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Ocean-atmosphere climate shift during the mid-to-late Holocene transition

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ABSTRACT

Climate records of the mid-to-late Holocene transition, between 3–4 thousand years before present (ka), often exhibit a rapid change in response to the gradual change in orbital insolation. Here we investigate North Atlantic Central Water circulation as a possible mechanism regulating the latitudinal temperature gradient (LTG), which, in turn, amplifies climate sensitivity to small changes in solar irradiance. Through this mechanism, sharp climate events and transitions are the result of a positive feedback process that propagates and amplifies climate events in the North Atlantic region. We explore these linkages using an intermediate water temperature record reconstructed from Mg/Ca measurements of benthic foraminifera (*Hyalinea balthica*) from a sediment core off NW Africa (889 m depth) between 0 to 5.5 ka. Our results show that Eastern North Atlantic Central Waters (ENACW) cooled by $\sim 1^\circ \pm 0.7\,^\circ\mathrm{C}$ and densities decreased by $\sigma_\theta = 0.4 \pm 0.2$ between 3.3 and 2.6 ka. This shift in ENACW hydrography illustrates a transition towards enhanced mid-latitude atmospheric circulation after 2.7 ka in particular during cold events of the late-Holocene. The presented records demonstrate the important role of ENACW circulation in propagating the climate signatures of the LTG by reducing the meridional heat transfer from high to low latitudes during the transition from the Holocene Thermal Maximum to the late-Holocene. In addition, the dynamic response of ENACW circulation to the gradual climate forcing of LTGs provides a prime example of an amplifying climate feedback mechanism.

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1. Introduction

Observations over the past century indicate that changes in the North Atlantic Oscillation (NAO), exert the dominant control on the path and strength of the mid-latitude Westerlies and climate in the North Atlantic on interannual to decadal timescales (Hurrell, 1995; Visbeck et al., 2003). The region with the strongest response to NAO-modulated wind-stress is the northeastern subpolar basin of the Atlantic Ocean, where the strength of the Icelandic Low enhances westerly air flow by up to 8 $\mathrm{m\,s^{-1}}$ (Hurrell, 1995) and thereby lowers sea surface temperatures (SST) by several tenths of degrees ($\sim 0.7\,^\circ\mathrm{C}$) during extremely positive NAO (+) years (Furevik and Nilsen, 2005; Johnson and Gruber, 2007). Subpolar Mode Water (SPMW) which forms in this region during winter convection (Tomczak and Godfrey, 1994) is thus highly susceptible to NAO phase shifts, and carries the signature of the atmospheric NAO pattern in its properties (e.g. temperature and salinity) (Johnson and Gruber, 2007). After formation SPMW comprises a large fraction of Eastern North Atlantic Central Water (ENACW) (Iselin, 1936; Poole and Tomczak, 1999).

ENACW integrates interannual NAO variability as smoother, longer-term multidecadal (60-to-90-year) oscillations (Morley et al., 2011). On these timescales the oceanic signature of positive NAO phases is associated with a tripole pattern of cold SST anomalies in the subpolar North Atlantic, warm anomalies in the West Atlantic between 20 and 45° N, and cold anomalies between 0 and 30° N in the East Atlantic (Marshall et al., 2001). On multidecadal timescales the oceanic signature of the NAO is captured by the Atlantic Multidecadal Oscillation (AMO) (Grossmann and Klotzbach, 2009; Marshall et al., 2001). The AMO describes basin-wide SST and sea level pressure anomalies, with warm anomalies during positive and cold anomalies during negative phases (Knight et al., 2005; Knudsen et al., 2011; Kushnir, 1994; Olsen et al., 2012). The intensity of mid-latitude Westerlies, strongest during positive NAO phases reinforce cold SST anomalies during AMO (−) (Häkkinen, 2000). In this way long-term positive phases of the NAO are linked to the negative phase of the AMO. However the precise forcing mechanism behind multidecadal SST variability in the North Atlantic including natural variability in the Atlantic Meridional

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Overturning Circulation, solar variability, and/or volcanism remains uncertain (Booth et al., 2012; Grossmann and Klotzbach, 2009; Ottera et al., 2010; Sicre et al., 2011). On centennial timescales, there is evidence (Ammann et al., 2007; Knudsen et al., 2009; Lockwood et al., 2010; Lohmann et al., 2004; Swingedouw et al., 2010) for the existence of similar ocean-atmosphere linkages that communicate and amplify relatively small changes in total solar irradiance (ΔTSI) into a climate signal extending beyond the northeastern Atlantic region (Lean, 2010; Morley et al., 2011; Shindell et al., 2001). A common approach to identify and interpret past climate records is to match proxy based climate reconstructions with modern ocean-atmosphere circulation modes such as the oceanic expressions of the NAO-AMO (Luterbacher et al., 2004; Mann et al., 2009; Trouet et al., 2009) or ΔTSI (Lean, 2010; Shindell et al., 2001; Steinhilber et al., 2012, 2009), recognizing that often these trends are far longer than the intrinsic interannual or multidecadal NAO-AMO variability.

The presence of non-NAO-AMO-like atmospheric variability in modern instrumental records provides a first indication that the focus on the NAO-AMO for past climate reconstructions may be too simplistic. Instrumental observations show for example that the relationship between the NAO and the strength of the mid-latitude Westerlies periodically breaks down, most prominently during the 1930s (American Dust Bowl) and more recently over the last decade (2000 to 2012) indicating the possibility of a different atmospheric circulation pattern operating during these times (Bengtsson et al., 2004; Drinkwater, 2006; Overland and Wang, 2005; Wood and Overland, 2010). During both periods, high latitudes experienced peak warming and sea ice loss (Barents Sea) in the absence of a positive NAO mode (Bengtsson et al., 2004; Overland and Wang, 2005). Similarly, high latitude warming and reduced Arctic sea ice extent prevailed during the Holocene Thermal Maximum (HTM) between 11 and 4 ka (Andersen et al., 2004a; Koç et al., 1993; Polyak and Mikhailov, 1996; Voronina et al., 2001), when high northern summer insolation was stronger and the latitudinal temperature gradient (LTG) (e.g. the difference in temperature between the high Arctic and the Tropics) was weaker than today (Davis and Brewer, 2009; Fischer and Jungclaus, 2011). The most recent analogue to a decrease in the LTG occurred during the 1930s (Rind, 1998) and more prominently during the past decade (Section 5.2).

Unlike the 1930s however several proxy and numerical based climate reconstructions propose that strong mid-latitude Westerlies (NAO +) prevailed during the warm HTM. Likewise the cooler late-Holocene is often associated with weaker westerly airflow (NAO −) (Renssen et al., 2005b; Rimbu et al., 2003, 2004; Wanner et al., 2008) whereas other records provide evidence for enhanced atmospheric circulation over North Atlantic mid- and high-latitudes during the late-Holocene (Brayshaw et al., 2010; De Angelis et al., 1997; Jennings et al., 2011; Moros et al., 2012; Renssen et al., 2005a). These conflicting interpretations suggest that the focus on the NAO-AMO as a modern analogue for the Holocene may oversimplify past climate dynamics (Pinto and Raible, 2012).

Morley et al. (2011) showed that past temperatures and the oxygen isotopic composition ($\delta^{18}O_{sw}$) of ENACW recorded off the Northwest African continental margin are determined by SPMW formation south and west of Iceland on both instrumental, multidecadal and multicentennial timescales over the past millennium. Essentially, ENACW circulation provides an 'oceanic tunnel' (Liu and Alexander, 2007) transmitting subpolar ocean-atmospheric climate anomalies to lower latitudes. Here we extend the investigation of ENACW variability over the past 5.5 ka to test the hypothesis that ENACW cooling (warming) during the Holocene enhances (reduces) the LTG and thereby amplifies climate sensitivity to small changes in insolation, creating a positive feedback loop that propagates and amplifies climate events in the North Atlantic region. To test this hypothesis we present a combination of modern observations alongside a 5.5 ka long paleotemperature and stable isotopic record based on benthic foraminifera collected within ENACW (889 m water depth) from the northwest African continental shelf in the eastern boundary of the subtropical gyre (STG) (Fig. 1). By analyzing and comparing our data with a wide range of proxy records in our discussion (both in terms of geographic locations and in proxy variety) we will investigate the possible link between gradually changing LTGs during the winter and the transmission of North Atlantic climate change at central water depth. Specifically, we focus on the transition from the HTM to the colder late-Holocene (or the mid-to-late Holocene transition) at subpolar latitudes between 3.5 and 4 ka (Came et al., 2007; Giraudeau et al., 2010; Ólafsdóttir et al., 2010; Pena et al., 2010).

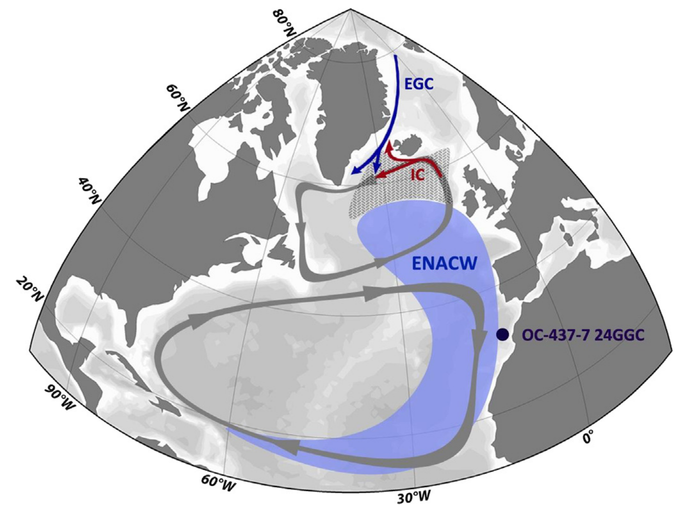

Fig. 1. Map of core location and schematic representation of the shallow overturning circulation in the North East Atlantic. The Eastern North Atlantic Central Water (ENACW) formation region is marked in light grey hatching and represents the area where SPMW form and winter surface water densities range between $\sigma_\Theta = 27.3$ and 27.7 (adapted from McCartney and Talley, 1982). The influence and circulation of ENACW (blue) represents potential density surfaces between $\sigma_\Theta = 27.3$ and 27.7 at mid-depth (adapted from Keffer, 1985). The location and flow of the East Greenland Current (EGC) and the Irminger Current (IC) are marked in blue and red arrows respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Oceanographic setting

Gravity core OC437-7 24GGC was collected at 889 m water depth [30.854° N, 10.272° W] in the eastern boundary of the STG during the CHEETA (Changing Holocene Environments of the Eastern Tropical Atlantic) coring cruise on the R/V Oceanus in July 2007 (McGee et al., 2013). At 889 m water depth ENACW is the dominant water mass at the core site, with average temperature and salinity values near 7.8–7.9 °C and 35.45 psu respectively. Cross-gyre transfer of subsurface ENACW (Keffer, 1985; McCartney and Talley, 1982; McDowell et al., 1982) occurs via SPMW formation in the eastern SPG between density surfaces σ_θ 27.3 and 27.6 kg/m^3 (Levitus, 1989; McCartney and Talley, 1982). ENACW formation and circulation thus establishes a direct link between both gyres and allows us to investigate the influence of subpolar ocean-atmosphere climate linkages on ENACW properties and cross gyre climate signal propagation. ENACW is underlain by a salinity minimum signaling the upper limit of Antarctic Intermediate Water (AAIW) between 900 and 1300 m (Knoll et al., 2002). Below this, the very high salinity Mediterranean Outflow Water (MOW) occurs near 1300 m (Arhan et al., 1994;