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Changes in the strength of the Nordic Seas Overflows over the past 3000 years

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ABSTRACT

The Nordic Seas Overflows constitute the densest component of the deep limb of the Atlantic Meridional Overturning Circulation (AMOC). Changes in the vigour of the overflows may have had important climatic effects in the past and may also have in the future. Yet, evidence for multidecadal to millennial changes in the deep limb of the AMOC and their potential relationship to North Atlantic climate variability during the Holocene remains weakly constrained. Here we present grain size data, as a proxy for near-bottom current speed, from sub-decadal to decadally resolved sediment cores located in the direct pathway of the two Nordic Overflows east and west of Iceland, the Iceland-Scotland Overflow Water (ISOW) and the Denmark Strait Overflow Water (DSOW), respectively. The results show no clear relationship between reconstructed changes in the vigour of the Nordic Overflows and the well-known periods of centennial-scale climate variability recorded in the North Atlantic region. However, well-defined millennial-scale trends are found in both of the overflow strength records over the last 3000 years, which were possibly related to hydrographic reorganizations in the Nordic Seas, driven by the decrease in Northern Hemisphere summer insolation over the Neoglacial period. A comparison between the near-bottom flow speed reconstructions from ISOW and DSOW suggests an anti-phased relationship between the Nordic Seas Overflows east and west of Iceland over the last 3000 years. This feature has been observed in climate models potentially as a result of shifts in the deep water formation sites as a response to changes in atmospheric patterns over the Nordic Seas.

1. Introduction

The warm salty surface waters, originating in the tropics, are transported to the higher latitudes across the North Atlantic reaching the Nordic Seas and Arctic Ocean. During their northward transit these inflowing Atlantic waters lose heat to the atmosphere, via air-sea exchange, increase their density and eventually sink to form intermediate and deep water masses, via convective processes, in the Nordic Seas. This process plays an important part in the Atlantic Meridional Overturning Circulation (AMOC).Since the AMOC regulates the transport and distribution of heat, nutrients and CO_2 around the Earth's oceans, changes in the strength and structure of it have often been thought to be involved in past climate variability, particularly in the North Atlantic region (e.g. Kuhlbrodt et al., 2007).

The submarine ridge that lies between Greenland and Scotland, the Greenland–Scotland Ridge (GSR), forms a physical barrier that controls the exchange of deep dense waters between the Nordic Seas and the North Atlantic (e.g. Meincke, 1983) (Fig. 1). The dense waters that flow across the GSR into the North Atlantic Basin are collectively referred to as the Nordic Seas Overflows. These overflows are of pivotal importance to the climate system since they provide ~30% of the volume transport of the lower limb of the AMOC and downslope entrainment with intermediate waters when entering the Atlantic Basin increases the volume transport of the deep waters by three fold (Dickson and Brown, 1994; Hansen et al., 2004). Furthermore, the overflow of deep waters into the North Atlantic also helps set the pressure gradient at the surface,

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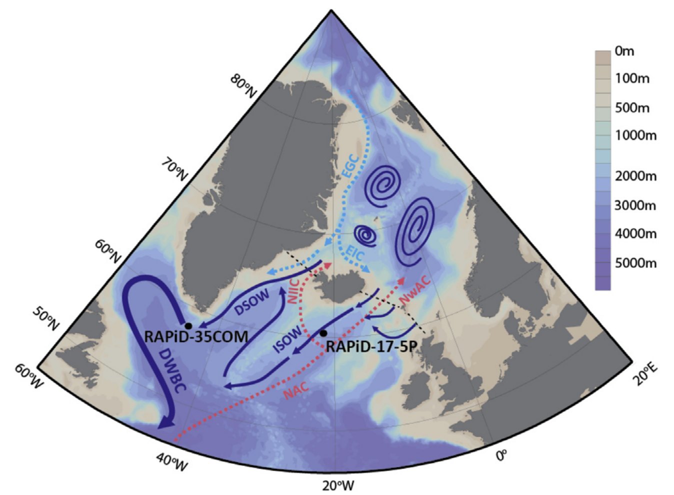

Fig. 1. Bathymetric map of the Nordic Seas and the North Atlantic indicating the location of RAPiD-17-5P and RAPiD-35-COM (black filled circles indicate the core locations used in this study). Black dashed fine lines indicate the Greenland–Scotland Ridge. Dark blue arrows represent the simplified deep ocean circulation of the Nordic Seas Overflows (ISOW and DSOW) and Deep Western Boundary Current (DWBC). Spirals indicate the sites of open ocean convection in the Nordic Seas, which feed the Nordic Overflows. The surface ocean circulation is represented by the dashed arrows, the pink indicating waters that originate from the North Atlantic Current (NAC), the Norwegian Atlantic Current (NwAC) and the light blue represent the polar-derived currents such as the East Greenland Current (EGC) and the East Icelandic Current (EIC). Base map adapted from Ocean Data View (Schlitzer, 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which contributes significantly to the the transport of northward inflow of warm waters into the Nordic Seas (Hansen et al., 2010). The advection of heat and salt to the high latitudes via the Atlantic inflow is important not only for ameliorating the climate in Western Europe (Rossby, 1996) but also for promoting deep water formation. Additionally, while models disagree on the role that overflows play in AMOC variability, modelling studies have suggested that the density of the overflows and their magnitude can influence the surface hydrography south of the GSR, namely the subpolar gyre circulation (Born et al., 2009; Zhang et al., 2011) and the structure and strength of the AMOC as well as North Atlantic climate (Wang et al., 2015).

Future climate simulations under increasing atmospheric CO_2 levels predict a change in the freshwater budget in the Arctic Ocean and Nordic Seas as a result of a decline in Arctic sea ice cover, melting of the Greenland Ice Sheet and increase in circum-Arctic river run-off (Stocker et al., 2013). The addition of freshwater into the high latitudes may lower the surface ocean salinity and reduce the formation of dense waters in the Nordic Seas, which would potentially weaken the overflow transport across the ridge, possibly affecting the AMOC (Hansen et al., 2004; Wilkenskjeld and Quadfasel, 2005; Rahmstorf et al., 2015).

However, prior to reaching any conclusion on the anthropogenic drivers of climate change and their potential effect on the freshening and weakening of the overflows and the AMOC, it is necessary to extend the instrumental records of overflow vigour back in time to improve our understanding of the natural variability of these key components of the AMOC. On centennial time-scales, proxy reconstructions have revealed abrupt changes in the strength and/or depth of the overflow boundary currents at times corresponding to well-known millennial–centennial scale climatic oscillations, such as the 8.2 kyr event (Ellison et al., 2006), the 2.7 kyr event (Hall et al., 2004), the Little Ice Age (Bianchi and McCave, 1999), and over the Holocene (Thornalley et al., 2013). This ocean-climate link suggests that the Nordic Seas Overflows, and their role in setting the strength of the AMOC, play a leading role in modulating climate variability over the current interglacial.

Here we present near-bottom flow speed reconstructions from two sub-decadal to decadally resolved marine sediment cores which are strategically located within the present day flow path of the two main Nordic Seas Overflows, namely Iceland Scotland Overflow Water (ISOW) and Denmark Strait Overflow Water (DSOW) respectively, and which span the last 3000–4000 years. In order to reconstruct the relative flow speed changes we use the paleocurrent proxy 'sortable silt' mean grain size ($\overline{SS}$), which is the average of the 10–63 μm terrigenous fraction (McCave et al., 1995). Size sorting in this size range responds to hydrodynamic processes and can therefore be used to infer relative changes in the speed of the depositing current (McCave et al., 1995; McCave and Hall, 2006).

2. Hydrographic setting: the Nordic Overflows

Deep water formation in the Nordic Seas sets a horizontal density gradient across the GSR which drives the transfer of these dense waters over the sill as the Nordic Sea Overflows (Hansen et al., 2001). The rate of dense water export by the overflows into the North Atlantic Basin is hydraulically controlled and is proportional to the cross-sill density difference of the water masses and to the upstream reservoir height (Whitehead, 1998). Alteration of these factors drives changes in the vigour of the overflows reaching the Atlantic Basin.

The densest overflow waters pass through the deepest passages of the GSR, the Denmark Strait and the Faroe Bank Channel. As such, the Nordic Seas Overflows are divided into two major branches east and west of Iceland: the ISOW and DSOW, respectively (Fig. 1). While the two overflows are different primarily because of the differing sill geometries and the physical properties of their upstream source waters, both overflows contribute ~3 Sv each (1 Sv = 10^6 m^3 s^{-1}) to the total volume flux of dense waters ventilating the deep subpolar North Atlantic (Olsen et al., 2008 and references therein). Once the overflows cross the GSR, they descend over the sill subsequently entraining intermediate waters found in the Irminger and Iceland Basins, such as Labrador Sea Water (LSW) and other Subpolar Mode Waters. Thereafter, the overflows continue as density-driven bottom currents, following the bathymetry whilst undergoing further mixing with the overlying waters. This intensive downstream entrainment and mixing increase the initial volume transport by three-fold and significantly alter the hydrographic properties of the overflow waters (Price and Baringer, 1994). The two overflows (ISOW and DSOW) merge south of the Denmark Strait forming the upper and lower branches of the Deep Western Boundary Current (DWBC) on reaching Cape Farewell, although here the different water masses are still distinguishable based on potential density (Holliday et al., 2009). The DWBC subsequently flows around the Labrador Basin (Fig. 1) and in combination with LSW eventually forms North Atlantic Deep Water, which constitutes the deep limb of the AMOC.

3. Materials

3.1. Core settings

Sediment core RAPiD-17-5P (61° 28.90′N, 19° 32.16′W, 2303 m water depth) is situated on the deeper section of the south Iceland insular rise that runs along the northern edge of the South Iceland Basin (Fig. 1) (Thornalley et al., 2010). Numerous hydrographic and hydro-chemical studies focussing on the deep circulation in the Iceland Basin (Van Aken, 1995; Van Aken and Becker, 1996; Bianchi