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Evolution of subpolar North Atlantic surface circulation since the early Holocene inferred from planktic foraminifera faunal and stable isotope records

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ABSTRACT

Past changes in the surface flow regime of two main eastern North Atlantic warm water pathways toward the Nordic seas were reconstructed based on faunal analyses in combination with carbon and oxygen stable isotope measurements in planktic foraminifera. The investigated sites, in the surroundings of the Faroe Islands, are located in the transitional area where surface waters of subpolar and subtropical origin mix before entering the Arctic Mediterranean. In these areas, large-amplitude millennial variability in the characteristics of the upper-water column appears modulated by changes in the intensity of the Subpolar Gyre circulation. From 7.8 to 6 ka BP, faunal records indicate a deep mixed-layer which, in conjunction with lighter $\delta^{18}O$ values, suggest that the inflowing Atlantic waters were dominated by a relatively cooler and fresher water mass, reflecting a strengthening of the Subpolar Gyre under conditions of enhanced positive NAO-like forcing and reduced meltwater input. A shift in the hydrographic conditions occurred during the Mid-Holocene (centered at 5 ka BP). At this time, increasing upper water column stratification and the incipient differentiation of the stable isotopic signal of the Iceland–Faroe and Faroe–Shetland surface water masses, suggest increasing influx of warmer, more saline surface waters from the Subtropical Gyre, as Subpolar Gyre circulation weakened. The mid-Holocene decline in Subpolar Gyre strength is presumably related to a shift toward a low state of the NAO-like forcing associated with decreased solar irradiance. Later in the Holocene, from 4 ka BP to present, the increased frequency and reduced amplitude of the surface hydrographic changes reflect corresponding fluctuations in Subpolar Gyre circulation. These high frequency oscillations in Subpolar Gyre strength suggest increased surface circulation sensitivity to moderate freshwater fluxes to the Labrador–Irminger Sea basin, highlighting the importance of the salinity balance in modulating Subpolar Gyre dynamics, particularly under conditions of low NAO atmospheric forcing.

1. Introduction

Surface waters in the eastern North Atlantic are much warmer than in every other ocean region at similar latitudes. The main reason for this is the large amount of ocean heat that is transported northward from tropical latitudes, across the Greenland–Scotland Ridge and into the Nordic seas and Arctic Ocean (e.g. Hansen and Østerhus, 2000). This transport of warm and saline water masses derived from the subtropics regulates climate over Europe and controls ocean convection and associated deep water formation (e.g. Hansen et al., 2004; Hátún et al., 2005; Holliday et al., 2008). It is here, north of the Greenland–Scotland Ridge, in the so-called Arctic Mediterranean (AM) where through air–sea exchange the warm Atlantic Inflow waters loose much heat but not salt, and are transformed into the denser water masses that return southwards as overflows through the deep Ridge passages (Hansen and Østerhus, 2000). This makes the AM region to play a crucial role for the Atlantic thermohaline circulation (Hansen et al., 2004). As density changes at these latitudes are largely controlled by salinity, changes in upper ocean salinity in this region will have a significant impact on the development of the thermohaline circulation (Rasmussen et al., 1996; Kuijpers et al., 1998; Holliday et al., 2008; Sarafanov et al., 2008). Accordingly, a predicted freshening of this region related to an enhanced hydrological cycle due to global warming (Cubasch et al., 2001) might have significant consequences for the strength of the Atlantic meridional overturning

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circulation, thus affecting the distribution of heat toward higher latitudes, and impacting the entire high latitude climate system. This assumption is further substantiated by modeling data (e.g. Bersch et al., 2007; Zhang, 2008), recent observations (Hansen and Østerhus, 2000; Häkkinen and Rhines, 2004) and numerous paleoceanographic studies (e.g. Boyle and Keigwin, 1987; Hall et al., 2004; Thornalley et al., 2009, 2010, 2011) which indicate that, on orbital and suborbital time scales, changes in the production of North Atlantic Deep Water are linked to climate variability and fluctuations in sea surface temperature (SST) and sea surface salinity (SSS). Nonetheless, reconstructions of Holocene climate variability in the North Atlantic show inconsistent results. Some paleoceanographic studies indicate basin-wide North Atlantic SST decrease during the Holocene—commonly attributed to insolation changes (e.g. Marchal et al., 2002)—while others have shown that North Atlantic oceanographic changes were not uniform in amplitude or spatial extent (e.g. Moros et al., 2004; Solignac et al., 2006; Renssen et al., 2009; Andersson et al., 2010). Thus, the need for a better understanding of the various components of the regional oceanic circulation as well as the modes of internal variability of the climate system, remains.

Here, we investigate Holocene oceanographic changes in two important pathway areas of warm surface flow to the high-latitude deep-water formation regions of the AM. Our paleoceanographic reconstructions are based on three sedimentary records from the Faroe Islands region. So far, relatively little detail is known about Holocene oceanographic changes in this area, as previous studies (Rasmussen et al., 1996; Kuijpers et al., 1998; Bäckström et al., 2001; Lassen et al., 2002) have mainly dealt with late Pleistocene ocean variability in this region. We have focused on the surface flow regime of the two main warm water pathways where today most of the volume flux into the Nordic seas is concentrated (Hansen and Østerhus, 2000), i.e. the warm water route crossing the Iceland–Faroe Ridge west of the Faroe Islands and the second important branch found in the Faroe–Shetland Channel gateway. There are indications that the water masses in these areas change over time in accordance with regional climate variability (Pollard et al., 2004; Hátún et al., 2005; Holliday et al., 2008). Past changes in the surface hydrography of each site were reconstructed based on planktic foraminiferal faunal analyses, the isotopic composition of planktic foraminifera carbonate, and textural/compositional analyses of sedimentary samples. The position of the selected locations (Fig. 1), in the transitional area where surface waters of subpolar and subtropical origin mix before entering the AM (Hátún et al., 2005, 2009; Sarafanov et al., 2008), provides the opportunity to evaluate past variability in the properties of the surface water masses feeding the deep convection areas, and therefore, to evaluate the influence of the North Atlantic Subpolar Gyre (SPG) relative to the Subtropical Gyre (STG) as a possible mechanism controlling the hydrographic characteristics of the Inflow waters.

1.1. Regional setting

North Atlantic surface waters flow into the AM by three paths: via the Irminger Current passing west of Iceland, through the Iceland basin over the Iceland–Faroe Ridge, and through the Rockall Trough into the Faroe–Shetland Channel gateway (Fig. 1). The flow pattern of warm and saline waters of subtropical origin across the North Atlantic shows a splitting of the Gulf Stream into a southern and a northern branch around 55°W (Holliday et al., 2008). Eventually, as the northern branch splits again, one branch turns north to form the Irminger Current, constituting one of the northern limbs of the SPG (Pollard et al., 2004), whereas a second branch flows eastward along the 50°N parallel, crossing the North Atlantic Basin to constitute the North Atlantic Current (NAC, Read, 2001). Further east, the NAC splits again. One branch flows toward the Iceland–Faroe Gap to become the relatively fresher and colder Modified North Atlantic Water (MNAW, Read, 2001; Brambilla and Talley, 2006; Holliday et al., 2008), while a second branch flows northeastward into the southern Rockall Trough. The second branch, commonly acknowledged as the Rockall–Hatton branch (RHB), also carries MNAW (Häkinen and Rhines, 2009). However, the RHB is significantly influenced by waters from the intergyre region (Holliday, 2003; Pollard et al., 2004). The intergyre waters are represented by the Eastern North Atlantic Water (ENAW), which compare to waters derived from the NAC is warmer, more saline and nutrient enriched. The ENAW moves northwards, following the path of the Slope Current (SC), which originates in the Bay of Biscay and constitutes one of the main ENAW carriers. The SC moves from the northern limb of the STG (Häkkinen and Rhines, 2009) through the Rockall Trough, into the Faroe–Shetland area (Fig. 1). Thus, in the Faroe–Shetland area the upper water mass results from the mixing of MNAW and ENAW (Holliday, 2003; Sherwin et al., 2011).

Modern inter-annual variability in the characteristics of the Atlantic Inflow is controlled by SPG dynamics (Hátún et al., 2005; Sherwin et al., 2011). Reduced freshwater input to the Labrador Sea causes the SPG to expand eastward, decreasing the influence of the warm saline STG waters (Fig. 1a), which allows the MNAW to dominate the Inflow. On the contrary, enhanced freshening of the Labrador Sea results in the westward retraction of the SPG, allowing the ENAW to dominate (Fig. 1b). Fluctuations in regional atmospheric patterns over the North Atlantic further affect the dynamics of the SPG. South of Iceland ocean conditions are episodically influenced by sea-ice and subsurface subpolar waters advected by the East Icelandic Current (EIC) exiting the AM, which typically occurs when the gradient between the Azores High and Icelandic Low centers of atmospheric pressure is reduced (Fig. 1b, Blindheim and Osterhus, 2005; Hátún et al., 2009; Thornalley et al., 2011). Consistently, a substantial part of the SPG dynamics and North Atlantic climate variability is associated with the North Atlantic Oscillation (NAO), which is a natural mode of atmospheric variability that refers to a meridional oscillation of the atmospheric pressure between the Azores High and the Icelandic Low (van Loon and Rogers, 1978). Because the signature of the NAO is strongly regional, to quantify its intensity, an index was defined as the difference between sea-level pressure anomalies in Portugal and in Iceland (Hurrell, 1996).

High (positive) NAO values denote larger sea-level pressure gradients, while low (negative) values indicate reduced gradients. Climatically, when the NAO index is positive, enhanced sea-level pressure gradients translate into enhanced westerly winds over the North Atlantic moving relatively warm and moist air over part of Europe toward Asia. Over Greenland and northeastern Canada, these enhanced gradients produce stronger northwesterlies that carry cold air southward decreasing land temperatures (Zhang et al., 2008). In the northern North Atlantic, stronger westerly winds increase the depth of the mixed-layer and strengthen the SPG (Sarafanov, 2009; Sarafanov et al., 2010). Eventually, the strengthening of the SPG produces the eastward expansion of the NAC (Fig. 1a). In the eastern North Atlantic, an expanded NAC produces the southward shift of the Subpolar Front (SF) and the retreat of the warm saline waters from the STG (Hátún et al., 2005; Holliday et al., 2008), resulting in lower surface temperatures and salinities within the northeast North Atlantic region (Bersch et al., 2007; Holliday et al., 2008; Sarafanov, 2009). Because the surface waters of this region get entrapped in the Iceland–Scotland surface overflow and contribute to the Atlantic Inflow that feeds the AM (Hátún et al., 2005; Sarafanov et al., 2009, 2010), the intensification of the SPG also produces the cooling and freshening of the entire