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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 and 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 parallelled 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

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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, 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 Fig. 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 150–200 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.