Early Holocene large-scale meltwater discharge from Greenland documented by foraminifera and sediment parameters

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Abstract

Records of foraminiferal assemblages combined with lithological properties (grain size, magnetic parameters and XRF data) of marine sediment cores from West Greenland coastal waters and the adjacent Labrador Sea document widespread early Holocene meltwater discharge. This discharge is concluded to originate from large-scale melting of the Greenland Ice Sheet (GIS) having started prior to 8,600 cal. yr BP and ended at about 7,700-7,500 cal. yr BP, when the GIS margin had withdrawn from the fjords and become mainly land-based. The benthic foraminiferal record from one of the coastal sites mainly reflects West Greenland Current (WGC) subsurface water properties and to a minor degree surface productivity. The most significant feature in this record is an abrupt shift to a higher-productivity regime around ~7,700 cal. yr BP. We suggest that the cessation of a widespread GIS meltwater discharge at that time favoured an increased influence of (sub)surface water of Atlantic origin and initiation of modern subpolar gyre circulation enabling Labrador Sea deep convection. Further offshore, a record of planktonic foraminiferal assemblages shows an oceanographic change at ca. 9,500 cal. yr BP, while a gradual but marked change in the planktonic foraminiferal assemblage between 8,800-7,000 cal. yr BP may be related to a narrowing of the WGC low-salinity surface water belt. The oceanic regime off West Greenland prior to ~7,800 cal. yr BP was thus characterised by the presence of a permanent and widespread meltwater surface layer, presumably preventing deep convection in this region. Apart from indications of a slight decrease in meltwater discharge by the benthic foraminiferal fauna data, neither of the records shows any clear signal of a regionally important 8.2 ka event.

Keywords: Greenland, early Holocene, meltwater discharge, foraminifera, sediment properties, magnetic susceptibility, 8.2 ka event
1. Introduction

Today we witness how melting of the Greenland Ice Sheet (GIS) has become a very important aspect of understanding the consequences of possible future climatic changes. The rising global average temperature may result in increased ice-sheet melting, a process that can be expected to accelerate in the future (e.g. IPCC 2007). Since 1979, the area of the inland ice influenced by melting has become significantly enlarged (Steffen et al. 2004), and satellite observations inform us that during the last decade, ice discharge from the GIS has led to a substantial increase in the annual ice-sheet mass deficit (Rignot and Kanagaratnam 2006, Nick et al. 2009, Rignot et al. 2011). Studies of ablation rates from ice cores furthermore indicate that GIS ice discharge rates over the last few decades in some areas surpass any rates reconstructed for the last 4,000 years (Mernild et al. 2012). In addition, during the past decades the temperature of the Arctic region has increased twice as much as in the rest of the world (ACIA 2004, AMAP 2009), demonstrating the high sensitivity of the Arctic region to climate change (Overpeck et al. 1997). Thus, the GIS is recognised as an important factor in future climate scenarios, not only because of sea-level rise, but also due to the possible meltwater impact on Atlantic Meridional Overturning Circulation (AMOC), which could eventually lead to marked cooling of the eastern North Atlantic region.

Past climate reconstructions attribute marked regional cooling to the effect of meltwater discharge into the North Atlantic, which may provide a possible analogue for future climate scenarios. For the early Holocene, evidence of such a North Atlantic cooling episode was first discovered in Greenland ice cores (Johnsen et al. 1992, 2001). This ‘8.2 ka cooling event’ has afterwards been recognised at numerous sites in the North Atlantic region (e.g., Klitgaard-Kristensen et al. 1998, Risebrobakken et al. 2003, Rohling and Pälike 2005, Alley and Ágústsdóttir 2005, Came et al.)
A generally accepted explanation for the origin of this event is a large-scale freshwater discharge from the Hudson Strait, Canada, where large proglacial lakes drained around 8,200 cal. yr BP, affecting the AMOC (Alley et al. 1997; Barber et al. 1999, Leverington et al. 2002, Hall et al. 2004, Ellison et al. 2006, Came et al. 2007, Kleiven et al. 2008). This also affected global atmospheric conditions, including a lowering of pCO$_2$ (Wagner et al. 2002). Only limited attention has, however, been given to the possible role of melting of the GIS, which represents the largest ice mass on the Northern Hemisphere since the early Holocene. Here, we study four high-resolution marine sediment records collected in West Greenland waters to test for a possible 8.2 ka event signal in this region and to investigate the potential influence of the GIS on early Holocene meltwater production. Lithology, magnetic susceptibility (MS) and anhysteretic remanent magnetization (ARM) records from three marine sediment cores taken in coastal waters off West Greenland illustrate the sedimentary regime and more specifically indicate the strength of meltwater discharge. For one of these records from Southwest Greenland, we additionally performed a high-resolution benthic foraminiferal study of the subsurface conditions, while the open-ocean conditions are documented by planktonic foraminiferal and stable isotope records from a fourth, deep-water core site in the northeastern Labrador Sea. Our discussions will focus on the early Holocene sections of these records.

2. Modern oceanographic conditions

Today the West Greenland region is mainly influenced by the West Greenland Current (WGC) (Fig. 1). At the surface, the WGC transports cold, low-salinity water masses consisting mainly of glacial meltwater and Polar Water from the East Greenland Current (EGC). At greater water depths (> 150-200 m), the WGC entrains warmer, saline Atlantic water-masses (Irminger Sea Water; ISW)
derived from the Irminger Current (IC) (Tang et al. 2004, Cuny et al. 2005). As the WGC flows northward along the West Greenland coast, its polar water component gradually turns westward, allowing the warmer, Atlantic component to rise towards the surface. On the western side of the basin, the Baffin-Labrador Current system transports cold, low-salinity Polar Water south along the Canadian coast.

3. Material and Methods

Our data derive from four marine sediment cores off West Greenland (Fig. 1; Table 1). Two piston cores, DA00-06P (hereafter DA06P) and DA00-04P (DA04P), were collected during a cruise in 2000 with the Danish research vessel RV Dana (Kuijpers et al. 2001) from Disko Bugt and Kangersuneq Fjord, respectively (Fig. 1). Piston cores DA04-31P (DA31P) and DA04-41P (DA41P) were obtained in 2004 during another GEUS-organised cruise with RV Dana (Dalhoff et al. 2005). DA31P was collected from the adjacent northeastern Labrador Sea, while DA41P is derived from Ameralik Fjord (Lysefjord) in the Godthåbsfjord region (Fig. 1).

The age control of the sediment cores is based on Accelerator Mass Spectrometry (AMS) $^{14}$C measurements carried out on planktonic and benthic foraminifera, mollusc shells and marine plant material at the AMS $^{14}$C Laboratory, Aarhus University (Denmark; AAR), the Leibniz-Laboratory for Radiometric Dating and Isotope Research, Kiel (Germany; KIA), Poznan Radiocarbon Laboratory (Poland; Poz) and the Utrecht van der Graaf Laboratorium (the Netherlands; UtC) (Table 2). The $^{14}$C ages were calibrated using the OxCal v. 4.1 program (Ramsey, 2008) and the marine calibration curve Marine09 (Reimer et al. 2009). Local reservoir ages, $\Delta R$, have been used for sites where $\Delta R$ information was available (Reimer and Reimer 2001, Table 2). To our knowledge,
information on local reservoir age variability for the Labrador Sea (DA04-31P) is non-existing and
a local reservoir age of ΔR = 0 ± 100 has therefore been used for the Holocene and ΔR = 0 ± 150 for
the pre-Holocene, i.e. a standard 400-year reservoir age with an uncertainty of the reservoir age of
100 years thus taking the general uncertainty of the reservoir age in the region into account (Fig. 2,
Table 2). Age models were constructed using depositional models in OxCal with k values between
50 and 100, yielding A_{model} > 95% for all sites. Where changes in sedimentation rate in the cores
occur, these have been placed at sedimentological and/or faunal boundaries when consistent with
the age model. For DA06P, an outlier model was further applied. In core 31P, the onset of the
Holocene at 55 cm (11,703 ±50 b2k), the Younger Dryas (12,896 ±69 b2k) and the Bølling (14,692
±93 b2k) were also used (Knutz et al. 2011). The above approach has resulted in a slight change in
age model compared to those previously published by Lloyd et al. (2005; DA00-06P), Knutz et al.
(2011; DA31P) and Ren et al. (2009; DA41P), which all used different approaches based on linear
interpolation between dating points. Cores DA06P, DA04P, and DA31P encompass the entire
Holocene, whereas a hiatus, or markedly reduced sedimentation rates, is found in core DA41P (ca.
7,400-4,400 cal. yr BP) (Ren et al. 2009; Fig. 2). For lists of ¹⁴C-dates and details on age models
see Table 2 and Lloyd et al. (2005; DA00-06P), Knutz et al. (2011; DA31P), Ren et al. (2009;
DA41P). All ages referred to below are given as calibrated years before present (cal. yr BP), where
BP equals 1950 AD. The age models are shown for the entire cores but the proxy data relevant to
this study will here be limited to the early Holocene sections.

Magnetic susceptibility (MS) measurements were carried out on three cores (Figs. 3, 4). The
measurements were performed on split halves of the cores using continuous 2x2x2 cm plastic boxes
at c. 2.25 cm intervals. The initial magnetic susceptibility (measured as mass specific magnetic
susceptibility (χ) in 10⁻⁶ m³kg⁻¹) of the subsamples was measured at Lund University using a
Anhysteretic remanent magnetization (ARM) was measured with a Molspin Minispin magnetometer and divided by the DC bias field to provide the mass specific susceptibility of ARM ($\chi_{\text{ARM}}$) (in $10^{-6}$ m$^3$ kg$^{-1}$). The $\chi_{\text{ARM}} / \chi$ ratios generally reflect the grain size of the magnetic mineral fraction; the use of magnetic parameters in palaeoceanographic studies has been widely discussed in the literature (e.g., Verosub and Roberts 1995, Stoner and Andrews 1999, Snowball and Moros 2003).

XRF core scan data from core 41P are described by Ren et al. (2009). The bulk geochemical composition was determined at the Royal Netherlands Institute for Sea Research, Texel, using an X-ray fluorescence (XRF) core scanner (Jansen et al. 1998) in 1-cm steps and reported as counts per second (cps). The intensity of the elements Fe, Ti, K, Ca and Br are included here (see also Ren et al. 2009). Grain sizes were obtained by use of wet sieving through mesh sizes of 0.063 and 0.100 or 0.150 mm.

Detailed benthic foraminiferal analyses were carried out on core DA41P (no or few planktonic foraminifera were present in the samples) at high resolution (Fig. 5). Except for the bottom part of the core containing low foraminiferal abundances, sub-samples for foraminiferal analyses were studied at 1-10 cm intervals with the main part of the relevant section studied at 1-5 cm resolution providing an average time resolution of 6.4 years for the section presented here; each cm of sediment comprises between 0.17 and 2.2 years. Planktonic foraminifera were analysed in DA04-31P (Fig. 6) at 0.5-10 cm intervals, generally giving a time resolution of 100-300 years. Each sample represents a 1cm slice of a core section. After weighing, the dried samples were immersed in a 5% solution of H$_2$O$_2$ for approximately 20 minutes. Subsequently, the samples were wet-sieved using mesh sizes of 1.0, 0.1 and 0.063 mm and they were further disintegrated using a peptizing agent (Na$_4$P$_2$O$_7$, 10H$_2$O). For a few samples only, it was necessary to concentrate the foraminifera.
through heavy liquid CCl₄ (density 1.66 g/cm³). Only foraminifera in the 0.1-1.0 mm fraction were analyzed. The 0.063-0.1 mm fraction yielded no species that were not also present in the 0.1-1.0 mm fraction and the >1.0 mm fraction was barren for foraminifera. The foraminifera were relatively well-preserved, and the occurrences of abrupt, significant changes in the faunas indicate that reworking and bioturbation were negligible. To obtain a statistically qualified dataset, we aimed at analyzing at least 300 benthic foraminifera in each sample, but a minimum of 60 specimens for one sample was accepted. Due to the loss of some counts after percentage calculation, the frequency of Cassidulina neoteretis cannot be shown for all samples. The flux of foraminifera was calculated assuming a mean sediment density of 1.89 g/cm³.

Oxygen and carbon isotope measurements of the planktonic species Neogloboquadrina pachyderma (sinistral) (core DA04-31P; Fig. 6) were performed on a Finnigan MAT252 mass spectrometer at Woods Hole Oceanographic Institution (WHOI) following the procedure described by Ostermann and Curry (2000). All values are calibrated to the PDB scale.

4. Results and palaeoenvironment

4.1. Greenland glacier retreat and meltwater production

The bedrock and thus the main provenance of the sediments at all three coastal sites (DA06P, DA04P, DA41P) consists of gneiss, while Cretaceous and Paleogene sedimentary strata and basalts are found on Disko Island and in parts of Disko Bugt (McGregor 1993; Henriksen et al. 2009). Except for the χARM/χ ratio from DA41P, the MS records from these three coastal sites show a general decrease from high values in the earliest part of the study period to considerably lower
values later, i.e. at around 7,700-7,500 cal. yr BP (Figs. 3, 4). For DA04P and DA06P the same is true for the $\chi_{ARM}/\chi$-ratio (Fig. 3), whereas the $\chi_{ARM}/\chi$-ratio in DA41P differs (Fig. 4). MS values depend on the content of magnetic grains but also on the grain size and mineralogy of the sediment (e.g. magnetite has a stronger signal than hematite). Generally, the MS signal is high in “glacier milk” (meltwater plume) deposits due to its high contents of hematite and it seems to be strongly linked to Fe in core DA41P. In contrast, $\chi_{ARM}/\chi$ ratios reflect more specifically the grain size of the magnetic mineral fraction (Moros et al. 2006) and are not simply linked to Fe. The XRF data from core DA41P show higher values of Iron (Fe), Potassium (K) and Titanium (Ti) (Fig. 4) prior to ca. 7,750 cal. yr BP. Fe, K and Ti are common elements in the bedrock surrounding the site (Steenfelt 1990), and may thus be used as indicators of terrestrial influence (Møller et al. 2006). Concurrently, fine-grained sediments (<0.063 mm sediment grain size) are found prior to ~7,700 BP in cores DA04P and DA41P (Figs. 3, 4), again dropping to lower values after ~7,550 BP in DA41P. A shift in magnetic grain size ($\chi_{ARM}/\chi$) in core DA06P at ca. 7,500 BP (Fig. 3) is coeval with the shifts in sediment seen in DA04P and DA41P within 2$\sigma$ errors, but the slightly later change may also be due to its closer proximity to the glacier. In general, the grain-size signal is less clear in core DA06P (Fig. 3). This may in fact be linked to its close proximity to the Jacobshavn Isbrae, which even today continues to exert strong influence on sediment deposition at this site, most notably with fine-grained sediments derived from meltwater plumes and coarser grains transported by icebergs.

All of these data indicate significant meltwater release from Greenland from at least as early as 8,600 cal. yr BP (core DA06P) until ca. 7,700±50 cal. yr BP (cores DA04P and DA 41P; 7,500 cal. yr BP in core DA06P) with a fine-grained unit marking deposition from large meltwater plumes. At relatively glacier-distal sites, meltwater plume deposits are typically characterized by structureless, homogeneous clays and silts (Dowdeswell and Cromack 1991), rich in hematite and goethite as
indicated by mineral magnetic parameters (I. Snowball, pers. comm. 2011), having accumulated at high sedimentation rates. As the ice retreated further towards land, the sediment grain size increased, suggesting a reduction of the meltwater plume possibly combined with a thinner surface meltwater layer and stronger bottom current activity, as also indicated by the increased frequencies of the benthic foraminifera A. gallowayi and C. lobatulus in core DA41P (Fig. 5). In the uppermost part of core DA41P, the coarser grained sediments again disappeared (Fig. 4), indicating a mainly land-based GIS margin and overall reduction in iceberg calving. A detailed analysis of core DA41P with the highest sedimentation rates documents that the decrease in meltwater discharge extended over a period of about 60 years from c. 7,760-7,700 cal. yr BP (Fig. 4). The complete transition to mainly land-based ice took, however, more time and continued until ca. 7,560 cal. yr BP.

The pattern arising from our core data thus indicates an initially fast ice retreat from the shelf to the coastal region and later further inland within a period of few hundred years. This episode represents the final stage of the deglaciation of the South and West Greenland shelf after the glacial period. Previous studies have dated a deglaciation of the West Greenland shelf at ~9-11,000 cal. yr BP (Knutz et al. 2011), with the ice reaching land about 10-11,000 cal. yr BP (Bennike and Björck 2002; Funder et al. 2004; Roberts et al. 2009; Long et al. 2011). Our data provide a more precise dating of the time (7,700-7,500 cal. yr BP), when the glaciers presumably no longer reached the fjords. However, as indicated by the studies referred to above, much of the surrounding land may have been deglaciated already prior to this time.

4.1. West Greenland Current palaeoceanography
The change in sediment composition in core DA41P was both preceded and accompanied by major changes in the benthic foraminiferal fauna. It is here noteworthy that the sill depth of about ~120 m of the Ameralik Fjord (Fig. 1) implies that the benthic foraminifera at this site reflect WGC subsurface conditions. The water depth at the sill notably represents the depth stratum of the upper boundary of the WGC Atlantic-derived (ISW) water masses. The lowermost part of the record contains only scant benthic foraminifera, which may be linked to a high meltwater supply from land (see above). After ca. 8,250 cal. yr BP the fauna was dominated by *Cassidulina reniforme*, *Cibicides lobatulus*, *Elphidium excavatum* f. *clavata* and *Astrononion gallowayi*, but with a characteristic component of *Melonis barleeanus* and *Stainforthia loeblichii* (Fig. 5). Dominance of the benthic foraminiferal species *E. excavatum* and *C. reniforme* indicates a glaciomarine, cold and unstable environment at the seafloor (Steinsund et al. 1994, Korsun and Hald 2000), and the presence of *S. loeblichii* supports the presence of sea ice (Steinsund et al., 1994) as was also suggested by the diatom assemblage (Ren et al. 2009). However, the presence of *M. barleeanus* as well as the common occurrence of high-energy species *C. lobatulus* and *A. gallowayi* (Rytter et al. 2002) indicate that a relatively strong influence of the WGC, entraining a significant ISW component, compensated the outflowing meltwater. *C. neoteretis*, which, despite its low numbers, may be considered a certain indicator of chilled Atlantic water (Seidenkrantz, 1995), indicates a further increase in influx of WGC/ISW water to this site after ca. 7,950 cal. yr BP.

Concurrently with the major changes in MS and grain size values (~7,750 cal. yr BP), *C. reniforme*, and *E. excavatum*, f. *clavata* became less abundant. In contrast, concentrations of *A. gallowayi*, *N. labradorica* and *G. auriculata arctica* increased together with a general rise in benthic foraminiferal flux (Fig. 5). Furthermore, the amount of Calcium (Ca) and Bromium (Br) increased (Fig. 4). With gneiss making out most of the bedrock in the area, no widespread Calcium-bearing rocks are found
in the proximity of the cores (McGregor 1993; Henriksen et al. 2009), and both Ca and Br may therefore be considered indicators of marine biological productivity (Ren et al. 2009). The high frequencies of *Nonionellina labradorica* indicate that this high-productivity period was, amongst others, linked to a nearby location of an oceanic polar front (Hald and Steinsund, 1992; Rytter et al., 2002) as the lower meltwater release from GIS would have allowed further penetration of WGC water into the coastal regions and fjords of West Greenland. After ca. 7,550 cal. yr BP, bottom currents weakened and high frequencies of *Brizalina pseudopunctata* and *Pullenia osloensis* (Fig. 5) indicate reduced bottom-water oxygenation.

Surface-water conditions in core DA41P were studied by Ren et al. (2009), who identified a corresponding major shift in diatom composition with an increase in the warm Atlantic-water indicator *Thalassionema nitzschioides* and a decline of the sea-ice species *Fragilariopsis cylindrus* in the period 7,800-7,600 cal. yr BP; this shift can now be more precisely dated to 7,720 cal. yr BP using our new age model.

The planktonic foraminifera from the adjacent, open northeastern Labrador Sea (deep-water core DA31P) were generally dominated by the polar species *Neogloboquadrina pachyderma* (sinistral) during the entire study period (Fig. 6). However, relatively high frequencies of *Turborotalita quinqueloba* are found prior to ~8,800 cal. yr BP. This is a species known to bloom in areas close to oceanic fronts (Johannesen et al. 1994). This indicates that the oceanic front between WGC water and the polar waters of the central Labrador Sea, which today is found east of the DA31P site, may at that time have been located closer to core DA31P, i.e west of its present location and further from the Greenland coast. Percentages of the warmer-water species *Neogloboquadrina incompta* (=*N. pachyderma* dextral, Darling et al. 2006, Be´ and Tolderlund 1971) were lower around 8,000 cal. yr
BP, while *N. pachyderma* (sinistral) increased (Fig. 6). At the same time fluxes of planktonic foraminifera were reduced. Stable oxygen isotope values remained relatively unchanged after ca. 9,500 cal. yr BP. In contrast, carbon isotopes show a clearer overall shift to heavier values at about 8,800 cal. yr BP, concurrent with the first decrease in *T. quinqueloba* and increase in *N. pachyderma* (sin). This suggests more stable stratification and surface water cooling presumably related to enhanced meltwater influx.

5. Discussion

The magnetic records from the studied coastal sediment cores (Figs. 3, 4) reflect lithological variations, with high values of MS and/or $\chi_{ARM}/\chi$ here being indicative of terrestrially-derived minerals as also supported by grain sizes and XRF data (Møller et al. 2006, Moros et al. 2006, Seidenkrantz et al. 2007, Ren et al. 2009). Meltwater plumes represent the main source for terrestrially-derived sediments in this region, and the MS records may thus in our study area be used as an indicator of Greenland Ice Sheet (GIS) meltwater discharge in the sense that high MS values in relation to massive silty clay and silt units reflect deposition of suspended matter associated with extensive meltwater plumes from the GIS. In fact, on visual inspection all three cores show massive silt deposition especially associated with the maximum MS values in the early Holocene (Figs. 3, 4) from before 8,600 cal. yr BP onwards (core DA06P; Fig. 3). This points to strong and widespread meltwater discharge at that time. The excessive meltwater production in the early Holocene corresponds to findings by Rinterknecht et al. (2009), who reported a general and fast thinning of the western margin of the GIS in the order of 240 m having occurred between about 12,300 cal. yr BP and 8,300 cal. yr BP. A significant GIS retreat during this period is also indicated for the Nares Strait region (England 1999, England et al. 2006), while Fagel et al. (1997) observed a
minimum in smectite suggesting a shorter-term intensified supply of meltwater from the South Greenland margin. The maximum meltwater discharge appears to have decreased near synchronously when comparing the sites from Disko Bugt (DA06P and DA04P) with that from Ameralik Fjord near Nuuk (DA41P). By ca. 7,700-7,500 cal. yr BP, meltwater production had drastically decreased, presumably related to an onshore retreat of the GIS to the coastal margins. Decreased GIS melting and thinning of the surface meltwater layer allowed increased deposition of coarser-grained sediments and stronger bottom current activity (Fig. 5). The marked synchronicity of this decrease in meltwater output may not only characterise the early Holocene retreat and GIS melting history of the West Greenland coastal area, but may be characteristic for the entire sector of Greenland coastal waters affected by warm, saline (subsurface) waters derived from the Irminger Current (IC). A marked intensification of this current system has been reported from Icelandic waters to have occurred at ca. 7,800 cal. yr BP (Castañeda et al. 2004; Olafsdottir et al. 2010), and an associated increase in coarser IRD deposition is documented in sediment records from the Southeast Greenland shelf (Kuijpers et al. 2003). By 6,800 cal. yr BP, the IC had penetrated far north into ocean waters north of Iceland (Jennings et al. 2011).

Benthic foraminiferal faunas from core DA41P from Ameralik show that the West Greenland Current (WGC) was already active at 8,400 cal. yr BP, but with Atlantic-derived waters having less influence prior to 8200 cal. yr BP at the DA41P coring site. The marked decrease in meltwater runoff shown in the MS and XRF records at ca. 7,700 cal. yr BP (Fig. 4), was accompanied by a further strengthening of the inflow of WGC water of Atlantic (ISW) origin into the fjord as shown by the drop in E. excavatum and C. reniforme and increased abundance of C. lobatulus and A. gallowayi, indicating higher bottom current activity. This is supported by virtue of the Atlantic-water indicator C. neoteretis, which was still present. This increased inflow of WGC water may
thus, amongst others, be linked to a retreat of originally marine-based glaciers causing a reduction in meltwater discharge. The accompanying increase in *G. auriculata, N. labradorica* and benthic foraminiferal flux as well as the higher intensities of Br and Ca after 7,750 cal. yr BP, suggest higher food availability, probably through increased primary production linked to this increased inflow of Atlantic-source water from the WGC. An increased inflow of WGC water is also supported by the diatom assemblage (Ren et al. 2009). Following the end of the high-productivity event at ca. 7,550 cal. yr BP, the benthic foraminifera indicate a reduction of bottom-water oxygenation and reduced bottom current speeds. This implies a shift to more locally influenced conditions and a somewhat reduced inflow of WGC water into the fjord, presumably associated with a continued weakening of the out-flowing meltwater along the surface. This may be linked to a weaker Greenland High and a weaker Subpolar Gyre as suggested by IC changes recorded east of Greenland (Jennings et al. 2011).

The planktonic foraminiferal record from the northeastern Labrador Sea (core DA31P; Fig. 6) supports the scenario of a large-scale meltwater episode affecting waters around Greenland in the early Holocene. The drop in planktonic δ¹⁸O concurrent with the peak occurrence of *T. quinqueloba* between ca. 9,500 and 8,800 cal. yr BP may be due to slightly reduced surface water salinity. Relatively high frequencies of *T. quinqueloba*, known to bloom in areas close to oceanic fronts (Johannesen et al. 1994), suggests that the oceanic front between WGC water and the polar waters of the central Labrador Sea was close to this site, i.e. much further west than its present location. This may be attributed to increased GIS meltwater release leading to expansion of the entrained WGC low-salinity surface layer. The following increase in *N. pachyderma* (sin) and decrease in *T. quinqueloba* and *Globigerina bulloides* at ~8,800 cal. yr BP may be caused by a decrease in sea-surface temperature in the northeastern Labrador Sea (Fig. 6) and more stable stratification. A more
stable stratification around 8,000 cal. yr BP leading to decreased productivity is also suggested by lowered planktonic foraminiferal fluxes. In addition, this episode also yields some evidence of a short-term intensified cooling suggested by a minimum percentage of *N. incompta*. Whether these relatively short-term changes may be related to the ‘8.2 ka cooling event’ would need further study. The more stable conditions after ~7,000 BP are in agreement with a Labrador Sea oceanographic regime marked by deep convection (see Hillaire-Marcel et al. 2001).

Evidence for a marked glacier retreat and an associated enhanced meltwater production prior to 8,400 cal. yr BP has also been identified in adjacent regions in the Arctic, in particular from the Nares Strait region (Mudie et al. 2004/2006; England et al. 2006). Such a high GIS meltwater output, possibly causing a widespread thick and cold, low-salinity meltwater surface layer offshore South and West Greenland and northeastern Canada from well before 8,200 cal. yr BP to shortly after that time, may also explain the significantly delayed start of the Holocene Thermal Optimum around Hudson Bay (until ca. 7,000 cal. yr BP) when compared with Alaska and northwest Canada (Kaufmann et al. 2004, Keigwin et al. 2005). This scenario is supported by studies concerning Labrador Sea Water formation (Hillaire-Marcel et al. 2001) showing that Labrador Sea deep convection did not take place before ca. 7,500 cal. yr BP, when also the western branch of the North Atlantic Drift may have become strengthened (Andersen et al. 2004). North of Iceland a similar strengthening of the northern branch of the IC was initiated at ~7,800 cal. yr BP (Castañeda et al., 2004; Olafsdottir et al. 2010).

Despite the high GIS meltwater release indicated by our data, the relatively warmer and saline ISW entrained at subsurface depths by the WGC thus influenced the Greenland coast already prior to 8,300 cal. yr BP (Lloyd et al. 2005), with the ISW component proportionally increasing after ca.
7,700 cal. yr BP. This also confirms the conclusions by Knudsen et al. (2008) who found that significant Atlantic Water influence occurred in the Nares Strait well before 8,200 cal. yr BP. In fact, ‘warm’ ISW entrained by the WGC may have played an important role in its contribution to subglacial melting of the floating glaciers and deglaciation of the West Greenland fjords and coastal waters. A combination of an active WGC and high GIS meltwater discharge may reflect the state of an intensified subpolar gyre circulation as suggested for the 8.2 ka event (Born and Levermann 2010). Based on model simulations, these authors suggest that the freshwater release stabilised the gyre through internal feedbacks causing an intensification of deep-water formation in its centre.

The 8.2 ka event is clearly identified in central GIS ice cores (e.g., Alley et al. 1997; Kobashi et al. 2007). However, apart from a possible slight increase in the >150 µm grain size fraction in core DA06P (8,400-8,100 BP; Fig. 3), possibly due to increased ice-rafting, neither of our records show an actual cooling episode around the well-known 8.2 ka event, even though several of the cores yield a sufficiently high resolution for potential detection of this event. Our data thus imply that the GIS was subject to strong melting already prior to the 8.2 ka event and that this meltwater discharge into Greenland coastal waters continued until about 7,700±50 cal. yr BP. Exposure dating may, however, indicate a stagnating ice front at ~8.3 ka near Kangerlussuaq (Rinterknecht et al. 2009). Although a marked change in GIS melting around 8,200 cal. yr BP affecting West Greenland coastal hydrographic conditions could not be found, we do observe some support for the findings by Rinterknecht et al. (2009) as the increase in benthic foraminifera in DA41P just prior to 8,200 cal. yr BP suggests a slight decrease in meltwater release. This meltwater reduction may have facilitated an increased influx of more saline WGC water into the fjord. The XRF and MS data from this core do, however, not indicate a more substantial change in meltwater discharge. The slight increase of the >150 µm (IRD) sediment fraction in DA06P may be due to a thinning of the surficial meltwater
layer favouring iceberg bottom melting, but may also be related to the reduction in meltwater
discharge causing a lower sedimentation rate as suggested by the age model (Fig. 2). Furthermore,
our data do not completely rule out the possibility that the 8.2 ka event caused a change in ocean
conditions further offshore West Greenland. Thus, as also previously concluded for the Disko Bugt
area by Long et al. (2006), the 8.2 ka event made only a minor imprint on the GIS melting pattern
in the region, if any.

A similar conclusion was drawn based on sediment cores from along the eastern margin of North
America, including the Hudson Strait. These cores did not show any evidence for a change in the
surface and deep ocean environment around the 8.2 ka cold event (Keigwin et al., 2005). These
sites can be expected to have been directly affected by a freshwater discharge from the glacial lakes
in North America. In the Spitsbergen region, sea-surface temperatures (Sarnthein et al. 2003;
Ebbesen et al. 2007) show a significantly earlier cooling, presumably related to a southward
expansion of Arctic Water masses already at 8,800 cal. yr BP (Ebbesen et al. 2007). This cooling
thus spans a much longer period than the relatively short 8.2 ka event. North of Iceland, the cooling
event was recorded as an episode of minor amplitude (Castañeda et al. 2004; Jennings et al. 2011),
whereas off East Greenland it is only observed as a very minor excursion in carbonate flux
(Jennings et al. 2002). In fact, the 8.2 ka cooling event has only been found as a clear spike in
certain areas of the North Atlantic that are directly influenced by the North Atlantic Current (e.g.,
Cane et al. 2007, Sachs 2007, Kleiven et al. 2008), but its signal is virtually absent in those areas
mainly influenced by the EGC, WGC, or Baffin-Labrador Current systems (Keigwin et al. 2005,
Sachs 2007), or in the high-Arctic Spitsbergen region (Ebbesen et al. 2007). These latter areas are
all characterised by the permanent presence of a low-salinity, cold, often ice-loaded, surface water
layer, which may prevent recording of a cooling event that is observed elsewhere in the North Atlantic.

Thus, our results indicate that meltwater and low-salinity water masses expanded in both the Greenland and Spitsbergen regions prior to 8,200 cal. yr BP. This may be related to the early Holocene warming of the circum-Arctic region, including Greenland (Kaufmann et al. 2004), which led to enhanced GIS and glacier melting around the Arctic. Subsequent marked freshening of the EGC and WGC systems as well as the B-LC region led to slowdown of high-latitude deep convection and thus contributed to North Atlantic cooling. In turn, major freshwater release peaking at about 8,200 cal. yr BP may subsequently have triggered internal ocean feedback processes leading to enhanced subpolar gyre convection (cf. Born and Levermann 2010). A stronger WGC with a proportionally increased ISW component eventually, i.e. after 7,700 cal. yr BP, led to a Labrador Sea subpolar gyre regime favouring deep convection. In summary, we propose that large-scale melting of the GIS may have significantly contributed to a lowering of North Atlantic surface salinity prior to 8,200 cal. yr BP. The fact that the West Greenland melting pattern seems virtually unaffected by the 8.2 ka event indicates, however, that the GIS was probably not a main driver for this event.

6. Conclusions

We have analyzed early Holocene sedimentary records from West Greenland coastal waters in order to test the possible role of the Greenland Ice Sheet (GIS) for meltwater production during this period. Special attention has been paid to the time around the well-known North Atlantic 8.2 ka cooling event (e.g., Klitgaard-Kristensen et al. 1998, Risebrobakken et al. 2003, Rohling and Pälike
2005). This event has been attributed to effects of a massive freshwater discharge from the Hudson Strait (Barber et al. 1999, Leverington et al. 2002).

Our data from three sedimentary records collected from the Greenland shelf region document high MS and in parts elevated $\chi_{ARM}/\chi$ values related to massive silt deposition. This is ascribed to deposition associated with large-scale meltwater plumes from the GIS over a longer period spanning the centuries before 8,200 cal. yr BP (earliest indications occurring approximately 8,600 cal. yr BP), and ending after ca. 7,700 cal. yr BP. XRF trace-element composition and foraminiferal faunas from one of the cores provide additional evidence for excessive meltwater production, which can be related to early Holocene warming of the circum-Arctic region including Greenland.

Planktonic foraminiferal fauna data from a deep-water site further offshore in the northeastern Labrador Sea indicate widespread presence of negative salinity anomalies reaching far offshore Greenland. Significant freshening of surface waters around Greenland already prior to 8,200 cal. yr BP can be expected to have led to a slowdown of deep-water formation and, in turn, a relatively weak Meridional Overturning Circulation during the early Holocene.

Our data indicate initiation of a modern Labrador Sea subpolar gyre system and West Greenland Current (WGC) configuration at about 7,700 cal. yr BP, leading to regional deep convection shortly after that time as previously reported by other authors (e.g., Hillaire-Marcel et al. 2001). This notably does not exclude the existence of a WGC prior to that time, and our data indeed indicate the presence of an early, strong WGC. This current probably played a major role in the deglaciation of the West Greenland shelf and fjords. The hydrographic structure of this older WGC system may, however, have been characterized by a very broad low-salinity surface layer reaching far beyond the shelf edge and originating from enhanced production of meltwater from the GIS. A similar
scenario has previously been reported for the East Greenland Current on the Southeast Greenland shelf (Kuijpers et al. 2003). Together with results from core studies in Iceland and East Greenland waters (Castañeda et al. 2004; Olafsdottir et al. 2010; Jennings et al. 2011), our data thus indicate that significant deglacial GIS melting ceased by ca. 7,700 cal. yr BP, which allowed the establishment of a modern subpolar gyre system and deep-water convection in the Labrador Sea.

We thus conclude that significant melting of the GIS should be taken into account when discussing driving mechanisms underlying the 8.2 ka event, as large-scale melting of the GIS may have contributed to a lowering of North Atlantic surface salinity prior to 8,200 cal. yr BP. Melting of the GIS was thus presumably an important factor for setting the stage for the 8.2 ka event. However, it was probably not a main driving mechanism for the 8.2 ka event itself.

7. Acknowledgements

Funding was provided by the Carlsberg Foundation (grants to HE and MFK), the Geological Survey of Denmark and Greenland (GEUS), The Danish Council for Independent Research | Nature and Universe (FNU Grants 21-04-0336 and 09-069833 to AKU and MSS), the EU FP7 project ‘Past4Future’ (project no. 243908), and the German Science Foundation DFG (grant MO1422/2-1 to MM). Shiptime on RV Dana (2000) was funded by FNU (grant to AKU), while the 2004 Dana cruise was financed by the Greenland Bureau of Mineral Resources, Nuuk, and GEUS. Master and crew of RV Dana are acknowledged for their assistance and engagement during the work at sea. We would like to thank Ian Snowball, Lund University, Sweden, for discussions on mineral magnetic parameters and supervision of measurements. We would also like to thank Ingerlise Nørgaard
(GEUS) and Svend Meldgaard Christiansen† (Aarhus University) for laboratory assistance. Finally, we are grateful for the suggestions and comments by the two anonymous reviewers.
8. References


Arctic Climate Impact Assessment (ACIA), 2004. Issued by the Fourth Arctic Council Ministerial Meeting, Reykjavik.


Figure captions

**Figure 1.** Location map of the study region. The modern surface ocean circulation is mainly influenced by waters from the East Greenland Current (EGC) and the West Greenland Current (WGC). At the surface, the WGC transports cold, low-salinity water masses including glacial meltwater and Polar Water derived from the EGC. At greater water depths (> 150-200 m), the WGC entrains warmer, saline Atlantic water-masses (Irminger Sea Water) derived from the Irminger Current (IC). NADW: North Atlantic Deep Water. The investigated marine sediment cores were collected at four sites off West Greenland. Two of the sites are located in the Disko Bugt area (DA00-04P and DA00-06P), while one core site is located in Ameralik Fjord (DA04-41P) near Nuuk. These core data were compared with a lower-resolution planktonic foraminiferal record from the northernmost Labrador Sea basin (DA04-31P).

**Figure 2.** Age models for cores DA06P, DA04P, DA31P and DA41P. The age models are based on calibrated $^{14}$C datings, the OxCal 4.1 program, and correlation with the Greenland ice core chronology.

**Figure 3.** Magnetic susceptibility ($\chi$) and $\chi_{ARM}/\chi$ ratios as well as >63 µm and >150 µm grain size fractions (in % of the total sediment) from cores DA06P and DA04P. For explanation, see text (Results and palaeoenvironment).

**Figure 4.** A detailed study of the early Holocene from core DA04-41P, illustrating magnetic susceptibility ($\chi$), $\chi_{ARM}/\chi$ ratios, the >63 µm grain size fraction (% of the total sediment), the
elements Fe (Iron), K (Potassium), Ti (Titanium), Ca (Calcium) and Br (Bromium) measured in cps (counts per second, x1000 or x100).

**Figure 5.** A detailed record of the early Holocene from core DA04-41P, illustrating the occurrence of the most important benthic foraminiferal species (%), as well as the benthic foraminiferal fluxes (no. specimens/year). Magnetic susceptibility ($\chi$) values are shown for comparison. Due to extreme surface water characteristics associated with meltwater outflow, the planktonic foraminiferal fauna in these cores is extremely scant or non-existent.

**Figure 6.** A detailed record of the planktonic foraminifera, production of planktonic foraminifera (numbers/gram sediment) and stable oxygen and carbon isotopes (measured in PDB) in core DA04-31P, during the period from 10,000-6,000 cal. yr BP.

**Table caption**

**Table 1.** Studied marine sediment cores.

**Table 2.** An overview of the AMS $^{14}$C dates and age correlation of the studied sediment cores. The individual age models for each core were performed by using OxCal 4.1 depositional models. The AMS $^{14}$C dates are shown in Table 2. The radiocarbon ages were converted into calibrated years by using OxCal 4.1 (Ramsey 2008) and the marine calibration curve, marine09 (Reimer et al. 2009) with local reservoir ages $\Delta R$. 
Figure
Figure

Foraminifera rare to absent
Table 1. Studied marine sediment cores

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<th>Latitude</th>
<th>Longitude</th>
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<th>Core length (cm)</th>
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### Table 2. Radiocarbon dates and calibrated ages

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<th>Material dated</th>
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<th>AR. (yrs)</th>
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<td>765-767</td>
<td>AAR-10792</td>
<td>Benthic foram. fauna</td>
<td>7525±65</td>
<td>129±84</td>
<td>7870-8335</td>
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<td>7765±75</td>
<td>129±84</td>
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<tr>
<td><strong>Core length</strong>: 861.5 cm</td>
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