# Late-Holocene Atlantic bottom-water variability in Igaliku Fjord, South Greenland, reconstructed from foraminifera faunas

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A HOLOCENE RESEARCH PAPER SET
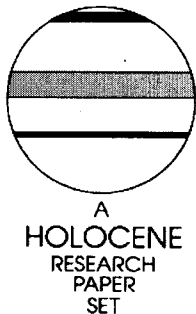
Abstract: A high-resolution record of late-Holocene subsurface water-mass characteristics in outer Igaliku Fjord, South Greenland, is presented based on benthic foraminifera faunas from core PO 243-451 collected from a water depth of 304 m. Stratification with Atlantic water masses present in the lower part of the water-column is suggested to have prevailed during the last 3200 cal. years, except for a period referred to as the 'Mediaeval Warm Period' (MWP). During the MWP (*c.* AD 885–1235) the outer part of Igaliku Fjord experienced enhanced vertical mixing and a high hydrodynamic energy level which we ascribe to increasing wind stress through this period, corresponding to the period of the Norse settlement. The transition from the MWP to the 'Little Ice Age' (LIA) shows a two-step pattern with a short climatic amelioration around AD 1520 before maximum cooling occurred. The intensified wind stress and the overall environmental change are suggested to have contributed to the loss of the Norse settlement in Greenland. Periods with strong stratification and marked influence of Atlantic subsurface water masses around 2.6, 1.3 ka BP and during the LIA are correlated to North Atlantic Holocene ice-rafting events reported by Bond *et al.* (1997).

Key words: Benthic foraminifera, palaeoceanography, hydrography, climatic change, Atlantic bottom water, ocean currents, Greenland, Norse settlement, late Holocene, 'Little Ice Age', 'Mediaeval Warm Period'.

Introduction

Evidence is mounting that the North Atlantic did not only experience millennial-scale climatic variability during glacial times (Dansgaard-Oeschgaard events; Bond *et al.*, 1993), but also during interglacial times, though the variations were less pronounced (e.g., O'Brian *et al.*, 1995; Bianchi and McCave, 1999; Bond *et al.*, 1997; 2001). The average pacing of the climatic changes during the Holocene is around 1500 years (Bond *et al.*, 1997; Bianchi and McCave, 1999; Arz *et al.*, 2001), but a variety of shorter periodicities with a series of spectral peaks ranging from 69 to 1046 years have also been noted (Hong *et al.*, 2000). A more recent example, and in some areas the most pronounced, of these climatic changes is the 'Mediaeval Warm Period' (MWP) to the 'Little Ice Age' (LIA) oscillation. The forcing causing these climatic oscillations is still an unsolved puzzle, but

the solar activity together with the ocean thermohaline circulation is considered to have played an important role (Bond *et al.*, 1997; 2001; Broecker, 2000).

The impacts of these natural climatic changes on mankind have been considerable. For instance, on Iceland widespread farming was rare before AD 1280, but after that time this happened frequently (Finsson, 1970). Thus, the Norse, under Eric the Red, were able to colonize South Greenland at AD 985, according to the Icelandic Sagas, owing to the mild MWP climate with favourable open-ocean conditions. This is close to the peak of Mediaeval warming recorded in the GISP2 ice core which was dated at AD 975 (Stuiver *et al.*, 1995). Their disappearance coincides with the onset of the LIA, but the timing of the ultimate loss of the Norse settlement in South Greenland ('Eastern Settlement') has not yet been determined. Studies of a Canadian high-Arctic ice core and nearby geothermal data (Koerner and Fisher, 1990) correspondingly show a significant temperature lowering at AD 1350–1400. This corresponds to the period

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when the Norse society in Greenland was declining and reaching its final stage probably before the end of the fifteenth century.

To improve our knowledge on the local marine processes and conditions during this final settlement stage, and compare these with hydrographic and climatic variability during the last millennia of the Holocene, we focused on the outer part of Igaliku Fjord, South Greenland. This area is part of the Eastern Settlement where the ruins and remains from the first European settlers on Greenland are concentrated, and at the same time well exposed to open-ocean influences, which implies that large-scale ocean-circulation changes may also be recorded. For this purpose, namely to reconstruct the hydrographic development of this outer part of Igaliku Fjord and establish possible links with the large-scale climate events involved, a multiproxy approach has been applied. The various parameters analysed and discussed below include benthic foraminiferal faunas, stable isotopes and magnetic susceptibility. In addition, analysis of diatom floras and palynofacies have been carried out on this core as well and published by Jensen *et al.* (2004) and Roncaglia and Kuijpers (2004), respectively.

Environmental setting

The entrance of Igaliku Fjord is formed by an 11 km long narrow sea inlet at the southwestern Greenland coast. There is no threshold and the fjord floor generally deepens offshore continuing as a narrow channel across the shelf. The maximum water depth in the outer Igaliku Fjord is around 475 m.

The modern hydrography in this area is characterized by two water masses. The (sub)polar cold, low-salinity surface waters originate from the East Greenland Current (EGC), which turns north around Cape Farewell and continues along the (south)west coast of Greenland as the West Greenland Current. Below these cold surface water masses, and outcropping at the surface further offshore, relatively warm (up to *c.* 4°C) and saline Atlantic water is found (Horsted, 1956; Buch, 2000). West of Cape Farewell increasing mixing between these two water masses occurs, but they can still be separated in our study area. Thus, the upper part of the water-column in the outer Igaliku Fjord derives from the EGC, whereas at greater subsurface depth (>200 m) Atlantic water advected by the Irminger Current is present. A normal seasonal trend shows increasing influence of Atlantic water masses in late summer and early autumn, whereas EGC water masses are dominant earlier in the year.

Previous studies of benthic foraminifera in fjords of Greenland have been carried out on recent sediments (e.g., Madsen and Knudsen, 1994; Jennings and Helgadottir, 1994), and occasionally also on sediment cores for palaeoenvironmental reconstruction (e.g., Jennings and Weiner, 1996; Jennings *et al.*, 2002). In the fjords of our study region very limited palaeoenvironmental work has so far been done (Herman *et al.*, 1972). The latter study dealt with benthic foraminifera from cores from the central Igaliku fjord. However, the stratigraphic control in this investigation is very poorly constrained due to a lack of ^{14}C dates.

Foraminiferal assemblages, ecology and water-mass characteristics

The calcareous species *Cassidulina neoteretis* is typical in the modern environments of the East Greenland shelf and found associated with Atlantic intermediate water masses (Jennings and Helgadottir, 1994). This species is also found in the chilled Atlantic water masses north of Norway in the Barents Sea (Steinsund, 1994).

The two Arctic species *Elphidium excavatum* and *Cassidulina reniforme* are also represented in these areas, but they are more

specifically associated with lower temperature and salinity in areas close to ice margins (Steinsund, 1994; Hald *et al.*, 1994; Jennings and Helgadottir, 1994). A suite of taxa, such as *Astrononion gallowayi*, *Cibicides* spp. and *Triferina angulosa*, occur in recent sediments characterized by a coarse substrate and a high-energy hydrodynamic environment (Sejrup *et al.*, 1984; Mackensen, 1987; Steinsund, 1994).

Areas in the proximity of the oceanic polar front show high abundance of, for example, *Nonionellina labradorica* (see Steinsund, 1994) and *Islandiella norcrossi* (see Hald and Steinsund, 1992), while the distribution of *Melonis barleeanus* is mainly controlled by the presence of partly decomposed organic material (Caralp, 1989).

Materials and methods

Core PO 245–451 is 351 cm long and was collected in 1998 by R/V *Poseidon* (Hoffmann *et al.*, 1999). The water depth at this site (60°41.96′N, 46°02.00′W) at the entrance of Igaliku Fjord close to Qaqortoq/Julianehaab is 304 m (Figure 1). The sediment in the lower part of the core consists of homogeneous grey silty clay. Between 131 and 93 cm the sediment consists mainly of sandy silt. The upper part of the core is olive-grey silt with isolated black specks. The core was subsampled at 5 cm intervals between 120 and 90 cm core depth and at 3 cm intervals in the remaining upper part. No samples were analysed from below 120 cm core depth.

For foraminiferal analysis the samples were dried, weighted and washed through sieves with mesh sizes 0.1 and 1.0 mm. Then the fractions were dried and weighted. Foraminifera were counted from the 0.1 mm fraction. Three hundred individuals were counted in each sample, if possible (a table showing the complete percentage distribution of benthic foraminifera in core PO 243–451
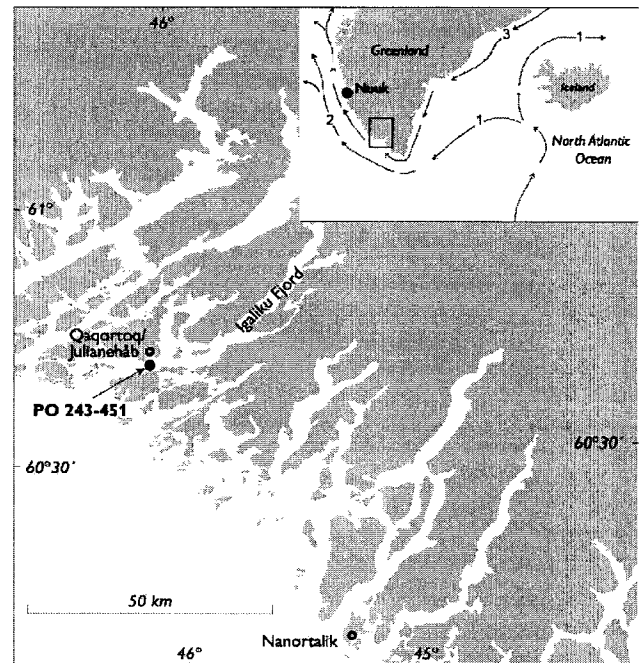

Figure 1 Map of the study area with indication of the position of core PO 245–451 in the outer Igaliku Fjord. The inset map displays the regional setting of the study area and the general ocean circulation pattern. (1) The Irminger Current is a branch of the warm North Atlantic Current and flows west of Iceland as well as south following the east coast of Greenland turns north around Cape Farewell and continues northward as the West Greenland Current (2). (3) The cold iceberg-loaded East Greenland Current (EGC). The Greenland inland ice is not illustrated on this figure.

is available online at http://www.arnoldpublishers.couk/journals/pages/holocene/data.htm).

Oxygen isotope ratios of the benthic species *Cassidulina neoteretis* were measured on a Finnigan MAT 252 mass spectrometer at Woods Hole Oceanographic Institute (WHOI). Given values are calibrated to the PDB scale. The total reproducibility amounts to 0.07‰ for $\delta^{18}O$.

The magnetic susceptibility measurements of core PO 243–451 were carried out with a hand-held Bartington magnetic susceptibility meter (MS2E1 probe) on the split core.

For stratigraphic control AMS ^{14}C dates were determined using various types of material, i.e., shell fragments, foraminifera and plant material (Table 1). In addition, non-destructive low-energy gamma-spectrometric measurements of ^{210}Pb and ^{37}Cs activities (for methods and results, see Kunzendorf *et al.*, 1998) were made on core PO 243–451 for determining recent (last 150 years) sediment-accumulation rates. These measurements where carried out at the Risø National Laboratory, Denmark.

Results

Chronology

The ^{210}Pb measurements document that the surface sediments are recent and the age model of core PO 243–451 is based accordingly on a compilation of the ^{14}C dates and the ^{210}Pb dates (Table 1), assuming constant sedimentation rates between the dated levels as shown in Figure 2. Two dates are omitted from the age model. At 57 cm core depth, two dates have been carried out on shell and plant material, respectively. The results of these two dates are only 70 ^{14}C years apart. Taking uncertainties in the measurements as well as the reservoir age into account allows us to consider the results as to yield an identical age. The age determined for the shell has been chosen for the age model. Furthermore, the age found for terrestrial plant material sampled from 99 cm core depth is only 20 ^{14}C years older than the age found for marine shell material collected from 90 cm core depth. Also, in this case, we gave priority to the measurement made on the shell material. We are aware that the older part of the age model might be erroneous. This, however, has hardly any relevance for the interpretations and conclusions of this paper. All the AMS ^{14}C dates have been corrected for a reservoir age of 400 years and calibrated. Within this context, it should be noted that the dated material originates from a bottom-water environment characterized by the presence of Atlantic water. The ages used in this
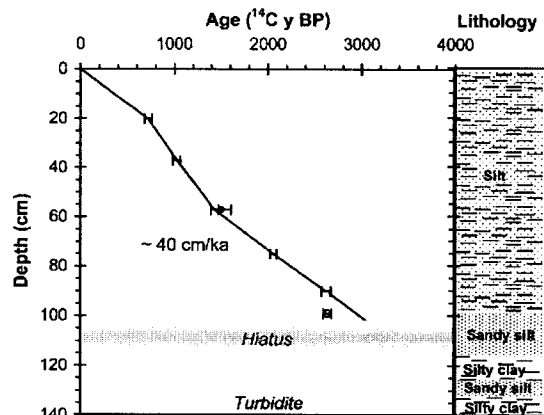

Figure 2 The age model for the upper 105 cm is based on the dates given in Table 1. ^{14}C ages are presented together with the average sedimentation rate (cm/ka, in calibrated years), when assuming constant sedimentation rates between the dated levels. The inferred hiatus separating the sandy sediment from the undisturbed upper section are marked with horizontal shading. In addition, the lithological column for the core is shown.

paper are calendar years unless otherwise indicated. Sedimentation rates in the upper metre are around 40 cm/ka in average.

Between 131 and 93 cm core depth the sediment is more sandy except for the interval between 122 and 116 cm, which consists of homogenous silty clay. The relative sharp lithological boundary to the silty sediment above may reflect either a hiatus or a period with very low sedimentation rates due to the AMS ^{14}C dates at 7910 and 8175 ^{14}C years BP from the sandy interval. Below 131 cm core depth the homogeneous sediment is interpreted as a turbiditic deposit. For the purpose of this paper, only the upper 105 cm of the core is used for reconstructing the palaeohydrographic history of the fjord. The 105 cm core depth is defined due to a marked change in the foraminifer fauna and not exactly at the lithological change.

Foraminifera, magnetic susceptibility and oxygen isotopes

A total of 53 different benthic foraminifera species has been determined through the analysed core section, of which only approximately eight (calcareous) species comprise 80–90 % of the fauna. A selection of the most important species is shown in Figure 3. Through the investigated time interval *C. neoteretis*, *C. reniforme*, *T. angulosa*, *A. gallowayi* and *Islandiella norcrossi/*

Table 1 Pb^{210}/Cs^{137} and AMS ^{14}C dates from core PO 253–451 and corresponding calibrated years, and for the upper part also calendar years (the ^{14}C ages are calibrated by use of the program Calib 4.0)

| Depth (cm)	Pb^{210}/Cs^{137} (AD)	AAR-lab. number	^{14}C age (uncorrected)	^{14}C age (reservoir corrected (400 years))	Error bars	Average calibrated years BP	Average calendar years AD	Dated material
0	1995							
2	1983							
3	1961							
4	1924							
5	AD 1875							
20		AAR-5937	1120	720	40	665	1285	plant
37		AAR-5938	1425	1025	40	935	1015	shell
57		AAR-5939-2	1830	1430	40	1310	640	shell
57		AAR-5959-1	1900	1500	110	1370	580	plant
75		AAR-5940	2460	2060	35	2000	–	shell
90		AAR-5468	3020	2620	50	2750	–	forams
99		AAR-5046	3035	2635	45	2755	–	plant
125		AAR-4990	8310	7910	70	8675	–	shell
126		AAR-5047	8575	8175	65	9135	–	shell
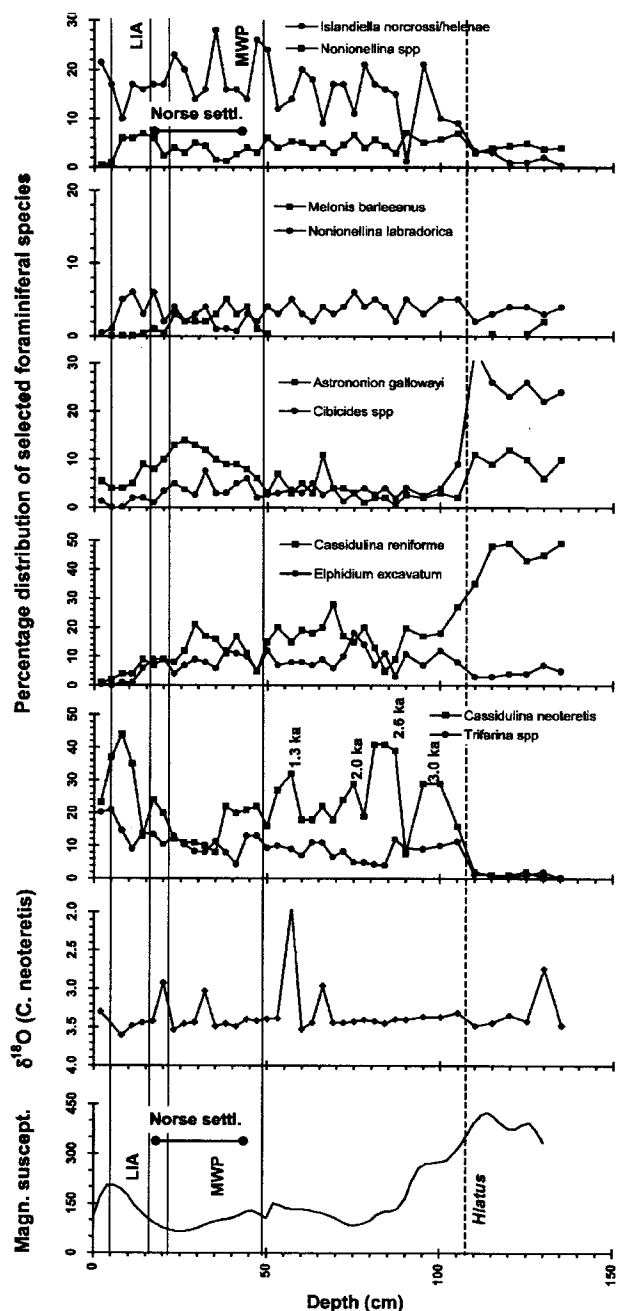
Figure 3 The relative abundance of the most important benthic foramini-fera species in core PO 243–451 are shown together with the magnetic susceptibility profile and the stable oxygen isotope record. The horizontal lines indicate the position of the 'Mediaeval Warm Period' (MWP) and 'Little Ice Age' (LIA). In addition, the vertical line indicates the duration of the Norse settlement. The inferred hiatus around 105 cm core depth is indicated by the dotted horizontal line. The calibrated age of the peaks in relative abundance of *Cassidulina neoteretis* is shown (1.3, 2.6 and 3.0 calibrated years BP).

helenae are the main constituents of the benthic fauna (in this study, the two species *Islandiella norcrossi* and *Islandiella helenae* have not been separated). The relative abundance of each of the individual species changes, however, through the interval. Thus, above the lithological boundary at 93 cm core depth (i.e., 2.76 ka BP) *C. neoteretis* dominates the fauna up to 38 cm (i.e., AD 1015), with peak values at 87–81 cm (i.e., 2.6–2.3 ka BP) and 57–53 cm (i.e., 1.3–1.2 ka BP/AD 640–715). Increasing abundance of *A. gallowayi* between 44 and 23 cm core depth (i.e., AD 884–1237) follows the high abundance of *C. neoteretis*. Characteristic for this interval is also the increased occurrence of *M. barleeanus*.

Hereafter the abundance of *C. neoteretis* increases again and peaks in the upper part of the core (11–5 cm, i.e., AD 1640–1875). Also *Bucella frigida* and *N. labradorica* peaks during this period. Several species reveal a general relative decrease after the interval with the appearance of *M. barleeanus*, such as *A. gallowayi*, *C. reniforme* and *E. excavatum*.

The magnetic susceptibility shows a low-frequency fluctuating pattern with high values around the transition to the *M. barleeanus* interval and again in the upper part of the core. Note the striking correlation between the magnetic susceptibility and percentage of *C. neoteretis* apparent in the upper metre of the core.

Throughout the studied interval the oxygen isotope ratio reveals rather constant values around 3.5‰ with four levels of well-defined excursions towards lighter isotope values at 66, 57, 32 and 20 cm core depth.

Palaeohydrographic interpretation and discussion

The sediment interval below the sample at 105 cm core depth is interpreted as resulting from a different environment separated from the above section by a hiatus. This is based both on the change in lithology as well as the change in the benthic foramin-iferal fauna. Though no stratigraphic interpretation can be made, a hint of the original depositional environment may be found. The benthic foraminifera fauna is comprised of species like *Cibicides* spp., *A. gallowayi* and *C. reniforme*. The first two are epifaunal (Murray, 1991) and found in areas with a coarse-grained substrate which often reflects a high-energy hydrodynamic environment with strong bottom currents. Being epifaunal, these species are considered more robust to unstable and fluctuating food supply and thus the depositional environment for the fauna represented in this part of the core may be characterized by marked changes in water-mass properties and associated with an intermittent food supply. This is confirmed by the high dominance of *C. reniforme* which is typical in glaciomarine environments (e.g., Hald and Korsun, 1997). A glacial proximal environment could explain the coarser grain sizes and unstable hydrographic conditions with fluctuating meltwater fluxes as well as food supply. Hence, this fauna may represent an earlier-Holocene depositional environ-ment with glacial proximity to the core site.

Through the past *c*. 3200 years BP (i.e., the upper 100 cm) the benthic foraminiferal fauna suggests that Atlantic water masses prevailed at the sea floor, i.e., in the lower part of the water-column. This is particularly evident from the presence of *C. neo-teretis*, with the strongest influence of Atlantic water at 100–95 cm (i.e., 3.2–2.8 ka BP), 87–81 cm (i.e., 2.6–2.3 ka BP), 57 cm (i.e., 1.3 ka BP) and 11–5 cm (i.e., AD 1640–1875). These epi-sodes are roughly coeval with periods of cooling recorded in the North Atlantic surface waters during intensive drift of icebergs (Holocene IRD events 2–1; Bond *et al.*, 1997). Lower surface water temperatures are shown to correlate with the solar activity favouring a strengthening of winds from northerly direction over the North Atlantic (Bond *et al.*, 2001; Table 2).

As also shown by the LIA sea-ice index for Iceland (Ogilvie, 1992), more widespread ice drift and stronger northerly winds indicate an intensified EGC transport of low-salinity, cold surface waters towards South Greenland. Thus, a more pronounced halo-cline would contribute to less mixing and better isolation of the Atlantic bottom-water masses in the outer Igaliku Fjord. Markedly enhanced advection of EGC water masses is clearly documented in the diatom record of core PO 243–443 taken in the innermost part of Igaliku Fjord (Jensen *et al.*, 2004). Furthermore, a generally intensified EGC may simultaneously favour stronger entrainment of subsurface Atlantic water originating from the Irminger Current. Thus, the warm Atlantic signal at the bottom

Table 2 The environmental episodes found in core PO 243–451 listed together with corresponding events known from the literature

Environmental episodes	Corresponding events
3.2–2.8 ka BP: stratification in the water-column/cooling 2.6–2.3 ka BP: stratification in the water-column/cooling	Cooling in the North Atlantic, Bond event 2 (2.8–2.7 ka BP) (Bond *et al.*, 1997)
2.0 ka BP: stratification in the water-column/cooling	• Cooling the Greenland ice cap (Dahl-Jensen *et al.*, 1998) • Glacial advance on Iceland (Stötter *et al.*, 1999) • Cooling on the Iceland shelf (Eiriksson *et al.*, 2000; Jiang *et al.*, 2002) • Minor cooling in the North Atlantic (Bond *et al.*, 1997)
1.3 ka BP: stratification in the water-column/cooling	Cooling in the North Atlantic, Bond event 1 (1.4 ka BP) (Bond *et al.*, 1997)
1070–75 yr BP ('Mediaeval Warm Period'): vertical mixing of the water-column, increasing wind activity	• Reduction of seasonal ice cover in Igaliku Fjord (Roncaglia and Kuijpers, 2004) • Stable and warm conditions on the Greenland East Coast (Jennings and Weiner, 1996) • Increased erosion and deposition of aeolian sediments on land around the fjord (Vebæk, 1992) • Large-scale change in wind regime in Eastern Canada (Kasper and Allard, 2001)
AD 1405: culmination of the first cooling after the 'Mediaeval Warm Period'	• Cooling signal on the East Greenland coast (Jennings and Weiner, 1996) • Cooling in the Canadian high Arctic (Koerner and Fischer, 1990)
AD 1520: short climatic amelioration	Same pattern on the Greenland East Coast (Jennings and Weiner, 1996)

during these cold periods is interpreted as a result of a strongly stratified water-column. Within this context it is noteworthy that also in the open northwestern North Atlantic off Nova Scotia subsurface warming has been found during the LIA from the sixteenth to the nineteenth centuries (Keigwin and Pickart, 1999).

Also around 2.0 ka BP (at 75 cm core depth) the fauna suggests an increased influx of Atlantic subsurface water masses. This corresponds to a period of minimum borehole temperatures recorded on the Greenland ice cap (Dahl-Jensen *et al.*, 1998; Johnsen *et al.*, 2001). In the Atlantic records only a minor cooling is recorded (Bond *et al.*, 2001), but on northern Iceland a glacier advance has been reported (Stötter *et al.*, 1999) as well as cooling on the north Iceland shelf (Eiriksson *et al.*, 2000; Jiang *et al.*, 2002). The solar activity does not seem to have decreased at this time (Be-reference; Bond *et al.*, 2001). However, probably not all the Holocene climate events are exclusively caused by solar forcing, as, for instance, the meltwater event leading to the Preboreal cooling (Hald and Hagen, 1998). Meltwater influence could also have played a role around 2.0 ka, since the dinoflagellates suggest a salinity decrease (Roncaglia and Kuijpers, 2004). The latter information may, however, also point to temporarily increased advection of low-salinity (ice-loaded) EGC water masses. The glacier advances on Iceland (Stötter *et al.*, 1999) also point to the possibility of a regionally lowered sea-surface temperature, possibly in combination with increased precipitation rates. In between the intervals with Atlantic water and a marked stratification, the fauna distribution shows an increased abundance of *E. excavatum* and

C. reniforme. These species possibly suggest lower bottom-water temperatures and a less stable hydrographic environment.

The light isotopic excursions occur mainly after 1655 BP (AD 295) and correspond to findings on the East Greenland shelf (Jennings *et al.*, 2001). Jennings *et al.* (2001) argue that this signal is caused by an overall freshening in the Atlantic intermediate water masses due to increased mixing between AIW and the polar water mass (PW) rather than increased temperature. As an alternative possibility they mention *in situ* sea-ice formation that could produce brines and thus transport the light isotopic signal to the bottom. The latter is unlikely to have been the situation in our study areas since the surface water proxies suggest low salinity in these intervals (Jensen *et al.*, 2004; Roncaglia and Kuijpers, 2004). Instead, an increase in the EGC is recorded (Jensen *et al.*, 2004). We speculate that this could also have increased the thickness of the PW and thus favour an increased mixing of PW into the Atlantic water mass resulting in the lower oxygen isotope values. A stronger and deeper-reaching EGC would be expected also to influence the East Greenland shelf and thus support the idea of general overall freshening in the Atlantic water masses (Jennings *et al.*, 2001).

The interval between 44 and 23 cm core depth corresponding to 1070 yr BP (AD 885) and 715 yr BP (AD 1240) is characterized by the sudden presence of *M. barleeanus*. This species can be related to an environment of high fluxes of partly decomposed organic material to the sea floor (Caralp, 1989). A more intensive mixing of the water-column and possible associated increased primary productivity would result in increased food supply to the benthic community. Another indicator for vertical mixing of the water-column in this time interval is the increase in the relative abundance of *A. gallowayi* and *Cibicides* spp., which are indicators of environments with a high hydrodynamic energy level. Increased wave and storm activity could produce such conditions. A considerable reduction of the seasonal ice cover as suggested from the dinoflagellates (Roncaglia and Kuijpers, 2004) is in support of increased mixing and wind stress. This interval corresponds to the warm period referred to as 'The Mediaeval Warm Period' (MWP). On the East Greenland coast this period is described as a warm and stable period with less wind compared to the following colder period (Jennings and Weiner, 1996). This would suggest that the lack of sea ice induced by warming could have been an important factor favouring more turbulent conditions in the Igaliku Fjord. However, during the period of enhanced mixing the record shows a continuously increasing energy level, peaking just before a marked fauna change. Under mainly ice-free conditions, such a trend can only be explained by increasing wind stress and associated wave action. This is supported by observations on land showing enhanced erosion and deposition of aeolian sediments in the time interval of the Norse settlement (Vebæk, 1992). It is worth noting that these features have been believed to be mainly due to increased erosion caused by Norse land use (Jacobsen, 1991; Sandgren and Fredskild, 1991). Support for a large-scale change in the wind regime is provided, however, by studies in eastern Canada (Kasper and Allard, 2001). These report intermittent aeolian episodes characterizing the climate in this region during the interval *c.* AD 850 to 1370.

The foraminiferal fauna reveals a two-step transition towards the peak cooling conditions reaching to a stable stratified water-column, around AD 1760. The disappearance of *M. barleeanus* and decrease in current/high-energy indicator species together with a marked increase in *C. neoteretis* indicate less wind forcing and increasing stratification. In our core record the first cooling step culminates AD 1405 (i.e., 17 cm core depth) and can be correlated to a cooling signal recorded off the East Greenland coast previously referred to as the onset of the LIA (Jennings and Weiner, 1996). They date the culmination of the cooling event to AD 1370, but given the error of the dating these ages are considered corre-

sponding. Moreover, these dates also correspond to the time (AD 1350–1400) of significant cooling in the Canadian high Arctic (Koerner and Fischer, 1990).

A short climatic amelioration punctating the cooling trend is suggested around 14 cm core depth (i.e., AD 1520) with less stratification (decrease in percentage of *C. neoteretis*) and increased mixing (increase in percentage of *A. gallowayi*). This short episode suggests that the transition from the 'warm' to the cold state was stepwise and not a gradual climatic deterioration. A similar pattern is found further north along the East Greenland coast with temporary warming here dated at around AD 1470 (Jennings and Weiner, 1996). Again, the age difference is within the one-sigma error of the dates and thus these climate signals can be considered to be coeval, indicating large-scale circulation changes. Written records of extensive sea-ice distribution between Greenland and Iceland during this time also suggest that the marine environment experienced intensive cooling (Ogilvie, 1991). However, this climate signal appears to be characteristic of the marine record as the high-altitude ice-core data suggest a more gradual transition towards the peak cold conditions (Dahl-Jensen *et al.*, 1998).

It is stressed that the time resolution of our record does not allow for any conclusion regarding climatic variability within the cold LIA as suggested from other studies in both the marine (Jennings and Weiner, 1996) and ice-core records (Dahl-Jensen *et al.*, 1998).

The clear correspondence between the magnetic susceptibility values and the percentage of the *C. neoteretis* suggest that in this area the magnetic susceptibility profile can be use as a proxy for the influence of subsurface Atlantic water masses and conditions of stable stratification, at least during the last 3000 years. This may be due to through transport of material from offshore, either by Atlantic water masses or by the EGC, found to be more active at times of stable stratification. Alternatively, dilution by material of relatively low magnetic susceptibility of more local origin during periods of increased mixing may explain such a trend. In the latter case, when wind force is thought to be stronger, aeolian deposition could play a role.

Implications for the Norse settlement

The Norse settled in South Greenland at AD 985 (corresponding to *c.* 40 cm core depth in core PO 243–451). According to the palaeohydrographic interpretation of the outer Igaliku Fjord environment, this was a period with a relatively warm climate in terms of surface water temperature, although with increasing wind stress peaking towards the end of the MWP (this study; Jensen *et al.*, 2004; Roncaglia and Kuijpers, 2004). This is in support of findings of an aeolian series of sand deposits accumulated during the final part of the settlement (Jacobsen, 1991). Evidence of episodes of markedly increased atmospheric circulation is also found in east Canada (Kasper and Allard, 2001). Thus, an important conclusion is that enhanced aeolian deposition in the settlement areas could largely be due to regionally intensified atmospheric circulation, and not only due to increased local erosion by Norse land use as suggested by, for example, Jacobsen (1991) and Sandgren and Fredskild (1991).

Based on the presence of *M. barleeanus* during the MWP, it is suggested that the surface productivity in the fjord has been high and thus could have provided a good supply of marine food for the Norse people. Archaeological studies of skeleton remains of the Norse (Arneborg *et al.*, 1999) have demonstrated a marked change in food sources during the Norse settlement period. Originally, 20% of the food originated from marine sources, whereas at the final stage 80% of the food had a marine source. From our study we may conclude, that, apart from the possible negative effect of climatic deterioration on Norse land use, this change to

some extent thus may also be attributed to an increased potential of marine food, particularly during later stages, when wind-induced surface water mixing was at a maximum. The increased wind activity may also explain why the Norse did not build an economy around intensive fishing in the fjords; given the few and valuable small boats they had, it would be very risky. Fishing requires not only more time at sea, with more day-to-day damage to the boats, but also more exposure to storms and hazards than the more intensive seal hunting.

Historical documents on Iceland report the presence of the Norse in South Greenland for the last time in AD 1408, after which we lack any further information about what happened to these people. As outlined above, the first cooling stage recorded in the fjord is dated at *c.* AD 1405, coinciding with the last report of the Norse presence in the area. This coincides with an unprecedented influx of (ice-loaded) EGC water masses into the innermost parts of Igaliku Fjord (Jensen *et al.*, 2004), where the bishop seat of Gardar, a major cultural centre of the Eastern Settlement, was located. Shortly after, i.e., around AD 1450, the climate further deteriorated with further increasing stratification of the water-column associated with stronger advection of (ice-loaded) EGC water masses. This suggests an increase of the ice season and a decrease of primary production and marine food supply. This could also have had a dramatic influence on the local seal population and thus the feeding basis for the Norse population (see also Jensen et al., 2004).

Finally, indications have been found for a relative fast subsidence (up to 3 m/1000 years) of this part of Greenland during the past 3000 years, leading to flooding of lowlands that formed important areas for Norse land use around the fjords (Kuijpers *et al.*, 1998). Thus, it can be concluded that climatic and hydrographic changes in the area of the Eastern Settlement were significant in the crucial period when the Norse disappeared. This may be in support of the view that environmental changes were an important factor contributing to the loss of the settlement.

Conclusion

The record of benthic foraminifera fauna changes during the last 3200 cal. yr BP have shown that the palaeohydrography of the outer part of Igaliku Fjord is closely linked to the variability of North Atlantic open-ocean circulation. Thus, the last three major Holocene cooling events with increased ice-rafting in the North Atlantic are reflected in the foraminifera faunas as periods with a strongly stratified water-column and Atlantic subsurface water masses prevailing in the bottom-water layer of the outer Igaliku Fjord.

The 'Mediaeval Warm Period' (MWP) was characterized by enhanced mixing of the water-column. In the course of this period, the hydrodynamic energy level in the fjord, and thus the wind stress, is concluded to have increased. In addition, the transition from the MWP towards the 'Little Ice Age' (LIA) is shown to have been stepwise with a short climatic amelioration punctuating the general cooling trend.

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