Mid to late Holocene strengthening of the East Greenland Current linked to warm subsurface Atlantic Water

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Abstract

The relatively fresh and cold East Greenland Current (EGC) connects the Arctic with the subpolar North Atlantic Ocean. Its strength and influence on the freshwater balance in the North Atlantic affects both the Subpolar Gyre dynamics and deep convection in the Labrador Sea. Enhanced freshwater and sea-ice expansion in the subpolar North Atlantic is suggested to modify the northward heat transport within the North Atlantic Current. High-resolution palaeoceanographic reconstructions, based on planktic and benthic foraminifera assemblage data, from the central East Greenland shelf (Foster Bugt) reveal distinct centennial to millennial-scale oceanographic variability that relates to climatic changes during the mid to late Holocene (the last *c.* 6.3 ka BP). Our data highlight intervals of cooling and freshening of the polar surface EGC waters that accompany warming in the subsurface Atlantic waters, which are a combination of chilled Atlantic Intermediate Water (AIW) from the Arctic Ocean and of the Return Atlantic Current (RAC) from the West Spitsbergen Current (WSC). Mid Holocene thermal optimum conditions prevailed until *c.* 4.5 ka BP. A thin/absent surface Polar Water layer, low drift/sea-ice occurrence and strong contribution of recirculating warm Atlantic waters at the subsurface, suggest a relatively weak EGC during this period. Subsequently, between 1.4 to 4.5 ka BP, the water column became well stratified as the surface Polar Water layer thickened and cooled, indicating a strong EGC. This EGC strengthening paralleled enhanced subsurface chilled AIW contribution from the Arctic Ocean after *c.* 4.5 ka BP, which culminated from 1.4 to 2.3 ka BP. This coincides with warming identified in earlier work of the North Atlantic Current, the Irminger Current, and the West Greenland Current. We link the enhanced contribution of chilled Atlantic Water during this period to the time of the 'Roman Warm Period'. The observed warming offshore East Greenland, centred at *c.* 1.8 ka BP, likely occurred in response to changes in the interactions of i) a weakened Subpolar Gyre;

ii) increased northward heat advection in the North Atlantic Current, and iii) a predominant positive North Atlantic and Arctic Oscillation mode, prevailing during the time of the Roman Warm Period.

1. Introduction

The East Greenland Current (EGC), a cold and low-salinity surface water current, exits the Arctic Ocean in western Fram Strait and spreads cold-water fluxes southward through Denmark Strait into the Subpolar Gyre, subsequently to the Labrador Sea and finally into the eastern North Atlantic Ocean. Potentially, an excess of cold-water fluxes can lead to a slowdown or shutdown of the Atlantic Meridional Overturning Circulation (e.g., Rahmstorf and Ganopolski, 1999; Delworth and Dixon, 2000; Clark et al., 2002). There are also indications that the strength of freshwater outflow is linked to both the strength of the North Atlantic Current (NAC) (Sundby and Drinkwater, 2007) and to deep convection in the Labrador Sea (Häkkinen and Rhines, 2004; Hansen and Østerhus, 2000; Hátún et al., 2005). Enhanced fluxes of cold freshwater of a Great Salinity Anomaly (GSA)-type event has been shown to lead to changes in the North Atlantic circulation, i.e., Subpolar Gyre dynamics (Otterå and Drange, 2004; Sundby and Drinkwater, 2007; Thornalley et al., 2009).

Palaeoceanographic studies from the North Atlantic region suggest that similar cold-spells, as seen during the GSAs, occurred during the mid to late Holocene, such as during the Little Ice Age (LIA) and the ‘2.7 ka BP cooling event’, (e.g., Giraudeau et al., 2004; Moros et al., 2012). However, there is also evidence of pronounced shifts in climate conditions starting earlier in the Holocene from *c.* 6 to 5 ka BP, related, for example, to the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO) pattern (O’Brien, 1995; Alley et al., 1999; Bakke et al., 2008), to changes in Subpolar Gyre circulation (Thornalley et al., 2009), to shifts in the current/water mass fronts (e.g., Rasmussen et al., 2002; Moros et al., 2012), and to glacial advance in Greenland and Scandinavia (e.g., Funder et al., 2011a; Nesje et al., 2004). Marine proxy records across the North Atlantic basin reveal opposite east-to-west trends during the late Holocene. Indeed, records located within the Northwest Atlantic Ocean indicate late Holocene (last 3.5 ka BP) cooling and enhanced southward advection of freshwater and drift/sea ice (e.g., Koç et al., 1993; Eiríksson et al., 2004; Giraudeau et al., 2004; Hall et al., 2004; Moros et al., 2006a,b, 2012; Sarafanov et al., 2009; Jennings et al., 2002, 2011; Ólafsdóttir et al., 2010; Perner et al., 2011; Telesiński et al., 2014a). In contrast, sites located within the Northeast Atlantic Ocean record a longer-term warming trend or relatively stable conditions during the late Holocene (e.g., Risebrobakken et al., 2003; Andersen et al., 2004b; Came et al., 2007; Farmer et al., 2008; Thornalley et al., 2009; Miller et al., 2011).

Sediment records from the central East Greenland shelf are ideally located to investigate the mid to late Holocene evolution of the EGC and thus the freshwater and drift/sea-ice export from the Arctic Ocean into the North Atlantic region. However, few palaeoceanographic studies from the East Greenland shelf, north of Denmark Strait, are available (e.g., Stein et al., 1993, 1996; Nam and Stein, 1999; Müller et al., 2012), due to the low phytoplankton productivity and carbonate dissolution and thus a lack of high-resolution undisturbed Holocene sediment records along the shelf (García et al., 2012). Here we present, high-resolution Holocene planktic and benthic foraminiferal assemblage data from site PS2641 from the central East Greenland shelf at 73°N. From this site, Müller et al. (2012) recently published a lower resolution record of the sea-ice proxy IP_{25}. Planktic and benthic foraminiferal abundance data allow the reconstruction of surface EGC and subsurface Atlantic Water mass characteristics over the last *c.* 6.3 ka BP. For this purpose, we use i) planktic foraminifera to investigate changes in the cold and fresh Polar Water surface layer properties and ii) benthic foraminifera to investigate changes in the subsurface warm and saline Atlantic waters. These reconstructions provide a new perspective on the relatively poorly studied palaeoceanographic evolution of the East Greenland shelf. This new record is then compared with published key records from the North Atlantic region to provide a broader context of changes in the eastern subpolar North Atlantic region.

2. Oceanographic settings and study area

The study area (73°N and 19°W) is located on the East Greenland shelf directly below the flow path of the East Greenland Current (EGC) in Foster Bugt, a wide embayment at the mouth of the Kejser Franz Joseph Fjord (Fig. 1). Sediment core PS2641 was obtained from a sedimentary basin, landwards from a mid-shelf moraine that was deposited around 14 ka BP (Evans et al., 2002). Phytoplankton productivity is generally low in the study area due to the presence of cold and low salinity surface waters from the EGC. The EGC flows southwards along the eastern Greenland margin and is a major conduit that ventilates the North Atlantic through Denmark Strait (Fig. 1; e.g., Strass et al., 1993; Mauritzen, 1996; Rudels et al., 2002, 2005).

Today, the study site is influenced by EGC waters, which consists of an upper Polar Water layer (uppermost 250 m), which carries cold (*c.* 0-1°C) and low salinity (≤ 30) waters from the Arctic Ocean (Fig. 2; Aagaard and Coachman, 1968a,b; Johannessen, 1986; Hopkins, 1991). As illustrated in figure 1, today, subsurface waters are influenced by overflowing Atlantic Water that originates to a varying extent from Arctic Ocean Atlantic Intermediate Water (AIW; T: ≥0°C, S: 34-35; Rudels et al., 2005) and the Return Atlantic Current (RAC) from the West Spitsbergen Current (WSC, Gladfelder, 1964; T: <2°C, S: 34-35; see Fig. 2). These two water masses merge at about 78°N and are difficult to separate at our location as they move southward on the East Greenland shelf (e.g., Quadfasel et al., 1987; Rudels et al., 2005; de Steur et al., 2014). However, observations by Rudels et al. (2012) show that the contribution of chilled Atlantic waters from the Arctic Ocean to the East Greenland shelf was much stronger in 1998 compared to in 2010. A strong halocline (at *c.* 250 m water depth) forms between the surface Polar Water and the subsurface Atlantic Water and produces a stable stratification (Fig. 2; Aagaard and Coachman, 1968a; Rudels, et al., 2000).

The EGC is about 150 to 200 km wide and transports drift/sea ice, and freshwater through Fram Strait via the Transpolar Drift from the Arctic Ocean into the subpolar North Atlantic. Surface water currents, such as the EGC, are driven by atmospheric circulation, which consequently influences the distribution of drift/sea ice and water masses (Rodwell, et al., 1999; Deser et al., 2000). Under the influence of northerly winds, surface Polar Water and drift/sea ice advance along the East Greenland margin. Within the study area, the Polar Front represents the eastward limit of perennial sea ice cover and its location during summer months depends on the outflow of drift/sea-ice export from the Arctic Ocean via Fram Strait along the East Greenland coast. During years of reduced summer outflow from the Arctic Ocean the Polar Front retreats north-westwards from our core site, while during winter months and periods of increased drift/sea-ice flow the Polar Front migrates to the south-east of Foster Bugt (Pedersen et al., 2011). Variations in the strength of the Transpolar Drift, and therefore drift ice and Polar Water input, is likely controlled by changes in the Arctic Oscillation (AO) pattern (e.g., Kwok, 2000; Mysak, 2001). A series of prominent periods of enhanced arctic freshwater and drift-ice export have been recorded in the late 1960s to early 1970s, 1980s and 1990s, known as the Great Salinity Anomalies (GSA) (e.g., Dickson et al., 1988; Aagaard and Carmack, 1989; Häkkinen, 1993; Belkin et al., 1998; Belkin, 2004). Freshwater pulses migrate from the Arctic Ocean downstream into the subpolar North Atlantic through the EGC, eventually merging with the Jan Mayen

Current (at *c.* 74°N) and the East Icelandic Current (at c. 70°N). The East Icelandic Current flows eastwards along the North Iceland shelf and contributes freshwater to the Subpolar Gyre, thereby affecting the gyre circulation strength (e.g., Hátún et al., 2005). During times of a 'GSA' event, freshening and cooling of sea surface temperatures (SST) occurred within the North Atlantic region, shifting the Polar/Subpolar Front and consequently the maximum extent of drift ice and freshwater south-eastwards (Dooley et al., 1984; Dickson et al., 1988).

3. Material and Methods

A large box core (LBC-PS2641-5, 49.5 cm depth) and gravity core (GC-PS2641-4, 6 m depth) were obtained during ARK-X-/2 cruise with RV *Polarstern* in 1995 (Huberten, 1995), at core site PS2641 (73°09.3 N and 19°28.9 W, 469 m water depth) in Foster Bugt on the central East Greenland Shelf (Fig. 1). In this study, we focus on the uppermost 3 m of Holocene sediment.

Accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates on mollusc shells and a mix of benthic foraminifera (Table 1, Fig. 2) provide age control. In this study, we supplement the published age model by Müller et al. (2012) with additional AMS ^{14}C dates. The composite record (LBC and GC; last *c.* 6.3 ka BP) now comprises of 24 AMS ^{14}C dates. AMS ^{14}C dates were calibrated using the Marine13 calibration curve (Reimer et al., 2013) in CALIB 7.0.2 software (Stuiver and Reimer, 1993). All ages are quoted in calibrated calendar years (ka BP). So far there are no estimates of reservoir ages (ΔR) available for this region. Therefore, and for comparison of distinct palaeoceanographic changes with other records from the region, we applied a marine reservoir age of 400 years (ΔR=0).

Total mercury (Hg) and ^{137}Cs analyses were performed on sediments from the short LBC core in order to identify deposition of modern (last 50-60 years) sediments.

In modern Arctic waters, a peak in ^{137}Cs is usually found at *c.* 1963 that originates from weapons testing fallout, which follows a slow decline as ^{137}Cs is augmented by reprocessing discharges (Aarkrog et al., 1999). In Arctic sediments there is also an observable increase of the total Hg content due to enhanced anthropogenic emission reported from the 1960s (Skov et al., 2004). About 100 mg of dried and ball-milled sediment was analysed for Hg content using a Direct Mercury Analyser (DMA) (MLS GmbH 2004). Measurements of ^{137}Cs were performed on a Brad Energy Reinst-Germanium Detektor (Canberra, BE3830-7500SL-RDC-6-ULB).

Fresh sediment samples of 20-40 g were taken for planktic and benthic foraminifera counts from 1 cm sample intervals. Samples were soaked in deionized water and gently sieved at 63 µm just before counting. Foraminifera were counted on a square picking tray and identified to species level under a stereomicroscope from the wet residue >63 µm in order to reduce the loss of the more fragile arenaceous species, which is caused by drying out of the sediment. For further details on foraminiferal counting refer to Perner et al. (2011, 2013a). From the combined short and long core, 330 samples were counted and 46 benthic foraminiferal species were identified, of which 15 were agglutinates and 27 were calcareous species.

4. Results

4.1 Chronology and Lithology

Sediments from Foster Bugt are composed of dark olive grey silty clay with occasional occurrence of ice rafted debris (IRD) > 1mm. We developed a combined age-depth model for the short LBC and GC core, using the information from both the Hg content and ^{137}Cs analyses and available AMS^{14}C dates (Fig. 3A). In the LBC, a distinctive increase in the ^{137}Cs and Hg profiles from 7 cm towards the top of the core marks the onset of anthropogenic emission of the 1960s. This depth is used as a stratigraphic marker. The age-depth model of the LBC is based on linear interpolation between 1960, as marked by the ^{137}Cs and Hg increase, and 1995, the year of core retrieval. The stratigraphies of the LBC and GC were spliced together based on the total benthic foraminifera per gram sediment and the overlapping AMS ^{14}C dates (Fig. 3). We decided to exclude two AMS dates from intervals with overall low foraminiferal content (64-82 cm, 202-228 cm depth) as AMS ^{14}C dates from the top and base of each interval gave similar ages (Table 1, Fig. 3B), probably due to sediment re-deposition or slide activity at the core site. Sediments from our combined cores cover the last 6.3 ka BP. From 4.5 to 6.3 ka BP we find an average sedimentation rate of *c.* 6 cm/ka that decreases in the following interval (2.4 to 4.5 ka BP) to an average of *c.* 4 cm/ka. For the later part of our record, from 2.4 ka BP to 1995 AD, the average sedimentation rate increased to *c.* 6 cm/ka.

4.2 Foraminiferal ecology

At site PS2641, the content of benthic foraminifera is relatively low and varies from *c.* 5 to 40 individuals/g (Fig. 3). Throughout the core, all specimens were well-preserved and showed minimal evidence of post-mortem (dissolution) changes. In order to address and identify changes in the water mass characteristics of the central East Greenland shelf over time, we group benthic foraminifera species into associations with certain species being related to specific water mass conditions. Based on the environmental preferences of these species, the associations presented here, are directly and/or indirectly linked to temperature and salinity (e.g., Murray, 1991; Rytter et al., 2002; Sejrup et al., 2004; Lloyd et al., 2011). In table 2, we present a list of foraminiferal species and groups along with information on environmental preferences of each group with references that support species allocations.

Within the subpolar North Atlantic region, *Cassidulina neoteretis* is reported from areas fed by 'true' warm and saline Atlantic Water. A high abundance of this species is linked to the inflow of relatively warm Atlantic waters underneath cold and low salinity surface waters (e.g., Gooday and Lambshead, 1989; Slubowska et al., 2005). We therefore link abundance changes of this species to the occurrence of warm Atlantic waters on the East Greenland shelf. Additionally, we use a chilled Atlantic Water group (AIW group) to identify changes in the relative contribution of the Atlantic waters from the Arctic Ocean. This group includes the calcareous species *Islandiella norcrossi* and *Melonis barleeanus*, as well as the agglutinated species *Reophax pilulifer* (Table 2). The Arctic Water group (AW) includes the calcareous taxa *Elphidium excavatum* f. *clavata* and *Stainforthia feylingi* and the agglutinated taxa *Trochammina nana*, *Ammoglobigerina globigeriniformis*, *Recurvoides turbinatus* and *Textularia torquata*.

The planktic foraminiferal assemblage is dominated by the polar species *Neogloboquadrina pachyderm*a (s.) accounting for *c.* 90 to 100%, accompanied by low abundance (< 5%) of the subpolar species *Turborotalita quinqueloba*. At site PS2641, the overall occurrence of planktic foraminifera is relatively low, averaging *c.* 5% of the total foraminiferal assemblage. Therefore, we choose to present counts per gram sediment of both planktic species in the following discussion (i.e., number of individuals/g, Fig. 4). Abundance changes of planktic foraminifera on the East Greenland shelf region have been reported to be predominantly controlled by food availability (position of chlorophyll α maximum) and the position of the Arctic summer sea-ice margin (Hembleben et al., 1989; Hemleben and Schiebel, 2005; Pados and Spielhagen, 2014).

4.3 Mid to late Holocene foraminiferal assemblage changes

The following section presents the foraminiferal assemblage zones (FAZ) based on single foraminiferal species and association trends.

FAZ I (*c.* 4.5 to 6.3 ka BP): This interval is characterised by highest content of planktic foraminifera during the last 6.3 ka BP. We find a distinct peak centred *c.* 5.5 ka BP (14 individuals/g, Fig. 4) followed by a decrease to a minimum level of about one individual/g. *Cassidulina reniforme* (*c.* 20-30%) and the warm Atlantic Water associated *C. neoteretis* (*c.* 15-35%) dominate the basal part of our record, in co-occurrence with the opportunistic AW species *E. excavatum* f. *clavata* (*c.* 20-40%, Fig. 4). We recognise a pronounced peak in AW species *E. excavatum* f. *clavata* (*c.* 45%), alongside productivity indicator species *N. labradorica* (*c.* 20%), centred at 5.2 ka BP and accompanied by reduced abundance of *C. neoteretis* (*c.* 10%) as well as *C. reniforme* (*c.* 15%, Fig. 3).

FAZ II (*c.* 2.3 to 4.5 ka BP): This zone is characterised by a marked reduction in the abundance of planktic foraminifera to an average of one individual/g. The subpolar species *T. quinqueloba* occurs only sporadically throughout this interval (Fig. 4). This accompanies notably lower abundance of *C. neoteretis* (averaging 7%), while the chilled Atlantic Water related species *I. norcrossi* and *M. barleeanus* gradually increase (Fig. 4). This is accompanied by a moderate to high abundance of AW species *E. excavatum* f. *clavata*. From *c.* 2.7 ka BP towards the end of this zone, we observe increased abundance of the productivity indicator *N. labradorica* that accompanies a distinct decrease in the overall foraminiferal content (Fig. 4).

FAZ III (*c.* 1.4 to 2.3 ka BP): Planktic foraminifera are almost absent, and we record the lowest overall benthic foraminiferal content (Fig. 4). Within the benthic assemblage *N. labradorica* is the dominant species, particularly in the early part of the zone with peak abundance at 2.2 ka BP. *Islandiella norcrossi* (up to 25%) and *M.*

barleeanus (*c.* 35%) increase in abundance throughout the second half of this zone. In addition to this, we recognise higher abundance of the agglutinated 'chilled' AIW related species *R. pilulifer* (*c.* 6%), while the warm Atlantic Water associated species *C. neoteretis*, and the AW species *E. excavatum* f. *clavata* are notably reduced in abundance.

FAZ IV (*c.* 1.4 ka BP onwards): In this zone, the occurrence of planktic foraminifera recovers and a pronounced peak of *c.* 3 individuals/g is centred at *c.* 1.3 ka BP, followed by a decrease to an average of 1 individual/g. Benthic foraminifera display a marked assemblage change over the last millennium. From c. 1.4 ka BP onwards, the overall abundance of agglutinated species increase. Agglutinated AW species, such as *T. nana*, A. *globigeriniformis* and *T. torquata*, comprise *c.* 30% of the total assemblage (Fig. 4). This feature accompanies an overall reduced abundance of 'chilled' AIW species. In particular, we observe a pronounced decrease in the abundance of *N. labradorica*, *C. reniforme*, *I. norcrossi* and *E. excavatum* f. *clavata* after *c.* 0.3 ka BP.

5. Discussion

Our new high-resolution planktic and benthic foraminiferal record from Foster Bugt illustrates distinct mid to late Holocene millennial-scale variability of the EGC, and of the underlying subsurface Atlantic Water during the last *c.* 6.3 ka BP. In the following section, we first discuss the regional mid to late Holocene palaeoceanographic changes and then place our findings within the broader context of oceanic and climatic changes in the North Atlantic region. Planktic foraminiferal abundance data are used to draw conclusions on the variability of; i) the surface water characteristics and strength of the East Greenland Current (EGC), ii) sea-ice coverage, and iii) the location of the Polar Front. Variability of the benthic foraminifera provide information on i) characteristics of EGC subsurface waters, i.e., the relative contribution of Atlantic waters to the East Greenland shelf and ii) changes in the stratification of the water column.

5.1 Long-term regional mid to late Holocene palaeoceanographic changes

5.1.1 Mid Holocene Thermal Optimum conditions

The early part of the record (FAZ I; *c.* 4.5 to 6.3 ka BP) is characterised by seasonal sea-ice cover and significant surface water productivity as indicated by relatively high, but varying, abundance of planktic foraminifera and phytoplankton IP_{25} indices (Müller et al., 2012; Fig. 5D and E). The Polar Front, which marks the extent of perennial sea ice, was likely located in the Foster Bugt area, suggested by a prominent peak in planktic foraminiferal abundance centred at *c.* 5.5 ka BP. Our data indicate a relatively narrow flow of the EGC that is presumably confined to the west of our core site on the East Greenland shelf, this supports previous findings from Koç et al. (1993). Simultaneously, we identify relatively warm subsurface water conditions on the shelf, as indicated by high abundance of *C. neoteretis* (Fig. 5B – red curve). The relatively low abundance of chilled Atlantic Water indicator species (AIW group - *I. norcrossi* and *M. barleeanus*; Fig. 5B – orange curve) supports this interpretation.

Our data thus points to reduced stratification of the water column, a seasonally migrating Polar Front and an absent/weak halocline, due to a thin surface Polar Water layer and likely an enhanced influence of the warm subsurface waters on surface water conditions. This is in broad agreement with palaeoceanographic reconstructions from the Greenland Sea (Koç et al., 1993; Telesiński et al., 2014a) as well as reported relatively warm surface water conditions and a strong Atlantic Water inflow in eastern Fram Strait (e.g., Werner et al., 2013). The warmer subsurface Atlantic Water at our site may therefore originate from the recirculation of the West Spitsbergen Current (WSC), the Return Atlantic Current (RAC), in Fram Strait. A stronger RAC flow at this time is also supported by additional evidence along the east Greenland margin. Terrestrial studies from central East Greenland (Funder, 1978; Fredskild, 1991; Wagner and Melles, 2002; Wagner et al., 2008; Bennike and Wagner, 2013) report Holocene thermal optimum-like conditions prevailing until *c.* 4.5 ka BP within this area. Further downstream on the North Iceland shelf, low drift ice occurrence (Moros et al., 2006; Fig. 5G; Andrews, 2009) and relatively warm surface water conditions (Knudsen et al., 2004a; Justwan et al., 2008) suggest a weak flow of the East Icelandic Current during the same time interval, this is in agreement with our findings further north. Also, reduced sea-ice cover and weak Polar Water influence from the EGC is reported from the Southeast Greenland shelf at this time (e.g., Jennings et al., 2011; Andersen et al., 2012).

5.1.2 Onset of Neoglaciation

After *c.* 4.5 ka BP (FAZ II; *c.* 2.3 to 4.5 ka BP) cooling of surface waters and a south-eastward advance of the Polar Front, leading to permanent sea-ice cover, is inferred from notably reduced abundance of planktic foraminifera (Fig. 5D), as well as from increasing phytoplankton IP_{25} indices and sea ice algae abundance (Müller et al., 2012; Fig. 5E). It is likely that the shelf area received an enhanced contribution of cooler and fresher surface waters that consequently led to a thickening of the surface Polar Water layer. This surface cooling is accompanied by cooling of the subsurface Atlantic Water as indicated by a prominent decrease in abundance of *C. neoteretis* (Fig. 5B – red curve), which is gradually replaced by increasing abundance of chilled Atlantic Water species (Fig. 5B – orange curve).

Compared to the preceding interval, we infer a strengthening of the EGC. This must have led to a well-stratified water column and presumably favoured the formation of a distinct halocline between the Polar Water and Atlantic Water layer within the EGC. In line with our inferred timing of a stronger/expanded EGC, lake records from central East Greenland report distinct cooling from *c.* 4.5 ka BP (Wagner and Melles, 2002). The observed cooling of subsurface waters may result from either less recirculating Atlantic Water (RAC) and/or enhanced contribution of chilled Atlantic Water (AIW) from the Arctic Ocean to the East Greenland shelf. A simultaneous increase in AIW flow and the wider extent of surface EGC waters potentially reduced the impact of recirculating Atlantic Water in western Fram Strait. A reduction of RAC strength is supported by an overall decrease in Atlantic Water inflow to eastern Fram Strait and shelf/fjord areas of Spitsbergen after *c.* 5.5 ka BP (e.g., Hald et al., 2007; Werner et al., 2013; Aargaard-Sørensen et al., 2014; Rasmussen et al., 2014).

Surface water cooling, increased sea-ice coverage and/or reduced summer sea-ice break up is also recognized in the Greenland-Norwegian Sea and in eastern Fram Strait after *c.* 5.5 ka BP (Koç et al., 1993; Müller et al., 2012; Werner et al., 2013; Telesiński et al., 2014a, b). Drift ice and SST records from the North Iceland shelf report a stronger Arctic/Polar Water influence, after *c.* 5.5 ka BP (Fig. 5G; Moros et al., 2006a; Justwan et al., 2008). In addition, a sudden occurrence of coccolith species indicating the presence of warm and saline Irminger waters in subsurface waters, suggests an enhanced stratification of the water column by a thicker surface freshwater layer and thus strengthening of the East Icelandic Current (Andrews and Giraudeau, 2003; Giraudeau et al., 2004).

From *c.* 1.4 to 2.3 ka BP (FAZ III), minimum surface water productivity and a thick, cold and fresh surface Polar Water layer is indicated by an almost absent planktic foraminiferal fauna (Fig. 5D). The low abundance of planktic foraminifera suggests that the Polar Front was likely located south of Foster Bugt. During this period Müller et al. (2012) report a gradual increase in phytoplankton productivity and sea-ice algae abundance based on IP_{25} data (Fig. 5E). However, the temporal resolution of the IP_{25} data is too low compared to our foraminiferal proxy data to provide a sound correlation at a centennial time scale. A distinct increase in abundance of chilled Atlantic Water species (AIW group; Fig. 5B – orange line) indicates a cooling of subsurface waters. We attribute these environmental conditions to an overall strengthened/expanded EGC flow that produced a permanently stratified water column, separated by a well-developed halocline from the underlying chilled Atlantic Water layer. The presence of such a distinct halocline may also explain the parallel increase in the productivity related species *N. labradorica* (e.g., Steinsund, 1994; Rytter et al., 2002; Fig. 5D). A well-stratified water column due to a thick freshwater layer over the East Greenland shelf is in line with findings from the Greenland Sea (Telesiński et al., 2014a). In addition, these authors identify a subsurface temperature increase of *c.* 1.5°C and reduced subsurface water ventilation from *c.* 2.5 to 1.5 ka BP, confined to the central part of the Greenland Sea, which was likely caused by enhanced Atlantic Water inflow. Furthermore, Werner et al. (2013) and Müller et al. (2012) report seasonally fluctuating ice in eastern Fram Strait, alongside cool/fresh and productive surface waters after *c.* 3.2 ka.

At our study site, the distinct peak of chilled Atlantic Water occurred at the time of the 'Roman Warm Period'. At this time, records from the North Iceland shelf indicate surface warming (Justwan et al., 2008; Patterson et al., 2010), a weakened East Icelandic Current/drift ice export (Moros et al., 2006; Fig. 5F) and increased abundance of NAD related coccolith species (Andrews and Giraudeau, 2003; Fig. 6D). In addition, records from the southeast Greenland shelf show a variable influence of EGC waters

(Sicre et al., 2008; Andresen et al., 2013) and increased Irminger Current contribution (Jennings et al., 2011).

Reoccurrence of planktic foraminifera from *c.* 1.4 ka BP (FAZ IV) indicate a less thick/extensive Polar Water layer and less severe drift/sea ice conditions compared to the preceding interval. This suggests a return to seasonal ice cover, presumably caused by sea-ice breaking up in late summer and seasonal migration of the Polar Front in the Foster Bugt area. The surface water conditions most likely became less harsh as surface productivity increased (Müller et al., 2012; Fig. 5D and E). An overall reduced contribution of chilled Atlantic Water species (AIW group) and a slight increase in *C. neoteretis* during the last millennium (Fig. 5B - red curve) supports this conclusion. It is likely that a weaker halocline was present during this period in Foster Bugt. In addition, harsher/less stable environmental conditions are suggested by an overall increase in abundance of agglutinated species, specifically of cold water associated agglutinated species (aggAW group, see Figs. 4 and 5A). The benthic foraminiferal fauna suggests a slightly weaker flow of the EGC, compared to the preceding interval. In line with previous research (e.g., Koç et al., 1993; Moros et al., 2006a; Telesińki et al., 2014a) we note that the EGC is still stronger and broader in extent compared to the interval *c.* 6.3 to 4.5 ka BP. Records located along the Southeast and West Greenland shelf report a similar timing in the increase of the agglutinated fauna during the last *c.* 1.5 ka BP (Jennings et al., 2002, 2011; Perner et al., 2011, 2013a). We argue that this increase of agglutinated taxa is not simply related to downcore taphonomic decay, but rather indicates harsher and more competitive environmental conditions, specifically during the last millennium. The causes of apparently more favourable conditions for agglutinated foraminifera, allowing them to be more competitive, is still not well understood and needs more detailed investigation.

Superimposed on the agglutinated faunal trend, a minor peak in the AIW group, centred at *c.* 1.0 ka BP, indicates a slight increase in chilled Atlantic Water (Fig. 5B – orange curve) that coincides with minor cooling of the surface Polar Water layer (Fig. 5D). This brief period of enhanced chilled Atlantic Water contribution coincides with the 'Medieval Climate Anomaly' and has been recognized on the Southeast Greenland shelf (e.g., Sicre et al., 2008; Andrews and Jennings, 2014).

5.2 Wider palaeoceanographic relevance of the EGC strengthening

Our foraminiferal assemblage-based reconstructions highlight a longer-term mid to late Holocene (last *c.* 6.3 ka BP) strengthening/expansion of the EGC that culminates at *c.* 1.8 ka BP. This parallels distinct changes in the composition of the subsurface Atlantic Water on the East Greenland shelf. The reduction in warm Atlantic Water (RAC) and gradual increase in chilled Atlantic Water (AIW) fauna, after 4.5 ka BP, likely occurs in response to an expanded and strengthened (colder) EGC.

An expanded EGC shifts the frontal system south-eastwards in the Nordic Seas, as prominently seen during the modern 'Great Salinity Anomalies' (Dooley et al., 1984; Dickson et al., 1988). This is consistent with the observed mid to late Holocene SST cooling and the salinity decrease during the onset of Neoglaciation caused by reduced summer and increased winter insolation along the North Atlantic Current (Andersen et al., 2004a, b; Calvo et al., 2002; Sachs, 2007). Coincident with this expanded EGC, studies from the Nordic Seas infer Atlantic Meridional Overturning Circulation weakening, which accompanies increased stratification of the upper ocean layer and a less ventilated subsurface during the late Holocene (e.g., Bauch et al., 2001; Sarnthein et al., 2003; Hall et al., 2004; Hald et al., 2007). The reduction of warm Atlantic Water may be attributed to reduced northward surface heat advection by the

North Atlantic Current from low latitudes into the subpolar North Atlantic region. Therefore, the WSC might have weakened during this period, and consequently recirculating warm and saline Atlantic Water (RAC) that eventually reached the East Greenland shelf might have been limited, and/or its position/latitude was located further south of Fram Strait. This in turn would allow an open passage for enhanced chilled Atlantic Water outflow from the Arctic Ocean as evident in our data and prominently seen by oceanographic observations in 1998 (Rudels et al., 2012).

The enhanced freshwater advection likely weakened the Subpolar Gyre circulation strength (e.g., Thornalley et al., 2009), and resulted in the observed contrasting oceanic trends in subsurface waters across the North Atlantic basin, i.e., cooling in the Northwest Atlantic (e.g., Koç et al., 1993; Giraudeau et al., 2004; Hall et al., 2004; Moros et al., 2006a,b, 2012; Sarafanov et al., 2009; Jennings et al., 2011; Perner et al., 2011; Telesiński et al., 2014a) and warm/stable conditions in the Northeast Atlantic region (e.g. Risebrobakken et al., 2003; Andersen et al., 2004b; Came et al., 2007; Farmer et al., 2008; Thornalley et al., 2009; Miller et al., 2011).

Superimposed on this longer-term mid to late Holocene cooling trend offshore East Greenland, we recognise millennial-scale cold-phases centred at 3.8, 3.0, 2.4, 1.9 - 1.4, 1.0, and 0.1 ka BP. Periods of severe sea ice conditions (almost absent planktic foraminifera; Fig. 5D) coincide with increased contribution of chilled Atlantic Water (increase in AIW group; Fig. 5B – orange curve) and minimum contribution of warmer Atlantic Water (*C. neoteretis*; Fig. 5B – red curve). These millennial scale phases correspond, within age-model uncertainties, to a southward shift of the Subpolar Front (Moros et al., 2012) and reduced deep convection in the Nordic Seas (e.g., Renssen et al., 2005; Telesiński et al., 2014a). Renssen et al. (2005) suggest that a reduced Nordic Sea deep convection is counterbalanced by enhanced deep convection in the Labrador Sea, which in turn strengthens the North Atlantic Current flow.

5.2.1 The Roman Warm Period

The most prominent of the millennial-scale cycles present in our record, is the interval from 1.4 to 2.3 ka BP. This phase of maximum outflow of cold and low salinity surface water, contributing to the surface flow of the EGC, and subsurface chilled Atlantic Water is recognized in reconstructions from: North of Iceland (Andrews and Giraudeau, 2003; Giraudeau et al., 2004; Fig. 6C); the Reykjanes Ridge (Moros et al., 2012; Fig. 6B – grey line); the Vøring Plateau (Risebrobakken et al., 2003; Fig. 6B – dark line); the Barents Sea (Sarnthein et al., 2003); southeast Greenland (Jennings et al., 2002); and the West Greenland shelf (Moros et al., 2006b; Perner et al., 2011, 2013a; Fig. 6A). A warming is also seen in the temperature anomaly of the GISP2 ice core (Alley et al., 1999) alongside increased terrestrial winter precipitation in northern Norway (Bakke et al., 2008). In addition, subsurface warming is also reported from offshore West Africa (Morley et al., 2014). We propose that the phase between 1.4 and 2.3 ka BP is linked to the Roman Warm Period, a climatic anomaly that was suggested to equal modern climatic warming (e.g., Moberg et al., 2005; Mann et al., 2008; Ljungqvist et al., 2010). Strong contribution of chilled Atlantic Water from the Arctic Ocean to the East Greenland shelf likely occurred in response to combined changes in; i) Subpolar Gyre circulation dynamics, and/or ii) atmospheric circulation, i.e., NAO and AO modes during this time period. The weakened Subpolar Gyre circulation after *c.* 3.5 ka BP (Thornalley et al., 2009), especially following the cooling event/anomaly at *c.* 2.6 to 2.8 ka BP, would lead to enhanced advection of warm and saline waters from the Subtropical Gyre into the subpolar North Atlantic region (e.g., Häkkinen and Rhines, 2004). Consequently, the North Atlantic Drift and North Atlantic Currents are strengthened and the northward heat transport within the northeast Atlantic increased causing, within age-model uncertainties, a simultaneous subsurface warming along the North Atlantic Drift/North Atlantic Current and its side braches (IC, WGC) during the time of the Roman Warm Period. A change from an intermittently negative NAO/AO to an overall positive mode has been interpreted from precipitation records (Nesje et al., 2001), storm intensity reconstructions (Jackson et al., 2005), drift-ice/drift-wood (Funder et al., 2011b; Darby et al., 2012), and lake sediment records (Olsen et al., 2012), after *c.* 2.5/2.0 ka BP. In line with our data, Funder et al. (2011b) report increased multi-year sea ice during the last *c.* 2.5 ka BP, which the authors link to enhanced ice export from the western Arctic Ocean. A positive NAO/AO mode around 2.0 ka BP and strong Transpolar Drift may act as a potential mechanism that likely favoured the expansion or strengthening of the EGC, which is essentially a response to increased freshwater contribution to the EGC from the Arctic Ocean.

We suggest that the high contribution of chilled Atlantic Water to the East Greenland shelf during the Roman Warm Period is largely due to the increased heat advection of the North Atlantic Currents into the Arctic Ocean during this time. This phase, centred on *c.* 1.8 ka BP, is an example of a large scale ocean-atmosphere teleconnection between circulation in the North Atlantic, Nordic Seas and the Arctic Ocean (Moros et al., 2012). However, the contribution of chilled Atlantic Water might have been considerably stronger during the time of the Roman Warm Period, compared to the Medieval Climate Anomaly. This provides further evidence that the northward heat advection by the NAC was considerably stronger during the Roman Warm Period than during the Medieval Climate Anomaly.

6. Summary and Conclusions

Planktic and benthic foraminiferal assemblage data record changes in the water mass composition of the East Greenland shelf during the mid to late Holocene (last *c.* 6.3 ka BP). We document mid Holocene thermal optimum-like conditions with a relatively low outflow of cold, low salinity water from the Arctic Ocean contributing to an overall weak/moderate EGC flow, and a thin and/or absent surface Polar Water layer, from *c.* 4.5 to 6.3 ka BP. This matches relatively low sea ice formation in the Arctic Ocean (e.g. Funder et al., 2011b). After *c.* 4.5 ka BP, our reconstructions highlight a progressive strengthening of the EGC flow representing an increase in freshwater/ice flux from the Arctic Ocean and the consequent south-eastward freshwater expansion substantially weakening the Subpolar Gyre circulation. In addition to the EGC strengthening, we note enhanced contribution of subsurface chilled Atlantic Water from the Arctic Ocean during this time. Between 1.4 and 2.3 ka BP the strongest EGC flow from the studied period is recorded. This coincides with a strong chilled Atlantic Water contribution and/or subsurface warming centred at *c.* 1.8 ka BP, which is likely linked to the Roman Warm Period. A similar warm phase is observed in marine records influenced by the North Atlantic Current from North Iceland, the SE and West Greenland shelf, on the Reykjanes Ridge, the Norwegian Sea, Barents Sea, Greenland Sea and eastern Fram Strait. This warming was considerably stronger than during the subsequent Medieval Climate Anomaly. Although the exact timing remains unclear, subsurface warming offshore East Greenland may relate to the warming of the North Atlantic Current, caused by the weakened Subpolar Gyre circulation.

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Author contributions

K.P., M.M., J.M.L, E.J., and R.S. contributed to the interpretation of the data and wrote the manuscript. K.P. carried out countings of planktic and benthic foraminifera and developed the figures and tables for the manuscript. All authors discussed and commented on the manuscript.

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Figure captions

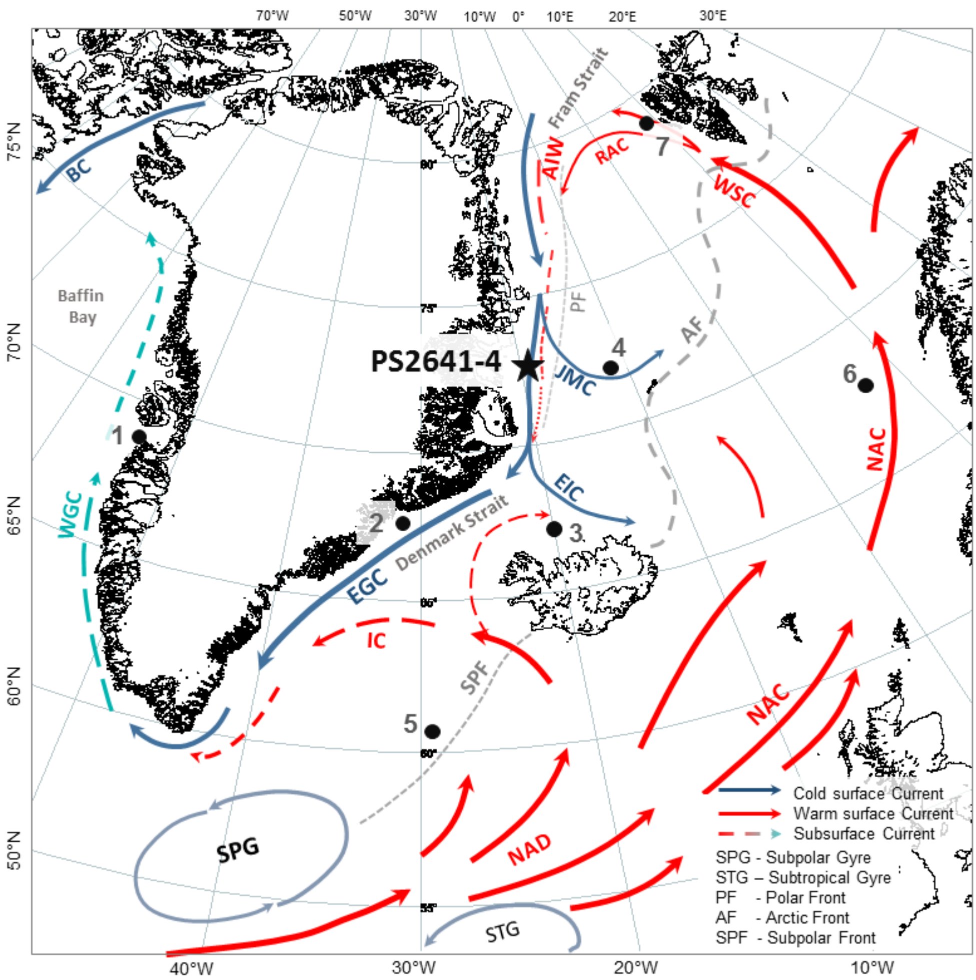

Figure 1. Map of the study area with schematic illustration of the major currents in the North Atlantic region. Abbreviations are as follows: East Greenland Current (EGC), East Icelandic Current (EIC), Jan Mayen Current (JMC), West Greenland Current (WGC), Baffin Current (BC), Irminger Current (IC), North Atlantic Current (NAC), North Atlantic Drift (NAD), West Spitzbergen Current (WSC), Return Atlantic Current (RAC). Key sites pertinent to this study: 1) West Greenland – 343310 (Perner et al., 2011); 2) SE Greenland shelf – MD2322 (Jennings et al., 2011); 3) North Iceland shelf – MD99-2269 (Andrews and Giraudeau, 2003; Moros et al., 2006a); 4) Greenland See – PS1878 (Telesiński et al., 2014a); 5) Reykjanes Ridge – DS2P (Moros et al., 2012); 6) Vøring Plateau – MD95-2011 (Risebrobakken et al., 2003); 7) Eastern Fram Strait – MSM5/5-712 (Werner et al., 2013).

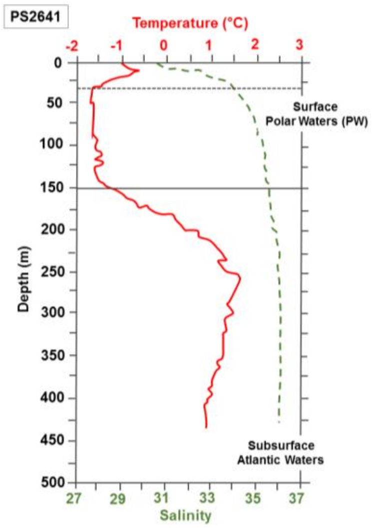

Figure 2. Temperature (red line) and salinity (green line) profile from site PS2641 in Foster Bugt, obtained during cruise ARK-X-/2 with the *Polarstern* in 1995 (Hubberten, 1995).

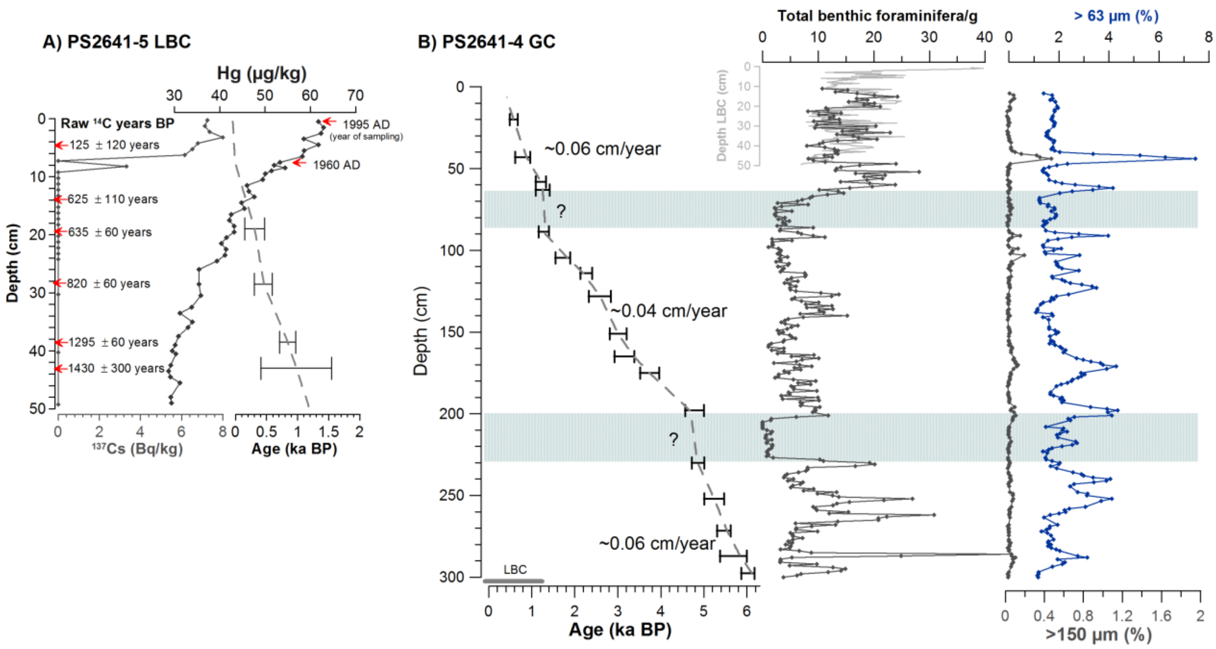

Figure 3. Age versus depth profile of cores PS2641-4 GC and PS2641-5 LBC, including AMS ^{14}C dates used for age model reconstruction. A) AMS ^{14}C dates, total Hg content and ^{137}Cs profile for the LBC. B) Sieve-fraction percentage data (>63 and >150 µm), counts of the total benthic foraminifera per gram sediment for the GC (dark line) and the LBC (grey line).

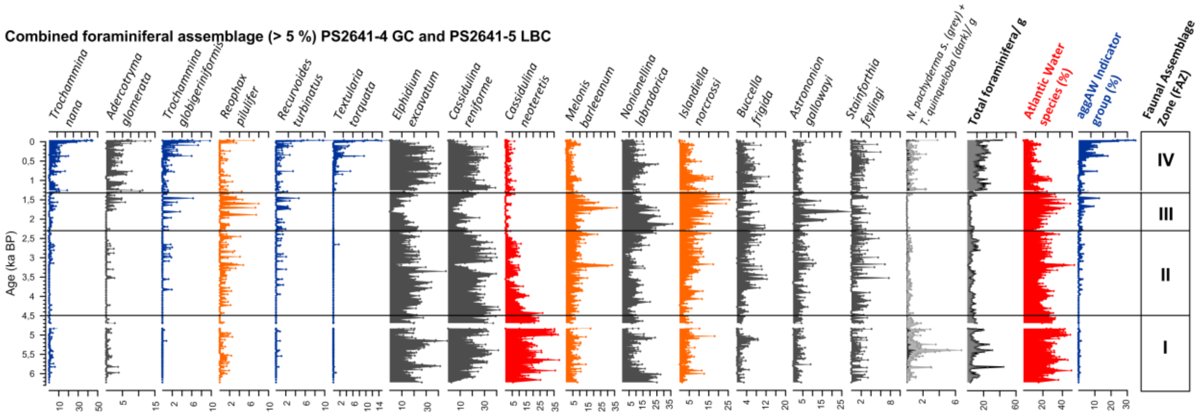

Figure 4. Percentage abundance > 5% of the total benthic foraminiferal assemblage. The content of planktic foraminifera is displayed as number of individuals counted per gram sediment. Chilled Atlantic Water (AIW) group – *I. norcrossi*, *M. barleeanus*, *R. pelulifer*; warm Atlantic Water indicator – *C. neoteretis*, agglutinated Arctic Water indicators (aggAW) – *R. recurvoides*, *A. globigeriniformis*, *T. nana*.

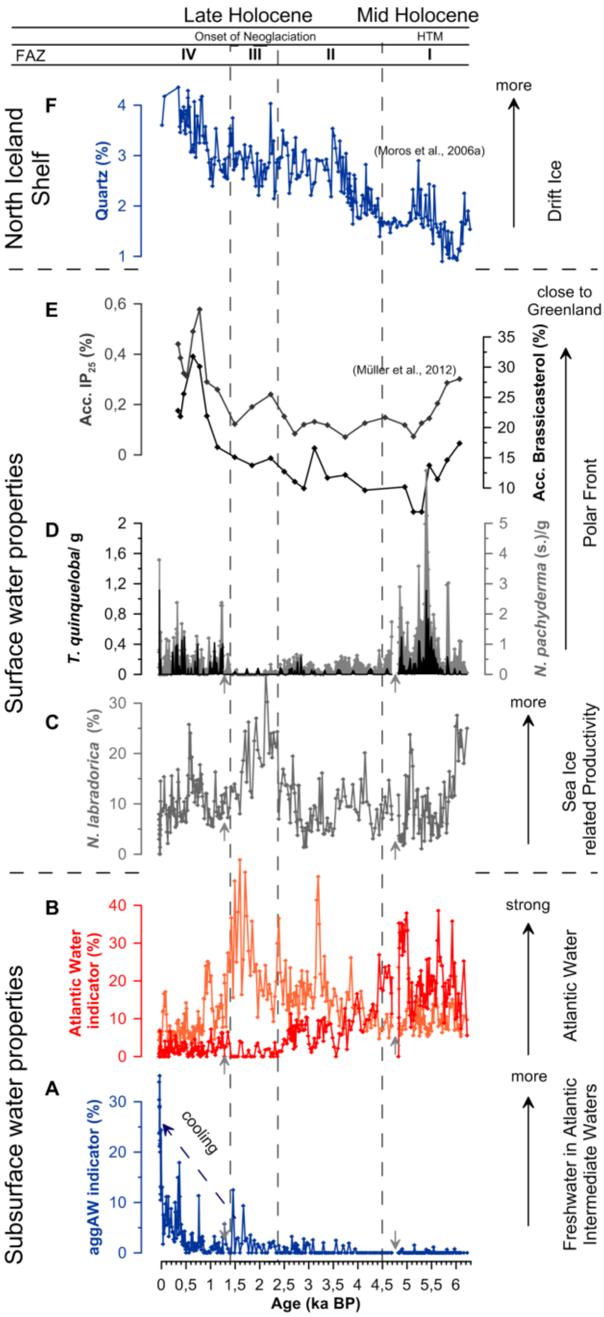

Figure 5. Regional mid to late Holocene (last *c.* 6.3 ka BP) paleoceanographic changes reconstructed from core PS2641-4GC. A) Abundance (%) of agglutinated Arctic Water species; B) Abundance (%) of warm Atlantic Water associated species *C. neoteretis*; C) Abundance (%) of the chilled Atlantic Water (AIW) group; D) Abundance (%) of *N. labradorica*; E) Content of planktic foraminifera *N. pachyderma* (s.) and *T. quinqueloba*; F) Accumulation (%) of IP_{25} and brassicasterol, phytoplankton marker from this core site, published by Müller et al. (2012); G) Drift ice proxy record (Quartz %) from North Iceland Shelf (MD99-2269, Moros et al., 2006a).

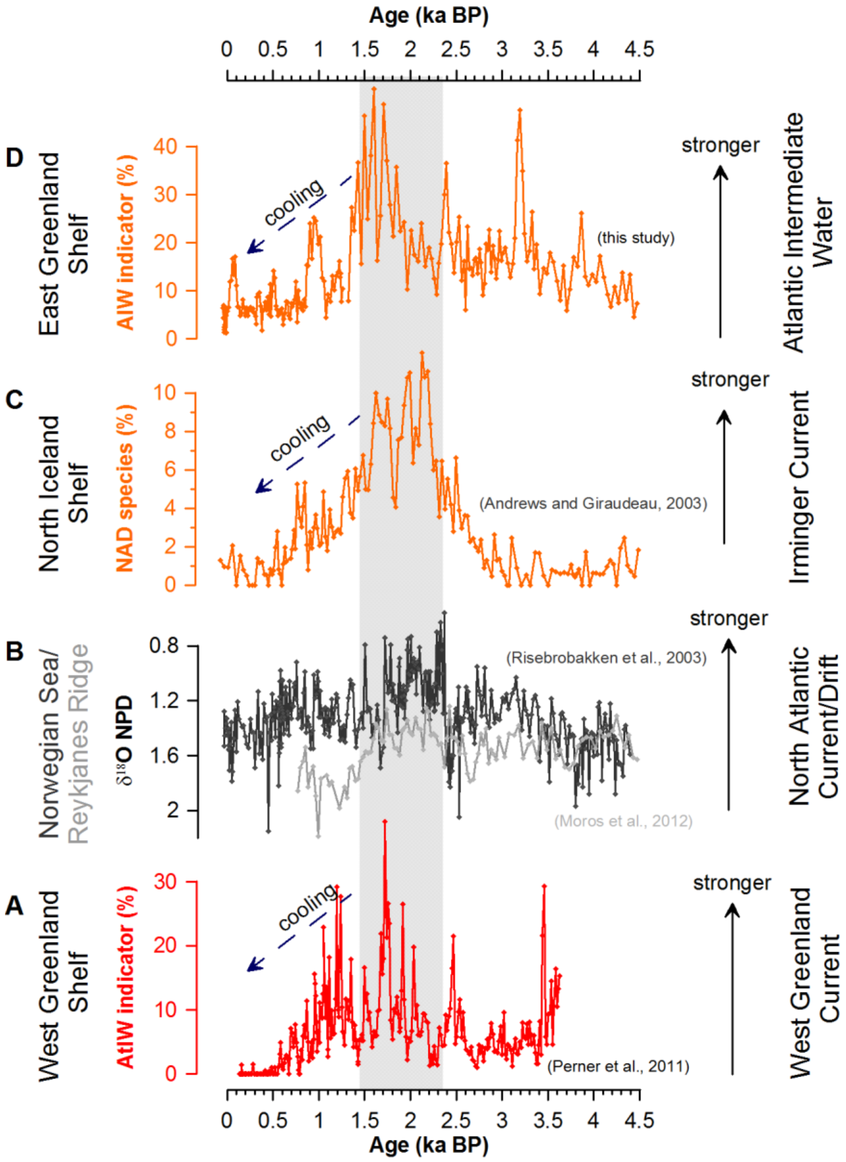

Figure 6. Palaeoceanographic changes within the subpolar North Atlantic region during the last *c.* 4.5 ka BP. A) Abundance (%) of Atlantic Water (AtlW) indicators (%) from the West Greenland shelf (red line MSM 343310, Perner et al., 2011); B) $\delta^{18}O$ of *N. pachyderma* (d.) from the Reykjanes Ridge (grey line, Moros et al., 2012) and the Norwegian Sea (dark line, Risebrobakken et al., 2003); C) North Atlantic Drift (NAD) coccolith assemblage from the North Iceland Shelf (MD99-2269, Andrews abd Giraudeau, 2003); D) chilled Atlantic Water (AIW) group (%) from East Greenland Shelf (PS2641, this study).