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Oceanic heat pulses fueling moisture transport towards continental Europe across the mid-Pleistocene transition

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ABSTRACT

The mid-Pleistocene Transition (MPT; approx. 1.2–0.7 Ma), is characterized by growing Northern Hemisphere ice sheets and the shift from a 41 kyr to a 100 kyr glacial-interglacial cyclicity. Concomitant to the growth of large ice sheets, atmospheric and oceanic circulation pattern have changed. One key feature of the North Atlantic is the wind-driven Subtropical Gyre, a major provider of heat and moisture for continental Europe. Here, we investigate changes in the strength and spatial configuration of the Subtropical Gyre during the MPT and its impact on the continental moisture balance.

To reconstruct Subtropical Gyre dynamics, we conducted paired $\delta^{18}O$ and Mg/Ca analyses on the deep-dwelling foraminifera *Globorotalia inflata* from Iberian Margin Site U1385 yielding thermocline temperature (T_{therm}) variability between 1400 and 500 ka at the eastern boundary of the Subtropical Gyre.

Long-term trends of T_{therm} at Site U1385 oppose the North Atlantic climatic evolution of progressively intensified glacials during the MPT. Particularly, glacials MIS 20 and 18 were marked by warm thermocline waters off Iberia. We infer that a southward shift of the (sub)polar front displaced the source region of thermocline waters within the Subtropical Gyre from high to mid-latitudes. In addition, a strong Mediterranean Outflow Water production during the MPT caused the advection of warm waters to Iberia. Humid conditions during MIS 20 and 18 in SE Europe indicate that atmospheric moisture derived from this warm water might have been advected deep into continental Europe and contributed to enhanced growth of Alpine glaciers.

1. Introduction

The mid-Pleistocene was characterized by fundamental changes in the global climate system. The most dramatic change was a switch from a 41 kyr obliquity-paced glacial/interglacial rhythm to the present-day 100 kyr cyclicity (Clark et al., 2006; McClymont et al., 2013; Mudelsee and Schulz, 1997). This so-called "Mid-Pleistocene Transition" (MPT), occurring between ca. 1200 to 700 ka, was accompanied by a significant increase of glacial ice volume (De Boer et al., 2014; Hao et al., 2012; Raymo et al., 2006; Sosdian and Rosenthal, 2009). Model and proxy data suggest that most of the excess ice-sheet accumulation across the MPT derives from Eurasia and North America due to the vast land masses available for unimpeded glacier expansion (Bintanja and van de Wal, 2008; Clark et al., 2006; McClymont et al., 2013). This intensified ice sheet growth was accompanied by general glacial cooling in the northern mid- and high-latitudes that became more intense over the course of the MPT (Hao et al., 2012; Lawrence et al., 2010; McClymont et al., 2013; Naafs et al., 2012; Ruddiman et al., 1989). Notably, glacial cooling over the course of the MPT occurred without long-term changes in atmospheric pCO_2 (Hönisch et al., 2009).

The growth of large continental ice sheets as well as more extended sea-ice cover alter the hemispheric wind fields and directly impact surface ocean circulation (e.g., Chiang et al., 2003; Löfverström et al., 2014; Ludwig et al., 2016; Slowey and Curry, 1992). As the surface ocean is the prime source for continental moisture a mechanistic understanding of the dynamics and

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interplay of atmospheric and oceanic processes is essential to fully appreciate the dynamics of Quaternary climate evolution (McClymont et al., 2008, 2013; Ruddiman et al., 1989). It is therefore the main goal of this study to constrain the factors modulating the heat distribution within the mid- and high-latitude North Atlantic during the MPT and its influence on the hydrological cycle in continental Europe.

The Subtropical Gyre is the dominant (sub)surface circulation system within the low-to mid-latitude North Atlantic. It plays a major role in distributing heat and moisture to the north. Enhanced Subtropical Gyre circulation strength could fuel northward moisture advection while a change in its spatial configuration could alter moisture transport pathways into continental Europe (Eshel and Farrell, 2000; Farneti and Vallis, 2013; Kwon et al., 2010). Because the Subtropical Gyre is mainly driven by the westerlies in the north and trade winds in the south (Barton, 2001; Schmitz and McCartney, 1993) (Fig. 1), the strength and position of the oceanic currents critically depend on the location and variability of the atmospheric wind fields. Growing continental ice shields and sea-ice expansion will cause a southward shift of (sub)polar frontal systems and intensify zonal wind systems (e.g., Costas et al., 2016; Laîné et al., 2009; Luetscher et al., 2015). Hence, ice sheet growth might impose feedbacks in the mid-latitude wind circulation that could enhance the Subtropical Gyre circulation and thereby the northward moisture transport.

Another factor that influences the (sub)surface water properties at the eastern boundary of the North Atlantic Subtropical Gyre is the formation of the Azores Current by the sinking motion of the Mediterranean Outflow Water (MOW) (Jia, 2000; Volkov and Fu, 2010) (Fig. 1). The MOW is a dense water mass discharging from the Mediterranean Sea into the North Atlantic via the Strait of Gibraltar, where it descends into greater water depths (Fig. 1). Model studies clearly indicate that the sinking of the MOW is the essential driver of the Azores Current formation by “dragging” warm water towards SW Europe (Jia, 2000; Volkov and Fu, 2010). In addition, the strength and position of surface wind fields influences the position and strength of the Azores Current as well, but lose their impact east of 20°W (i.e. in our study area), where MOW-forcing predominates (Volkov and Fu, 2010).

To explore the Subtropical Gyre circulation strength, we reconstruct thermocline water temperatures (T_{therm}) at the Iberian Margin (Integrated Ocean Drilling Program (IODP) Site U1385, Fig. 1) between 1.4 and 0.5 Ma. To understand long-term trends of T_{therm} from Site U1385 in the context of hydrographic and climatic changes in the North Atlantic realm, we compare our data with SST records from the North Atlantic that cover the MPT in sufficient resolution, i.e. high-latitude Site 983 (60°N; McClymont et al., 2008) and mid-latitude Site U1313 (41°N; Naafs et al., 2012) (Fig. 1). This comparison allows us to constrain potential shifts in the source region of the thermocline waters off Iberia and their influence on the subsurface hydrography.

2. Hydrographic setting

The North Atlantic Subtropical Gyre is characterized by the accumulation of warm and saline (sub)surface waters driven by zonal wind systems, i.e. westerlies at the northern and trade winds at the southern boundary of the gyre. At the eastern margin of the Subtropical Gyre, the upper ~100 m of the water column are formed by warm (15–18 °C) and saline (36.2 PSU) Eastern North Atlantic Central Waters of subtropical origin ($ENACW_{ST}$, Fig. 1) which is advected by the Azores Current (Fiúza et al., 1998; Peliz et al., 2005; Voelker and De Abreu, 2011; Voelker et al., 2009). $ENACW_{ST}$ is underlain by the colder (12 °C) and fresher (35.7 PSU) Eastern North Atlantic Central Waters of subpolar origin ($ENACW_{SP}$), which forms the permanent thermocline down to ~500 m water depth (Fig. 1). At present, $ENACW_{SP}$ is subducted in the northeastern North Atlantic during winter time cooling north of 50°N (Brambilla et al., 2008; McCartney and Talley, 1982, Fig. 1). Hence, changing hydrographic properties (e.g. T, S, nutrient availability) in this region will ultimately alter $ENACW_{SP}$ properties at the Iberian Margin. At Site U1385, a positive salinity (36.2 PSU) anomaly in 500–1500 m water depth is formed by the Mediterranean Outflow Water (MOW) (Fig. 1).

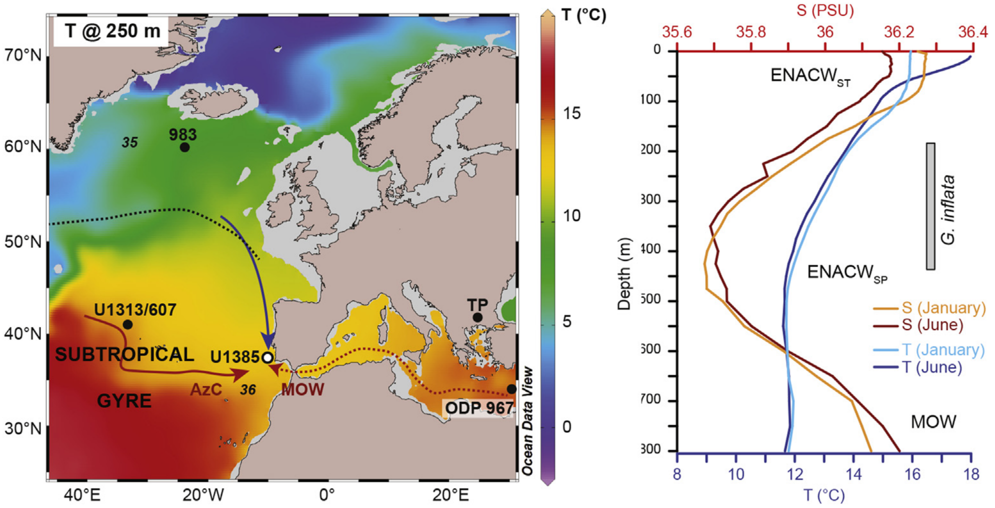

Fig. 1. Left: hydrographic map with temperature (color shading) in 250 m depth approximating the calcification depth of *Globorotalia inflata* (Elderfield and Ganssen, 2000). A dashed line marks the outcropping of the 27.0 σ isopycnal (equal to the potential density at 250 m water depth at Site U1385). This area approximates the southernmost region where $ENACW_{SP}$ is currently subducted and transported to the Iberian Margin (blue arrow). Warm subtropical water ($ENACW_{ST}$) is transported by the Azores Current to the Iberian Margin. Sites mentioned in the text are indicated (TP – Tenaghi Philippon). Right: Hydrographic section at Site U1385 with temperature (blue) and salinity (red) for January and June. The calcification habitat of *G. inflata* is marked by a grey bar (Elderfield and Ganssen, 2000). Characteristic water masses and (sub)surface currents are indicated: AzC – Azores Current; $ENACW_{ST, SP}$ – Eastern North Atlantic Central Water of subtropical and subpolar origin, respectively; MOW – Mediterranean Outflow Water; NAC – North Atlantic Current). Data are based on the World Ocean Atlas 2013 (Locarnini, 2013; Zweng et al., 2013), plotting was done using the program ODV (Schlitzer, 2009). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)