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Subpolar North Atlantic sea surface temperature since 6 ka BP: Indications of anomalous ocean-atmosphere interactions at 4-2 ka BP

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ABSTRACT

Atmospheric circulation may change with future climate change in response to modification of meridional temperature gradients, but the potential influence on ocean circulation is as yet unclear. Over the mid-late Holocene, atmospheric circulation in the North Atlantic region has fluctuated on millennial timescales; therefore, the ocean response to these changes can be investigated using the paleoceanographic records that have been developed in the north-eastern subpolar North Atlantic. Here, we present a diatom-based sea surface temperature reconstruction from the Iceland Basin, south of Iceland; the reconstruction shows the warmest temperatures of the record at 6.1–4 ka BP, cooler temperatures at 4-2 ka BP and warmer temperatures thereafter. Inter-record comparisons indicate that the cold period at c. 4-2 ka BP may have resulted from a strengthened East Greenland Current and/or melting of the Greenland ice sheet, in response to a negative North Atlantic Oscillation. The findings highlight that atmospheric circulation changes are likely to cause pronounced variations in the latitudinal exchange of heat, which may have consequences for deep-water formation and global ocean circulation.

1. Introduction

The dominant mode of variability in the atmospheric circulation of the North Atlantic region is the North Atlantic Oscillation (NAO). This index, calculated as the pressure gradient between the Subpolar Low, centred over Iceland, and the Azores High, controls the latitudinal position of storm tracks and wind strength in the North Atlantic region (e.g. Hurrell and Van Loon, 1997). During Northern Hemisphere summer, the NAO generally weakens, with lower amplitude variability and a northward shift of the pressure cells, while they move southward and display a higher amplitude of variability in winter (Folland et al., 2009). A positive NAO (with the greatest difference between the pressure dipoles) is associated with a northward-shifted storm track, driving a stronger and northward-shifted North Atlantic Current (NAC) and potentially a greater E-W extension of the subpolar gyre (SPG; Taylor and Stephens, 1998; Curry and McCartney, 2001; Frantantoni, 2001), although this latter response has been questioned (Foukal and Lozier, 2017). Weaker and southward-shifted storm tracks occur during negative NAO phases (characterised by a reduced pressure difference), resulting in a weaker and southward-shifted NAC

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(Taylor and Stephens, 1998; Curry and McCartney, 2001).

During a positive (negative) NAO, over sub-annual timescales, the response to air-sea heat fluxes and wind-driven Ekman transport is cooling (warming) in a zonal band spanning the North Atlantic north of 45°N (Kushnir, 1994; Seager et al., 2000; Visbeck et al., 2003). However, over multi-annual to decadal/centennial timescales it is suggested that a positive (negative) NAO causes increased (decreased) convective activity in the Labrador Sea and strengthening (weakening) of the SPG and meridional overturning circulation, resulting in warming (cooling) north of 55°N (Eden and Jung, 2001; Visbeck et al., 2003; Häkkinen and Rhines, 2004; Latif et al., 2006). During a negative NAO strengthened northerly winds to the east of Greenland can reinforce the East Greenland Current (EGC) and increase the export of sea ice and freshwater from the Arctic to the North Atlantic, a scenario which in the twentieth century caused 'Great Salinity Anomalies' (Dickson et al., 1996: Delworth et al., 1997; Belkin et al., 1998; Blindheim et al., 2000; Ionita et al., 2016). Similar episodes have been identified over decadal-centennial timescales in model and paleoclimate analyses (Delworth et al., 1997; Renssen et al., 2005; Sicre et al., 2008; Ran et al., 2011). Nevertheless, the interactions between the ocean and atmosphere are complex. Models indicate that, due to the coupling of the ocean and atmosphere system, sea surface temperature (SST) changes themselves may force NAO variability. Here, potential feedbacks include changes in heat transport by the subtropical gyre (STG) and the SPG (Bellucci et al., 2008) as well as changes in evaporation, precipitation and atmospheric heating processes (Rodwell et al., 1999).

The NAO is also negatively correlated with atmospheric temperatures over the Greenland ice sheet and is therefore a potentially important factor controlling past and future melting (Serreze et al., 1997; Chylek et al., 2004; Fettweis et al., 2013). The melting of the Laurentide ice sheet in the early Holocene is known to have lowered SSTs in this region (Andersen et al., 2004b; Berner et al., 2008; Blaschek and Renssen, 2013; Jiang et al., 2015; Sejrup et al., 2016), however there has been less research on the ocean temperature response to fluctuations in the extent of the Greenland ice sheet during the mid to late Holocene (Briner et al., 2016).

Compilations of SST reconstructions from the subpolar North Atlantic show that during the mid-late Holocene the dominant feature in the region was cooling (e.g. Calvo et al., 2002; Rimbu et al., 2003; Sundqvist et al., 2014; Sejrup et al., 2016), which was primarily thought to result from orbital forcing (e.g. Andersen et al., 2004a, 2004b; Renssen et al., 2005; Hald et al., 2007; Berner et al., 2008; Kissell et al., 2013; Jiang et al., 2015; Sejrup et al., 2016). However, reconstructions indicate differences between regions, as there is also some evidence for a warming after 2 ka BP in the Iceland and Greenland Seas (e.g. Justwan et al., 2008; Miettinen et al., 2012; Telesiński et al., 2014; Moossen et al., 2015; Sejrup et al., 2016; Kristjánsdóttir et al., 2017). Thus, understanding the past oceanographic changes is complex due to differences between reconstructions from the same region and even the same site, which may result from real spatial patterns but also factors related to the specific proxy used for the different SST reconstructions (climate-sensitivity, seasonal growth and habitat water-depth, as well as the statistical methods used).

Our understanding of the NAO variability during the Holocene is based on just a few records. Trouet et al. (2009) and Faust et al. (2016) suggest that the Medieval Climate Anomaly (~950–1250 A.D.) had a persistent positive NAO and the Little Ice Age (1250/1400–1850 A.D.) a negative NAO, and an imprint of these changes has been found in some marine reconstructions (e.g. Abrantes et al., 2005; Seidenkrantz et al., 2007, 2008; Sicre et al., 2014). Longer NAO reconstructions indicate that beginning at 6–4.5 ka BP until 2 ka BP the NAO was more neutral and negative, which was followed by a more frequently positive NAO after 2 ka BP (Olsen et al., 2012; Nesje et al., 2000; Faust et al., 2016), a trend supported by a compilation of SST reconstructions (Rimbu et al., 2003). The validity of basing NAO reconstructions on single sites has been questioned due to non-stationarity in the proxy-NAO relationship through time (e.g. Lehner et al., 2012; Ortega et al., 2015). However, the NAO reconstructions are supported by storm track reconstructions from Europe, which show a southward storm track position (reflecting a more negative NAO) before 2 ka BP, followed by a northward storm track shift (reflecting a more positive NAO pattern) after 2 ka BP (Bakke et al., 2008; Orme et al., 2017). These results therefore suggest that through the Holocene there have been long-term millennial shifts in atmospheric circulation.

The CMIP5 multi-model ensemble predicts that up until the end of the 21st century, storm tracks will stay within the range of natural variability in the northern hemisphere, although there is substantial uncertainty in this prediction (Collins et al., 2013). However, some studies based on modelling, observational and palaeoclimate records (Francis and Vavrus, 2012; Yang and Christensen, 2012; Kim et al., 2014; Orme et al., 2017) suggest that greater warming over the polar regions compared to that of the mid-latitudes could weaken the temperature gradient, driving a weaker meridional circumpolar circulation and a negative NAO. Such negative NAO circulation may result in changes in the subpolar North Atlantic, by reducing the amount of wind-driven northward heat transport, increasing the southward export of Arctic water and altering ocean-atmosphere heat fluxes, which may then alter rates of deep-water formation and the wider ocean circulation (e.g. Taylor and Stephens, 1998; Blindheim et al., 2000; Curry and McCartney, 2001; Eden and Jung, 2001; Latif et al., 2006). Thus, a central aim of this paper is to investigate the changes to the North Atlantic Ocean circulation that occurred as a result of the possible long-term negative phase of the NAO at 4-2 ka BP (Olsen et al., 2012; Faust et al., 2016). As such, here we present a new diatom-based SST reconstruction from the Iceland Basin for the last 6.1 ka BP and compare this with other SST reconstructions from the subpolar North Atlantic to understand the spatial temperature patterns. We then compare these with past variations in atmospheric circulation, to better understand the long-term ocean-atmosphere interactions in a region of high importance for the global climate system.

2. Oceanographic setting

The core site DA12-11/2-GC01 is located in the Iceland Basin which is bounded by the Reykjanes Ridge to the west, Iceland and the Iceland-Faroe ridge to the north and northwest and the Rockall Plateau to the southwest (Fig. 1). Within the Iceland Basin sediment transported by deep currents has accumulated to form the Björn and Gardar Drifts (Bianchi and McCave, 2000).

The NAC transports warm Atlantic water to the subpolar North Atlantic along several pathways (Fig. 1). A western branch turns northwest towards Iceland; part of the current passes over the Iceland-Faroe Ridge into the Nordic Seas while the other part travels as the Irminger Current (IC) first to the south and then to the north around the Reykjanes Ridge (Jakobsen et al., 2003; Pollard et al., 2004). The IC bifurcates in the Denmark Strait with a small part flowing to the north of Iceland while a larger branch recirculates to the south and converges with the south flowing EGC (Jakobsen et al., 2003; Pollard et al., 2004; Våge et al., 2011). The eastern branch of the NAC remains close to the European continental slope as it heads northwards, passing through the Rockall Trough to the Faroe-Shetland channel before entering the Nordic Seas (Orvik and Niiler, 2002; Jakobsen et al., 2003). The two currents that entered the Nordic Seas head northwards along separate