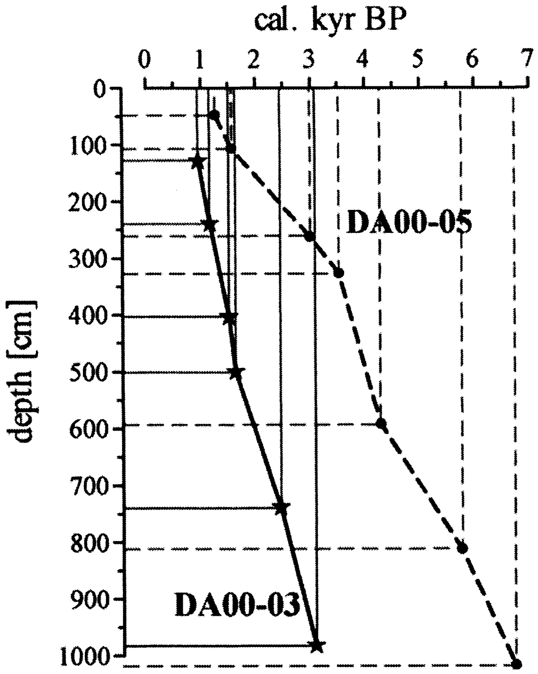

Figure 2 Age–depth models of DA00-03 and DA00-05 based on radiocarbon dates. For the age models the calibrated ages (Table 1) were linearly interpolated against core depth

was measured with a Molspin Minispin magnetometer and divided by the DC bias field to provide the susceptibility of ARM (χ_{ARM}). The χ_{ARM}/χ_{in} ratio was calculated where high values indicate finer magnetic grains. The use of magnetic parameters in palaeoceanographic studies has been widely discussed, eg, Verosub and Roberts (1995), Stoner and Andrews (1999), Snowball and Moros (2003). The content of material >63 μm and >150 μm (as weight percentage, wt%) was determined by wet-sieving.

Results

Age control

The sediment cores cover a timespan of almost 7000 years (Figure 2), and are characterized by ultra-high accumulation rates, up to 300 cm/1000 yr. For the age models and the calculations of accumulation rates the calibrated ages were linearly interpolated against core depth. In core DA00-05 which covers the time span 6.9 to *c.* 1.0 kyr BP, the accumulation rates varied from 0.11 cm/yr to 0.31 cm/yr with maximum rates indicated in the interval *c.* 4.2–3.4 kyr BP (592–327 cm core depth). In core DA00-03 which covers the time span 3.1–0.7 kyr BP, the rates varied from 0.36 to 0.52 cm/yr with maximum rate in the interval *c.* 1.2–0.9 kyr BP (239–138 cm core depth).

Diatom stratigraphy of core DA00-05, Kangersuneq Fjord (Figure 3)

A total of 41 diatom taxa were identified from the core. The lower part of the diatom record (6.9–5.0 kyr BP; 1048–753 cm) is characterized by an increasing and high relative abundance of sea ice-associated taxa that are primarily represented by *Fragilariopsis cylindrus* and *Fragilariopsis oceanica*. Maximum relative abundance of sea ice-associated species is centred at 5.0 and 1.5 kyr BP. Species, that usually occur under ice-free conditions are recorded in relatively high numbers. Among these are *Bacterosira bathyomphala*, *Chaetoceros furcellatus*, *Detonula confervaceae*, *Porosira glacialis* and *Thalassiosira antarctica* v. *borealis*, which are considered to occur at different successive stages (spring to summer) in an Arctic diatom growth season (Grøntved and Seidenfaden, 1938; von Quillfeldt, 1996; Munk *et al.*, 2003).

The genus *Chaetoceros* has been reported as the last successive stage in the West Greenland diatom growth season (Grøntved and Seidenfaden, 1938). Resting spore formation in this genus is a response to suboptimal growth conditions, and

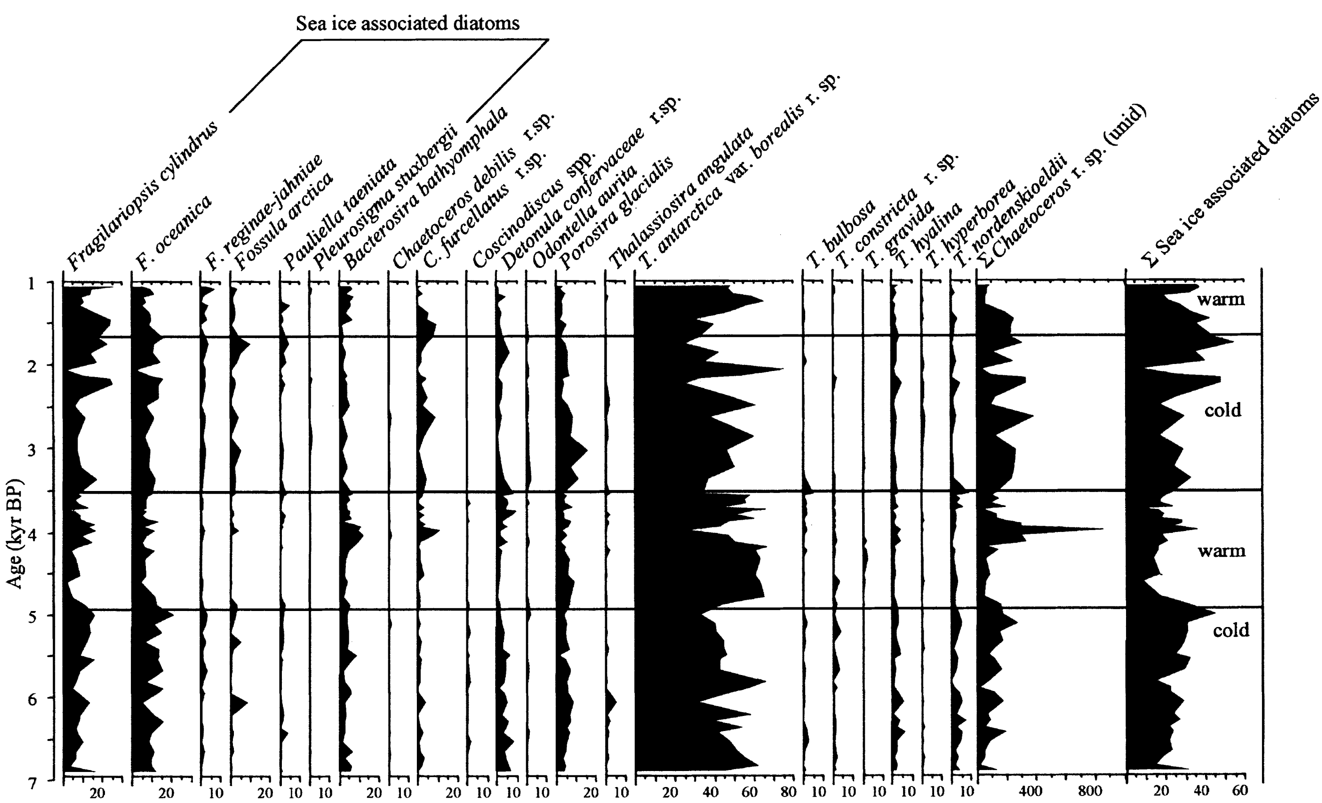

Figure 3 Percentage plot of most important diatom species (> 3%) in core DA00-05, Kangersuneq Fjord

often triggered by nutrient deficiency (McQuoid and Hobson, 1996). Previous studies indicate a relationship between high abundance of *Chaetoceros* r. sp. and distinct stratification of the water column, where nutrients have been depleted in the surface layer (Leventer, 1992; Crosta *et al.*, 1997; Jensen *et al.*, 2004). The *Chaetoceros* r. sp. record is therefore a proxy for late summer stratification in the working area. In the lower core part the abundance of *Chaetoceros* r. sp. fluctuates but increases on an average level from 6.9 towards 5.0 kyr BP.

There is a marked reduction in the relative abundance of total sea ice species at *c.* 4.8 kyr BP. The abundance remains at lower, but on average increasing, levels until 3.5 kyr BP. Also the record of *Chaetoceros* r. sp. shows minimum values indicating less stratification of the water column in the time intervals 4.8–4.0 and 3.8–3.5 kyr BP. An abrupt increase in *Chaetoceros* r. sp. in the intermittent period from *c.* 4.1 to 3.8 kyr BP is concurrent with a slight increased abundance of sea ice-associated diatoms and a maximum input of very fine-grained material as shown by lithological parameters (see Figure 5).

There is a long-term tendency to increasing relative abundances of the sea ice-associated species between 3.5 (a slight increase starts already from about 4.6 kyr BP) and 1.7 kyr BP. A renewed low in total sea ice-associated species occurs at 1.2 kyr BP. The latter minimum is also reflected in the record of *Chaetoceros* r. sp. An otherwise high relative abundance of *Chaetoceros* r. sp. in period 3.5–1.7 kyr BP suggests a stratified water column.

Diatom stratigraphy of core DA00-03, Egedesminde Dyb-Disko Bugt (Figure 4)

A total of 49 diatom taxa were recorded from core DA00–03. Based on sea ice-associated taxa the core can be split into three intervals. The lower (3.1–2.2 kyr BP, maximum centred at 2.6 kyr BP) and the upper (1.5–0.7 kyr BP) intervals are characterized by high relative abundances of sea ice-associated diatoms, *Chaetoceros furcellatus* r. sp. and unidentified *Chaetoceros* r. sp., which suggests cold conditions and a stratified water column. *Thalassiosira* spp., *Chaetoceros* spp. and other spring and summer species point to open water conditions during summer. It is worth noting, that generally lower abundances of sea ice-associated diatoms indicate slightly warmer surface waters between 3.1 and 2.2 kyr BP than during 1.5 to 0.7 kyr BP. Interval 2.2–1.5 kyr BP is a phase of decreased sea ice-associated diatom abundance, which is indicative of warmer sea surface temperatures (maximum at 2.0–1.8 kyr BP). The reduction of sea ice is mainly reflected in increased abundance of *Thalassiosira antarctica* v. *borealis* r. sp., but otherwise little change takes place in the assemblages until 1.5 kyr BP when *Fragilariopsis cylindrus* increases in relative abundance showing the shift to cold conditions.

As mentioned above, in the upper cold interval (1.5–0.7 kyr BP) relative abundance of sea ice-associated species increases to a level slightly higher than during the older cold phase which may indicate a long-term cooling trend. Over the whole record and in particular from 1.5 to 0.7 kyr BP a decrease is observed in the relative abundance of *Odontella aurita*, *Detonula confervaceae*, *Porosira glacialis* and *Thalassiosira nordenskioeldii.* The latter three species are usually present in the Arctic spring bloom event and persisting sea ice cover may hinder this bloom. *Odontella aurita* is regarded as cosmopolitan (Hasle and Syvertsen, 1996), and is observed in Disko Bugt in July when SST is relatively high (K.G. Jensen, unpublished data, 2004). Cooling of the surface waters may produce poor growth conditions for this species, and may consequently lead to decreased abundance. Also the relative abundance of *Chaetoceros* r. sp. decreases.

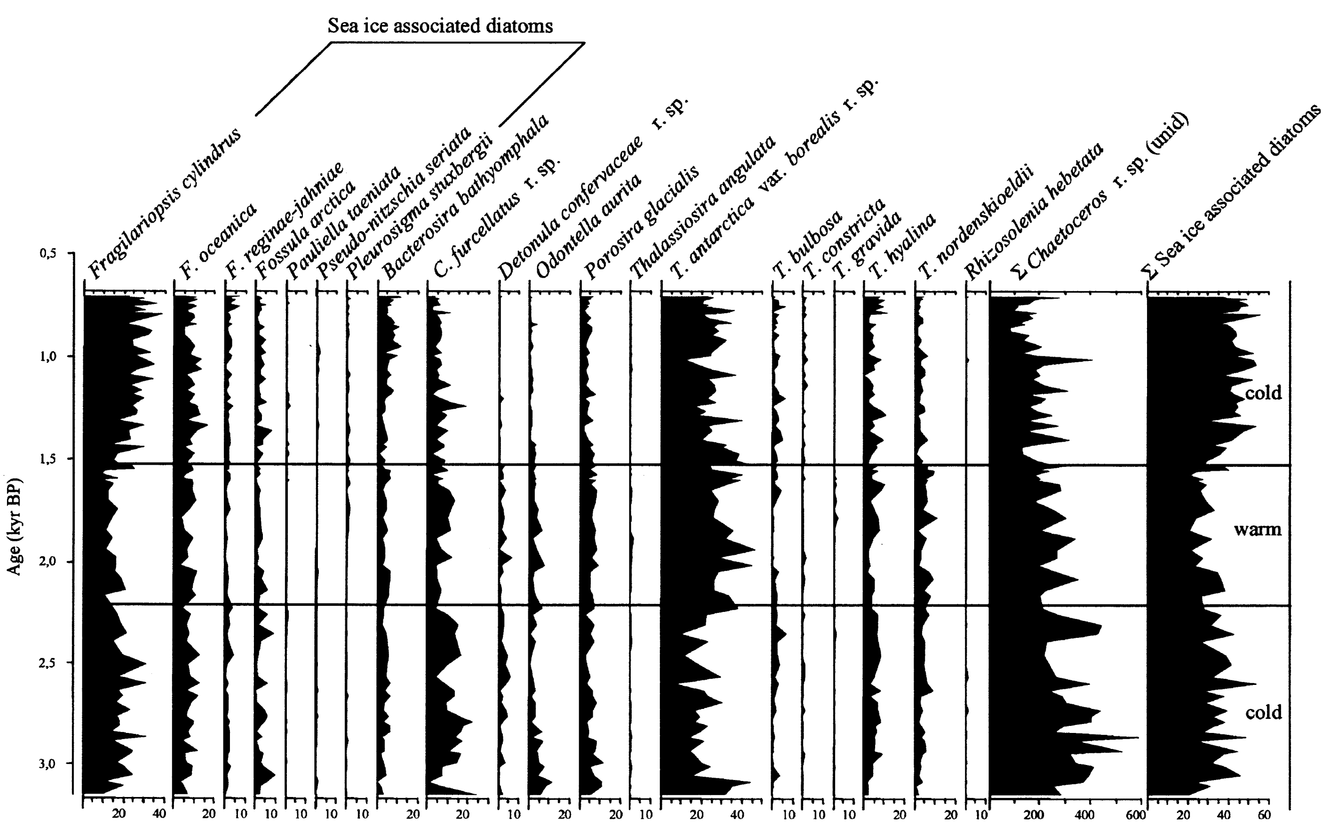

Figure 4 Percentage plot of most important diatom species (> 3%) in core DA00-03, Disko Bugt

Lithological changes

The most distinct feature of the χ_{ARM}/χ_{in} ratio record of core DA00-05 is a steady increase in the fine fraction magnetic material from *c.* 5.0 to 4.0 kyr BP (Figure 5). Higher ratios indicate finer magnetic grains. Peak χ_{ARM}/χ_{in} values correspond to maximum values in *Chaetoceros* r. sp. abundance (Figure 5). A marked feature of the sand content record is an increase in the wt.% > 63 μm from *c.* 2 wt.% prior to 4.0 kyr BP to about 15–20 wt.% in the interval 3.9–3.5 kyr BP. After 3.5 kyr BP the content returns to a level of *c.* 2 wt.%. This increase is also reflected by the wt.% > 150 μm record, while during this time interval the input of fine fraction magnetic material is low. The wt.% > 63 μm of DA00-03 are not presented here as the values are less than 1% and vary only slightly downcore.

Discussion

Lithological and diatom data from the Disko Bugt area show several distinct changes in the hydrographic and climatic regime between 6.9 and 0.7 kyr BP. The different hydrographic setting of the coring sites implies that the records provide information on both oceanic scale (Disko Bugt) and on more local processes, such as meltwater runoff (Kangersuneq Fjord).

The period 6.9–3.5 kyr BP, Kangersuneq Fjord

The presumably limited influence of large-scale open ocean circulation on the surface waters of Kangersuneq Fjord suggests that the climate signal captured mainly reflects local hydrographic conditions. By comparison, the inferred cold conditions lasting until 5.0 kyr are consistent with the sea salt and terrestrial dust records of the GISP2 ice core (O'Brien *et al.*, 1995). The latter suggests increased winter-style atmospheric circulation in 6.1–5.0 kyr BP caused by expansion of the north polar vortex or intensified meridional circulation. In Kangersuneq Fjord, this cold period terminated by an abrupt decrease in the relative abundance of sea ice-associated diatoms at 4.8 kyr BP. At the same time there is a distinct increase in the loading of fine-grained sediment material to the fjord bed. This is expressed by the magnetic χ_{ARM}/χ_{in} ratio (Figure 5). There are no indications of glaciers in the fjord system during this period, hence, the fine-grained sediment most likely originates from meltwater flow from land caused by increased air-temperatures in the region. The warmer period (4.8–3.5 kyr BP) only interrupted by temporary cooling between *c.* 4.0 and 3.8 kyr BP observed in the fjord area has not yet been reported from other marine sites off West Greenland. However, recent studies of a sediment core taken in Ameralik Fjord near Nuuk, more to the south, also document a late-Holocene Thermal Maximum (HTM) terminating at about 3.2 kyr BP (Møller *et al.*, 2006). Based on conventional ^{14}C dates on molluscs preferring higher temperature, Donner and Jungner (1975) found an earlier HTM (6.8–5.0 ^{14}C BP) at Christianshaab a site very close to our study area. In addition, based on boreal molluscs, Funder and Weidick (1991) show conditions 1–3°C warmer than present in central West Greenland from 9.2 to 5.6 kyr BP. However, a later HTM terminating about 3 kyr BP is reconstructed by numerous studies on terrestrial archives from Baffin Land, NE Canada, and West Greenland (Fredskild, 1973, 1988; Willemse and Törnquist, 1999; Kaplan *et al.*, 2002; Kaufman *et al.*, 2004). In addition, ice core borehole temperature reconstructions (Dahl-Jensen *et al.*, 1998) show a HTM between 5 and 4 kyr BP, ie, during the warmer period we observe in the fjord area (Figure 5). Contrary to the borehole temperature reconstructions for DYE-3 and GRIP ice cores, the GISP2 ice core reveals increasing air temperature from *c.* 4.0 kyr BP based on mean-annual temperature reconstructions by Alley *et al.* (1999; Figure 5). The GISP2 and GRIP sites are influenced by air masses from both the North Atlantic and northeastern Canada in relation to the Baffin trough (Dahl-Jensen *et al.*, 1998), and the GISP2 ice core record seems to show a good correlation to the synoptic climatology of West Greenland (Dawson *et al.*, 2003).

Although marine studies off East Greenland reveal a complex pattern (Kaufman *et al.*, 2004), benthic foraminifera records offshore East Greenland suggest strong influence of Atlantic Intermediate Water in the EGC during the mid Holocene lasting until at least 4.0 kyr BP (Jennings *et al.*, 2002), and also the North Iceland shelf is strongly influenced by the IC from 4.6 to 3.6 kyr BP (Jiang *et al.*, 2002). A strong influence of Atlantic water in the East Greenland and Icelandic regions probably reflects an active North Atlantic Current and enhanced advection of Irminger Current water also into the WGC system, which in turn may have affected the hydrography and climate of the Disko Bugt region.

In the period 4.0–3.5 kyr BP, substantial environmental changes are captured in a variety of proxies. At 4.0 kyr BP, the sea ice diatoms indicate a short cold spell, which lasts until 3.8 kyr BP that is probably caused by maximum meltwater input as indicated by the magnetic parameter. Maximum meltwater input coincides with a strong water column stratification indicated by highest abundances of *Chaetoceros* r. sp. Simultaneously there is a shift in the benthic foraminiferal fauna from a mixed calcareous and agglutinated assemblage to a solely agglutinated assemblage that persists to the core top (Park, 2003). This feature indicates that cold conditions reached the fjord bottom. The absence of calcareous foraminifera species is a dissolution signal probably caused by long-lasting sea ice cover and/or a strong pycnocline preventing bottom water ventilation and CO_2-exchange with the atmosphere.

Decreasing fine-fraction input from 3.9 kyr BP and a marked increase in coarse-grained material between 4.0 and 3.5 kyr BP may indicate frequent break-up of land-fast sea ice transporting coarse grains from the coastline and adjacent shallow areas towards the coring site. We have to exclude coarse fraction input by icebergs or drift ice derived from glaciers as there is no sign of glacier outlets in the fjord area. Low relative abundance of sea ice-associated diatoms during this period may be ascribed to prevailing limited sea ice cover and relatively high SST. These conditions may have been favoured by strong surface-water mixing under the influence of a windy climate associated with frequent frontal passages of maritime air masses. The *Chaetoceros* r. sp. record shows low values in this interval suggesting weak stratification (Figure 5) thus confirming wind-induced mixing of the water column. It should be noted that the interval characterized by a high fraction of coarse-grained sand most likely represents a period of increased sediment accumulation, because of this we cannot determine how long these conditions prevailed apart from to conclude that the termination was at 3.5 kyr BP.

The period 3.5–0.7 kyr BP; Disko Bugt and Kangersuneq Fjord

The diatom records of DA00-05 and DA00-03 suggest a late-Holocene long-term cooling trend in the Kangersuneq Fjord and Disko Bugt, respectively. In the nearby Disko Fjord, West Disko, the foraminiferal fauna of this time period is also dominated by agglutinated species (Øhlenschlæger, 2000).

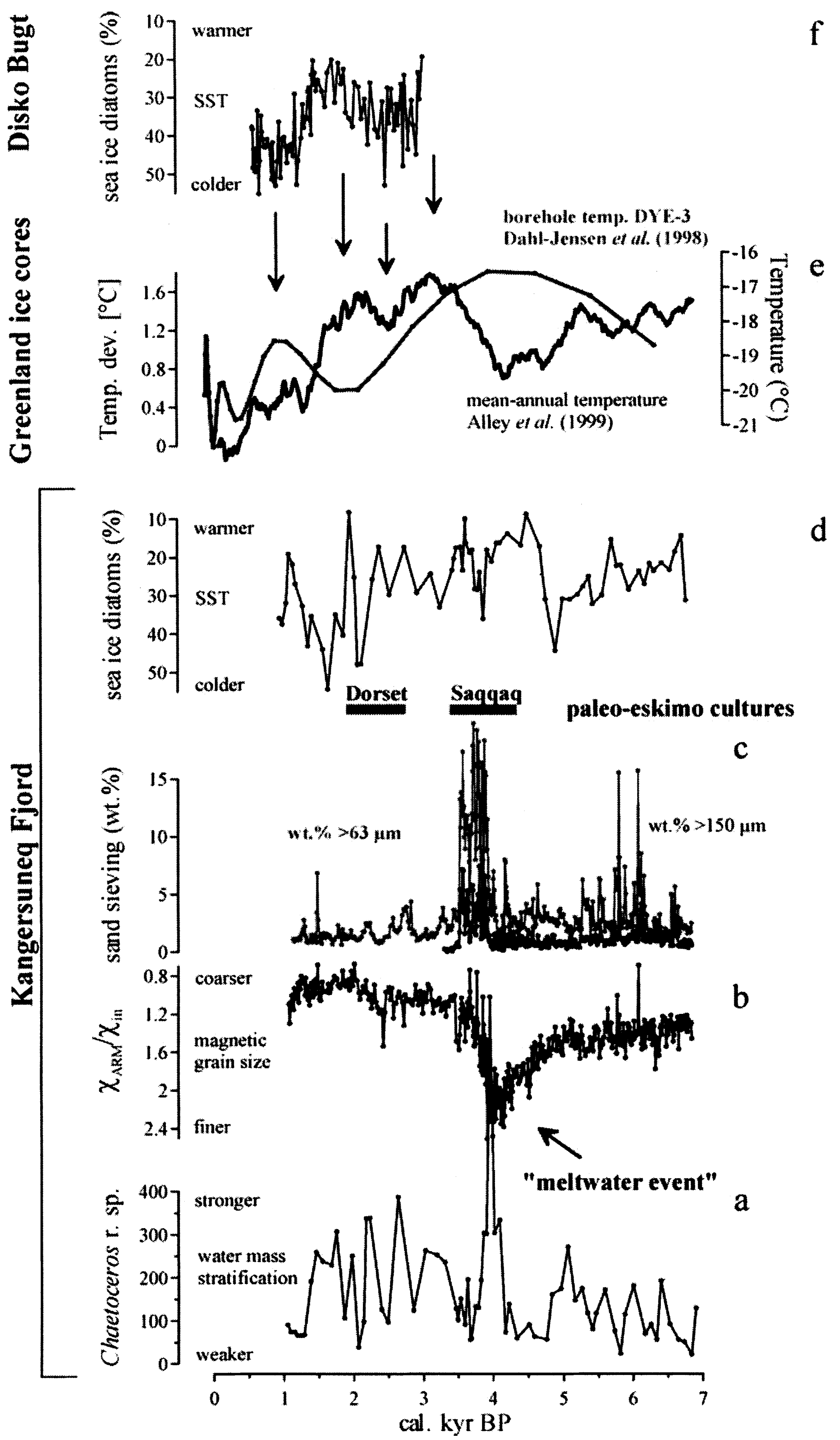

Figure 5 Kangersuneq Fjord (DA00-05) and Disko Bugt (DA00-03) data. DA00-05: (a) abundance record of *Chaetoceros* r. sp. a proxy for water column stratification; (b) magnetic grain size information – the plot of χ_{ARM}/χ_{in} ratio reveals a distinct change in ratio after 5.0 kyr BP; (c) particle size data, light shaded graph is the plot of weight% > 63 µm and black graph is the plot of weight% > 150 µm, note the abrupt increase in weight percentage of the sand fractions shortly after 4.0 kyr BP; (d) abundance plot of sea ice-associated diatoms indicating sea-surface temperature changes. Note high input of fine-fraction material most likely reflecting a meltwater event follows a warming of the surface waters. The meltwater event, in turn, cooled the surface waters and lead to a strong water mass stratification as reflected by sea ice-associated diatom and *Chaetoceros* r. sp. abundance records, respectively. DA00-03: Plot (f) shows the relative abundance record of sea ice-associated diatoms. In addition, in (e) the ice core borehole temperature reconstruction for DYE-3 by Dahl-Jensen *et al.* (1998) and the mean-annual temperature reconstruction for GISP2 by Alley *et al.* (1999) are shown. Note the similar long-term late-Holocene cooling trend in records (d)–(f) but also the differences at submillennial timescale. At millennial timescale there is a close correspondence between the GISP2 and the Disko Bugt data. The local conditions reflecting Kangersuneq Fjord data resemble, to some extent, the DYE-3 borehole temperature reconstructions. Grey bars in (d) mark the timing of palaeo-eskimo cultures in Disko Bugt area (Meldgaard, 2004)

Øhlenschlæger (2000) proposed that the absence of calcareous foraminifera in Disko Fjord may be ascribed to dissolution caused by enhanced iceberg drift and water mass stratification. This suggests that lower air temperatures prevailed in the Disko Bugt region, which is also supported by re-advance of the Jacobshavn Icestream (Weidick *et al.*, 1990) and generally decreasing air temperatures above the Greenland ice cap (Dahl-Jensen *et al.*, 1998; Alley *et al.*, 1999). Cold climatic conditions have been proposed from several other places in the Baffin and Greenland regions during this period, though with some temporal variation (eg, Williams and Bradley, 1985; Dyke *et al.*, 1996; Levac *et al.*, 2001; Kaplan *et al.*, 2002). The long-term, late-Holocene cooling trend of the water masses in Kangersuneq Fjord and also in Disko Bugt is consistent with the onset of the neoglaciation reflected in several places in the Greenland region (eg, Williams and Bradley, 1985; Weidick *et al.*, 1990; Dahl-Jensen *et al.*, 1998; Cremer *et al.*, 2001; Levac *et al.*, 2001; Jennings *et al.*, 2002; Jiang *et al.*, 2002). Interestingly, although there is a similar long-term cooling trend observed in the local environment of Kangersuneq Fjord as well as the WGC-influenced Disko Bugt proper, there are contrasting signals at millennial timescales. Thus, there is a warming observed in Disko Bugt, peaking at 2.0–1.8 kyr BP, but a cooling in local environment of Kangersuneq Fjord. Here we should note that regional warming in combination with enhanced advection of moist, maritime air masses and stronger winds will favour glacier melting and production of (cold) meltwater, the latter particularly affecting isolated fjord basins. In general, at millennial timescales the Disko Bugt record follows the GISP2 mean-annual temperature reconstructions by Alley *et al.* (1999; Figure 5). The warm event inferred from core DA00-03, peaking at about 2.0–1.8 kyr BP, is corroborated by proxy records from a fjord in South Greenland, which indicate increased SST during this period (Roncaglia and Kuijpers, 2004; Lassen *et al.*, 2004). At a more regional scale a similar warming as shown in DA00-03 around 2.0 kyr BP and also the sharp temperature drop at 1.7 kyr BP have been inferred from records off East Greenland, the Norwegian Sea and off North Iceland (Jennings *et al.*, 2002; Andrews and Giraudeau, 2003; Risebrobakken *et al.*, 2003; Moros *et al.*, 2004), which provide strong evidence for the regional character of these climatic fluctuations. In addition, a cold phase centred at about 2.7 kyr BP, which is also evident in our DA00-03 data, is widely recorded in terrestrial and marine archives in the North Atlantic region. While the environmental changes captured in the Disko Bugt record can clearly be linked to the large-scale Holocene climatic variability in the North Atlantic region, the Kangersuneq Fjord signal reflects the more local, climate regime onshore West Greenland. The fjord core record tends to follow the ice core borehole temperature reconstructions by Dahl-Jensen *et al.* (1998). The Dahl-Jensen record shows, superimposed on the long-term cooling, a colder phase at *c.* 2 kyr BP and a warming around 1.2 kyr BP.

At 1.2 kyr BP diatom data from Disko Bugt point to a marked cooling whereas relatively warmer SSTs are observed in the fjord area. As discussed above, higher SST in the fjord may reflect, apart from warmer summers, a reduced meltwater production, which, in turn, suggests regional cooling of West Greenland offshore areas (eg, Baffin Bay) as seen in the Disko Bugt record. The *Chaetoceros* r. sp. record shows a decreasing trend in core DA00-03 at 1.5 kyr BP, while an abrupt reduction of this group takes place in core DA00-05 at 1.3 kyr BP indicating that enhanced vertical mixing prevailed in the Disko Bugt region. Increasing surface water mixing at this time (1.3 kyr BP; *c.* AD 700) may be linked to an increasingly more windy climate as reported from South Greenland (eg, Lassen *et al.*, 2004) to have prevailed during the 'Mediaeval Warm Period' (MWP, *c.* AD 800–1300).

The period of 1.5 to 0.7 kyr BP, which notably includes also the MWP, appears to represent the overall coldest interval in Disko Bugt of the entire investigated period. This observation confirms studies in western Baffin Bay and offshore Labrador stating that cooling prevailed here during the past 1500 years (Keigwin and Pickart, 1999). Although the MWP has been recognized both in Disko Fjord, West Disko (Øhlenschlæger, 2000) and in Disko Bugt (Lloyd, 2006; K.G. Jensen, unpublished data, 2004), data suggest that this episode was cooler than the preceding mid- to late-Holocene mild periods in the Disko Bugt area. Recent core studies in Ameralik Fjord, to the south (Møller *et al.*, 2006), similarly demonstrate that marked MWP warming did not occur in this region. This pattern strongly resembles the cooling trend of the past decades observed in Baffin Bay (Grumet *et al.*, 2001) and in the Labrador Sea region (Hanna and Cappelen, 2003) at a time of widespread Northern Hemisphere warming. Proxy indicators from South and East Greenland infer cooling and freshening of the EGC from 1.5 kyr BP onwards (Jennings *et al.*, 2002; Roncaglia and Kuijpers, 2004) which suggests generally increased sea ice formation in Greenland waters. In contrast, the Kangersuneq Fjord record and south Greenland fjord records (Roncaglia and Kuijpers, 2004; Jensen *et al.*, 2004, Lassen *et al.*, 2004) as well as the ice core borehole temperature reconstructions by Dahl-Jensen *et al.* (1998) display the MWP as the usually reported warm event, which clearly demonstrates that also in the Greenland region climatic anomalies are characterized by complex patterns.

Linking environmental changes to palaeo-eskimo history

The cultural history of Greenland began 4.5 kyr BP with the immigration of palaeo-eskimo cultures from high Arctic North America. The history of human occupation in Greenland is characterized by arrival and disappearance of several cultures rather than continuous human settlement, and it has been suggested that environmental change was the major cause for this pattern (McGovern, 1991; McGhee, 1996). In Disko Bugt, numerous dwellings and artefacts have been recovered from the Saqqaq and Dorset people, who inhabited the region in the time periods *c.* 4.4–3.4 kyr BP and *c.* 2.8–2.1 kyr BP, respectively (Jensen *et al.*, 1999).

The lithological and diatom records of core DA00-05 in Kangersuneq Fjord suggest that the period of Saqqaq settlement was characterized by relatively high SST and air temperatures (Figure 5), and assumed extended open water conditions when compared with the previous period 6.9–5.0 kyr BP. Such an environment agrees well with the archaeological records that describe the Saqqaq people as preferential open water hunters (Meldgaard, 2004). In the later period of their settlement the proxy records indicate increasing climate instability and cooling episodes. Excavations from Qeqertasussuk in Sydostbugten have shown that from *c.* 4.2 to 3.5 kyr BP this site was inhabited primarily in spring and summer, which was the season when harp seal was the primary game (Meldgaard, 2004). Based on the archeological data, Meldgaard (2004) speculates that at this time an environmental shift took place from subarctic to arctic conditions, which considerably affected the food source and caused the Saqqaq people to leave Disko Bugt. The diatom and lithological data from DA00-05 indicating generally warmer climate terminating at *c.* 3.5 kyr BP supports this theory. Hence, the coincidence between the onset of cold climatic conditions and the disappearance of the Saqqaq culture from Disko Bugt area suggest that this environmental change caused adverse living conditions for these traditional open water hunters.

The Dorset people were adapted to a higher degree to sea ice hunting than were the Saqqaq (J.F. Jensen, personal communication, 2004). The oldest records of this culture (Jensen *et al.*, 1999) are coincident with cool sea and air temperatures and most probably extended sea ice cover as inferred by the diatom and lithological record. From *c.* 2.6 kyr BP a shift took place, with increased inflow of warmer WGC water masses into the Disko Bugt, although the air temperature of the region appears to have remained relatively low. However, diatom data in Kangersuneq Fjord reveal unstable but probably relatively warmer SSTs between 2.8 and 2.0 kyr BP than during 2.0 and 1.5 kyr BP when the Dorset disappeared. The change in large-scale hydrographic conditions may have caused a shift in marine resources from arctic to boreal species in a similar manner as happened in the more recent warm period from AD 1920 to 1940 in Disko Bugt (Meldgaard, 1995). During that period, species diversity as well as standing stock density increased during the summer season, but because of decreased sea ice conditions winter resources fell and, by combination with increased wind activity, marine food was less available (Meldgaard, 1995, and references therein). The initiation of a period of relatively warm surface waters with limited sea ice in Disko Bugt peaking between 2.0 and 1.8 kyr BP, accompanied by persisting cold summer SST conditions in Kangersuneq Fjord (2.0–1.5 kyr BP), may well have exerted a great impact on the ecosystem and, in turn, the living conditions of the Dorset, and contributed to the disappearance of this culture from the Disko Bugt region.

Conclusions

The fossil diatom assemblages and the lithology of the present study reveal marked hydrographic and climatic changes in the Disko Bugt area in the period from *c.* 6.9 to 0.7 kyr BP. The diatom flora record points to variations in sea-surface temperature, sea ice cover and stratification through time. Both sea ice-associated species and open water planktonic species were observed in all samples studied, which suggests that the Disko Bugt area was seasonally ice covered throughout the entire investigated period. The lithological data from Kangersuneq Fjord reveal distinct changes in flux and composition of material coinciding with floristic changes that mark the termination/initiation of climatic events.

A major feature of the 6.9–3.5 kyr BP interval in Kangersuneq Fjord is a warmer phase starting at 4.7 kyr BP, which was characterized by enhanced meltwater input in that area. This warm phase reflects a late-Holocene Thermal Maximum recorded in terrestrial archives on West Greenland and recently also documented in a core from Ameralik Fjord (another West Greenland fjord to the south; Møller *et al.*, 2006). From 3.5 kyr BP towards 0.7 kyr BP a long-term cooling trend is observed in both the local hydrographic conditions of Kangersuneq Fjord and the West Greenland Current (WGC) as recorded in the Disko Bugt core. However, there are marked differences in the climatic records at submillennial timescales. A cold phase at 2.0–1.5 kyr BP in Kangersuneq Fjord coincides with warmer SST conditions in Disko Bugt and is concluded to reflect the local effect of increased meltwater production because of regional warming. Further contrasting signals are found at 1.2 kyr BP with a warming in Kangersuneq Fjord and a cooling in the Disko Bugt. Relatively high SST in the fjord may be ascribed to decreased meltwater flow affecting the (isolated) fjord basin. Notably no marked warming was recorded for the MWP interval in the Disko Bugt core.

In general, the sediment record of Disko Bugt has clearly captured millennial-scale late-Holocene climatic fluctuations as recorded offshore East Greenland and in a wider area of the North Atlantic and, notably, as recorded by the GISP2 mean-annual temperature reconstructions. The more local environmental signal captured in proxy records of the Kangersuneq Fjord core, however, correlates well with submillennial scale features of the DYE-3 and GRIP borehole temperature reconstructions and fit to climatic variations inferred from terrestrial records on West Greenland.

The timing of environmental shifts corresponds to archaeological datings of changes in human settlement in the Disko Bugt area. The life and hunting styles known to characterize the Saqqaq and Dorset cultures correspond well to the hydrographic, and in particularly ice, conditions and climatic scenarios inferred by the diatom and lithology records. Hence, the present study supports the concept of climate change and its impact on the ecosystem being a major factor determining changes in human culture and settlement.

Acknowledgements

Karin G. Jensen was supported by the Danish Research Agency (grant no. 9802945 to A. Kuijpers, GEUS), the Geological Survey of Denmark and Greenland and the European Union 'PACLIVA' project (Contract EVK2-CT-2002-00143). MM acknowledges EU Marie-Curie postdoc funding at Bergen University and support by BCCR. NERC is thanked for providing additional radiocarbon dates. Svend Funder and Jeremy Lloyd are thanked for their constructive and very helpful reviews. We thank Jens Fog Jensen, Martin Appelt and Morten Meldgaard for providing information and unpublished data on the living conditions and chronology of the Saqqaq and Dorset people. Beth Stavngaard, Johnny E. Hansen and Benny Schark are thanked for technical assistance. This is publication no. A123 from the Bjerkner Centre for Climate Research.

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