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Millennial-scale tropical atmospheric and Atlantic Ocean circulation change from the Last Glacial Maximum and Marine Isotope Stage 3

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ABSTRACT

Abrupt, millennial-scale climate oscillations, known as Dansgaard–Oeschger (D–O) cycles, characterized the climate system of the last glacial period. Although proxy evidence shows that D–O cycles resulted in large-scale changes in atmospheric circulation patterns around the planet, an understanding of how Atlantic Meridional Overturning Circulation (AMOC) varied across these events remains unclear. Here, we take advantage of the fact that both tropical atmospheric circulation changes corresponding to north–south shifts in the Intertropical Convergence Zone (ITCZ) and large-scale changes in ocean circulation associated with AMOC variability can be reconstructed in the same sediment core from the Florida Straits to examine the relationship between atmospheric and ocean circulation changes across D–O events. To reconstruct surface water conditions, Mg/Ca-paleothermometry and stable isotope measurements were combined on the planktonic foraminifera *Globigerinoides ruber* (white variety) from sediment core KNR166-2 JPC26 (24°19.61′N, 83°15.14′W; 546 m depth) to reconstruct a high-resolution record of sea surface temperature and $\delta^{18}O_{seawater}$ (a proxy for upper mixed layer salinity) during Marine Isotope Stages (MIS) 2 and 3 from 20–35 ka BP. As an additional proxy for upper water column salinity change, we also generate a faunal abundance record of the salinity-sensitive planktonic foraminifera *Neogloboquadrina dutertrei*. Our results suggest that rapid reductions in sea surface salinity occurred at the onset of D–O interstadials, while stadials are characterized by increased surface salinities. The most likely cause of these salinity changes was variation in the strength and position of the ITCZ across D–O events. Finally, we examine the relationship between millennial-scale atmospheric circulation changes recorded in the planktonic records and ocean circulation changes inferred from the benthic $\delta^{18}O$ record from our core. Our results provide some of the first evidence that AMOC strength did vary across at least one of the millennial-scale D–O cycles of MIS 3.

1. Introduction

Today, heat and salt are transported from low to high latitudes in the North Atlantic via the Gulf Stream. These saline upper-waters release heat to the atmosphere as they encounter the much colder high-latitude climate and eventually become dense enough to sink and form North Atlantic Deep Water (NADW). NADW then flows south and eventually becomes part of the Circumpolar Deep Water flowing around Antarctica. This circulation, known as the Atlantic Meridional Overturning Circulation (AMOC), maintains a modern transfer of heat from the South Atlantic to the North Atlantic. It has been proposed that changes in the strength of the AMOC are responsible for abrupt climate changes observed in the North Atlantic region over the last glacial cycle. Reconstructing past changes in AMOC is therefore fundamental to understanding its relation to abrupt climate change. Most research has focused on understanding how AMOC has varied across the abrupt climate events since the Last Glacial Maximum (LGM), including Heinrich Event 1, the Younger Dryas, and the 8.2 kyr event. Both geochemical and sedimentological evidence suggest that these cold events in the North Atlantic are indeed linked to a reduction in AMOC and a cooler climate, most likely due to a reduced poleward heat flux (Alley and Clark, 1999; Boyle, 2000; Rahmstorf, 2002; Piotrowski et al., 2005; Evans and Hall, 2008; Lynch-Stieglitz et al., 2011; Bradtmiller et al., 2014).

Nevertheless, much less is known about the role of AMOC in the older, millennial-scale climate oscillations of Marine Isotope

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Stages (MIS) 2 and 3 known as Dansgaard–Oeschger (D–O) cycles (Dansgaard et al., 1993). Although the prevailing paradigm holds that rapid climate shifts associated with the extreme climate swings of the last glacial period were forced by changes in the strength and northward extension of AMOC, resulting in abrupt temperature changes recorded in the Greenland ice core records (Broecker et al., 1990; Sarnthein et al., 1995; Rahmstorf, 2002; Lohmann, 2003; Stouffer et al., 2006; Kageyama et al., 2013; Zhang et al., 2014; Barker et al., 2015), the role of AMOC as the primary driver of these millennial-scale climate events remains unclear (Jackson, 2000; Seager et al., 2002; Romanova et al., 2006; Wunsch, 2006; Skinner and Elderfield, 2007; Otto-Bliesner and Brady, 2010; Thornalley et al., 2013; Lynch-Stieglitz et al., 2014; Roberts et al., 2014).

Regardless, previous research suggests D–O events had dramatic, worldwide effects on climate (Voelker et al., 2002; Clement and Peterson, 2008). In particular, cold phases in the North Atlantic were associated with a southward shift in the Intertropical Convergence Zone (ITCZ) (Peterson and Haug, 2006; Peterson et al., 2000; Koutavas and Lynch-Stieglitz, 2004), resulting in a weakening of the Indian and East Asian Monsoon systems (Dykoski et al., 2005; Wang et al., 2001; Yuan et al., 2004) and a concomitant strengthening of the South American Monsoon (Kanner et al., 2012; Wang et al., 2007, 2008). Furthermore, it has been hypothesized that changes in tropical Atlantic evaporation/precipitation (E–P) ratios associated with a southward shift in the ITCZ have the potential to cause significant increases in tropical Atlantic surface salinity that could eventually impact surface water density and deep-water formation in the North Atlantic (Schmidt et al., 2004; Schmidt and Spero, 2011; Carlson et al., 2008).

Here, we take advantage of the fact that ITCZ shifts co-occur with D–O events to reconstruct atmospheric circulation changes in the tropical North Atlantic at our core site. North Atlantic stadial events cause a southward shift of the ITCZ and increased aridity in the tropical North Atlantic (Peterson et al., 2000; Peterson and Haug, 2006), resulting in elevated tropical North Atlantic sea surface salinity (SSS) (Dahl et al., 2005; Krebs and Timmermann, 2007a, 2007b; Lohmann, 2003; Stouffer et al., 2006; Vellinga and Wood, 2002; Zhang and Delworth, 2005; Schmidt et al., 2006). Schmidt and Lynch-Stieglitz (2011) showed that these north–south shifts in the ITCZ across the last deglacial are recorded in the Florida Straits as changes in upper water column salinity. Therefore, we extend the Schmidt and Lynch-Stieglitz (2011) records using the same sediment core and methods to reconstruct a millennial-scale record of upper water column salinity change in the Florida Straits from 20 to 35 ka BP. We combine $\delta^{18}O$ measurements and Mg/Ca ratios (a proxy for SST) in the planktonic foraminifera *Globigerinoides ruber* (white variety) from sediment core KNR166-2-26JPC (herein referred to as JPC26). Using the Mg/Ca-based SST, we then generated a record of past $\delta^{18}O_{seawater}$ ($\delta^{18}O_{SW}$) variability. Because $\delta^{18}O_{SW}$ varies linearly with SSS (Fairbanks et al., 1992), it can be used as a proxy for past SSS change, if we assume the local $\delta^{18}O_{SW}$: SSS relationship has not changed significantly over time. As an additional proxy for past changes in upper water column salinity, we also calculate the relative abundance of the upper-thermocline dwelling planktonic foraminifera *Neogloboquadrina dutertrei*, a species shown to prefer reduced salinity conditions in the Caribbean and western tropical Atlantic (Hertzberg et al., 2012; Rasmussen and Thomsen, 2012).

Finally, we investigate the timing of atmospheric and ocean circulation changes across millennial-scale climate events by comparing our new salinity records from MIS 2 and 3 with the recently published record of ocean circulation change from the same sediment core (Lynch-Stieglitz et al., 2014). These researchers used the $\delta^{18}O$ in benthic foraminifera from JPC26, along with several other benthic $\delta^{18}O$ records from both margins of the Florida Straits, to estimate past changes in geostrophic flow through the Florida Straits from the Younger Dryas to the present (Lynch-Stieglitz et al., 2009; 2011). Lynch-Stieglitz et al. (2014) argued that since changes in geostrophic flow over this time interval were reflected in changes in benthic $\delta^{18}O$ from JPC26, the changes deeper in the core most likely reflect millennial-scale changes in AMOC strength. While Lynch-Stieglitz et al. (2014) argue that benthic $\delta^{18}O$ change in JPC26 is sensitive to changes in AMOC, other processes including changes in the strength of the wind driven gyre circulation may also contribute to the observed signal. Assuming that the signal is driven predominantly by AMOC changes, we directly compare the timing of atmospheric and ocean circulation changes across our best resolved D–O event at ∼32.5 ka BP.

2. Regional setting

Sediment core JPC26 (24°19.61′N, 83°15.14′W; 546 m depth) was recovered from the Florida Straits near the Dry Tortugas (Fig. 1). The Florida Current overlaying the core site is comprised of wind-driven recirculated gyre water (∼17 Sv) and cross-equatorial flow from the South Atlantic (∼13 Sv) (Schmitz and McCartney, 1993) forming the northward flowing surface branch of the AMOC. The waters in the Florida Current are sourced from the Caribbean, the tropical Atlantic, and western tropical South Atlantic, and travel through the Yucatan Straights and the Gulf of Mexico before reaching the Florida Straits (Murphy et al., 1999; Schmitz and Richardson, 1991). Thus, the surface waters maintain physical and chemical properties that are generally characteristic of the Caribbean.

The modern average annual sea surface temperature (SST) in the Florida Straits is 27.5 °C, with a seasonal cycle that varies from a minimum of 25.0–26.0 °C from December to March and a maximum of 29.0–29.4 °C from July to September (Locarnini, 2006). Modern average annual SSS offshore of the Dry Tortugas is ∼36.1, varying from a high of 36.1 to 36.2 from January to June and decreasing to a low of 35.9 from August to December (Antonov, 2009). The shallow depth of the core (546 m), well above the carbonate compensation depth, results in fossil foraminifera that are not affected by dissolution. Although some researchers have found issues with diagenetic overgrows on benthic foraminifera from the Bahama margin of the Florida Straits (Marchitto et al., 2007), foraminifera from the Florida Margin are not affected by this issue (Schmidt and Lynch-Stieglitz, 2011).

3. Materials and methods

3.1. Stable isotope analyses

The planktonic foraminifera *G. ruber* (white variety, *sensu stricto*) was picked in JPC26 at 2 cm intervals spanning 784.25–1120.25 cm in the core. To reduce size-dependent isotope fractionation differences (Lea et al., 2000; Spero et al., 2003), *G. ruber* was picked from the 250–350 μm size fraction. 10–12 individual shells were pooled and analyzed for stable oxygen and carbon isotopes at the Georgia Institute of Technology on a GV Instruments Isoprime mass spectrometer with Multiprep or a Finnigan MAT 253 mass spectrometer with Kiel Device. Samples were sonicated in methanol for approximately 3–8 s and dried prior to isotope analysis.

3.2. Minor and trace metal analyses

Foraminiferal metal/Ca (Me/Ca) ratios were measured on the same intervals and size fraction of *G. ruber* specimens used for the stable isotope analyses. Around 580 μg of *G. ruber* shell material/sample (∼35–45 shells) were crushed, homogenized, split