Surface and sub-surface multi-proxy reconstruction of middle to late Holocene palaeoceanographic changes in Disko Bugt, West Greenland

Matthias Moros[1*], Jeremy M. Lloyd[2], Kerstin Perner[1], Diana Krawczyk[3], Thomas Blanz[4], Anne de Vernal[5], Marie-Michele Ouellet-Bernier[5], Antoon Kuijpers[6], Anne E. Jennings[7], Andrzej Witkowski[8], Ralph Schneider[4], Eystein Jansen[9,10]

1 Leibniz Institute for Baltic Sea Research, Department of Marine Geology, Germany
2 Durham University, Department of Geography, UK
3 Greenland Climate Research Centre, Greenland Institute of Natural Resources, Greenland
4 Institute of Geosciences, Department of Geology, Kiel University, Germany
5 GEOTOP, Université du Québec à Montréal, Canada
6 Geological Survey of Denmark and Greenland, Copenhagen, Denmark
7 Institute of Arctic and Alpine Research, University of Colorado, United States
8 Faculty of Geosciences, University of Szczecin, Mickiewicza 18, 70-383 Szczecin, Poland
9 Bjerknes Centre for Climate Research, Allégaten 55, Bergen 5007, Norway
10 Department of Earth Science, University of Bergen, and Bjerknes Centre for Climate Research, Allégaten 70, Bergen 5007, Norway

*Corresponding author: Matthias Moros
Leibniz Institute for Baltic Sea Research
See Str. 15, 18119 Rostock, Germany
E-mail: matthias.moros@io-warnemuende.de
Tel.:+49/381/5197399

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Abstract

We present new surface water proxy records of meltwater production (alkenone derived), relative sea surface temperature (diatom, alkenones) and sea ice (diatoms) changes from the Disko Bugt area off central West Greenland. We combine these new surface water reconstructions with published proxy records (benthic foraminifera - bottom water proxy; dinocyst assemblages – surface water proxy), along with atmospheric temperature from Greenland ice core and Greenland lake records. This multi-proxy approach allows us to reconstruct centennial scale middle to late Holocene palaeoenvironmental evolution of Disko Bugt and the Western Greenland coastal region with more detail than previously available.

Combining surface and bottom water proxies identifies the coupling between ocean circulation (West Greenland Current conditions), the atmosphere and the Greenland Ice Sheet. Centennial to millennial scale changes in the wider North Atlantic region were accompanied by variations in the West Greenland Current (WGC). During periods of relatively warm WGC, increased surface air temperature over western Greenland led to ice sheet retreat and significant meltwater flux. In

contrast, during periods of cold WGC, atmospheric cooling resulted in glacier advances.

We also identify potential linkages between the palaeoceanography of the Disko Bugt region and key changes in the history of human occupation. Cooler oceanographic conditions at 3.5 ka BP support the view that the Saqqaq culture left Disko Bugt due to deteriorating climatic conditions. The cause of the disappearance of the Dorset culture is unclear, but the new data presented here indicate that it may be linked to a significant increase in meltwater flux, which caused cold and unstable coastal conditions at *ca.* 2 ka BP. The subsequent settlement of the Norse occurred at the same time as climatic amelioration during the Medieval Climate Anomaly and their disappearance may be related to harsher conditions at the beginning of the Little Ice Age.

1. Introduction

From the perspective of future climate change, the behaviour of the Greenland Ice Sheet (GIS) is of critical interest, due to its potential impact on global sea-level changes and ocean circulation (e.g. Howat et al., 2007; Pritchard et al., 2009). Enhanced freshwater contribution of the GIS to the North Atlantic Ocean may affect the northward heat transport in the North Atlantic Drift (Oppo et al., 2003; Thornalley et al., 2009, Moros et al., 2012). Many tidewater glaciers in southeast and west Greenland show significant changes in velocity and consequent ice flux to the ocean since 2000 (e.g. Andresen et al., 2013; Holland et al., 2008; Howat et al., 2007, 2008, 2011; Moon and Joughin, 2008; Rignot and Kanagaratnam, 2006; Straneo et al., 2010; Walsh et al., 2012; Zwalley et al., 2002). The forcing mechanism for the enhanced ice velocity is unclear although there is strong support for the importance of the influence of changing ocean temperatures driving glacier dynamics (e.g. Holland et al., 2008; Lloyd et al., 2011; Rignot et al., 2010). On longer time scales the ‘ocean forcing’ may have played an important role in triggering large-scale ice sheet destabilization (e.g. Moros et al., 2002). A better understanding of the linkages between past GIS behaviour and forcing mechanisms such as changes in ocean circulation is, therefore, critical to predicting future changes in ice sheet behaviour.

The area of Disko Bugt in central west Greenland has been of particular interest because of the significant changes in ice velocity of Jakobshavn Isbræ, one of the largest ice streams draining approximately 7% of the GIS (Bindschadler, 1984). This area has been intensively studied over recent years with special attention paid to the late Quaternary variation of the ice sheet (e.g. Briner et al., 2010; Kelley et al., 2013; Larsen et al., 2015; Weidick and Bennike, 2007; Young et al., 2011), the deglaciation and the Holocene variations in nearshore to offshore ocean circulation (e.g. Lloyd et al., 2005, 2007, 2011; Jennings et al., 2014; Krawczyk et al., 2010, 2012, 2013; Moros et al., 2006b; Ouellet-Bernier et al., 2014;

Perner et al., 2011, 2013a,b; Ribeiro et al., 2012; Seidenkrantz et al., 2008). More recently, a number of studies from Disko Bugt have identified areas of high accumulation rate, suitable for investigating decadal to multi-centennial scale variations in ocean circulation (site 343310 and 343300, Figure 1; Lloyd et al., 2011; Perner et al., 2011, 2013a). To date, the studies from Disko Bugt have focused on a limited number of proxies, commonly either surface water proxies (diatoms, dinocysts; e.g. Krawczyk et al., 2010, 2013; Ribeiro et al., 2012; Ouellet-Bernier et al., 2014) or bottom water proxies (benthic foraminifera; e.g. Lloyd et al., 2005, 2007, 2011; Perner et al., 2011, 2013a).

Here, we combine published surface (diatoms, dinocysts) and sub-surface (benthic foraminifera) water proxy data (343310: Krawczyk et al., 2013; 343300: Ouellet-Bernier et al., 2014; 343310: Lloyd et al. 2011; Perner et al., 2011; 343300: Perner et al., 2013a) from these core sites (Figure 1) with new records of sea surface salinity (the relative proportion of tetra-unsaturated C_{37} ketones - $\%C_{37:4}$ - in alkenones) and relative estimates of sea surface temperature (biomarker alkenone derived U^{k}_{37}, diatoms in 343300). By combining the different proxies (measured on the same sample sets) and by comparing our marine data with terrestrial lake and the ice core records, a more complete picture of the evolution of ocean circulation, atmospheric temperature and ice stream behaviour over the middle to late Holocene can be proposed. Linkages between climate and the history of human occupation of West Greenland, along with middle to late Holocene ocean circulation changes observed off West Greenland in the broader context of the North Atlantic are also discussed.

2. Study area and regional environmental setting

Disko Bugt (Figure 1) is a large marine embayment (40,000 km^2) off central West Greenland with relatively shallow water depths of 200 to 400 m and with maximum water depths up to 900 m in Egedesminde Dyb, a deep-water trough of glacial origin (Long and Roberts, 2003; Roberts and Long, 2005; Zarudski, 1980). The Disko Bugt area is typically covered by seasonal sea-ice from January to March-April/May and the present day climatic conditions are low arctic maritime with mean surface air temperatures of ~ 4.8°C in summer and ~ -5.2°C throughout the year (Fredskild, 1996, Nielsen et al., 2001; Ribergaard et al., 2006).

The West Greenland Current (WGC), which dominates the regional oceanography is a water mass resulting from the mixing of: (i) Arctic-sourced cold, low-salinity water from the East Greenland Current (EGC, found at 0-200 m water depth), termed Polar Water (Buch, 1981); (ii) relatively warm and saline Atlantic-sourced water from the Irminger Current (IC, >200 m water depth), a branch of the North Atlantic Current (NAC; Buch, 1981; Tang et al., 2004); and (iii) surface local meltwater discharge from the south-west Greenland margin. The WGC is formed at the southern tip of Greenland (Cape Farwell) and flows northwards on the West Greenland shelf (Cuny et al., 2002) and turns gradually westwards into Baffin Bay.

Reaching central West Greenland, a side branch of the WGC enters Disko Bugt from the southwest and flows northwards exiting the embayment primarily through the Vaigat Strait (Figure 1 and inset; Andersen, 1981; Bâcle et al., 2002; Ribergaard et al., 2006). Along its flow path in Disko Bugt, the WGC carries icebergs and meltwater from outlet glaciers located in eastern Disko Bugt, such as Jakobshavn Isbræ, Semerq Avangnardleq, Sermeq Kujadleq and Kangersuneq (Figure 1). Exiting Disko Bugt through the Vaigat Strait, a branch of the WGC deflects westwards into Baffin Bay, while the major current continues to flow further northwards along the West Greenland coast. The Atlantic Water core of the WGC is relatively warm and saline with temperatures > 5°C and salinity > 34.9 PSU off Cape Farewell gradually cooling and freshening to 3.5-4.5°C and 34.2-34.9 PSU in the Disko Bugt area forming the bottom waters in Disko Bugt and the adjacent shelf (Andersen, 1981; Buch, 1981; Buch et al., 2004; Lloyd, 2006; Ribergaard et al., 2013). There are no indications that deep Baffin Bay waters penetrate onto the shelf along the west Greenland margin or into Disko Bugt below 300 m water depth (Andersen, 1981). However, meltwater flux and icebergs from outlet glaciers, as well as the winter season's pack ice and low-salinity polar surface water from Baffin Bay influence surface water properties along the west Greenland margin. In the Disko Bugt area, sea-surface conditions record large variations. Sea-surface conditions at coring site 343300 (Figure 1) show significant interannual variability: data compiled from the National Oceanographic Data Center (NODC, 2001) indicate mean summer sea-surface temperature of 3.1 to 5.7°C (one sigma) and salinity of 32.9 to 33.4; 1953-2003 data from the National Snow and Ice Data Center (NSIDC) indicate mean sea-ice cover of 3.8 ± 1.3 months/yr. Surface water productivity in Disko Bugt is influenced by the nearby sea ice edge of the so-called 'West Ice', which forms in Baffin Bay during late autumn and winter. At present this frontal zone lies northwest of Disko Bugt in spring (Hansen et al., 1999; Levinsen et al., 2000; Tang et al., 2004).

3. Methods

3.1 Chronology

The age control of cores 343300 and 343310 (Figure 1) is provided by accelerator mass spectrometry (AMS) ^{14}C dates on benthic foraminifera and mollusc shells, calibrated with Marine09 (Reimer et al., 2009) using OxCal 4.1 (Bronk Ramsey, 2009) and a marine reservoir age correction ΔR of 140 ± 35 years (Lloyd et al., 2011). For full details of core chronologies see Perner et al. (2011, 2013a). Multi core (MUC) and gravity core (GC) records from both core sites do not overlap. At site 343300 there is a 500 year gap between MUC and GC and at site 343310 there is a gap of *ca.* 100 years between MUC and GC. The chronology of core 343310 is based on a larger number of AMS^{14}C dates and the core is characterized by a higher sedimentation rate than core 343300. Therefore, discussions on the timing of late Holocene oceanographic changes are based on core 343310.

3.2 Multi-proxy approach

The combination of proxies presented here provides information on a range of oceanographic parameters. The individual studies were performed on samples from the same depths except where resolution differed between proxies. The alkenone biomarker derived data (%$C_{37:4}$, U^{k}_{37}) provide information on salinity variations and relative sea-surface temperature (SST); diatom and dinocyst assemblages provide estimates of sea surface temperature, salinity and sea ice conditions, which are used qualitatively here; benthic foraminifera provide information on bottom conditions, in particular the relative strength of the Atlantic water component of the WGC, but also on supply of organic material linked to surface water productivity.

3.2.1 Alkenone biomarkers

Analytical method: Alkenones are specific organic compounds synthesized by haptophyte algae such as coccolithophores. In this study alkenone (U^{k}_{37}, %$C_{37:4}$) analyses were carried out at the Biomarker Laboratory of the University of Kiel. At site 343300, samples were analyzed every 3 cm with a temporal resolution of about 70 years, covering the time period from *ca.* 8 ka BP and at site 343310 every 4 cm with a temporal resolution of 12-15 years for the time period from *ca.* 3.6 ka BP. Long-chained alkenones (C_{37}) were extracted from homogenized bulk sediment (2 to 3 g), using an Accelerated Solvent Extractor (Dionex ASE-200) with a mixture of 9:1 (v/v) of dichloromethane:methanol (DCM:MeOH) at 100°C and 100 bar N_2 (g) pressure for 20 minutes. At *c.* -20°C extracts were cooled and subsequently taken to near dryness by Synore polyvap at 40°C and 490 mbar. We used a multi-dimensional, double gas column chromatography (MD-GC) set up with two Agilent 6890 gas chromatographs for $C_{37:2}$, $C_{37:3}$ and $C_{37:4}$, identification and quantification (Etourneau et al., 2010). Quantification of the organic compounds was achieved with the addition of an internal standard prior to extraction (cholestane [$C_{27}H_{48}$] and hexatriacontane [$C_{36}H_{74}$]). The proportion of each alkenone was obtained using the peak areas of the specific compounds. The $U^{k'}_{37}$ index is calculated using the equation from Prahl et al. (1987): $U^{k'}_{37} = (C_{37:2})/(C_{37:2}+C_{37:3})$, U^{k}_{37} index according to Brassell et al. (1986): $U^{k}_{37}=(C_{37:2}- C_{37:4})/(C_{37:2}+C_{37:3}+C_{37:4})$. However, Rosell-Melé (1998) and Bendle and Rosell-Melé (2004) point out that U^{k}_{37} based estimates are more robust down to 6°C than $U^{k'}_{37}$.

Proxy for sea surface temperature: We present a high-resolution record of the alkenone unsaturation index U^{k}_{37} to reconstruct relative SST changes for the middle to late Holocene. However, as noted earlier (Rosell-Melé, 1998) at $C_{37:4}$ values above 5 % – which is the case here – alkenone based SSTs have increasing errors. Therefore we use the alkenone-based temperature reconstructions qualitatively (using the U^{k}_{37})rather than quantitatively here.

%$C_{37:4}$ – Proxy for meltwater input: We also present the proportion of tetra-unsaturated C_{37} ketones relative to the sum of alkenones (%$C_{37:4}$) for the middle to late Holocene. This ratio serves as an indicator of changes in meltwater discharge from the GIS as the amount of $C_{37:4}$ rises at lower surface salinities in polar and sub-

polar waters (Rosell-Melé, 1998; Rosell-Melé et al*.,* 2002; Sicre et al., 2002; Harada et al*.,* 2003; Bendle et al., 2005; Blanz et al., 2005).

3.2.2 Diatom analyses

Preparation and counting method: Diatom counting results of site 343310 are published in Krawczyk et al. (2013), and gravity core results of site 343300 are presented here for the first time. The 343300 samples were prepared using a chemical cleaning process (hydrochloric acid and hydrogen peroxide) and microscope slides were prepared following the method described in Krawczyk et al. (2013). The identification of species was carried out using light microscopy and scanning electron microscopy. For each sample over 300 valves were counted, excluding unidentifiable *Chaetoceros* resting spores (after Schrader and Gersonde, 1978). Identification of diatom species follows Fryxell (1975), Syvertsen (1979), Hasle and Syvertsen (1996), Witkowski et al. (2000), Quillfeldt (2001), Throndsen et al. (2003).

Ecological preferences: In arctic environments the diatom flora can be used to investigate surface water characteristics based on the ecological preferences of key indicator species (e.g. Koç Karpuz and Schrader, 1990; Justwan and Koç, 2008; Krawczyk et al., 2012, 2014). Two selected key species, *Fragilariopsis cylindrus* and *Thalassiosira kushirensis* resting spores (r.s.)*,* are used here based on their specific ecological preferences associated with surface water characteristics (Hasle and Syvertsen, 1996; Krawczyk et al., 2014). *Fragilariopsis cylindrus* is associated with sea-ice (e.g. Koç Karpuz and Schrader, 1990; Jiang et al., 2001; Justwan and Koc, 2008) and cold, open marine waters, and occurs mainly in arctic regions (Quillfeldt, 2001, 2004). This species is abundant in Disko Bugt in spring-summer (Jensen, 2003), suggesting that meltwater is important for blooms of this species (Krawczyk et al., 2013). Krawczyk et al. (2014) observed *Fragilariopsis cylindrus* in modern water samples mainly in the northern-most samples of the West Greenland coastal waters, associated with sea ice and/or strong meltwater flux. *Thalassiosira kushirensis* r.s. is known to have a sub-Arctic and Arctic distribution (Hasle and Syvertsen, 1996; Krawczyk et al., 2012; Weckström et al., 2014), and in previous studies from Disko Bugt this species has been linked to temperate waters (Krawczyk et al., 2010, 2013). It should be noted that in different regions of the North Atlantic three morphologically similar species have been identified: *Thalassiosira kushirensis* r.s. (e.g. Krawczyk et al., 2013); *Thalassiosira antarctica* var. *borealis* r.s. (e.g. Jiang et al., 2001) and; *Thalassiosira gravida* r.s. (e.g. Koç Karpuz and Schrader, 1990), each with slightly different ecological interpretations. However, in West Greenland modern water samples, the occurrence of *T. kushirensis* r.s. can be linked to relatively high surface water temperatures (Krawczyk et al., 2014), hence in this study we associate higher abundance of this species with warmer surface waters.

3.2.3 Benthic foraminiferal analysis

Preparation and counting method: The benthic foraminiferal data presented here are from Lloyd et al. (2011) and Perner et al. (2011, 2013a) where details of sampling methods can be found.

Ecological preferences: Benthic foraminifera are influenced by a range of ecological parameters including factors such as food availability, nutrient content, oxygen content, water temperature and salinity (e.g. Murray, 1991; Rytter et al., 2002; Sejrup et al., 2004). Research in West Greenland has used benthic foraminifera to reconstruct variations in water mass characteristics; specifically bottom water temperature and salinity associated with variability in the WGC flow (e.g. Lloyd et al., 2005; Lloyd 2006; Perner et al., 2011, 2013a). In these studies, foraminifera with similar ecological preferences are often grouped to identify changes in the relative temperature and salinity of the WGC associated with variations in the flux of IC and EGC components to the WGC. Perner et al. (2011) identified a chilled Atlantic water group to indicate an increase in the IC contribution to the WGC (whilst chilled Atlantic water indicates some mixing of Atlantic water with a colder water mass, along the west Greenland margin this is still the warm water end member)– here we also use the dominant species from this group, *Islandiella norcrossi,* indicative of an increase in the Atlantic water component (IC) in the WGC. This species is commonly found on high latitude continental shelf environments influenced by chilled Atlantic water (e.g. Vilks, 1981; Mudie et al., 1984; Jennings and Helgadottir, 1994; Hald and Korsun, 1997; Duplessy et al., 2001; Lloyd, 2006). To identify increased influence of relatively cold, lower salinity Arctic Waters (EGC component in the WGC, or Polar Water cf. Buch, 1981) we use the Arctic water agglutinated species group identified by Perner et al. (2011) and also additional indicator species such as *Elphidium excavatum f. clavata* and *Islandiella helenae* (see Perner et al., 2011 for detailed faunal abundances). These species are able to tolerate relatively unstable, cold, lower salinity water and arctic sourced waters (e.g. Williamson et al., 1984; Schafer and Cole, 1986, Alve, 1990; Jennings and Helgadottir, 1994; Korsun and Hald, 1998). Additionally, higher abundance of *I. helenae* is often linked to summer ice-edge productivity in areas of seasonal sea-ice cover (e.g. Polyak and Solheim, 1994; Steinsund et al., 1994). We also use the abundance of *Nonionellina labradorica* as an indicator of increased productivity – this species is widely distributed in the North Atlantic region and is closely associated with increased flux of fresh phytodetritus to the sea floor produced by surface water productivity blooms at oceanic fronts (e.g. Cedhagen, 1991; Hald and Steinsund, 1992; Hald and Korsun, 1997).

3.3.4. Dinocyst analyses

Preparation and counting method: The dinocyst data presented here are from Ouellet-Bernier et al. (2014), where details of sampling methods can be found.

Ecological preferences: The dinocysts are produced as part of the life cycle of dinoflagellates, which represent an important part of primary production together with diatoms and coccolithophorids. The organic-walled dinocysts are usually well preserved in marine sediments (e.g. de Vernal and Marret 2007 for an overview of their use in paleoceanography). They represent only a fraction of original populations but reflect optimal conditions associated with reproduction. Dinocysts include both phototrophic and heterotrophic taxa. In subpolar and sea ice environments, they are particularly useful tracers as species diversity is relatively high and they are distributed depending upon several parameters including salinity, sea ice, temperature and productivity (de Vernal et al., 2013a, b). Hence, they were used to reconstruct late Quaternary sea-surface salinity, temperature and sea ice cover from sediment cores collected in northern Labrador Sea and Baffin Bay (Levac et al., 2001; de Vernal et al., 2013b; Ouellet-Bernier et al., 2014; Gibb et al., 2014).

Among dinocyst taxa occurring in seasonal sea ice environment, *Islandinium minutum* is common. It dominates quasi-exclusively together with *Brigantedinium* in areas marked by dense sea ice cover for most of the year (Buck et al., 1998; Rochon et al., 1999; de Vernal et al., 2001, 2013a). Other subpolar taxa include the cyst of *Pentapharsodinium dalei*, which is cosmopolitan and described as Arctic "warmer water" species (Dale, 1996; Rochon et al., 1999). In Disko Bugt samples, the common occurrence of *Operculodinium centrocarpum* and *Spiniferites elongatus*, which are accompanied by *Nematosphaeropsis labyrintus* and *Spiniferites ramosus*, point to the influence of mild conditions, likely under the influence of the Atlantic water through the WGC after 7.5 ka BP (Ouellet-Bernier et al., 2014).

4. Alkenone results

A number of previous studies have used $\%C_{37:4}$ to estimate qualitative salinity changes (Rosell-Melé, 1998; Rosell-Melé et al., 2002; Sicre et al., 2002; Harada et al., 2003; Bendle et al., 2005; Blanz et al., 2005). Here, the variations in $\%C_{37:4}$ are used as a tracer of salinity changes related to meltwater flux from the West Greenland ice sheet, since meltwater off the ice sheet is the dominant freshwater source in the region. High $\%C_{37:4}$ levels make SST estimates based on U^k_{37} less reliable (Rosell-Melé, 1998, Bendle and Rosell-Melé, 2004). Nevertheless, given the close connection of low salinity and low temperature in meltwater plumes, U^k_{37} estimates are likely to reflect qualitative temperature (SST) changes.

Between 8.0 and 7.5 ka BP, very high $\%C_{37:4}$ values and low U^k_{37} suggest cold SSTs with strong ice and meltwater flux from the margins of the GIS. From 7.5 to 6.5 ka BP maximum U^k_{37} and low $\%C_{37:4}$ reflect milder SSTs and lower meltwater fluxes (Figure 2). A pronounced $\%C_{37:4}$ increase between 6.2 and 5.5 ka BP indicates a significant oceanographic change with colder SSTs and an increase in meltwater flux at the core site. From 5.5 to 2.8 ka BP, $\%C_{37:4}$ values decrease and, accordingly, U^k_{37} increase slightly, suggesting reduced meltwater influx and higher SST. From 2.7 to 0.8 ka BP a peak of $\%C_{37:4}$ values corresponding to very low U^k_{37} values is present in both cores 343300 and 343310 (Figure 2). This suggests increased meltwater flux and SST decrease with particularly cold SSTs at about 1.8 ka BP (Figure 2). Recurring low $\%C_{37:4}$ values and high U^k_{37} from 0.8 to 0.3 ka BP suggest meltwater flux decrease and SST warming. At site 343310, the multicore record of the last 100 years (Figure 2) displays significant increase in $\%C_{37:4}$ values suggesting enhanced meltwater supply during the last few decades.

5. Discussion

The multi-proxy approach presented here, using a combination of multiple surface water proxies and a bottom water proxy obtained from the same set of samples, allows comprehensive investigation of oceanographic changes in the Disko Bugt area. In particular this combination highlights the interaction of surface and bottom (West Greenland Current) water circulation on a multi-centennial scale during the middle to late Holocene. The marine records are compared with air temperature estimates from the Camp Century ice core and from lake sediment records.

The multi-proxy records presented here illustrate that the different proxies do not always show the same patterns, both between the two cores and also between proxies from the same cores. There are a number of observations to be made regarding this issue. Differences between the two cores can be partly explained from their respective locations. Core 343300 was recovered from a water depth of 519 m on the southern edge of the Egedesminde Trough, while core 343310 was recovered from a water depth of 855 m from the deepest part of the trough (Figure 1). Both cores have robust chronologies and relatively consistent sedimentation rates, averaging 0.57 mm/yr in core 343300 and 2.7 mm/yr in core 343310. The lower sediment accumulation rate in core 343300 results in greater smoothing of the record (1 cm slice equates to 17.5 years) than in core 343310 (1 cm slice equates to 3.7 years). The difference in smoothing might explain the generally higher amplitude of variations recorded in core 343310.

The high and different rates of sedimentation at the two sites suggest that a significant proportion of the sediment is not related to pelagic fluxes. A high proportion of sediment is fine grained material delivered to the depocentre of the Egedesminde Trough by ocean currents (the WGC) from the south. Hence the record of surface water proxies reconstructed from the cores presented here most likely integrates a regional south-west Greenland signal rather than reflecting local pelagic fluxes. Bottom water records based on benthic foraminifera are likely to reflect in-situ bottom water conditions but may differ because water depths of the two sites differ. Moreover, the temperature of the WGC impinging on the sea floor at the two locations is different. The core of the WGC tends to lie between 200 and 400 m (CTD profile see Figure 1 inset) hence bottom water temperatures at core 343300 (519 m) are likely to be slightly higher than for core 343310 (855 m), as also indicated in Figure 3I.

Meltwater from land ice has a significant influence on surface water conditions in this region, as identified by the various surface water proxies. Land ice meltwater flux to this region is largely controlled by the dominant northward flowing current regime. The WGC carries meltwater delivered to the West Greenland margin from melting land based ice and tidewater glaciers along the West Greenland coastline. Hence, the surface water proxies record a meltwater signal at a regional scale. However, a significant contribution of meltwater from calving glaciers in eastern Disko Bugt to the study sites can be expected after strong glacier re-advances such as during the Little Ice Age (see below). The meltwater signal may also include that of summer sea ice melt. Whatever the source, the presence of meltwater results in the development of a buoyant low salinity surface layer in summer and a strong halocline and thermocline in the photic zone (Figure 1 inset), in addition to large amplitude gradients of seasonal temperatures. This complex upper water column structure might explain differing signals recorded by biogenic tracers from the upper water layer.

5.1 Middle to late Holocene oceanographic changes, atmospheric temperature and glacier behaviour in West Greenland, in a wider North Atlantic context

The full record of the past 8.3 ka BP shows trends in ocean circulation at the entrance to Disko Bugt related to variations of the WGC, surface water conditions and meltwater production. These trends broadly follow the surface air temperature proxy-record from the Camp Century ice core (Figure 3; for location of Camp Century see inset of Figure 1). This ice core location is close to the West Greenland coast and, therefore, surface air temperature changes recorded at Camp Century are likely to have been also related to changes in the oceanic conditions. The initial warming trend at the base of the Camp Century record shown in Figure 3J is an extension of the general warming trend of the early Holocene when insolation was at a maximum and the Northern Hemisphere was still recovering from the deglaciation of the mid-latitude ice sheets, though the record may also be influenced by decreasing altitude as the ice sheet thinned during the Holocene (Vinther et al. 2009). The relatively cold (but warming) interval in the ice core corresponds to generally cold oceanic conditions with high meltwater flux off West Greenland (Figure 3). At Camp Century, a Holocene Thermal Maximum is recorded from *ca.* 6.8 to 3.5 ka BP and is followed by Neoglacial cooling as evident from other ice cores (Vinther et al., 2009; Dahl-Jensen et al., 1998) and terrestrial records from West Greenland (Kaufman et al, 2004; Axford et al., 2013; Larsen et al., 2015). A significant reduction of melt water discharge in the fjords around Nuuk at about 3.2 ka BP (Møller et al. 2006). This shift towards cooler conditions matches the general pattern of ocean tracers presented here (Figure 3 and 5).

Superimposed on the long-term trend, four distinct cold pulses of variable intensity can be identified from the Camp Century record and correspond to changes seen in our marine proxy data: i) 8.3 to 7.5 ka BP, ii) *ca.* 6.2 to 5.5 ka BP, iii) *ca.* 3.5 to 2.6 ka BP, and iv) *ca.* 0.7 to 0.2 ka BP (grey shaded bars in Figures 3, 4 and 5). These periods also correspond to periods of glacier retreat or re-advances in West Greenland (see below). The cold pulses are generally in phase with sub-surface WGC related trends as recorded from benthic foraminifers (e.g. Figures 3H, 3I and 4E, 4F), but not necessarily with the changes recorded by the surface water tracers. We relate the equivocal phase relationships to the influence of meltwater from both sea ice and land ice on surface water conditions at regional scale (discussed in more detail below; cf. also Ouellet-Bernier et al., 2014). Based on the marine proxy data we divided the last 8.3 ka BP record into 8 zones (Figures 3 and 4), which reflect regional changes as discussed below:

Zone I: *Early Holocene, 8.3 – 7.5 ka BP.* The early part of the record is characterized by in-phase relationship of all tracers, which together indicate cold surface and sub-surface water conditions (Figure 3). Relatively cold sub-surface water conditions are recorded by the benthic foraminifera with high abundance of Arctic water foraminifera, though some variability is also present with occasional spikes in *I. norcrossi* abundance (Figure 3H, and I). This interval corresponds with cold surface water conditions as indicated by the diatom assemblage (Figure 3D) and dinocyst assemblages (Figures 3B and 3C). It is also characterised by cold surface air temperatures as recorded in the Camp Century ice core (Figure 3J). The alkenone concentrations in this interval are low. Nevertheless, the calculated values of %$C_{37:4}$ are relatively high (>15%, Figures 2 and 3F), suggesting that the study area was strongly influenced by enhanced meltwater supply from sea-ice or from the GIS, which is consistent with dinocyst assemblages exclusively dominated by *I.minutum* and *Brigantedinium* that reflect dense sea ice cover throughout most of the year except during a brief summer season (Ouellet-Bernier et al., 2014). An abundance peak of *N. labradorica* at *ca.* 7.5 ka BP (Figure 3G) suggests that the edge of the arctic sea-ice front lingered on the shelf west of Disko Bugt. Cold surface and sub-surface water conditions coincide with the final phase of deglaciation of the Laurentian ice sheet (e.g. Dyke, 2004; Jennings et al., 2015) and landward recession of the Greenland ice margins in eastern Disko Bugt (e.g. Weidick and Bennike, 2007; Young et al., 2011; Young and Briner, 2015) and along the West Greenland margin generally (e.g. Seidenkrantz et al., 2013).

Zone II: *Early to middle Holocene* transition*, 7.5 – 6.2 ka BP*. This interval is characterized by in-phase relationship of all proxies suggesting relatively warm surface and sub-surface conditions. Sub-surface water conditions are variable but generally warm as recorded by the benthic foraminifera (Figure 3I, and H), which coincides with increasing air temperatures over northwestern Greenland (Figure 3J). Surface water conditions are rather stable with little indication of melt water supply (Figure 3F), and relatively low SSTs in summer as shown by the U^{k}_{37} (Figure 3A), dinocysts (Figures 3B, and C) and diatoms (Figure 3D). Low abundance of sea-ice associated diatoms also indicates low spring sea ice occurrence (Figure 3E) although winter sea ice was a consistent feature according to dinocyst data (Figure 3C). This zone is representative of warm conditions in summer and can be associated with the delayed Holocene Thermal Maximum identified over the Canadian Arctic (e.g. Kaufman et al., 2004) and from the Greenland ice cores (e.g. Dahl-Jensen et al., 1998; Alley et al., 1999; Vinther et al., 2009) and lake records (e.g. Kaplan and Wolfe, 2006). The ice sheet margin in the Disko Bugt area had retreated to a position behind the current ice margin (e.g. Weidick and Bennike, 2007; Corbett et al., 2011; Young et al., 2011, 2013b; Kelley et al., 2013; Larsen et al., 2015) as elsewhere in Greenland. A retreat of the ice sheet further from the coastline may have led to a reduced signal of regional meltwater supply preserved in our records. During this interval a relatively warmer WGC signal in the study area is consistent with warm conditions in the North Atlantic and a stronger Irminger Current component to the WGC (the major source of warm water to the WGC) (e.g. Castañeda et al., 2004; Jennings et al., 2011; Olafsdottir et al., 2010).

Zone III: *Middle Holocene, 6.2 – 5.5 ka BP*. This interval is marked by an abrupt sub-surface cooling event as suggested by the decline of *I. norcrossi, which is a* relatively warm water benthic foraminifera, as colder water fauna such as *Islandiella helenae*, *Elphidium excavatum f. clavata* (see Perner et al., 2013a for faunal record) and other agglutinated arctic fauna (Figure 3G) increase. There is also evidence of high productivity in surface water as indicated by an increase in *N. labradorica* (Figure 3H) and also from productivity estimates based on dinocyst assemblages (Ouellet-Bernier et al., 2014). Increased productivity at the sea ice ('West Ice') edge close to the site is also evident by an increase in planktonic foraminifera *Neogloboquadrina pachyderma* (Perner - unpublished data). Surface waters are influenced by increase in meltwater supply as $\%C_{37:4}$ values record an increase (Figure 3F), which is somewhat consistent with the low salinity estimates from dinocyst based reconstruction of salinity showing minimum of about 27 psu at 5.5 ka BP (Ouellet-Bernier et al., 2014).. This interval coincides with an increase in sea-ice associated diatoms and reduction in relatively warm diatom flora (Figures 3D and 3E). Paradoxically, the dinocyst assemblages (Figures 3B, and C) show maximum abundance of subpolar-temperate taxa together with evidence of increased winter sea-ice, which might reflect particularly large annual amplitude of temperatures in the surface water layer then characterized by low salinity and low thermal inertia.

A cooling pulse is also seen in the Camp Century ice core record with a pronounced decrease of $\delta^{18}O$ values at 5.8-5.6 ka BP (Figure 3J). It might reflect weaker and/or cooler WGC due to a southward migration of the sea ice marginal zone, which affected the local hydrography in Disko Bugt. This is compatible with increased surface water productivity due to ocean mixing and associated flux of nutrients in response to spring ice melt (e.g. Hansen et al., 1999; Levinsen et al., 2000). The low isotopic excursion recorded in the Camp Century ice core after 6 ka BP is likely linked to the temporary cooling-freshening in oceanic conditions affecting northeast Baffin Bay. The colder WGC conditions may well be related to a cooling identified in the East Greenland Current at about this time (Müller et al., 2012; Ran et al., 2006), and to a marked temperature drop in the northern North Atlantic (e.g. Moros et al., 2004, Telesiński et al., 2014) that is likely linked to the most pronounced North Atlantic Holocene IRD event (Bond et al., 2001).

Zone IV: *Middle Holocene, 5.5 – 3.5 ka BP*. This zone is marked by a return to relatively warm sub-surface conditions (Figure 3I). Diminishing $\%C_{37:4}$ values suggest a gradual decrease of meltwater influence (Figure 3F). Diatom and dinocyst assemblages both show relatively mild surface water despite a gradual trend towards cooler conditions (diatoms - Figure 3D, dinocysts – Figures 3B and 3C). The reduction in *N. labradorica* indicates lower surface water productivity (Figure 3G) as also reconstructed based on dinocyst assemblages (Ouellet-Bernier et al., 2014). This, combined with the reduced meltwater influence, suggests that the productive ice edge frontal zone had migrated further north. This migration could be due to the increased strength and/or warmth of the WGC but may have been further influenced by changes in meltwater flow and the end of ice blocking of the Vaigat Strait at *ca.* 6.0 ka BP (Perner et al., 2013b), leading to an increased iceberg flux northwards through the Vaigat rather than westwards across the Disko Bugt shelf (Figure 1).

The relatively warm oceanic conditions during this time also correspond to relatively warm air temperatures (e.g. Camp Century ice core, Figure 3J). Several lake records near Jakobshavn Isbræ display high loss on ignition values representing high productivity under relatively warm terrestrial conditions and relatively high chironomid-based temperature reconstructions from one of the Lakes, North Lake (Axford et al., 2013). High lake levels linked to warmer conditions are also reported in the Kangerlussuaq region, just south of Disko Bugt (Aebly and Fritz, 2009). Geomorphological studies in the eastern Disko Bugt area report a largely land-based ice sheet and reduced meltwater runoff from the GIS after 6 ka BP (Briner et al., 2010; Weidick and Bennicke, 2007; Weidick et al., 1990). Briner et al. (2015) also reconstruct minimum ice extent from *c.* 5 – 3 ka BP based on a chronology from reworked shells. A strong and relatively warm IC likely causing the warm/strong WGC is reported from the East Greenland shelf (Jennings et al., 2002, 2011) and southwest and south of Iceland (e.g. Knudsen et al., 2008b; Olafsdottir et al., 2010).

Zone V: *Middle to late Holocene* transition*, 3.5 - 2.6 ka BP.* This zone is characterized by a shift toward cooler conditions as shown by some proxies. The warm sub-surface water conditions of the previous zone end with a rather abrupt decrease of *I. norcrossi* in benthic foraminifera assemblages at *ca.* 3.5 ka BP (Figures 3H and 3I; Perner et al., 2013a, also show an increase in other arctic foraminifera such as *Elphidium excavatum* f. *clavata* at this time). The sub-surface cooling coincides with very low %$C_{37:4}$ values (Figure 3F) the occurrence of cold diatom assemblages (Figure 3D), with increasing sea-ice species (Figure 3C). Cooling is also recorded from the Camp Century ice core record (Figure 3J).

This cold period differs from the one identified in zone III by having no indication of meltwater supply. This cool episode recorded in the archives from Disko Bugt and the wider West Greenland terrestrial archives appears to be the culmination of a longer climate cooling trend in the North Atlantic (Wanner et al., 2011). The cooling of the WGC most likely results from a weaker IC and/or stronger EGC and coincides with the beginning of Neoglaciation as shown by IRD deposition off southeast Greenland (e.g. Andersen et al., 2004, Jennings et al., 2002, 2011; Jiang et al., 2002). Colder oceanic and atmospheric conditions led to an advance of land based ice marking the initial phase of the Neoglacial (Briner et al., 2011; Weidick and Bennike, 2007; Young et al., 2011). This is in line with relatively low meltwater production. A marked reduction in meltwater discharge at *ca.* 3.2 ka BP has also been documented in a southwest Greenland fjord (Møller et al., 2006).

Colder and dryer conditions are also indicated by relatively low lake levels in the Kangerlussuaq area (Aebly and Fritz, 2009) and decreased LOI values from lakes in the Disko Bugt area reflecting low primary productivity (Axford et al., 2013).

Zone VI: *Late Holocene, 2.6 - 0.7 ka BP*. Oceanic conditions during this period were highly variable. The first part of this zone from 2.6 to 1.7 ka BP is characterized by centennial scale fluctuations and general warming of sub-surface waters (Figures 4E and 4F). The meltwater influence identified from $\%C_{37:4}$ values is also variable, but overall increases to relatively stable and high levels from *ca.* 2 ka BP (Figure 4D). The diatom flora suggest surface waters initially warm in phase with sub-surface waters until 1.7 ka BP (Figure 4B), however, the dinocyst assemblage shows a continuation of the gradual cooling trend from the previous zone culminating in cool conditions at about 1.5 ka BP (Figures 3B and 3C; see also reconstructions in Ouellet-Bernier et al., 2014). Benthic foraminifera then record gradual cooling of sub-surface waters, but with centennial scale fluctuations superimposed on the longer term cooling. This trend culminates in cold conditions from 0.7 ka BP during the LIA (Figures 4E and 4F). The diatom flora show highly variable conditions from 1.6 ka BP onwards and a trend of increasing sea ice-associated flora reaching a peak at the end of this zone (Figures 4B and 4C). An expansion of sea ice is supported by data from the fjords around Nuuk, more to the south, where a marked increase of sea ice occurred and regional lake records indicate significant cooling shortly after 0.8 ka BP (Kuijpers et al. 2014).

The initial warming in sub-surface conditions from 2.6 to 1.6 ka BP coincides with a slight increase in $\delta^{18}O$ in the Camp Century ice core (Figure 4G). The variability in the sub-surface WGC record is generally consistent with centennial scale climate changes from the eastern North Atlantic region, such as the Roman Warm Period (RWP), Dark Ages (DA), Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) (Figure 4). The WGC and the atmospheric conditions in West Greenland seem closely coupled to the oceanographic changes in other areas of the North Atlantic, such as the Reykjanes Ridge, where a pronounced warming pulse is also recorded at *ca.* 2 ka BP (Moros et al., 2012). There is a peak of relatively warm sub-surface water from *ca.* 1.8 to 1.65 ka BP that occurs during a period of increased $\%C_{37:4}$ values that could relate to high meltwater flux. This time interval corresponds to the RWP, which is the warmest period of the late Holocene recorded at our sites. The influence of relatively warm oceanic conditions at *ca.* 2 ka BP were also reported based on sedimentological proxies from Narsaq Sound, southwest Greenland (Norgaard-Pedersen and Mikkelsen, 2009). Increased meltwater release most likely results from WGC-induced melting of marine-based outlet glaciers and icebergs after the ice sheet margin had re-advanced and major glaciers extended again into the fjords during Neoglacial cooling. The period from 1.3 ka BP (coinciding with the MCA) marks a transitional period with gradually cooling sub-surface waters, highly variable meltwater flux, sea-ice cover and sea surface conditions.

The period after *ca.* 2.0 ka BP, when meltwater flux was at a maximum, seems to be characterized by particularly harsh terrestrial conditions in the Disko

Bugt area. Weidick and Bennike (2007) report youngest ages from lakes in southeast Disko Bugt of *ca.* 2.2 ka BP, indicating limited sedimentation thereafter and lakes near Jakobshavn Isbræ also show very low accumulation from this time onwards (Axford et al., 2013) which could reflect nearly year-round frozen conditions. The high meltwater flux initiated by the strong sub-surface ocean warming may have contributed to a rather moderate atmospheric temperature warming recorded at Camp Century around 2 ka BP. After *ca*. 1.0 ka BP, with transition into the LIA, sub-surface waters continue to cool, while surface waters show a clear warming. Diatom (Figure 4B) and dinocyst floras both show this warming (Figure 3C and core 343310, Ribeiro et al., 2012; Ouellet-Bernier et al., 2014). This transition to an anti-phase relationship most likely reflects a marked hydrographic variability (Krawczyk et al., 2013) related to a regionally unstable climate regime (e.g. increased storminess and enhanced mixing of water masses).

Zone VII: Late Holocene, *0.7 – 0.2 ka BP*. A clear cooling is seen in sub-surface waters during this interval (Figures 4E and 4F), correlating with cold atmospheric conditions seen in the Camp Century ice core (Figure 4G). In contrast surface water conditions are characterized by a relative warming (Figure 4B) along with a decrease in sea-ice occurrence from a peak at the beginning of this interval (Figure 4C). Ribeiro et al. (2012) present dinocyst assemblages covering this period showing warming at the beginning but cooling from *c.* 0.5 ka BP until 0.1 ka BP. Meltwater influence is low during this interval (Figure 4D). Benthic foraminifera suggest sub-surface conditions during this period were colder than the rest of the record, with the exception of zone 1 (Figures 3G and 3H). One significant difference with this earlier cooling event, however, is the out-of-phase relationship with surface water conditions in Zone VII.

The timing of Zone VII corresponds closely with the LIA.The significant advance of the GIS and outlet glaciers in the Disko Bugt area at this time (Briner et al., 2010; Young et al., 2011) and low lake levels in the Kangerlussuaq region (Aebly and Fritz, 2009) may have been caused by a combination of the cold oceanic and atmospheric conditions in the area corresponding to the LIA. Relatively cold sub-surface waters (reflecting a cool WGC) led to the reduced meltwater influx by melting of icebergs/outlet glaciers and sea-ice at this time. This lack of meltwater has been invoked to explain the increase in SST identified from the diatom flora (Figure 4B, Krawczyk et al., 2010) and, may also explain the initial warm dinocyst flora (Ribeiro et al., 2012). The reduced meltwater flux may also explain the slight decrease in sea-ice associated diatoms during this period – though sea-ice is still present (Figure 4C).

Zone VIII: *20th Century*. Sub-surface water conditions over the last 100 years, in the context of the preceding conditions, remain relatively cold (Figure 4E, F and 5C). However, there is a slight warming in sub-surface conditions, particularly since AD 2000, as discussed in more detail in Lloyd et al. (2011), which is accompanied by a significant increase in meltwater production (Figure 4D). The minor sub-surface ocean warming is also demonstrated by instrumental data over recent decades and correlates with a significant retreat of the tidewater calving margin of Jakobshavns Isbrae. The historical retreat of the calving margin of Jakobshavns Isbrae during the 20th Century is well constrained and coincides with a period of significant increase in $\%C_{37:4}$, the alkenone based meltwater proxy, supporting our interpretation of this proxy from our records. This also corresponds to low SST estimates based on the alkenone data (Figure 3A) also supporting our interpretation of increased meltwater production leading to colder surface water temperatures earlier in the records presented here. This highlights the sensitivity of the ice margin to relatively small changes in ocean forcing. As discussed in Lloyd et al. (2011), the conditions in Disko Bugt correlate well with broader North Atlantic conditions as recorded in the Atlantic Multidecadal Oscillation (Gray et al., 2004) and the Arctic-wide surface air temperature anomaly from Polyakov et al. (2002).

5.2. Linking environmental changes to the history of human occupation in West Greenland

The cultural history of Greenland began 4.5 ka BP with the immigration of the Saqqaq from high Arctic North America. The history of human occupation in Greenland is characterized by arrival and disappearance of several cultures rather than continuous human settlement. It has been suggested that environmental change was the major cause for this pattern (McGovern, 1991; McGhee, 1996; Jensen, 2006). In Disko Bugt, numerous dwellings and artifacts have been recovered from the Saqqaq and Dorset people who inhabited the region between 4.5 and/3.4 ka BP and 2.8 - 2.2 ka BP, respectively (Jensen et al., 1999; Jensen 2006).

Based on the oceanographic and climatic inferences presented here the Saqqaq settled in West Greenland during a time of relatively mild conditions towards the end of the Holocene Thermal Maximum, when only winter sea-ice cover prevailed. Such an environment agrees well with the archaeological records that describe the Saqqaq people as preferential open water hunters (e.g. Meldgaard, 2004; Jensen, 2006). In the later period of their settlement, the proxy records indicate increasing climate instability and cooling. Excavations from Qeqertasussuk in Sydostbugten have shown that from 4.2 to 3.5 ka BP this site was inhabited primarily in spring and summer, which was the season when harp seal was the primary game (e.g. Meldgaard, 2004; Jensen, 2006). The environmental change to colder and more unstable conditions we reconstruct after *ca.* 3.5 ka BP (Figure 4) is likely to have affected their food source and supports the view that the Saqqaq people left Disko Bugt due to deteriorating climatic conditions (Meldgaard, 2004).

While the link between appearance/disappearance of the Saqqaq culture to environmental changes appears straightforward (e.g. Meldgaard, 2004; Jensen, 2006; Moros et al., 2006; D´Andrea et al., 2011), the influence of environmental changes on the Dorset culture is not entirely clear (e.g. D´Andrea et al., 2011). The Dorset people were better adapted to sea ice hunting than the Saqqaq (Jensen, 2006). The oldest records of Dorset occupation provide a date of about 2.8 ka BP (Jensen et al., 1999) and coincide with cool sea and air temperatures and relatively extended sea ice cover evident from our marine records (see Figure 4).

From *ca.* 2.7 ka BP a shift in environmental conditions took place in the Disko Bugt area with increasing temperatures in sub-surface and surface waters (i.e. by diatom flora) together with indications for increased freshwater (meltwater) input (Figures 4C and 4E) and low sea-surface salinity (Ouellet-Bernier et al., 2014). A progressive warming at this time is also noted from dinocyst-based reconstruction in Disko Bugt (Ouellet-Bernier et al., 2014), and at the Kangerlussuaq lake from alkenones (D´Andrea et al., 2011) and further south along the Greenland margin from sedimentological data (Nørgaard-Pedersen and Mikkelsen, 2009). Moros et al. (2006) argued that the inferred warm sea-surface temperatures and limited sea ice in the Disko Bugt region were unfavorable to the Dorset, given that they were predominantly sea-ice hunters. Archaeological evidence (Jensen, 2006) provides three key pieces of information: (i) the latest population is noted in West Greenland at *ca.* 2.2 ka BP, (ii) in some areas Dorset food is dominated by caribou, indicating that the living resource base was diverse and not solely tied to sea-ice hunting; (iii) there is no northward migration of the Dorset at this time, which would seem likely during warming over West Greenland. Combining the archaeological evidence with the inferences from the new marine proxy data there appears to be a plausible alternative to the warming link proposed by Moros et al. (2006). The drop in temperature after 2 ka BP and associated harsh conditions on land (see above) may have had a negative effect on terrestrial living resources and thus may have been another factor that forced the Dorset to leave the area.

The Norse migrated to West Greenland at about 1.0 ka BP, which corresponds to a time of transition recorded by all proxies that suggest a shift towards warm conditions in surface waters. The abandonment of the Western Settlement of the Norse at about 0.65 ka BP could be linked to climate deterioration evident from sub-surface ocean and Greenland air temperatures accompanied by significant glacier advances and sea ice expansion, which in West Greenland waters started already shortly after 0.8 ka BP (e.g Kuijpers et al., 2014).

6. Conclusions

The multi-proxy approach adopted here identifies the complex nature of the changes in ocean circulation and interaction between surface and sub-surface waters and also with the ice margin history of the GIS. We document broad scale coherent patterns in the interaction between the relatively warm WGC and surface conditions that are influenced by freshwater and meltwater discharge from the GIS. Increases in meltwater flux may lead to highly stratified upper water masses and large amplitude gradients of seasonal temperature and sea-ice cover. Therefore, atmospheric warming and/or enhanced strength of the WGC that may accelerate the melt of the ice margins result in low surface salinity, cooling and sharp stratification in the upper water masses. This will also influence surface water temperature, salinity, seasonality, sea ice extent, productivity, and timing of surface water algal blooms. This, of course, complicates the interpretation of proxy data, which may capture different signals related to climate changes, e.g. depending on where in the water column the signal were acquired.

The overall records show high frequency variations superimposed on longer-term trends. The combination of different records help to identify key changes in benthic and pelagic environments related to large-scale climate changes. One striking feature is the linkage that may be established between the sub-surface water conditions (benthic foraminifera), the atmospheric temperature (Camp Century ice core) and the surface water conditions based on North Atlantic-associated dinocysts. The coherency of the long-term changes captured by these independent sets of data points to consistent vectors and strength in the atmospheric circulation and ocean circulation patterns. They all show that in the Disko Bugt region the onset of postglacial circulation pattern occurred at about 7.5 ka BP, with an optimum in the warm Atlantic component until about 4 ka BP. From 4 ka BP a general cooling started as a regional signature of the middle to late Holocene cooling.

Beyond the above mentioned general trends, variations in the marine proxies record local to regional changes resulting from large scale climate events influencing ocean circulation, but also from more local effects of meltwater discharges from the GIS margins. Several phases can be distinguished, as summarized below (Figure 5).

An early postglacial phase from 8.5 to 7.5 ka BP. This period is strongly influenced by the deglaciation of the Laurentide Ice Sheet and southern margins of the GIS, which together resulted in significant meltwater flux in Baffin Bay and along the West Greenland margin and led to variable but predominantly cold ocean and dense sea ice cover (Figure 5).

The following period from about 7.5 to 3.5 ka BP corresponds to the regional Holocene Thermal Maximum as identified from terrestrial records in the West Greenland - Baffin Island area by Kaufman et al. (2004). This interval is characterized by relatively mild air and ocean conditions (Figures 5) and GIS margins more inland than the current position (e.g. Kelley et al., 2013; Larsen et al., 2015). During this interval, the influence of meltwater may have remained low due to the inland position of the ice margin, but apparently increased during a period of relatively cold bottom waters and an air temperature cooling in west Greenland (5.9 – 5.7 ka BP, Figure 5). This increase in meltwater could be the response to a re-advance of the ice margin and ice flux from tidewater glaciers along the west Greenland coast. The warmest conditions in west Greenland in the ocean (WGC and surface waters) and atmosphere appear to occur between 5.5 and 4 ka BP (Figure 5). The Saqqaq culture colonized the area at *ca*. 4.5 ka BP towards the end of this period, probably taking advantage of the relatively mild conditions.

Late Holocene cooling after *ca.* 3.5 ka BP leading to re-advance of the ice margins (e.g. Kelly 1980) marks the end of the Holocene Thermal Maximum on a regional scale and coincides with Neoglacial ice advance (Figure 5). The onset of offshore cooling identified in our records coincides with the disappearance of the Saqqaq culture from West Greenland. The last 3500 years were apparently marked by large amplitude oscillations with regard to bottom and surface water conditions. Alternation of very cold (3.5-2.7 ka BP) and milder (2.7-1.2 ka BP) conditions are most likely linked to variations in meltwater discharge and the advance of tidewater glaciers along the West Greenland margin (Figure 5). During the episodes of advanced ice margin, meltwater discharge and unstable coastal conditions prevailed. These variable conditions are likely to have had an impact on the history of human occupation along the West Greenland coastline. While it is still unclear what the key drivers influencing human occupation of West Greenland are, our records highlight clear changes in the offshore environment during this period of changing human settlement. The Dorset arrived during a relatively cold interval, and their disappearance at *ca.* 2.2 ka BP may have been related to harsh coastal conditions. The Norse culture arrived during the relatively mild conditions of the MCA, and seems to have also disappeared because of harsh conditions at the onset of the LIA (Figure 5).

The multi-proxy approach discussed here sheds light on the interaction between the oceans, atmosphere and the GIS and identifies the complex influence of the ocean on glacial behaviour in the West Greenland region. Oceanographic conditions may also have been important for the history of human occupation.

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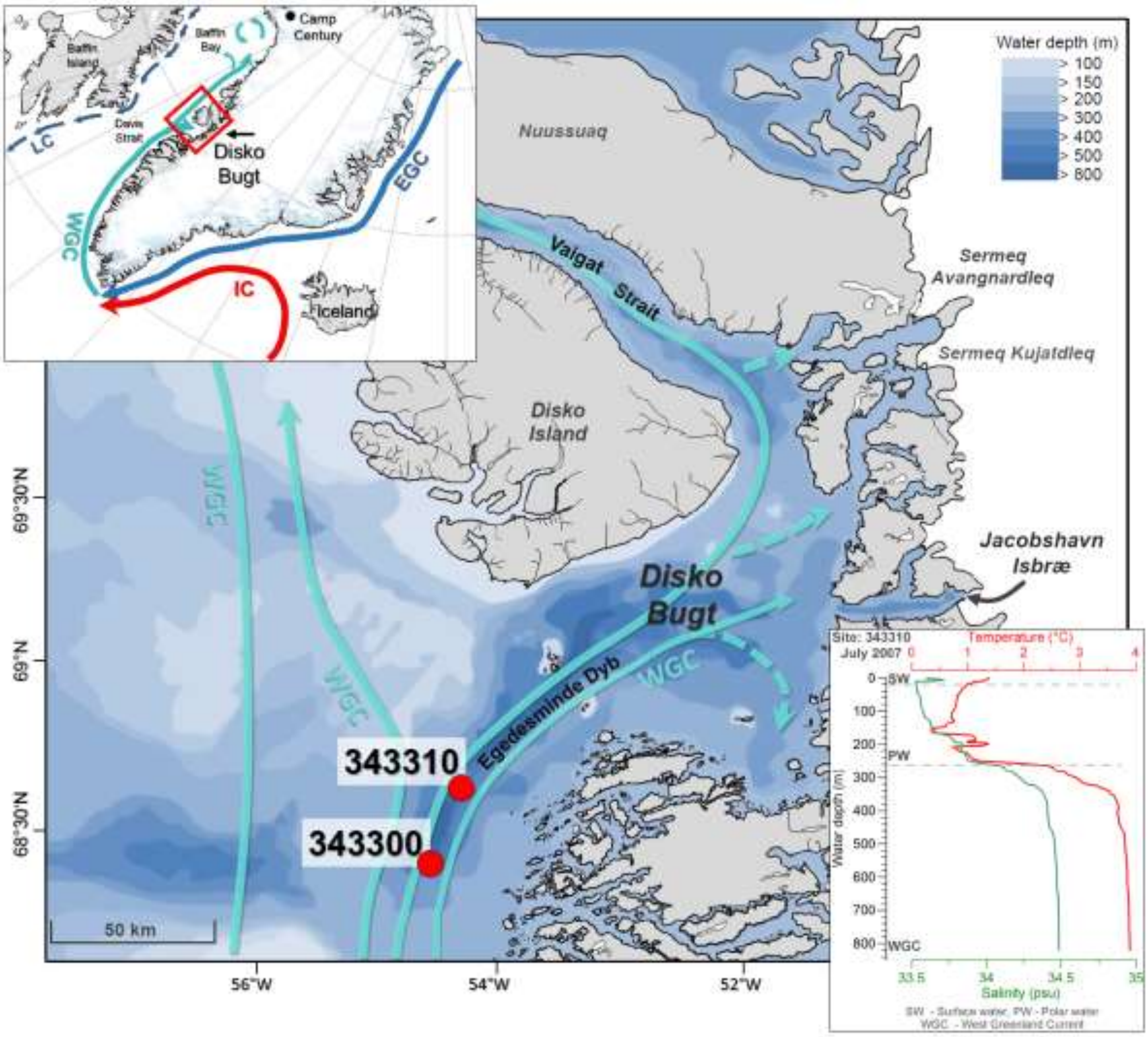


Figure 1: Bathymetric map of Disko Bugt, adapted from Jakobsson et al. (2008) and the present day oceanographic setting of the study area. The location of core 343300 at the southwest edge of Egedesminde Trough and of core 343310 in the main Egedesminde Trough, are shown by red dots. The upper left inset shows the oceanographic setting around Greenland. Abbreviations are as follows: EGC - East Greenland Current; IC – Irminger Current; WGC – West Greenland Current; LC – Labrador Current. Lower right inset: CTD profile at site 343310 from July 2007 the year of sampling.

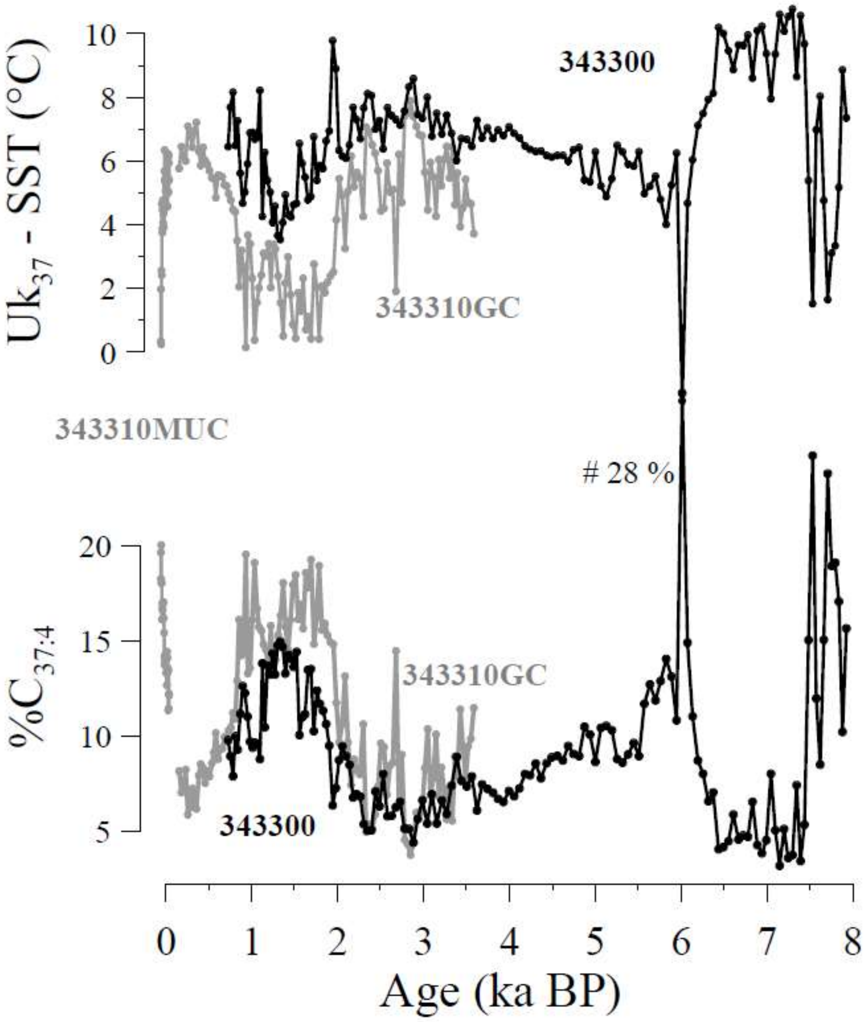


Figure 2. Holocene alkenone derived records of relative sea surface temperature (U^{k}_{37} index) and salinity variations (%$C_{37:4}$) from the core sites 343300 and 343310 in Egedeminde Trough. The dark line is from core 343300 and the grey line is from core 343310.

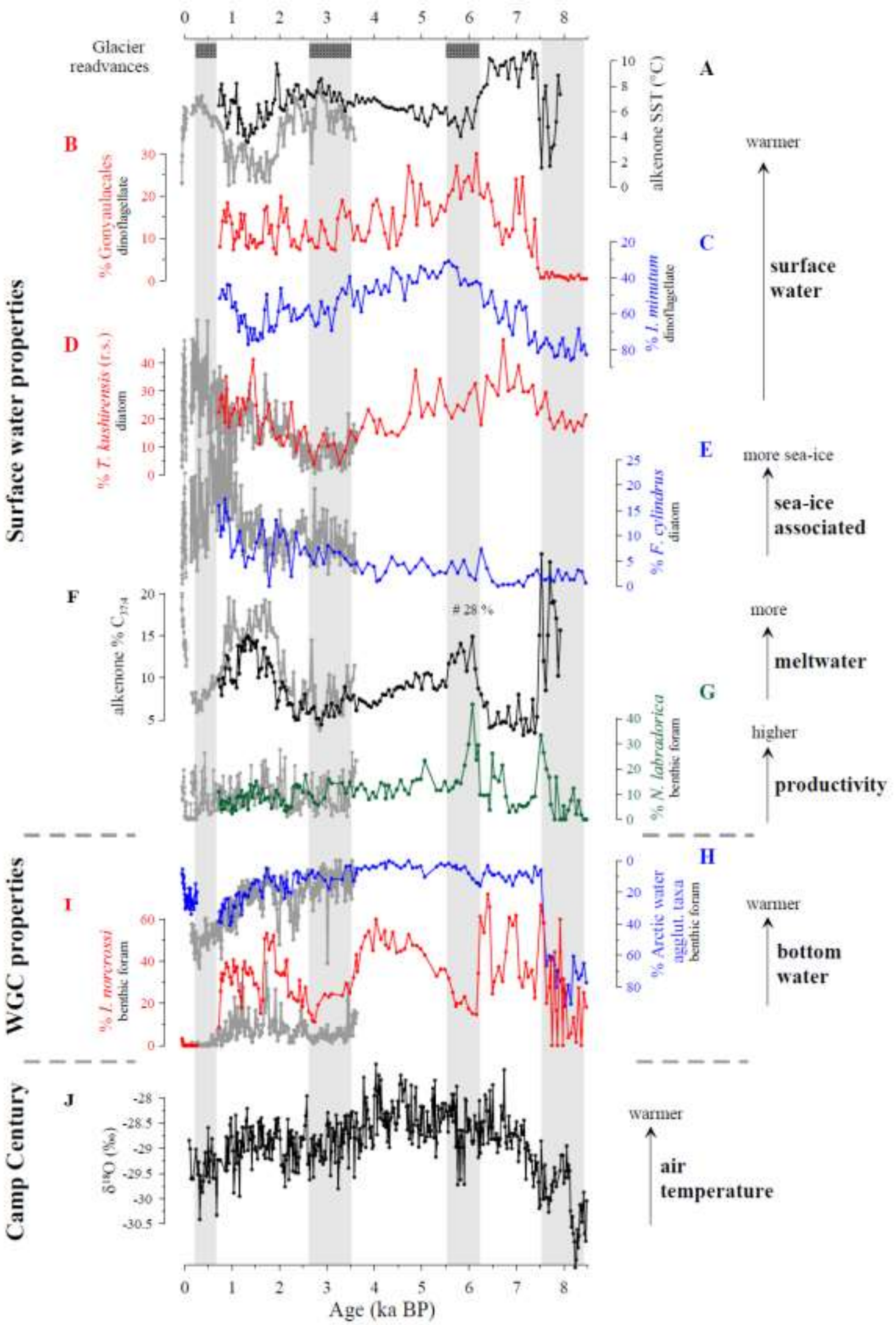
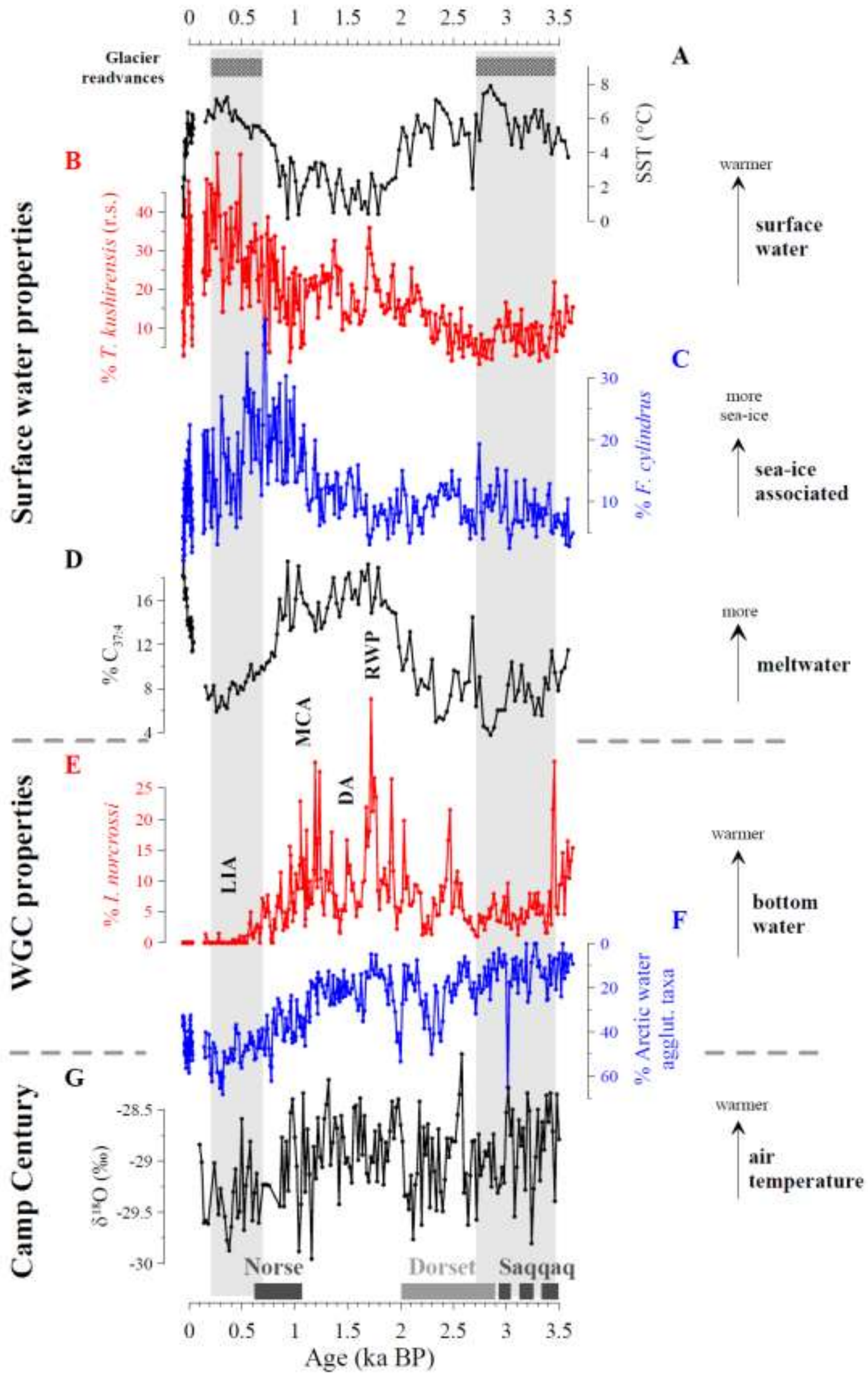
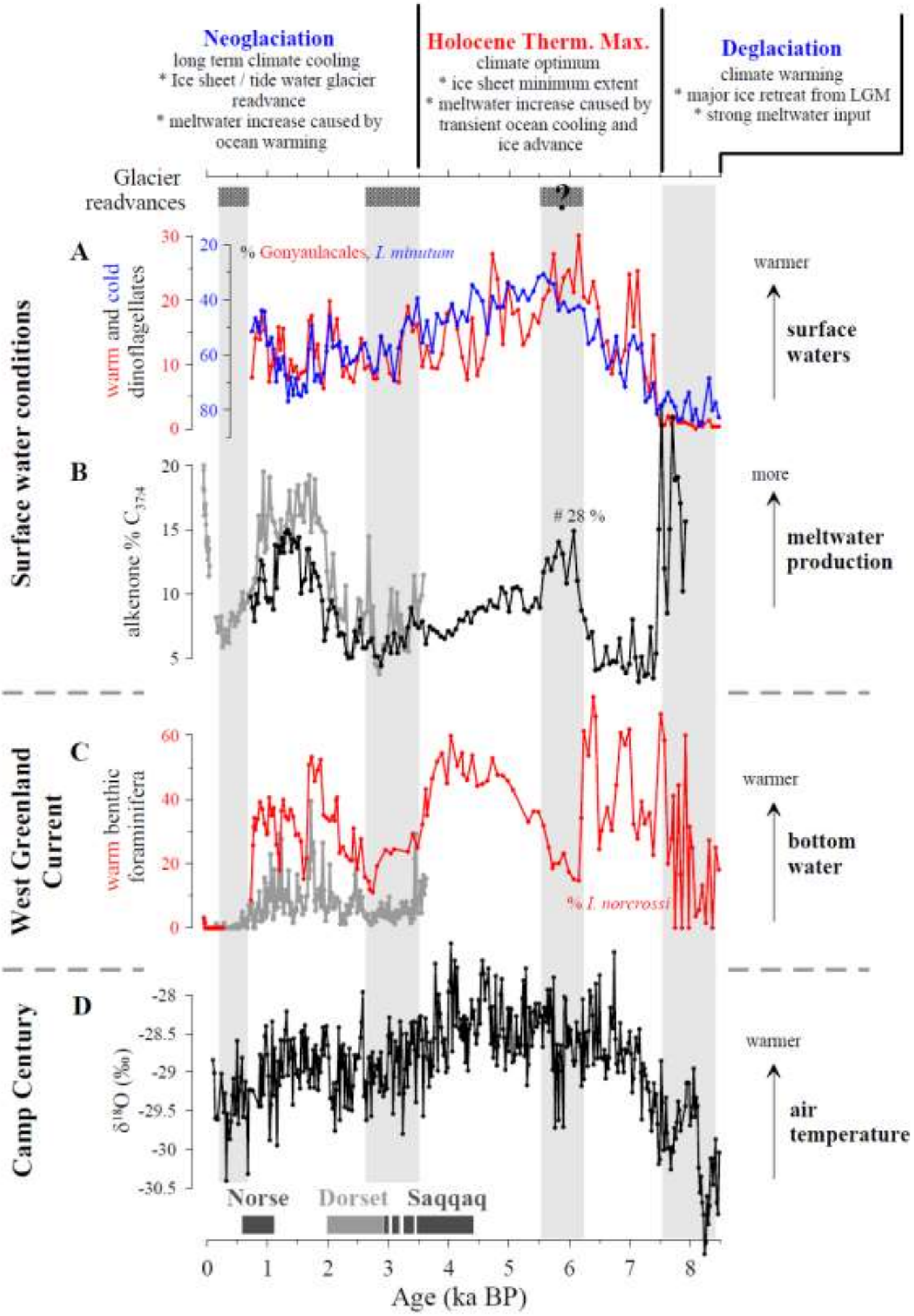

Glacier readvances
A
alkenone SST (°C)
B
% Gonyaulacales
dinoflagellate
C
% I. minutum
dinoflagellate
D
% T. kushirensis (r.s.)
diatom
E
% F. cylindrus
diatom
F
alkenone % $C_{37:4}$
28 %
G
% N. labradorica
benthic foram
H
% Arctic water agglut. taxa
benthic foram
I
% I. norcrossi
benthic foram
J
$\delta^{18}O$ (‰)
Surface water properties
WGC properties
Camp Century
warmer
surface water
more sea-ice
sea-ice associated
more
meltwater
higher
productivity
warmer
bottom water
warmer
air temperature
Age (ka BP)

Figure 3



1274

1275 Figure 4.



1276

1277 Figure 5.

Figure 3: Holocene palaeoenvironmental changes within the Disko Bugt area (longer time series shown in dark shade are from core 343300, shorter time series shown in grey shade are from core 343310). Surface water reconstructions (A – G): A) Alkenone derived U^{k}_{37} index; B) Relative abundance (%) of dinoflagellate cysts of *P. dalei*, a warm end member species; C) Relative abundance (%) of dinoflagellate *I. minutum*, a cold end member taxa (note inverted scale); D) Relative abundance (%) of diatom *T. kushirensis* r.s., the warmer water end member species; E) Relative abundance of diatom *F. cylindrus* – the colder water end member species associated with sea ice; F) the biomarker $\%C_{37:4}$ – reflecting salinity variability; G) Relative abundance (%) of the benthic foraminifer *N. labradorica* – indicating surface water productivity variability. West Greenland Current properties (bottom water proxies) (H – I): H) Relative abundance (%) of Arctic water agglutinated taxa – the cold water end-member of the benthic foraminiferal assemblage (note inverted scale); I) Relative abundance (%) of benthic foraminifera *I. norcrossi* - the warm water end-member and; J) $\partial^{18}O$ record of the Camp Century ice core shows variations of atmospheric temperature from West Greenland. Vertical grey shaded bars mark interpreted cold periods during the last ~8.3 ka BP. Dark grey horizontal bars at the top of the diagram indicate Greenland glacier advances.

Figure 4: Late Holocene palaeoenvironmental changes from core 343310. Surface water reconstructions (A – D): A) Alkenone derived U^{k}_{37} index records; B) Relative abundance (%) of warmer water diatom species *T. kushirensis* r.s.; C) Relative abundance (%) of the colder water, sea-ice associated diatom species *F. cylindrus*; D) Relative abundance of $\%C_{37:4}$ – reflecting salinity variability. West Greenland Current properties (bottom water proxies) (E – F): E) Relative abundance (%) of *I. norcorssi,* warm water benthic foraminiferal end member and; F) relative abundance (%) of Arctic water benthic foraminiferal agglutinated taxa (note inverted scale); G) $\partial^{18}O$ record of the Camp Century ice core showing variations of atmospheric temperature from West Greenland. Vertical grey shaded bars mark interpreted cold periods during the last ~3.5 ka BP. Dark grey horizontal bars at the top of the diagram indicate Greenland glacier advances, shaded bars at the base of the diagram indicate periods of Palaeo-Eskimo and Norse settlements in West Greenland. Timing of known climate fluctuations: RWP - Roman Warm Period, DA – Dark Ages, MCA – Medieval Climate Anomaly, LIA – Little Ice Age.

Figure 5. Summary of palaeoenvironmental interpretation: Upper panel) General interpretation of the records split into the Deglaciation, Holocene Thermal Maximum and Neoglaciation. Surface water conditions based on A) dinoflagellate warm (red) and cold (blue) water taxa in core 343300 and on B) $\%C_{37:4}$ from core 343300 (black shade) and core 343310 (grey shade); C) West Greenland Current properties based on % *I. norcrossi* warm end member benthic foraminiferas species from core 343300 (red shade) and core 343310 (grey shade); D) $\partial^{18}O$ record of the Camp Century ice core showing variations of atmospheric temperature from West Greenland. Vertical

grey shaded bars mark interpreted cold periods during the last ~3.5 ka BP. Dark grey horizontal bars at the top of the diagram indicate Greenland glacier advances, shaded bars at the base of the diagram indicate periods of Palaeo-Eskimo and Norse settlements in West Greenland. Timing of known climate fluctuations: RWP - Roman Warm Period, DA – Dark Ages, MCA – Medieval Climate Anomaly, LIA – Little Ice Age.