Centennial scale benthic foraminiferal record of late Holocene oceanographic variability in Disko Bugt, West Greenland

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Abstract:

We present a new centennial to decadal scale benthic foraminiferal record of late Holocene climate variability and oceanographic changes off West Greenland. The investigated site from southwest Disko Bugt highlights substantial subsurface water mass changes (e.g. temperature and salinity) of the West Greenland Current (WGC) over the past 3.6 ka BP. Benthic foraminifera reval a long-term late Holocene cooling trend, which may be attributed to increased advection of cold, low salinity water masses derived from the East Greenland Current (EGC). Cooling becomes most pronounced from *c.* 1.7 ka BP onwards, as the calcareous Atlantic benthic foraminiferal fauna decreased significantly, while being replaced by an agglutinated Arctic fauna. Superimposed on this cooling trend, centennial scale variability in the WGC reveals a marked cold phase at *c.* 2.5 ka BP, which may correspond to the 2.7 ka BP cooling-event recorded in marine and terrestrial archives elsewhere in the North Atlantic region. A warm phase recognized at *c.* 1.8 ka BP is likely to correspond to the 'Roman Warm Period' and represents the warmest bottom water conditions recorded in Disko Bugt during the last 3.6 ka BP. During the time period of the 'Medieval Climate Anomaly' we observe only a slight warming of the WGC. A progressively more dominant cold water contribution from the EGC on the WGC is documented by the prominent rise in abundance of agglutinated Arctic water species from 0.9 ka BP onwards, which culminates at c. 0.3 ka BP. This cooling event represents the coldest episode of the 'Little Ice Age'.

Gradually increased influence of cold low salinity water masses derived from the EGC may be linked to enhanced advection of Polar and Arctic water by the EGC. These changes are possibly associated with a reported shift in the large-scale North Atlantic Oscillation atmospheric circulation pattern towards a more frequent negative North Atlantic Oscillation mode during the late Holocene.

1. Introduction

The Disko Bugt area in central West Greenland (Fig.1) is linked to the large-scale North Atlantic current system and climate variability via the West Greenland Current (WGC). The relative influence of Atlantic (e.g. Irminger Current) vs. Arctic (e.g. East Greenland Current) derived water masses within the WGC determines the hydrographic conditions off West Greenland with significant impact on the benthic foraminiferal fauna. Previous studies reported postglacial re-appearance of the WGC in the Disko Bugt area from *c.* 9 to 10 ka BP, based on mollusc, dinocyst and foraminifera data (e.g. Kelly, 1979 and 1985; Ostermann and Nelson, 1989, Feyling-Hanssen and Funder, 1990; Funder and Weidick, 1991; Lloyd et al., 2005). Cooling is reported from *c.* 5 ka BP in Disko Bugt, possibly associated with Neoglacial cooling identified throughout much of western Greenland (Kelly, 1980; Dahl-Jensen et al., 1998; Kaufman et al., 2004). A variety of studies from Disko Bugt and the West Greenland margin document increased temperature and salinity variability in the WGC during the late Holocene (Lassen et al., 2004; Lloyd, 2006a,b; Lloyd et al., 2007; Møller et al., 2006; Moros et al., 2006b; Lloyd et al., 2007; Seidenkrantz et al., 2007, 2008; Krawczyk et al., 2010). In addition, WGC temperature changes on a multi decadal timescale has been noted to have a profound impact on subsurface melting of Disko Bugt outlet glaciers (e.g. Jakobshavn Isbræ), at least during the last 60 years (Holland et al., 2008; Rignot et al., 2010; Lloyd et al., 2011).

One proxy method to investigate changes in ocean current properties is to study benthic foraminifera. Their faunal diversity and species distribution is highly dependent on ecological parameters (Murray, 1991). The distribution of certain species, particularly in high arctic environments, is strongly controlled by water mass characteristics, such as temperature and salinity (e.g. Rytter et al., 2002; Sejrup et al., 2004) and surface water productivity (i.e. food supply). This close relationship has been well documented in a number of benthic foraminiferal studies from west and south Greenland (e.g. Lassen et al., 2004; Lloyd, 2006a,b; Seidenkrantz et al., 2007), the Baffin Bay area (e.g. Schröder-Adams et al., 1990; Schafer and Cole, 1986), fjords along the East Greenland margin and fjords and in the northern North Atlantic region, including Iceland (e.g. Jennings and Helgadottir, 1994; Andrews et al., 2001; Jennings et al., 2002) and Svalbard (e.g. Hald and Steinsund, 1992).

In the present study a new marine sediment core from south-western Disko Bugt is used for high-resolution paleoenvironmental reconstruction to elucidate qualitative changes in bottom water mass properties of the WGC through the late Holocene (since 3.6 ka BP). We use benthic foraminifera to achieve this aim, which provide now a highly detailed picture of late Holocene oceanographic evolution in West Greenland (i.e. WGC property changes). In addition, our data will allow investigation of the link between oceanographic changes off West Greenland and North Atlantic circulation changes as recorded in other marine and terrestrial records in the North Atlantic region.

2. Study area and oceanographic setting

Disko Bugt, located in central West Greenland, is a large marine embayment (Fig.1). The topography of the area is characterized by a rugged sea bed with relatively shallow water depths, typically varying between 200 and 400 m. Maximum water depths of up to 990 m occur in the deep water trough, 'Egedesminde Dyb' (Fig. 1). The Egedesminde Dyb channel has a glacial origin and continues to the shelf edge where a large trough-mouth fan is found (Zarudzki, 1980). CTD data from Disko Bugt (Andresen, 1981; Buch, 1981; Buch et al., 2004; Lloyd et al., 2006) show that the WGC (3.5–4 °C, 34.2–34.4 PSU) forms the bottom waters in the bay. Surface waters, in contrast, are influenced by fresh-meltwater flux from land, icebergs and the previous season's pack ice as well as relatively low-salinity polar surface water advected from Baffin Bay. Temperature and salinity profiles along a transect from south-west to central Disko Bugt show that the WGC constitutes the water mass below *c.* 150 m water depth (Harff et al., 2007). Further Andresen (1981) found no indications of an admixture of deep Baffin Bay waters below 300 m water depth, penetrating into Disko Bugt. The WGC constitutes a mixture of the following water masses: Atlantic-sourced relatively warm and saline water from the North Atlantic Irminger Current (IC), a side branch of the North Atlantic Current (NAC); Arctic-sourced cold, low-salinity water from the East Greenland Current (EGC) (Buch, 1981); and local meltwater discharge into the WGC along the SW Greenland coast (see Fig.1). The WGC enters Disko Bugt from the southwest and flows northwards exiting primarily through the Vaigat into Baffin Bay. A branch of the WGC is deflected into Baffin Bay in an anticyclonic gyre west of Disko Island, while the remainder of the WGC continues to flow northward into northern Baffin Bay (Andresen, 1981; Humlum, 1999; Bâcle et al., 2002). Recent studies show that the WGC also penetrates the deeper parts of the fjords in Disko Bugt, for example Jacobshavn Isfjord and Torssukatak (Holland et al., 2008; Rignot et al., 2010). The presence of the WGC in Disko Bugt has a significant impact on the distribution of agglutinated and calcareous benthic foraminifera (Lloyd et al., 2006b; Lloyd et al., 2011). The study site investigated here reflects open-marine environmental conditions rather than glaciomarine, as sedimentation in Egedesminde Dyb is linked to current activity.

3. Material and Methods

3.1 Sediment sampling

Sediments were collected from site MSM 343310 (68°38’861N, 53°49’493W, Fig. 1) by using a multi and a gravity core in the deep-water trough Egedesminde Dyb, south-western Disko Bugt (water depth: 855 m) during cruise MSM05/03 of the *R/V* “Maria S. Merian” (Harff et al., 2007). The multi core (length: 32

cm) was sampled in 0.5 cm and the gravity core (length: 939 cm) in 1 cm intervals and stored at 4°C in a cold storage facility.

3.2 Chronology

Age control is provided by accelerator mass spectrometry AMS ^{14}C dates on mollusc shells and benthic foraminifera (Table 1, Fig. 2). The chronology of the multi core is based on 10 AMS ^{14}C dates, ^{210}Pb/^{137}Cs measurements and other chronological evidence (Lloyd et al., 2011). The chronology of the gravity core is based on 20 AMS ^{14}C dates. AMS radiocarbon dates were calibrated with the Marine09 (Reimer et al., 2009) calibration curve using OxCal 4.1 (Bronk Ramsey, 2009). The marine reservoir offset was estimated using the marine reservoir age database of Reimer and Reimer (2001). This database includes six entries for Disko Bugt from bivalves (*Mytilus edulis and Astarte montagui*) and seal bones (Krog and Tauber, 1974; Tauber 1979; McNeely et al., 2006). Most of these samples are from shallow water, so we use the larger and more precise ΔR of 140 ± 30 years, than the smaller ΔR of two measurements on *Astarte* collected in 60-70m water (McNeely et al., 2006). An age model was fitted to the calibrated ^{14}C using mixed effect modeling (Heegaard et al., 2005).

3.3 Foraminiferal sample processing

For foraminiferal analysis of the calcareous and agglutinated fauna, a standard volume of 5 ml sediment was soaked in deionized water overnight and sieved at 63 µm just before counting. The multi core was counted at 0.5 cm intervals and gravity core at 4 cm intervals. Foraminifera were counted from the wet residue >63 µm to reduce the loss of the more fragile arenaceous species caused by drying out of sediment. More than 350 benthic foraminiferal specimens were counted per sample, on a squared picking tray and identified to species level under a stereomicroscope. Planktonic foraminifera, all *Neogloboquadrina pachyderma* (sin.), were also picked and identified from the 63 µm fraction. However, abundance of *N. pachyderma* is very low (<1 %) and therefore not included in the following discussion.

4. Results

4.1 Lithology

Sediments from site 343310 are composed of moderate olive brown to olive gray mottled organic rich silty clay. The total organic carbon content is on average 2.8%. The sand content (fraction >63µm) of the sediment is relatively low and averages *c.* 4% of dry weight. X-radiograph analysis revealed that only a small quantity of ice-rafted detritus (IRD) occurs in the sediments. Further, no turbidites are observed in the record.

4.2 Age models

The age model reveals a high and almost linear sedimentation rate of 3.5 mm per year (Fig. 2). Hence, our sample resolution of 4 cm allows the proxies to be resolved at decadal scale (12-15 years, Fig. 2). According to our age models the multi core and gravity core do not overlap. The composite record shows a gap of approximately 100 years, which is due to the gravity core coring technique. Parallel dating of mollusc shells and benthic foraminifera from same depth intervals revealed no divergence between respective AMS ^{14}C dates as variation is within the error (see Table 1). The applied ΔR of 140 ± 30 years (Lloyd et al., 2011) represents the modern day value in Disko Bugt, as the water mass composition of the WGC is predominantly influenced by the EGC. This ΔR fits with the reported range of ΔR of

130 to 115 ± 25 years for the EGC (Tauber and Funder, 1975). Because of the variable influence of the EGC on WGC water mass properties through time (see following discussion) we are aware of possible variations in ΔR with time, which should be considered when comparing our results to other records/ events in the North Atlantic region.

4.3 Benthic foraminifera

4.3.1 General faunal characteristics

A total of 53 benthic foraminiferal species were identified: 20 agglutinated and 33 calcareous taxa. A complete list of identified species is given in appendix A.1. An average of 30 species was identified and species abundance averages 150 specimens per ml of wet sediment per sample. We find good preservation of agglutinated and calcareous taxa and only minimal evidence of post mortem (dissolution) changes, supported by low numbers of counted test linings per sample (Fig. 3). The total benthic foraminiferal fauna is characterized by high abundance of *Cuneata arctica*, *Deuterammina ochracea*, *Eggerella advena* and *Spiroplectammina biformis* (agglutinated taxa) and by *Cassidulina reniforme*, *Elphidium excavatum* forma *clavata*, *Islandiella norcrossi* and *Nonionellina labradorica* (calcareous taxa, see Fig. 3).

To address and identify changes in water mass characteristics of the WGC, we use summary curves of benthic foraminifera based on their ecological tolerance (associated directly or indirectly with temperature and salinity). We use a chilled Atlantic water group (AtlW), including relative warm water taxa and an Arctic water group (AW), including relatively cold water taxa (see Table 2). Atlantic water indicators are: *Cassidulina reniforme*, *Islandiella norcrossi, Pullenia osloensis, Cassidulina neoteretis* (calcareous species), and *Adercotryma glomerata,* *Ammoscalaria pseudospiralis*, *Reophax fusiformis* and *Reophax pilulifer* (agglutinated species). These species are often reported from fjord and shelf areas associated with Atlantic water influence (Vilks, 1981; Mudie et al., 1984; Mackensen et al., 1985; Jennings and Helgadottir, 1994; Hald and Steinsund, 1996; Hald and Korsun, 1997; Duplessy et al., 2001; Wollenburg et al., 2004; Lloyd 2006a). The species *C. reniforme* is often associated with glaciomarine conditions from relatively shallow and glacially influenced fjords (e.g. Nagy, 1965; Elverhøi et al., 1980; Ostermann and Nelson, 1989; Vilks, 1989; Jennings and Helgadottir, 1994; Hansen and Knudsen, 1995; Hald and Korsun, 1997, Lloyd, 2005). However, we include *C. reniforme* in the Atlantic group, which has been associated with chilled Atlantic water (e.g. Hald and Steinsund 1996). This is supported by the context of our study, as the site investigated here is from a deep-water trough (855 m water depth) in relatively open water conditions (relatively high TOC content, average of 2.8%) under the direct influence of the WGC (Atlantic sourced water) and approximately 100 km from modern tidewater glaciers in the fjords of Disko Bugt. Importantly the site is not subjected to any direct melt water discharge from the Greenland Ice Sheet during the late Holocene (Andresen, 1981; Buch, 1981; Buch et al., 2004; Lloyd et al., 2006a).

The Arctic water group (Table 2) includes *Stainforthia feylingi*, *Elphidium excavatum* f. *clavata* and *Islandiella helenae* (calcareous taxa) and *Cuneata arctica, Spiroplectammina biformis* and *Recurvoides turbinatus* (agglutinated taxa). *Elphidium excavatum* f. *clavata*, a known opportunistic species, is able to tolerate relatively unstable and colder environmental conditions (e.g. variability in food supply, salinity and temperature) (Ostermann and Nelson, 1989; Vilks et al., 1989; Hald et al., 1994; Hald and Korsun, 1997). This species is also found in high abundance (up to 30% of the total assemblage) in certain intervals, which cannot be linked to any direct meltwater discharge, and hence we cannot consider *E. excavatum* f. *clavata* as a glaciomarine species in this context, though we classify it as a AW indicator in terms of representing relatively harsh and variable environmental conditions. *Stainforthia feylingi* is described by Knudsen and Seidenkrantz (1994) as indicative and tolerant of unstable environmental conditions. There is generally poor knowledge of the environmental controls on *S. feylingi*. Species of the genus *Stainforthia* are commonly recorded in areas of very harsh, limiting ecological conditions, often with only episodic food supply, variable salinity levels and anoxic conditions when most species are unable to survive/ compete (Alve, 1994; Bernhard and Alve, 1996; Knudsen and Seidenkrantz, 1994; Rasmussen et al., 2002). Polyak and Solheim (1994) and Steinsund et al. (1994) link relatively high abundance of *I. helenae* to summer ice-edge productivity in areas of seasonal ice cover in the Barents Sea. *Cuneata arctica* and *S. biformis* are associated with cold less saline or arctic sourced waters (Williamson et al., 1984; Schafer and Cole, 1986; Alve, 1990, 1991; Jennings and Helgadottir, 1994; Madsen and Knudsen, 1994; Korsun and Hald, 1998; Jennings et al., 2001).

In our record we use the calcareous AtlW species (AtlWcalc) as the ‘warm end member’ assemblage, representing the NAC/IC influence on the WGC, whereas agglutinated AW species (AWagg) are the ‘cold end member’ assemblage, representing predominant EGC influence. A subdivision of our benthic foraminiferal record into 4 zones (A-D) is based on distinct changes in the combined percentage abundance of agglutinated and calcareous species; the ratio of calcareous vs. agglutinated specimens (Fig.3) and is supported by the distribution of AtlW and AW indicator species (Tab. 2).

The calculated ratio of calcareous vs. agglutinated specimens reveals marked shifts from a predominantly calcareous to agglutinated fauna through the last 3.6 ka BP (Fig. 3). We find highest abundance of calcareous foraminifera in zones A and C, forming up to 70 % of the total assemblage. By contrast, agglutinated foraminifera form up to 80 % of the total assemblage in zones B and D. Therefore, a more detailed consideration of the agglutinated and calcareous fauna is useful. The high abundance of total foraminifera (>100 specimens per ml sediment) allows this. Accordingly, percentage calculations for agglutinated and calcareous species were made separately and are presented in Fig. 4 (agglutinated species) and Fig. 5 (calcareous species). In the following sections the faunal composition of zones A-D is presented separately for the calcareous and agglutinated species.

4.3.2 Agglutinated species distribution

The Assemblage zone A (3.6 to *c.* 2.6 ka BP) is characterized by high abundance of *Deuterammina ochracea* (mean 40%) and *Eggerella advena* (mean 35%). From 2.6 to *c.* 1.9 ka BP (zone B) the abundance of AWagg species is below 20%. An increase of AWagg species *C. arctica* (15%) and *S. biformis* (10%) is seen in this interval. Notable peak abundance of *R. turbinatus* (up to 20%), is found at *c.* 2.4 and 2.1 ka BP (see Fig. 4). Lowest percentage abundance of total agglutinated species is found between 1.9 and 1.7 ka BP (zone C, see Fig.4). By 1.3 ka BP AWagg species (*C. arctica* and *S. biformis*) become more important and reach a maximum of *c.* 45% by 0.9 ka BP. A rise in AtlWagg species (up to *c.* 10%, Fig. 4) is noted from 1.5 ka BP onwards. In assemblage zone D (0.9 ka BP to the present) we find a major increase of AWagg species *C. arctica* (average 35%) and *S. biformis* (average 20%) with maximum abundance at 0.3 ka BP is found (see Fig. 4). We also note a prominent rise in abundance of *Textularia torquata* (>10%) and *R. turbinatus* (up to 10%). AtlW species *R. fusiformis* (12 %) along with lower levels of *Reophax pilulifer* (6%) become an important component of the assemblage over the last century (Fig. 4).

4.3.3 Calcareous species distribution

From 3.6 to *c.* 2.6 ka BP (zone A) we find a calcareous fauna, which is dominated by the AtlWcalc species C*. reniforme* and *I. norcrossi*, with maximum abundance of 60% at 3.2 ka BP. The infaunal species *N. labradorica* averages 20% in this zone. A relatively high abundance of *E. excavatum* f. *clavata* is found, with a distinct drop in abundance from *c.* 40% to below 5% seen at *c.* 3.5 and 3.0 ka BP (Fig. 5). In assemblage zone B (2.6 to 1.9 ka BP) AtlWcalc species average 30% and decrease to *c.* 20% at *c.* 2.5 ka BP, driven by a pronounced drop in abundance of *C. reniforme* (10% at 2.5 ka BP, Fig. 5). In this interval AWcalc species *E. excavatum* f. *clavata* fluctuates markedly in abundance and at 2.7 ka BP and 2.4 ka BP a peak of *c.* 40% is found. Detritus feeder *N. labradorica* averages *c.* 20%, with notably low abundance (below 10%) at *c.* 2.5 ka BP (see Fig. 5). In zone C (1.9 to 0.9 ka BP) we record marked changes in the calcareous fauna. From 1.9 to 1.7 ka BP AtlWcalc species dominate the calcareous assemblage (up to 50%), accompanied by high abundance of *N. labradorica* (25%) and *G. auriculata arctica* (30%, see Fig. 5). Relatively low abundance of AWcalc species *E. excavatum* f. *clavata* (~5%) is recorded from 1.9 to 1.6 ka BP. From 1.5 ka BP a pronounced rise in abundance of *E. excavatum* f. *clavata* (up to 30%) is seen alongside a gradual fall at 1.0 ka BP in the abundance of AtlWcalc species, which average *c.* 25% from 1.5 to 0.9 ka BP. From 0.9 ka BP onwards (zone D) we record a sharp change in the calcareous assemblage. A notable decrease in abundance of AtlWcalc species *C. reniforme* and *I. norcrossi* at 0.9 ka BP and calcAW species *E. excavatum* f. *clavata* down to *c.* 5% is seen at 0.7 ka BP. These species are replaced by a major rise in abundance of AWcalc species *S. feylingi* up to 40%, with a large spike at 0.3 ka BP (see Figs. 3 and 5). Additionally, we find increasing abundance of *I. helenae* (5%) during this interval. Detritus feeder such as *N. labradorica*, *G. auriculata arctica* and *B. pseudopunctata* still represent about 30% of the calcareous assemblage (Fig. 5), but show low abundance at 0.3 ka BP.

5. Discussion

5.1 Long-term late Holocene cooling and paleoceanographic implications

Our new high-resolution benthic foraminiferal record from Disko Bugt documents a marked long-term cooling trend over the last 3.6 ka BP. This trend is clearly seen in the percentage decrease of the chilled Atlantic Water species *C. reniforme* (see Figs. 3, 4 and 5) and average increase of AWagg indicators, reflecting the gradually increased influence of the EGC within the WGC over the late Holocene. Trends we recognized in AtlWcalc and AWagg indicators show cooling becomes most pronounced from *c.* 1.7 ka BP onwards, as AtlWcalc species decrease significantly and AWagg species increase notably (Fig. 6). We suggest that this cooling is a consequence of increasing EGC influence on the water mass composition of the WGC. This agrees with studies from the Denmark Strait and from the SE Greenland margin, documenting an expansion and intensification of the EGC during the late Holocene (Kuijpers et al., 2003; Jennings et al., 2011). Jennings et al. (2011) report a predominant agglutinated fauna, marking the strong EGC influence from the Denmark Strait from 3.3 ka BP. Further studies reported an increased contribution of colder/fresher arctic water masses and increased drift ice within the EGC from *c.* 5.0 ka BP (Andrews et al., 1997; Eiríksson et al., 2004; Moros et al., 2006a). From *c.* 0.9 ka BP onwards, we find this influence to be more persistent and intense, as a dominant agglutinated fauna is established and peak abundance of AWagg species mark the culmination of the cooling trend at *c.* 0.3 ka BP during the

Little Ice Age (LIA). Longer-term late Holocene cooling is recognized in a variety of marine (Jennings et al., 2002; Andersson et al., 2003; Risebrobakken et al., 2003; Giraudeau et al., 2004; Eiríksson et al., 2004; Hall et al., 2004; Moros et al., 2004; de Vernal and Hillarie Marcel, 2006; Kaufmann et al., 2009; Ólafsdóttir et al., 2010) and terrestrial arctic temperature proxy data from the North Atlantic region (e.g. Alley et al., 1999; Kaufman et al., 2009, see Fig. 6d, e).

5.2 Millennial to centennial scale variability in subsurface waters of the WGC

Superimposed on the longer-term late Holocene cooling trend we identify millennial to centennial scale variability in Disko Bugt bottom waters since 3.6 ka BP. The basal part of the record, Zone A - spanning the interval 3.6 to 2.6 ka BP, is characterized by high abundance of AtlWcalc species (Fig. 6c). Hence, we infer warmer bottom water conditions prevailing in Egedesminde Dyb and accordingly a relatively strong influence of the NAC/IC. This assumption is supported by a relative low abundance of AWagg species (Fig. 6b). The occurrence of detritus feeder's *N. labradorica* and *G. auriculata arctica* (Schafer and Cole, 1986; Corliss and Chen, 1988; Corliss, 1991; Rytter et al., 2002; Jennings et al., 2004, see Fig. 5) reflects relatively high food availability and supply of phytodetritus to the seafloor during this interval. The warm WGC corresponds to relatively high and stable air temperatures over the Greenland ice cap (Alley et al., 1999, Fig. 6e) and is associated with enhanced meltwater production as demonstrated in sediment core records from Ammarilik fjord, West Greenland (e.g. Møller et al. 2006).

We recognize a marked change to relatively colder oceanographic conditions off West Greenland in the 2.6 to 1.9 ka BP interval (Zone B). The prominent rise in agglutinated AW species at *c.* 2.4 - 2.5 ka BP, reflects cooling and freshening of bottom waters in Disko Bugt. This is highlighted by a pronounced peak in cold water species *C. arctica*, *S. biformis* and *R. turbinatus* and *E. excavatum* f. *clavata* (Figs. 5 and 6a, b, c). Additionally, we note the reduced abundance of organic detritus feeder's *N. labradorica* and *G. auriculata arctica* (Figs. 3 and 5) suggesting that environmental conditions became harsher compared to the previous interval. We interpret this as a result of a relatively colder WGC reaching Disko Bugt, as a consequence of an increased EGC contribution to the WGC. During this interval, the abundance of sea-ice diatoms from site DA00-03 increases significantly, indicating colder surface waters in Disko Bugt (Fig. 6d; Moros et al. 2006b). The pronounced cooling inferred from benthic foraminifer at *c.* 2.5 ka BP (Fig. 6b) is possibly related to the 2.8-2.7 ka BP cooling event, given the ∆R uncertainty in the age-depth model(see section 4.1). This cold event is widely reported from marine and terrestrial records over the North Atlantic region (e.g. Oppo et al., 2003; Risebrobakken et al., 2003; Hall et al., 2004; Moros et al., 2004). At about this time, there is evidence of relatively colder temperatures over the Greenland ice sheet, and additionally a cold and relatively fresher EGC from the East Greenland shelf as well as reduced influence of the IC off North Iceland is found (Alley et al., 1999, see Fig. 6e; Andrews et al., 2001; Jennings et al., 2002).

A shift towards relatively warmer bottom water conditions off West Greenland is documented from 1.9 to 1.7 ka BP. We find highest abundance of AtlWcalc species at *c.* 1.8 ka BP, implying a warm phase (see Fig. 6c), which possibly corresponds to the 'Roman Warm Period' and documents the overall 'warmest' bottom water conditions during the last 3.6 ka BP. The predominant calcareous fauna and minimum percentages of AW species *C. arctica, S. biformis* and *E. excavatum* f. *clavata* during the RWP (Figs. 4 and 5) documents reduced contribution of the EGC to the WGC at this time in Disko Bugt. A warm phase between 2.2 to 1.4 ka BP in bottom and surface waters (reduced abundance of sea-ice diatoms, see Fig. 6d, Moros et al., 2006b) is also reported from site DA00-03 (Lloyd et al., 2007). In addition, reconstructed temperatures from GISP2 indicate relatively warm atmospheric conditions over the Greenland ice sheet at this time (Alley et al., 1999). This is supported by findings from Jennings et al. (2002), who report a warming within the EGC on the East Greenland shelf from *c.* 2.1 to 1.4 ka BP, promoted by increased advection of intermediate Atlantic water, which is possibly linked to a strong flow of the NAC.

From *c.* 1.7 ka BP onwards a gradual cooling with decreasing influence of NAC/IC and enhanced advection of EGC waters into the WGC is demonstrated by a progressive rise in abundance of AW species (e.g. *E. excavatum* f. *clavata*, *C. arctica* and *S. biformis*, see Fig. 3 Zone-C). A notable decrease in AtlWcalc species is seen at *c.* 1.5 ka BP, which coincides remarkably well with a pronounced drop in reconstructed air temperatures from GISP2 ice core (Alley et al., 1999, Fig. 6c,e). These colder conditions in bottom waters lasted only a few decades and possibly correspond to the time period of the Dark Ages.

At the transition from the Dark Ages to the time period of the 'Medieval Climate Anomaly' (MCA) we observe only a slight warming in bottom waters in Disko Bugt (rise in AtlWcalc indicators, Fig. 6), as found in studies off East Greenland (Jennings and Weiner, 1996) and the North Iceland shelf (Eiríksson et al., 2006). Compared to the preceding warm phase, the RWP, benthic foraminifera record relatively colder bottom waters during the MCA. This coincides with a pronounced decrease in mean-annual air temperatures recorded in the GISP2 ice core (Alley et al. 1999, Fig. 6e). In support, diatom and dinoflagellate cysts studies from nearby coring sites in Disko Bugt (DA00-02 and DA00-03) identified surface water cooling at about the same time interval (Moros et al., 2006b, see Fig. 6d; Seidenkrantz et al., 2008; Krawczyk et al., 2010). From *c.* 0.9 ka BP to the present we find a predominant agglutinated fauna established, which indicates a distinct reduction in the contribution of Atlantic water masses (NAC/IC) to the WGC during the LIA. Simultaneously, a decrease in Atlantic water influence on surface-water masses in Disko Bugt is also documented from 0.9 ka BP at sites DA00-02 and DA00-03 (Moros et al., 2006b; Lloyd et al., 2007; Seidenkrantz et al., 2008). An ecological threshold was exceeded at 0.7 ka BP. The sudden fall in abundance of *I. norcrossi*, *C. reniforme* and *E. excavatum* f. *clavata* (Fig. 3 and 5, Zone D) and high abundance of AWagg species *C. arctica* and *S. biformis*, confirming that environmental conditions became much harsher during this interval. Thus, bottom water temperatures (and possibly salinity) must have dropped to a critical point and chilled AtlW species such as *I. norcrossi* and *C. reniforme* were not able to compete anymore. The disappearance of *E. excavatum* f. *clavata* and other species (e.g. *I. norcrossi* and *C. reniforme*) at the same time as *S. feylingi* increases significantly, supports the interpretation of coldest and harshest conditions in bottom waters from 0.7 ka BP. The peak in *S. feylingi* might also indicate poor ventilation of the water column and depleted/low oxygen content. We believe that *S. feylingi* replaces *E. excavatum* f. *clavata* as a consequence of these extreme environmental conditions, supported by highest abundances of agglutinated species. During this time the EGC influence appears strongest on the bottom water mass composition of the WGC is at its strongest over the last 3.6 ka BP (see Fig. 5 and 6b). This interval also coincides with coldest temperatures reconstructed from the GISP2 ice core and reconstructed arctic summer temperatures (Alley et al., 1999; Kaufman et al., 2009, see Fig. 6e,f). There is also evidence of a prolonged drift ice pulse off East Greenland during the time of the LIA (Jennings et al., 2002, Moros et al., 2006a) and several authors document glacial advance around Greenland at the same time (e.g. Weidick, 1968; Weidick et al., 1990; Geirsdóttir et al., 2000).

Reconstructions from terrestrial archives by Kaufman et al. (2009) document a strong increase in arctic summer temperature during the last *c.* 100 years. A comparable trend is not observed in subsurface waters in Disko Bugt.

5.3 Regional climatic implications

The distinct variability in subsurface water mass properties in Disko Bugt point to broader scale changes in ocean circulation patterns in the source regions of the WGC (e.g. variability in the water mass contribution of the NAC/IC and the EGC). The strong influence of the EGC we document during the late Holocene might be linked to enhanced outflow of arctic water masses into the polar North Atlantic. This is supported by evidence of increased drift ice occurrence (Andrews et al., 1997; Jennings et al., 2002; Moros et al., 2006a) and increased IRD deposition in the Denmark Strait (Jennings et al., 2011). Increased advection of fresher Arctic-derived waters into the northern North Atlantic by the EGC can lead to reduced deep-water formation in the Labrador and Nordic Seas and can consequently cause a weakening of the Subpolar Gyre (SPG). Weakening of the SPG may in turn have a strong impact on the flow of the NAC and Atlantic Meridional Overturning Circulation (Hillaire-Marcel et al., 2001; Häkkinen and Rhines, 2004; Hátún et al., 2005). However, Thornalley et al. (2009) discuss a relatively reduced and more fluctuating SPG activity during the late Holocene and suggest a weakened SPG circulation is likely to be linked to atmospheric circulation, i.e. decreased wind stress rather than enhanced freshwater flux from the Arctic. This would allow a stronger EGC influx to the WGC. Studies from eastern Canada (Kasper and Allard, 2001) and south Greenland (Lassen et al., 2004; Kuijpers and Mikkelsen, 2009; Jessen et al., in press), relate changes in atmospheric circulation patterns to a shift from a predominant NAO^+ to a NAO^- regime over this time period. Intervals of relative increase in the influence of the warm NAC/IC on the WGC 3.6 to 2.6 ka BP and at *c.* 1.8 ka BP, may imply a more NAO^+ regime, while intervals of stronger EGC influence 2.6 to 1.9 ka BP and from 0.9 ka BP onwards, possibly reflect a more NAO^- like regime in West Greenland.

6. Summary and conclusions

Our new high-resolution benthic foraminiferal study from Egedesminde Dyb provides a long-term record at decadal resolution of variations in subsurface water mass (WGC) composition off West Greenland during the late Holocene (since 3.6 ka BP). A longer-term cooling trend is observed, which becomes most pronounced from *c.* 1.7 ka BP onwards, as calcareous Atlantic water species decrease significantly and agglutinated Arctic water species increase. This cooling trend reflects increasing EGC influence on the WGC which can be either attributed to increasing meltwater and drift ice input in the EGC source region or to changes in the atmospheric North Atlantic Oscillation system from a NAO^+ to a predominant NAO^- regime over the late Holocene. This longer-term late Holocene cooling trend in the basal waters of Disko Bugt culminates with the Little Ice Age at 0.3 ka BP.

Our findings support previous studies from Disko Bugt and adjacent West Greenland fjords, which reported a gradual cooling of subsurface waters since the Holocene Thermal Maximum at *c.* 6 to 5 ka BP. Superimposed on this longer-term late Holocene cooling trend, we document millennial to centennial scale variability. A pronounced cooling event is found at *c.* 2.5 ka BP (corresponding to the 2.7 - 2.8 ka BP cooling event), which is also recorded in marine and terrestrial archives elsewhere in the North Atlantic region. A warm phase in bottom waters is recorded at *c.* 1.8 ka BP, which corresponds to the ‘Roman Warm Period’ and is seen to represent the warmest bottom water conditions recorded in Disko Bugt during the last

3.6 ka BP. However, only a slight warming is observed in subsurface waters during the 'Medieval Climate Anomaly'. From 0.9 ka BP we find pervasive and even harsher environmental conditions (e.g. limited food availability), highlighted by the sudden fall in abundance of *Cassidulina reniforme*, *Islandiella norcrossi* and *Elphidium excavatum* f. *clavata* as an ecological threshold is exceeded. Peak abundance of *Stainforthia feylingi* and agglutinated Arctic water species (e.g. *Cuneata arctica* and *Spiroplectammina biformis*) reflect the culmination of this cooling trend at 0.3 ka BP (Little Ice Age). Reconstructions from arctic terrestrial archives match, to some extent the late Holocene longer-term cooling trend in the basal waters in Disko Bugt. The reconstructed increased influence of the EGC on bottom waters in Disko Bugt may also have a strong influence on the flow of the North Atlantic Current.

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References

Alley, R.B., Agustsdottir, A.M., and Fawcett, P.J., 1999. Ice-core evidence of late-Holocene reduction in North Atlantic Ocean heat transport. Geophysical Monograph 112, 301–312.

Alve, E., 1990. Variations in estuarine foraminiferal biofacies with diminishing oxygen conditions in Drammensfjord. SE Norway. *In:* Hemleben, C., Kaminski, M. A., Kuhnt, W., and Scott, D. B. (eds.), Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera: NATO AS1 Series., Series C, Mathematical and Physical Sciences, Kluwer Academic Publishers, Dordrecht, 327, 661-694.

Alve, E., 1994. Opportunistic features of the foraminifer Stainforthia fusiformis (Williamson): evidence from Frierfjord, Norway. Journal of Micropalaeontology 13, 24.

Andersen, C., Koç, N., Jennings, A.E., and Andrews, J.T., 2004. Nonuniform response of the major surface currents in the Nordic Seas to insolation forcing: implications for the Holocene climate variability. Paleoceanography 19, PA2003.

Anderson, L., Abbott, M.B., Finney, B.P., and Burns, S.J., 2006. Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada. Quaternary Research 65, 350-351.

Andersson, C., Risebrobakken, B., Jansen, E., and Dahl, S.O., 2003. Late Holocene surface ocean conditions of the Norwegian Sea (Vöhring Plateau). Paleoceanography 18, PA1044.

Andresen, O.G.N., 1981. The annual cycle of temperature, salinity, currents and water masses in Disko Bugt and adjacent waters, West Greenland. Meddelelser om Grønland, Bioscience 5, 1-36.

Andrews, J. T., Smith, L. M., Preston, R., Cooper, T., and Jennings, A. E., 1997. Spatial and temporal patterns of iceberg rafting (IRD) along the east Greenland margin, ca.68 N, over the last 14 cal. ka. J. Quat. Sci. 12, 1 –13.

Andrews, J. T., Caseldine, C., Weiner, N. J., and Hatton, J., 2001. Late Quaternary (_4 ka) marine and terrestrial environmental change in Reykjarfjőrdur, N. Iceland: Climate and/or settlement? J. Quat. Sci. 16, 133–144.

Bâcle, J.E., Carmack, C., and Ingram, R.G., 2002. Water column structure and circulation in the North Water during spring transition: April-July 1998, Deep Sea Research 49, 4907 – 4925.

Bernhard, J. M., and Alve, E., 1996. Survival, ATP pool, and ultrastructural characterization of benthic foraminifera from Drammensfjord (Norway): response to anoxia. Marine Micropaleontology 28, 5–17.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, pp. 337.

Buch, E., 1981. A Review of the oceanographic conditions in subarea O and 1 in the decade 1970- 79. NAFO Symposium on Environmental conditions in the Northwest Atlantic during 1970-79. NAFO Scientific Council Studies no.5.

Buch, E., Pedersen, S.A., and Ribergaard, M.H., 2004. Ecosystem Variability in West Greenland Waters. Journal of Northw. Atl. Fish. Sci. 34, 13-28.

Corliss, B.H., 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. Marine Micropaleontology 17, 195-236.

Corliss, B.H. and Chen, C., 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. Geology 16, 716-719.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D.,Johnsen, S.J., Hansen, A.W., and Balling, N., 1998. Past temperature directly from the greenland ice sheet. Science 282, 268–271.

de Vernal, A., and Hillaire-Marcel, C., 2006. Provincialism in trends and high frequency changes in the northwest North Atlantic during the Holocene. Global and Planetary Change 54, 263-390.

Duplessy, J-C., Invanova, E.V., Murdmaa, I.O, Paterne, M., and Labyrie, L., 2001. Holocene palaeoceanography of the northen Barents Sea and variations of the northward heat transport by the Atlantic Ocean. Boreas, 30(1), 2-16.

Elverhøi, A., Liestøl, O., and Nagy, J., 1980. Glacial erosion, sedimentation and microfauna in the inner part of Kongsfjord, Spitsbergen: Norsk Polarinstitutt Skrifter, 172, 33–61.

Feyling-Hansen, R., and Funder, S., 1990. Fauna and flora. In: S. Funder (Editor), Late Quaternary Stratigraphy and Glaciology in the Thule area. Medd. Gronl. Geosci., 22, 19-33.

Fréchette, B. and de Vernal, A., 2009. Relationship between Holocene climate variations over southern Greenland and eastern Baffin Island and synoptic circulation pattern. Climate of the Past 5, 247-359.

Funder, S. and Weidick, A., 1991. Holocene boreal molluscs in Greenland – palaeoceanographic implications. Palaeogeography,Palaeoclimatology, Palaeoecology 85, 123–35.

Geirsdóttir, A., Hardardóttir, J. and Andrews, J.T., 2000. Late-Holocene terrestrial glacial history of Miki and I.C. Jacobsen Fjords,East Greenland. The Holocene 10, 123–34.

Giraudeau, J., Jennings, A.E., and Andrews, J.T., 2004. Timing and mechanisms of surface and intermediate water circulation changes in the Nordic Seas over the last 10 000 cal. Years: a view from the North Iceland shelf. Quaternary Science Reviews 23, 2127-2139.

Hald, M., and Steinsund, P.I., 1992. Distribution of surface sediment benthic foraminifera in the southwestern Barents Sea. Journal of Foraminiferal Research 21, 347–62.

Hald, M., Dokken, T., Korsun, S., Polyak, L., and Aspeli, R., 1994. Recent and Late Quaternary distribution of *Elphidium excavatum* f. *clavata* in Arctic seas: Cushman Foundation Special Publication 32, 141–153.

Hald, M. and Steinsund, P.I., 1996. Benthic foraminifera and carbonate dissolution in surface sediments of the Barents- and Kara Seas. Ber. Polarforsch., 21 2 (1 996).

Hald, M. and Korsun, S., 1997. Distribution of modern benthic foraminifera from fjords of Svalbard, European Arctic. Journal of Foraminiferal Research 27, 101–22.

Hall, I.G., Bianchi, G., and Evans, J.R., 2004. Centennial to millennial scale Holocene climate-deep water linkages in the North Atlantic. Quaternary Science. Reviews 23, 1529– 1536.

Hansen,A., and Knudsen, K.L., 1995. Recent foraminiferal distribution in Freemansundet and Early Holocene stratigraphy on Edgeøya, Svalbard: Polar Research 14, 215–238.

Harff, J., Dietrich, R., Endler, R., Hentzsch, B., Jensen, J. B., Kuijpers, A., Krauss, N., Leipe, Th., Lloyd, J., Mikkelsen, N., Moros, M., Perner, K.

Richter, A., Risgaard-Petersen, N., Rysgaard, S., Richter, Th., Sandgren, P., Sheshenko, V., Snowball, I., Waniek, J., Weinrebe, W., and Witkowski, A., 2007. Deglaciation history, coastal development, and environmental change during the Holocene in western Greenland. Cruise report R/V Maria S. Merian, cruise MSM 05/03.

Häkkinen, S. and Rhines, P. B., 2004. Decline of subpolar North Atlantic circulation during the 1990s. Science 304, 555–559.

Hátún, H., Sando, A.B., Drange, H., Hansen, B. and Valdimarsson, H., 2005. Influence of the Atlantic subpolar gyre on the thermohaline circulation. Science 309, 1841–1844.

Heegaard, E., Birks, H.J.B., Telford, J.T., 2005. Relationships between calibrated ages and depth in stratigraphical sequences: an estimation procedure by mixedeffect regression. The Holocene 15, 612–618.

Hillaire-Marcel, C., de Vernal, A., Bilodeau, G. and Weaver, A., 2001. Absence of Deepwater formation in the Labrador Sea during the last interglacial period. Nature 410, 1073–1077.

Holland, D.M., Thomas, R.H., De Young, B., Ribergaard, M.H., and Lyberth, B., 2008. Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. Nature Geoscience 1, 659.

Humlum, O., 1999. Late Holocene Climate in Central West Greenland: Meteorological Data and Rock Glacier Isotope Evidence. The Holocene 9 (5), 581-594.

Jennings, A.E., and Helgadottir, G., 1994. Foraminiferal assemblages from the fjords and shelf of eastern Greenland. Journal of Foraminiferal Research 24, 123–44.

Jennings, A., and Weiner, N., 1996. Environmental change in eastern Greenland during the last 1300 years: evidence from foraminifera and lithofacies in Nansen Fjord, 68°N. The Holocene 6, 179–91.

Jennings, A.E., Hagen, S., Hardardottir, J., Stein, R., Ogilvie, A.E.J. and Jonsdottir, I., 2001. Oceanographic change and terrestrial human impacts in a post A.D. 1400 sediment record from the southwest Iceland shelf. *Climatic Change* 48 (Special Issue, The Iceberg in the Mist: Northern Research in Pursuit of 'A Little Ice Age', guest editors Ogilive, A.E. and Jónsson, T.), 83–100.

Jennings, A., Knudsen, K.L., Hald, M., Hansen, C.V. and Andrews, J.T., 2002. A mid-Holocene shift in Arctic sea-ice variability on the East Greenland Shelf. The Holocene 12, 49–58.

Jennings, A., Weiner, N.J., Helgadottir, G. and Andrews, J.T., 2004. Modern foraminiferal faunas of the southwestern to northern Iceland shelf: oceanographic and environmental controls. Journal of Foraminiferal Research 34, 180–207.

Jennings, A., Andrews, J., Wilson, L., 2011. Holocene environmental evolution of the SE Greenland Shelf North and South of the Denmark Strait: Irminger and East Greenland current interactions. Quaternary Science Reviews 30, 980-998.

Jessen, C., Solignac, S., Nørgaard-Pedersen, N., Kuijpers, A., and Seidenkrantz, M.S., 2011. Exotic pollen as an indicator of variable atmospheric circulation over the Labrador Sea region during the mid to late Holocene. Journal of Quaternary Science 26, 286-296.

Jorissen, F.J., de Stigter, H.C., and Widmark, J.G.V., 1995. A conceptual model explaining benthic foraminiferal microhabitats. Marine Micropaleontology 26, 3-15.

Kalish, J.M., Nydal, R., Nedreaas, K.H., Burr, G.S., and Eine, G.L., 2001. A time history of pre- and post-bomb radiocarbon in the Barents Sea derived from Arcto-Norwegian cod otoliths. Radiocarbon 43, 843.

Kaufman, D.S., Ager, T.A., Anderson, N.J., Anderson, P.M., Andrews, J.T., Bartlein, P.J., Brubaker, L.B., Coats, L.L., Cwynar, L.C., Duvall, M.L., Dyke, A.S., Edwards, M.E., Eisner, W.R., Gajewski, K., Geirsdóttir, A., Hu, F.S., Jennings, A.E., Kaplan, M.R., Kerwin, M.W., Lozhkin, A.V., MacDonald, G.M., Miller, G.H., Mock, C.J., Oswald, W.W., Otto-Bliesner, B.L., Porinchu, D.F., Rühland, K., Smol, J.P., Steig, E.J. and Wolfe, B.B., 2004. Holocene thermal maximum in the western Arctic (0–180°W). Quaternary Science Reviews 23, 529–60.

Kaufman, D.S., Schneider, D.P., McKay, N.P., Ammann, C.A., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.M., and Arctic Lakes 2k Project Members, 2009. Recent warming reverses long-term Arctic cooling. Science 325, 1236.

Kasper, J.N., and Allard, M., 2001. Late Holocene climatic changes as detected by the growth and decay of ice wedges on the southern shore of Hudson Strait, northern Quebec, Canada. The Holocene 11, 563–577.

Kelly, M., 1979. Comments on the implications of new radiocarbon dates from the Holsteinsborg region, central West Greenland. Gronl. Geol. Unders. Rep., 95, 35-42.

Kelly, M., 1980. The status of the Neoglacial in western Greenland. Rapport Grønlands Geologiske Undersøgelse 96, 1–24.

Kelly, M., 1985. A review of the Quaternary geology of western Greenland. In: J. T. Andrews (Editor), Quaternary Environments eastern Canadian Arctic, Baffin Bay and western Greenland. Allen and Unwin, Boston, pp. 461-501.

Knudsen, K.L., and Seidenkrantz, M.-S. 1994. *Stainforthia feylingi* new species from artic to subartic environments, previously recorded as *Stainforthia schreibersiana* (Czjzek). Cushman Foundation for Foraminiferal Research Special Publication, 32:5-13.

Knudsen, K.L., Eiríksson, J., Jansen, J., Jiang, H., Rytter, F., and Gudmundsdóttir, E.R., 2004. Palaeoceanographic changes off North Iceland through the last 1200 years: foraminifera, stable isotopes, diatoms and ice rafted debris. Quaternary Science Reviews 23, 2231–2246.

Korsun, S., and Hald, M., 1998. Modern benthic foraminifera off Novaya Zemlya tidewater glaciers, Russian Arctic. Arctic and Alpine Research 30, 61–77.

Krawczyk, D., Witkowski, A., Moros, M., Lloyd, J.M., Kuijpers, A. and Kierzek, A. 2010. Late-Holocene diatom-inferred reconstruction of temperature variations of the West Greenland Current from Disko Bugt, central West Greenland. The Holocene 20 (5), 659-666.

Krog, H. and Tauber, H., 1974. C-14 chronology of Late and Postglacial marine deposits in North Jutland, Danmarks Geologiske Undersøgelse Årbog 1973**,** 93–105.

Kuijpers, A. and Mikkelsen, N., 2009. Geological records of changes in wind regime over south Greenland since the Medieval Warm Period: a tentative reconstruction. Polar Record 45 (232),1-8.

Lassen, S.J., Kuijpers, A., Kunzendorf, H., Hoffman-Wieck, G., Mikkelsen, N. and Konradi, P., 2004. Late-Holocene Atlantic bottom water variability in Igaliku Fjord, South Greenland, reconstructed from foraminifera faunas. The Holocene 14, 165–171

Lloyd, J.M., Park, L.A., Kuijpers, A. and Moros, M., 2005. Early Holocene palaeoceanography and deglacial chronology of Disko Bugt, West Greenland. Quaternary Science Reviews 24, 1741–1755.

Lloyd, J.M., 2006a. Late Holocene environmental change in Disko Bugt, west Greenland: interaction between climate, ocean circulation and Jakobshavn Isbrae. *Boreas* 35, 36–49.

—— 2006b. Modern distribution of benthic foraminifera from Disko Bugt, west Greenland. Journal of Foraminiferal Research 36, 315–331.

Lloyd, J.M., Kuijpers, A., Long, A., Moros, M., and Park, L.A., 2007. Foraminiferal reconstruction of mid- to late-Holocene ocean circulation and climate variability in Disko Bugt, West Greenland. The Holocene17, 1079-1091.

Lloyd, J.M., Moros, M., Perner, K., Telford, R., Kuijpers, A., Jansen, E., and McCarthy, D.J., 2011. A 100 year record of ocean temperature control on the stability of Jakobshavn Isbrae, West Greenland. Geology (in press).

Mackensen, A., Sejrup, H.P., and Jansen, E., 1985. The distribution of living benthic foraminifera on the continental slope and rise off southwest Norway. Marine Micropaleontology 9, 275–306.

Madsen, H.B. and Knudsen, K.L., 1994. Recent foraminifera in shelf sediments of the Scoresby Sund fjord, East Greenland. Boreas 23, 495–504.

McNeely, R., Dyke, A.S, and Southon, JR., 2006. Canadian marine reservoir ages, preliminary data assessment. Open File 5049. Geological Survey of Canada, pp.3.

Møller, H.S., Jensen, K.G., Kuijpers, A., Aagaard-Sørensen, S., Seidenkrantz, M.-S., Prins, M., Endler, R. and Mikkelsen, N., 2006. Late-Holocene environment and climatic changes in Ameralik fjord, southwest Greenland: evidence from the sedimentary record. The Holocene 16, 685–695.

Moros, M., Emeis, K., Risebrobakken, B., Snowball, I., Kuijpers, A., McManus,

J. and Jansen, E., 2004. Sea surface temperatures and ice rafting in the Holocene North Atlantic: climate influences on northern Europe and Greenland. Quaternary Science Reviews 23, 2113–2126.

Moros, M., Andrews, J.T., Eberl, D.D. and Jansen, E., 2006a. Holocene history of drift ice in the northern North Atlantic: Evidence for different spatial and temporal modes. Paleoceanography 21, 2017.

Moros, M., Jensen, K.G. and Kuijpers, A., 2006b. Mid- to late- Holocene hydrological and climatic variability in Disko Bugt, central West Greenland. The Holocene 16, 357–367.

Mudie, P.J., Keen, C.E., Hardy, I.E. and Vilks, G., 1984. Multivariate analysis and quantitative paleoecology of benthic foraminifera in surface and Late Quaternary shelf sediments, northern Canada. Marine Micropalaeontology 8, 283–313.

Mudie, P.J., Rochon, A. and Levac, E., 2005. Decadal-scale sea ice changes in the Canadian Arctic and their impacts on humans during the past 4,000 years. Environmental Archaeology 10, 113–126.

Murray, J.W., 1991. Ecology and palaeoecology of benthic foraminifera. Longman, London, 397pp.

Nagy, J., 1965. Foraminifera in some bottom samples from shallow waters in Vestspitsbergen: Norks Polarinstitutt Arbok 1963, p. 109–125.

Oppo, D.W., McManus, J.F., and Cullen, J.R., 2003. Palaeoceanography: deepwater variability in the Holocene epoch. Nature 422, 277.

Osterman, L.E. and Nelson, A.R., 1989. Latest Quaternary and Holocene paleoceanography of the eastern Baffin Island continental shelf, Canada: benthic foraminiferal evidence. Canadian Journal of Earth Science 26, 2236–2248.

Ólafsdóttir, S., Jennings, A. E., Geisdóttir, Á., Andrews, J., and Miller, G., 2010. Holocene variability of the North Atlantic Irminger current on the south- and northwest shelf of Iceland. Marine Micropaleontology 77 (3-4), 101-118.

Polyak, L. and Solheim, A., 1994. Late- and postglacial environments in the northern Barents Sea west of Franz Josef Land. Polar Research 13, 197–207.

Ran, L., Jiang, H., Knudsen, K.L., and Eiríksson, J., 2008. The mid- to late Holocene paleoceanographic changes in the northern North Atlantic. Front. Earth Sci. China, 1(4), 449-457.

Rasmussen, T.L., Thomsen, E., Troelstra, S.R., Kuijpers, A., and Prins, M.A., 2002. Millennial-scale glacial variability versus Holocene stability: changes in planktic and benthic foraminifera faunas and ocean circulation in the North Atlantic during the last 60 000 years. Marine Micropaleontology, 47, 143-176.

Reimer, P.J., and Reimer, R.W., 2001. A marine reservoir correction database and on-line interface. Radiocarbon 43, 46.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S, Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M, van der Plicht, J., and Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon **51**, 1111-1150.

Rignot, E., Koppes, M., and Velicogna, I., 2010. Rapid submarine melting of the calving faces of West Greenland glaciers. Nature Geoscience 3, 187.

Risebrobakken, B., Jansen, E., Andersson, C., Mjelde, E., and Hevroy, K., 2003.

A high-resolution study of Holocene paleoclimatic and paleoceanographic changes in the Nordic Seas. Paleoceanography 18, 1017–1031.

Rytter, F., Knudsen, K.L., Seidenkrantz, S. and Eiriksson, J., 2002. Modern distribution of benthic foraminifera on the North Icelandic shelf and slope. Journal of Foraminiferal Research 32, 217–244.

Schafer, C.T and Cole, F.E., 1986. Reconnaissance survey of benthonic foraminifera from Baffin Fjord environments. Arctic 39, 232–239.

Schröder-Adams, C.J., Mudie, P.J., Cole, F.E., and Mediolil, F.S., 1990. Late Holocene Benthic Foraminifera beneath Perennial Sea Ice on an Arctic Continental Shelf. Marine Geology 93, 225-242.

Seidenkrantz, M.-S., Aagaard-Sørensen, S., Sulsbrück, S., Kuijpers, A., Jansen, K.G. and Kunzendorf, H., 2007. Hydrography and climate of the last 4400 years in a SW Greenland fjord – implications for Labrador Sea palaeoceanography. The Holocene 17, 387–401.

Seidenkrantz, M.-S., Roncaglia, L., Fischel, A., Heilmann-Clausen, C., Kuijpers, A., and Moros, M., 2008. Variable North Atlantic seesaw patterns documented by a late Holocene marine record from Disko Bugt, West Greenland. Marine Micropaleontology 68, 66-83.

Sejrup, H.P., Birks, H.J.B., Klitgaard-Kristensen, D., Madsen, H., 2004. Benthonic foraminiferal distributions and quantitative transfer functions for the northwest European continental margin. Marine Micropaleontology 53, 197-226.

Steinsund, P.I., Polyak, L., Hald, M., Mikhailov, V. and Korsun, S., 1994. Distribution of calcareous benthic foraminifera in recent sediments of the Barents and Kara Sea. In Steinsund, P.I., Benthic foraminifera in surface sediments of the Barents and Kara Seas: modern and late Quaternary application. Ph.D. thesis, Department of Geology, Institute of Biology and Geology, Univeristy of Tromsø.

Tauber, H. and Funder, S., 1975. ^{14}C content of recent molluscs from Scoresby Sund, central East Greenland. Gronlands Geologiske Undersogelse, Rapport 75, 95–99.

Tauber, H., 1979. ^{14}C activity of arctic marine mammals. In: R. Berger and H.E. Suess, Editors, *Radiocarbon Dating*, University of California Press, 447–452.

Thornalley, D.J.R., Elderfield, H., and McCave, I.N., 2009. Holocene oscillations in temperature and salinity of the surface subpolar North Atlantic. Nature, 457 (5) 711-714.

Vilks, G., and Rashid, M.A., 1976. Post-glacial paleo-oceanography of Emerald Basin, Scotian Shelf. Canadian Journal of Earth Sciences 9, 1256-1267.

Vilks, G., 1981. Late glacial–postglacial foraminiferal boundary in sediments of eastern Canada, Denmark and Norway. Geoscience Canadian 8, 48–56.

Vilks, G., 1989. Ecology of Recent foraminifera on the Canadian continental shelf of the Arctic Ocean, *in* Herman, Y. (ed.), The Arctic Seas—Climatology, Oceanography, Geology and Biology: Van Nostrand Reinhold, New York, p. 497–569.

Vinther, B. M., Buchardt, S. L., Clausen, H. B., Dahl-Jensen, D., Johnsen, S . J., Fisher, D. A., Koerner, R. M., Raynaud, D., Lipenkov, V., Andersen, K. K., Blunier, T., Rasmussen, S. O., Steffensen, J. P., and Svensson, A.M., 2009. Holocene thinning of the Greenland ice sheet. Nature 461, 385-388.

Weidick, A., 1968. Observations on some Hoiocene glacier fluctuations in West Greenland. Medd. Gronl., 165 (6), 202 pp.

Weidick, A., Oerter, H., Reeh, N., Thomsen, H.H. and Thorning, L., 1990. The recession of the Inland Ice margin during the Holocene climatic optimum in the Jakobshavn Isfjord area of West Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology 82, 389–399.

Williamson, M.A., Keen, C.E., and Mudie, P.J., 1984. Foraminiferal distribution on the continental margin off Nova Scotia. Marine Micropaleontology 9, 219–239.

Wollenburg, J., Knies, J., Machensen, A., 2004. High-resolution palaeoproductivity fluctuations 245 during the last 24 kyr indicated by benthic foraminifera in the marginal Arctic Ocean: 246 Palaeogeography, Palaeoclimatology, Palaeoecology 204, 209-238.

Zarudzki, E.F.K., 1980. Interpretation of shallow seismic profiles over the continental shelf in West Greenland between latitudes 64° and 69° 30' N. Geological Survey of Greenland Report 100, 58-61.

Figure captions

Fig.1: Map of Disko Bugt showing location of core 343310 in south-western Egedesminde Dyb. The insert map shows the present day oceanographic setting of the study area. Abbreviations are as follow: EGC - East Greenland Current; IC – Irminger Current; WGC – West Greenland Current; LC – Labrador Current.

Fig.2: Age/depth model of 343310 (gravity core). AMS ^{14}C dates are calibrated with the Marine09 (Reimer et al., 2009) calibration curve using OxCal 4.1 (Bronk Ramsey, 2009). For AMS ^{14}C dates refer to Table 1.

Fig.3: **Combined calcareous** and **agglutinated foraminiferal assemblage** from site 343310 versus age. Foraminiferal frequencies are expressed as a percentage of the total specimens counted. Only species with an abundance greater than 10% are included. Additionally, the percentage abundance of agglutinated species, total counts and grouping of AtlW (red color) and AW (blue color) indicator species are presented.

Fig.4: **Agglutinated foraminiferal assemblage** of site 343310 versus age. Foraminiferal frequencies are expressed as a percentage of total agglutinated specimens counted. Only species with an abundance greater than 5% are included.

Fig.5: **Calcareous foraminiferal assemblage** of site 343310. Foraminiferal frequencies are expressed as a percentage of total calcareous specimens counted. Only species with an abundance greater than 5% are included plus selected specimens.

Fig.6: Summary from 343310 and other regional datasets for comparison. (a) Ratio of calcareous vs. agglutinated specimens; (b) Relative abundance of agglutinated

Arctic water species, note the inverse scale; (c) Relative abundance of calcareous chilled Atlantic water species; (d) Relative abundance of sea-ice diatoms from site DA00-03 from Moros et al. (2006b); (e) mean annual temperature reconstructions from GISP2 ice core from Alley et al. (1999); (f) Reconstructed arctic summer temperature from Kaufmann et al. (2009). Known climatic events such as the Roman Warm Period (RWP), The Dark Ages (DA), the Medieval Climate Anomaly (MCA) and the ‘Little Ice Age’ (LIA) are indicated. Grey arrows indicate 2.7-2.8 ka cooling event.

Table 1. Radiocarbon dates for gravity core 343310.

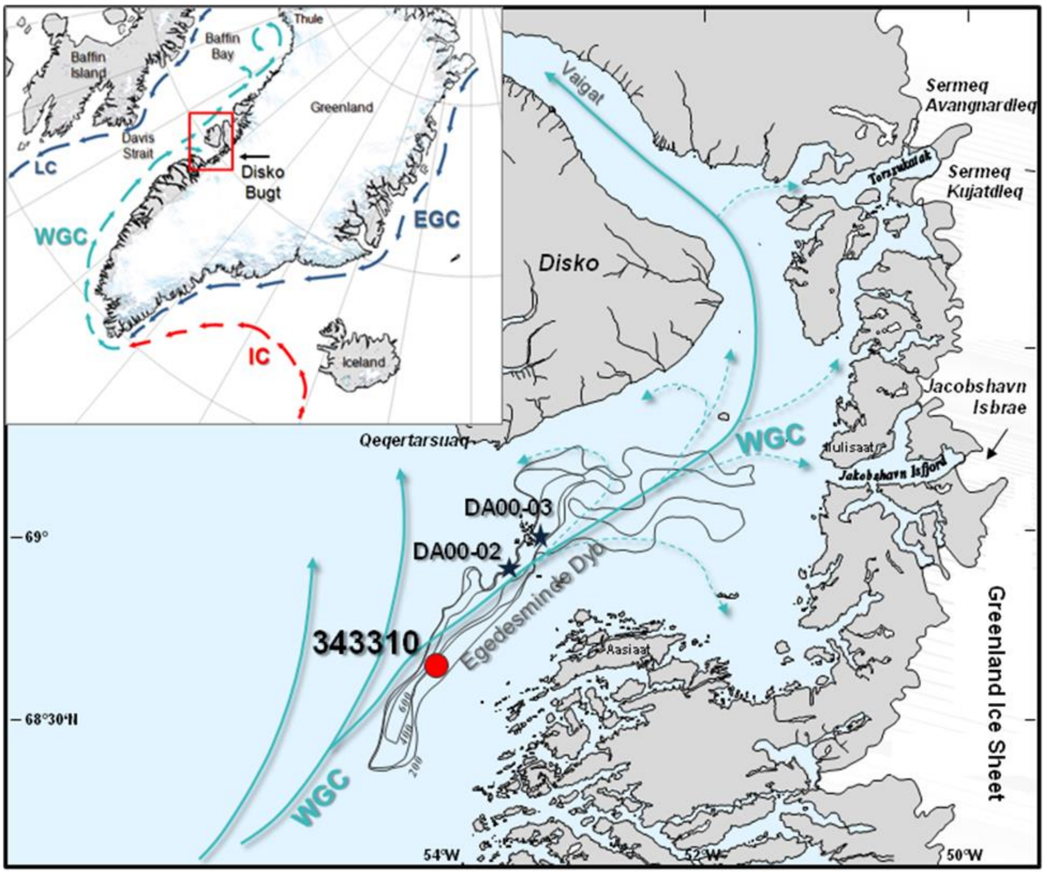
depth (cm)	Lab. code	Material	Mass mgC	^{14}C date yrs BP (pMC)	Calibrated yrs BP 1950	Years (A.D./B.C.)
6 – 10	Poz-33417	mix benthic forams	NA	671 ± 29 (92 ± 0.4 pMC)	110 – 250	AD 1840 - 1710
18 – 20	Poz-33412	mix benthic forams	NA	659 ± 33 (92.1 ± 0.4 pMC)	90 – 240	AD 1860 - 1710
18 – 19	Poz-22357	Mollusc shell	NA	682 ± 32 (91.8 ± 0.4 pMC)	120 – 260	AD 1830 - 1690
90 – 92	Poz-33453	mix benthic forams	NA	909 ± 35 (89.3 ± 0.4 pMC)	360 – 470	AD 1590 - 1480
149 - 151	Poz-33411	mix benthic forams	NA	1216 ± 30 (86 ± 0.3 pMC)	600 – 680	AD 1350 - 1270
204 - 205	Poz-30969	Mollusc shell	NA	1384 ± 27 (84.2 ± 0.3 pMC)	730 – 840	AD 1220 - 1270
269 - 271	Poz-33413	mix benthic forams	NA	1526 ± 34 (82.7 ± 0.4 pMC)	880 - 990	AD 1070 - 960
340 - 342	Poz-33488	mix benthic forams	NA	1768 ± 46 (80.2 ± 0.5 pMC)	1130 - 1260	AD 820 - 690
400 - 401	Poz-33414	mix benthic forams	NA	2074 ± 29 (77.2 ± 0.3 pMC)	1410 - 1530	AD 540 – 420
401 - 402	Poz-22359	Mollusc shell	NA	2029 ± 28 (77.7 ± 0.3 pMC)	1380 - 1490	AD 570 - 460
457 - 458	Poz-30970	mix benthic forams	NA	2198 ± 31 (76.1 ± 0.3 pMC)	1560 - 1690	AD 390 - 260
519 - 521	Poz-33416	mix benthic forams	NA	2356 ± 35 (74.6 ± 0.3 pMC)	1750 - 1880	AD 200 - 70
600 - 601	Poz-30971	Mollusc shell	NA	2733 ± 30 (71.2 ± 0.3 pMC)	2210 - 2330	260 - 380 BC
633 - 634	AAR-1699	Mollusc shell	NA	2845 ± 37 (70.2 ± 0.3 pMC)	2330 - 2460	380 - 510 BC
691 - 692	Poz-30972	Mollusc shell	NA	2956 ± 30 (69.2 ± 0.3 pMC)	2500 - 2660	550 - 710 BC
740 - 742	Poz-33418	mix benthic forams	NA	3217 ± 34 (67 ± 0.3 pMC)	2780 - 2910	830 - 960 BC
782 - 783	Poz-30973	Mollusc shell	NA	3430 ± 33 (65.2 ± 0.3 pMC)	3060 - 3210	1110 - 1260 BC
856 - 857	Poz-30974	Mollusc shell	NA	3544 ± 32 (64.3 ± 0.3 pMC)	3220 - 3340	1270 - 1390 BC
855 - 857	Poz-33419	mix benthic forams	NA	3541 ± 36 (64.4 ± 0.4 pMC)	3220 - 3340	1270 - 1390 BC
905 - 906	Poz-30975	Mollusc shell	NA	3746 ± 26 (62.7 ± 0.2 pMC)	3440 - 3550	1490 - 1600 BC

Table 2. Grouping of chilled Atlantic Water species (AtlW) and Arctic Water species (AW).

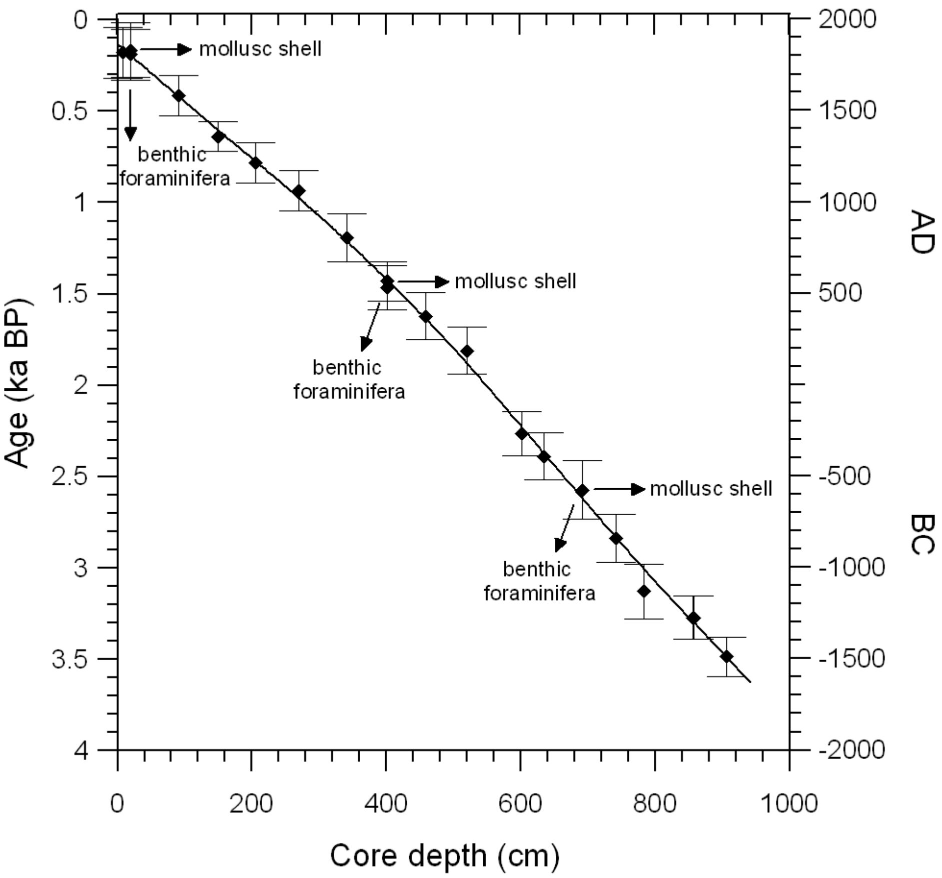
Atlantic Water Species (AtlW)	**Arctic Water species (AW)**
agglutinated species	
Ammoscalaria pseudospiralis	*Cuneata arctica*
Reophax fusiformis	*Recurvoides turbinatus*
Reophax pilulifer	*Spiroplectammina biformis*
calcareous species	
Cassidulina reniforme	*Elphidium excavatum* f. *clavata*
Pullenia osloenesis	*Islandiella helenae*
Islandiella norcrossi	*Stainforthia feylingi*

Figures

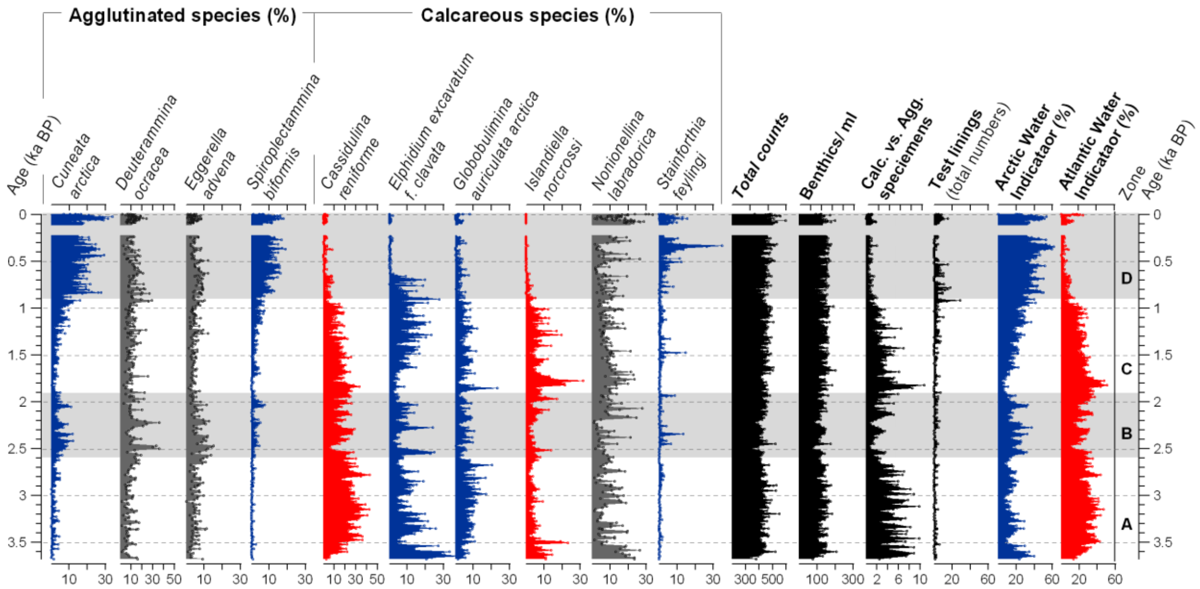
1)


Baffin Island
Baffin Bay
Thule
Greenland
Davis Strait
LC
Disko Bugt
WGC
EGC
IC
Iceland
Vaigat
Sermeq Avangnardleq
Torssukatak
Sermeq Kujatdleq
Disko
Jacobshavn Isbrae
Qeqertarsuaq
WGC
Ilulisaat
Jakobshavn Isfjord
DA00-03
DA00-02
69°
Egedesminde Dyb
343310
Aasiaat
68°30'N
Greenland Ice Sheet
WGC
54°W
52°W
50°W

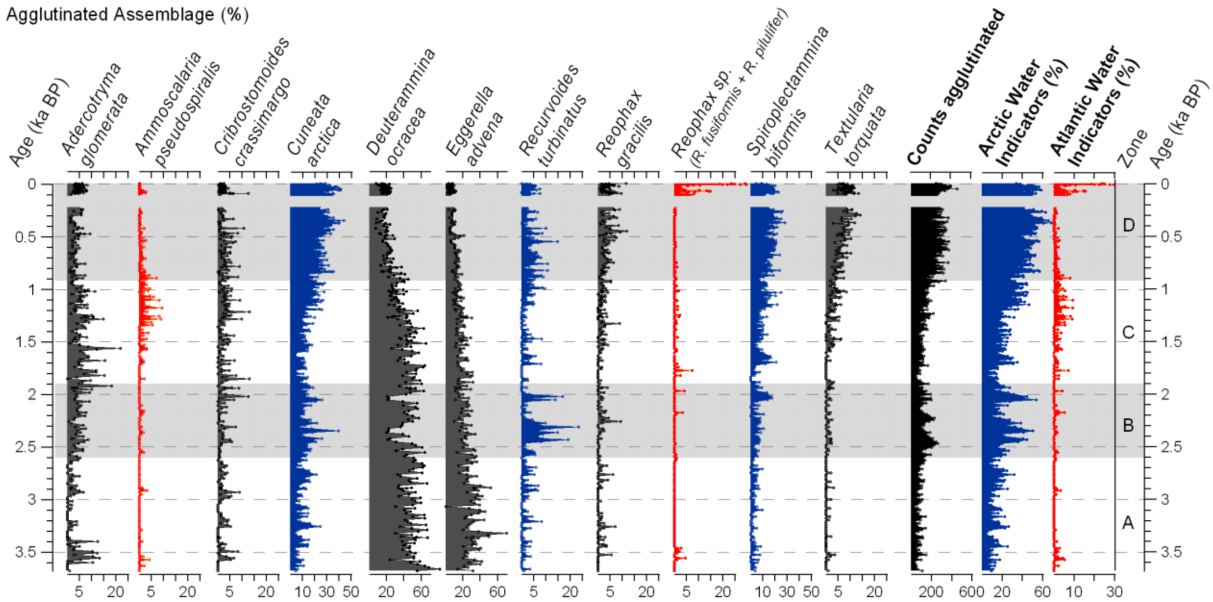
2)


Age (ka BP)
Core depth (cm)
AD
BC
mollusc shell
benthic foraminifera
0
0.5
1
1.5
2
2.5
3
3.5
4
0
200
400
600
800
1000
2000
1500
1000
500
-500
-1000
-1500
-2000

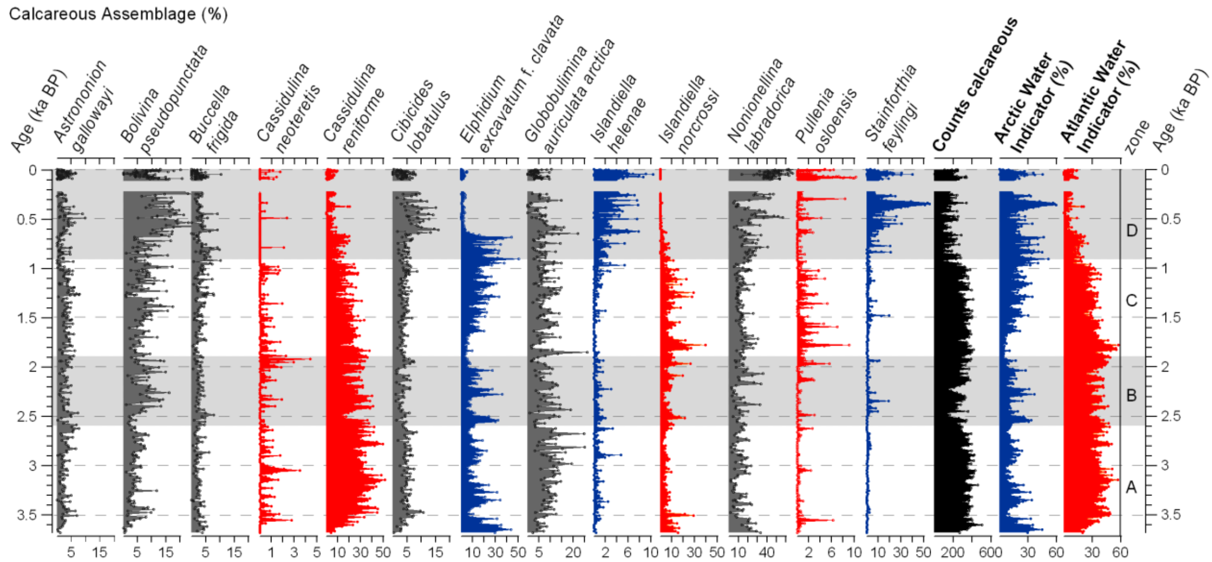
3)

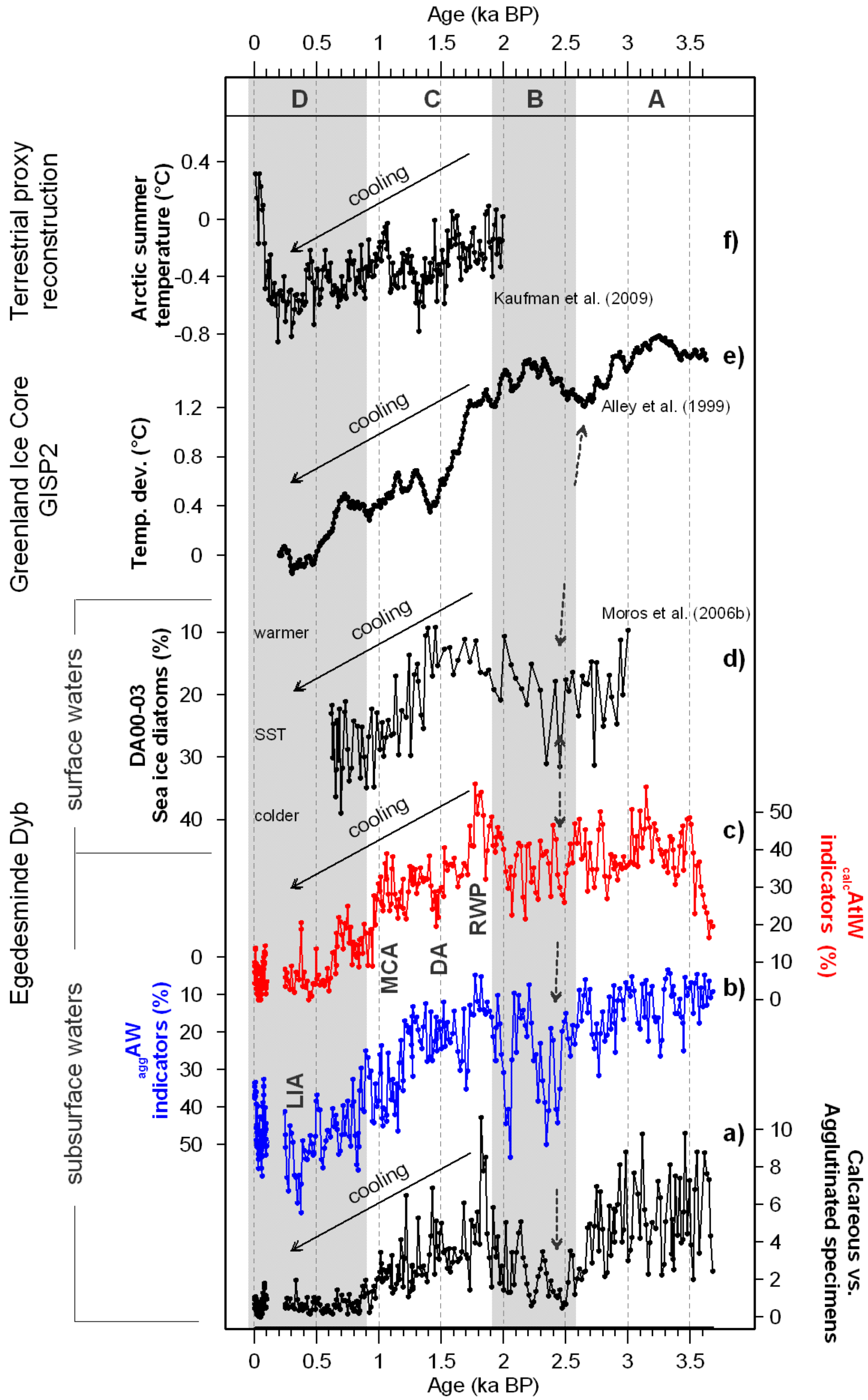

Agglutinated species (%)
Calcareous species (%)
Age (ka BP)
Cuneata arctica
Deuteramina ocracea
Eggerella advena
Spiroplectammina biformis
Cassidulina reniforme
Elphidium excavatum f. clavata
Globobulimina auriculata arctica
Islandiella norcrossi
Nonionellina labradorica
Stainforthia feylingi
Total counts
Benthics/ ml
Calc. vs. Agg. speciemens
Test linings (total numbers)
Arctic Water Indicataor (%)
Atlantic Water Indicataor (%)
Zone
Age (ka BP)
A
B
C
D

4)


Agglutinated Assemblage (%)
Age (ka BP)
Adercotryma glomerata
Ammoscalaria pseudospiralis
Cribrostomoides crassimargo
Cuneata arctica
Deuterammina ocracea
Eggerella advena
Recurvoides turbinatus
Reophax gracilis
Reophax sp. (R. fusiformis + R. pilulifer)
Spiroplectammina biformis
Textularia torquata
Counts agglutinated
Arctic Water Indicators (%)
Atlantic Water Indicators (%)
Zone
Age (ka BP)
A
B
C
D

5)


Calcareous Assemblage (%)
Age (ka BP)
Astrononion gallowayi
Bolivina pseudopunctata
Buccella frigida
Cassidulina neoteretis
Cassidulina reniforme
Cibicides lobatulus
Elphidium excavatum f. clavata
Globobulimina auriculata arctica
Islandiella helenae
Islandiella norcrossi
Nonionellina labradorica
Pullenia osloensis
Stainforthia feylingi
Counts calcareous
Arctic Water Indicator (%)
Atlantic Water Indicator (%)
zone
Age (ka BP)
A
B
C
D


Age (ka BP)
D
C
B
A
Terrestrial proxy reconstruction
Arctic summer temperature (°C)
cooling
Kaufman et al. (2009)
f)
Greenland Ice Core GISP2
Temp. dev. (°C)
Alley et al. (1999)
e)
Egedesminde Dyb
surface waters
DA00-03 Sea ice diatoms (%)
warmer
SST
colder
Moros et al. (2006b)
d)
c)
calcAtlW indicators (%)
MCA
DA
RWP
LIA
subsurface waters
aggAW indicators (%)
b)
a)
Calcareous vs. Agglutinated specimens

6)