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Millennial-scale versus long-term dynamics in the surface and subsurface of the western North Atlantic Subtropical Gyre during Marine Isotope Stage 5

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ABSTRACT

Subtropical Gyres are an important constituent of the ocean–atmosphere system due to their capacity to store vast amounts of warm and saline waters. Here we decipher the sensitivity of the (sub)surface North Atlantic Subtropical Gyre with respect to orbital and millennial scale climate variability between ~140 and 70 ka, Marine Isotope Stage (MIS) 5. Using (isotope) geochemical proxy data from surface and thermocline dwelling foraminifers from Blake Ridge off the west coast of North America (ODP Site 1058) we show that the oceanographic development at subsurface (thermocline) level is substantially different from the surface ocean.

Most notably, surface temperatures and salinities peak during the penultimate deglaciation (Termination II) and early MIS 5e, implying that subtropical surface ocean heat and salt accumulation might have resulted from a sluggish northward heat transport. In contrast, maximum thermocline temperatures are reached during late MIS 5e when surface temperatures are already declining. We argue that the subsurface warming originated from intensified Ekman downwelling in the Subtropical Gyre due to enhanced wind stress.

During MIS 5a-d a tight interplay of the subtropical upper ocean hydrography to high latitude millennial-scale cold events can be observed. At Blake Ridge, the most pronounced of these high latitude cold events are related to surface warming and salt accumulation in the (sub)surface. Similar to Termination II, heat accumulated in the Subtropical Gyre probably due to a reduced Atlantic Meridional Overturning Circulation. Additionally, a southward shift and intensification of the subtropical wind belts lead to a decrease of on-site precipitation and enhanced evaporation, coupled to intensified gyre circulation. Subsequently, the northward advection of this warm and saline water likely contributed to the fast resumption of the overturning circulation at the end of these high latitude cold events.

1. Introduction

As an enormous reservoir for heat and salt, the wind-driven Subtropical Gyres play an important role for the upper ocean circulation (Schmitz and McCartney, 1993). They react furthermore very sensitively to climatic disturbances due to the close feedback between atmospheric and oceanic processes on the gyre circulation and (sub)surface water properties (e.g. Mignot et al., 2007; Mildner, 2013). This is particularly evident for millennial-scale climate change during Dansgaard/Oeschger (D/O)-cycles or Heinrich Events. In the case of the North Atlantic Subtropical Gyre, the southward migration of the wind fields in response to high latitude cooling and weakened Atlantic Meridional Overturning Circulation (AMOC) causes an intensification of the wind stress and a more negative precipitation-evaporation balance (e.g. Lohmann, 2003; Vellinga and Wu, 2004; Mildner, 2013). This leads to a deepening of the thermocline by increased Ekman pumping and enhances the salinity of the gyre waters (Slowey and Curry, 1995; Schmidt et al., 2006a). Subsequently, the accumulation of salt in the subtropics might help to strengthen AMOC intensity after the end of a stadial (e.g. Schmidt et al., 2006a,b; van Meerbeeck et al., 2011). Mignot et al. (2007) further pointed out that the subsurface response to a severe reduction of AMOC is highly sensitive to the location of the freshwater input and that subsurface warming might be a crucial mechanism for re-invigorating deep water formation at high latitudes.

However, modeling and proxy data suggest a complex response of the subtropical hydrography to high latitude climate change, depending on the boundary conditions (namely ice volume) and the magnitude of forcing: Fresh water hosing experiments imply that AMOC weakening or shut-down during Heinrich Events leads to cooling in the North Atlantic, extending into subtropical regions (c.f. inter-model comparison studies of Stouffer et al., 2006; Kageyama et al., 2010, 2013). Proxy records confirm wide spread cooling at Bermuda Rise (Sachs and Lehman,

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1999), Outer Blake Ridge (Sachs and Lehman, 1999) and the mid-latitude Atlantic (Calvo et al., 2001). However, there is also contrary evidence for local warming (Naafs et al., 2013) which is reproduced by one model (CCSM Version 3.0, Stocker et al., 2007; Renold et al., 2010). The subsurface temperature evolution has been less studied so far, but modeling indicates that both, warming or cooling might occur, depending on the latitude of the freshwater injection (Mignot et al., 2007).

Although oceanic circulation is not as severely disturbed as during Heinrich Events, stadial/interstadial conditions during the D/Os in MIS 3 are also faithfully recorded in the subtropics. Here, stadial conditions are accompanied by a distinct cooling in alkenone records and faunal SST reconstructions from Blake and Bahama Outer Ridge (Sachs and Lehman, 1999). Interestingly, Mg/Ca-based sea surface temperatures (SST) are devoid of any anomalies, but combined planktonic $\delta^{18}O$ measurements suggest abrupt salinity increases (Schmidt et al., 2006a). Similarly, Greenland Stadials during MIS 5 and earlier interglacials were also recorded by alkenone-paleothermometry at Bermuda Rise and negative planktonic $\delta^{18}O$ excursions on Blake Ridge (Oppo et al., 2001; Heusser and Oppo, 2003; Billups et al., 2004; Evans et al., 2007). While the $\delta^{18}O$ records from Blake Ridge have been commonly interpreted as cooling, the MIS 3 data from Schmidt et al. (2006a) suggests that a salinity component might be included in the signal as well.

Hence, the yet available data (observational and modeled) gives the impression that different boundary conditions as well as the strength of forcing might lead to a considerably different response of the subtropical Atlantic to high-latitude climate disturbances. Clearly, a broader proxy data base is needed to improve our understanding of the fundamental processes involved and to ground-truth model predictions. To evaluate the relationship of the upper ocean hydrography in the subtropical North Atlantic to high northern latitude climate change, we generated paleoceanographic proxy records (Mg/Ca and $\delta^{18}O$ on shallow and deep dwelling foraminifers) for Marine Isotope Stage (MIS) 5 at ODP Site 1058 located on Blake Ridge off the west coast of North America. Blake Ridge records have been frequently used to reconstruct Gulf Stream strength (e.g. Oppo et al., 2001; Billups et al., 2004, 2006; Vautravers et al., 2004) and the dynamics of the Deep Western Boundary Current (e.g. Evans et al., 2007; Evans and Hall, 2008; Hall et al., 2011). Site 1058 is furthermore located at the western boundary of the wind-driven Subtropical Gyre and can therefore be used to reconstruct the expansion or retraction of the pool of warm and saline waters accumulated in this area.

The covered period from ca. 70–140 ka has been chosen because it provides the opportunity to study and compare time intervals of considerably different paleoclimatic background: (1) the penultimate deglaciation (Termination II), (2) the glacial inception after the climatic optimum of MIS 5e, and (3) the increasingly more intense high latitude cold events (Greenland Stadials) punctuating MIS 5a–d. The major issues investigated are concerned with the role of atmospheric versus oceanic forcing on the subtropical hydrography and whether there is a coherent pattern of long-term (e.g. insolation-driven) and millennial-scale paleoenvironmental change.

2. Oceanographic setting

Blake Ridge is a sedimentary drift structure formed by the bottom currents of the southward flowing Deep Western Boundary Current. On surface and subsurface levels, ODP Site 1058 is located close to the western boundary of the North Atlantic Subtropical Gyre (Fig. 1). Due to the dominant westerly winds and enhanced evaporation, an homogenous pool of warm and saline water ("Central Water") created by Ekman downwelling is dominating surface and subsurface waters down to almost 800 m water depth (Schmitz and McCartney, 1993) (Fig. 1). Upward (downward) shifts of the permanent thermocline occur when wind forcing is reduced (enhanced) (Slowey and Curry, 1995). Hence, tracking the spatial expansion of Central Water is important for deciphering changes in the atmosphere-driven component of the oceanic circulation.

Surface waters at Site 1058 are mainly affected by the Gulf Stream, which circulates northward toward Cape Hatteras where it deflects to the east (Fig. 1). The geostrophic nature of the boundary current is clearly imprinted as NW-wards tilted isopycnals in the upper 200 m of the water column (Fig. 1). At present, the density structure of the upper water masses is primarily a function of temperature, as indicated by the isopycnals running parallel to the isotherms (Fig. 1). If the Gulf Stream strength weakened, vertical shear will be reduced and pycnoclines would be tilted less steeply. The latter depends on the intensity of the gyre circulation (the wind driven component), but is also related to the intensity of the thermohaline circulation (Stommel, 1965; Schmitz and McCartney, 1993). The warm "Central Water" masses are separated by a sharp hydrographic front from the cold and fresh "Slope Waters" north of the Gulf Stream (Fig. 1A and B). These originate from coastal input and are fed by water from the Labrador Sea. Hydrographic properties of the surface water masses vary seasonally with significantly reduced stratification in the upper ~100 m during winter (Fig. 1).

Formation of thermocline waters, relevant for the record of the deep dweller *Globorotalia truncatulinoides* (s) (e.g. Cléroux et al., 2007), are formed by subduction of cold and dense surface waters during winter time in the northern part of the Subtropical Gyre between ~33 and 40°N (McCartney, 1982; McCartney and Talley, 1982; Talley and Raymer, 1982; Joyce et al., 2000; Palter et al., 2005). Excessive winter cooling in consecutive years can cause thickening of mode water (Hazeleger and Drijfhout, 1998) which can be more effective than deep mixing by storm activity. As a consequence, the reconstruction of thermocline water properties includes a potential winter bias.

Underlying the subtropical Central Water are the constituents of the Deep Western Boundary Current, with the shallow component of Labrador Sea Water reaching water depths between 1000 and 1800 m (Stahr and Sanford, 1999). Labrador Sea Water is currently subducted down to ~2800 m, underlain by Lower North Atlantic Deep Water (~2500–4100 m) and Antarctic Bottom Water (AABW) below ~3400 m water depth (Stahr and Sanford, 1999).

3. Material and methods

Samples were retrieved from ODP Leg 172, Site 1058, drilled on the Blake Outer Ridge at 31°41′N, 75°25′W in 2996 m water depth. Sampling of the uppermost 2 m (MIS 1–2) of Hole ODP 1058C was performed in 1 cm intervals, while MIS 5 samples were retrieved at 2 cm spacing. After freeze-drying, samples were wet-sieved, dried, and fractionated into discrete size fractions prior to the selection of foraminifera. For stable isotope analyses of benthic foraminifera, we selected 1–3 specimens of *Cibicidoides wuellerstorfi* or *Uvigerina peregrina* (depending on availability) from the fraction >250 μm. For stable isotope and Mg/Ca analyses of planktonic foraminifera, a total of 30 individual tests were picked from narrow size fractions to avoid size-related effects on the Mg/Ca-temperature reconstructions (Anand and Elderfield, 2005; Cléroux et al., 2008; Friedrich et al., 2012). These were 315–355 μm for *Globigerinoides ruber* (white) and 355–400 μm for *G. truncatulinoides* (sinistral). In case of an insufficient number of individuals, we expanded the sampled size fractions to 315–400 μm for Mg/Ca while the less size-dependent stable isotope measurements were done on the fractions 250–315 μm for *G. ruber* (w) ($n = 44$) and >400 μm for *G. truncatulinoides* (s) ($n = 15$). For stable carbon and oxygen isotope analyses, subsamples were cleaned with ethanol and ultra-pure water. Analyses were done with a ThermoFisher MAT 253 equipped with a Kiel IV-Carbonate Unit at GEOMAR. Results are given in the common δ-notation relative to the Vienna PDB-standard with an analytical precision <0.06‰ for $\delta^{18}O$ and <0.03‰ for $\delta^{13}C$. Replicates yielded following standard deviations (SD): *G. truncatulinoides*: $\delta^{18}O = 0.21$‰, $n = 101$; *G. ruber* (w): $\delta^{18}O = 0.34$‰, $n = 8$.