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The control of the tropical North Atlantic on Holocene millennial climate oscillations

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ABSTRACT

Changes in ocean dynamics in the northern North Atlantic affect the thermohaline circulation that controls global climate. During glacial and deglaciation periods these dynamics are enhanced due to large variations in the surface ocean density caused by changes in glacier volumes. During full interglacial conditions, the dominant role of the northern North Atlantic on global climate is limited due to the reduced discharge of freshwater to the ocean, causing other regional dynamics to gain importance. Here we present a speleothem $\delta^{18}O$ record from the Iberian Peninsula that supports that the northern North Atlantic and tropical North Atlantic were both source regions of millennial climate oscillations during the Holocene. The speleothem $\delta^{18}O$ signal records millennial time-scale changes in the hydrological cycle as a result of persistent anomalies of the Gulf Stream–North Atlantic Current dynamics. In addition, the speleothem $\delta^{18}O$ record shows synchronous variability with records from the eastern Pacific region though the entire Holocene, whereas records from western Pacific region have limited or no correlation beyond periods of major instability of the northern North Atlantic. The discontinuous climate connection among the studied records is the result of different mechanisms affecting the climate system that originated in distant regions. We suggest that two regions, the tropical North Atlantic and northern North Atlantic, alternate their dominance as source regions causing millennial climate anomalies in large planetary regions. The duration of these persistent climate changes and the extension of the regions affected depend on the region triggering the anomaly because different mechanisms affecting the climate system are involved.

INTRODUCTION

Changes in ocean conditions of the high-latitude North Atlantic are known to affect global climate due to their impact on thermohaline circulation (Rahmstorf, 2002). However, millennial oscillations recorded during the Holocene in tropical regions of the eastern Pacific are related to internal variability of the tropical ocean-atmosphere system (Moy et al., 2002; Koutavas et al., 2002), and consequently independent of climate changes in the northern North Atlantic. Persistent anomalies of the ocean dynamics in the tropical North Atlantic are propagated by the Gulf Stream–North Atlantic Current out of the tropics to northern latitudes. However, ocean dynamics in the northern North Atlantic influence Gulf Stream–North Atlantic Current by transferring persistent anomalies through the subpolar and subtropical gyres. The climate of the North Atlantic, dominated by the Gulf Stream–North Atlantic Current dynamics, has great influence on the hydrological cycle of the Iberian Peninsula in western Europe (Gimeno et al., 2010). Thus, continental records from the Iberian Peninsula are ideally located to record the influence of ocean anomalies that originated in both tropical and high latitudes of the North Atlantic. Persistent changes in ocean dynamics in the tropical North Atlantic also affect the climate variability of the tropical eastern Pacific due to an atmospheric bridge (Oppo et al., 2007). In addition, the link between climate variability in the northern North Atlantic and eastern Asia is well known (Chiang and Bitz, 2005). This general picture shows how the variability of the ocean-atmospheric dynamics in the North Atlantic basin affects the climate worldwide. Here we present a well-dated speleothem $\delta^{18}O$ record from the Iberian Peninsula that shows millennial oscillations similar to those recorded in key paleoclimate records from the North Atlantic and Pacific regions. The aim of this study is to characterize the millennial oscillations of the speleothem $\delta^{18}O$ record, identify their main controls, and describe the climate mechanisms that caused them.

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RESULTS AND DISCUSSION

Kaite Cave Speleothems and $\delta^{18}O$ Record Interpretation

Kaite Cave (43°2′N, 3°39′W; 860 m above sea level) is located in the northern Iberian Peninsula. We used four speleothems from this cave to construct a record that covers most of the Holocene. A robust chronology is based on 63 U-Th dates supported by annual laminations during the early Holocene (Fig. DR1 and Table DR1 in the GSA Data Repository[1]). Time series from these speleothems contain more than 1400 oxygen and carbon stable isotope analyses (Fig. DR2). These speleothem records have a good replication, allowing the construction of a $\delta^{18}O$ composite record with an average sampling interval of 9 yr. The $\delta^{18}O$ values of the composite record were corrected for ice volume effect (Fig. DR3). The Kaite Cave $\delta^{18}O$ record shows clear oscillations at multicentennial to millennial time scales (Fig. 1). Wavelet analysis confirms the nonstationary periodicity of these oscillations (Fig. 2). During the early Holocene a significant (p value < 0.05) periodicity of ~1000 yr (from 650 to 1200 yr) dominates the frequency spectrum, whereas during the middle and late Holocene the latter is replaced by a period of ~2000 yr (from 1300 to 2600 yr). Similar nonstationary patterns of millennial climate oscillations were described

[1]GSA Data Repository item 2017089, supplemental material description and methods, Figures DR1–DR3 (speleothem records), Figure DR4 (pressure fields-ratio of recycled precipitation and $\delta^{18}O_p$ correlation maps), Figure DR5 (comparison with millennial reconstructions of NAO), Figure DR6 (climograph), Figure DR7 (moisture sources over Kaite Cave) Figures DR8 and DR9 (tuned and original chronologies of ocean records), Table DR1 (speleothem U-Th dates), Table DR2 (correlation among records), and Table DR3 (means and standard deviations of speleothem isotope values), is available online at http://www.geosociety.org/datarepository/2017/, or on request from editing@geosociety.org.

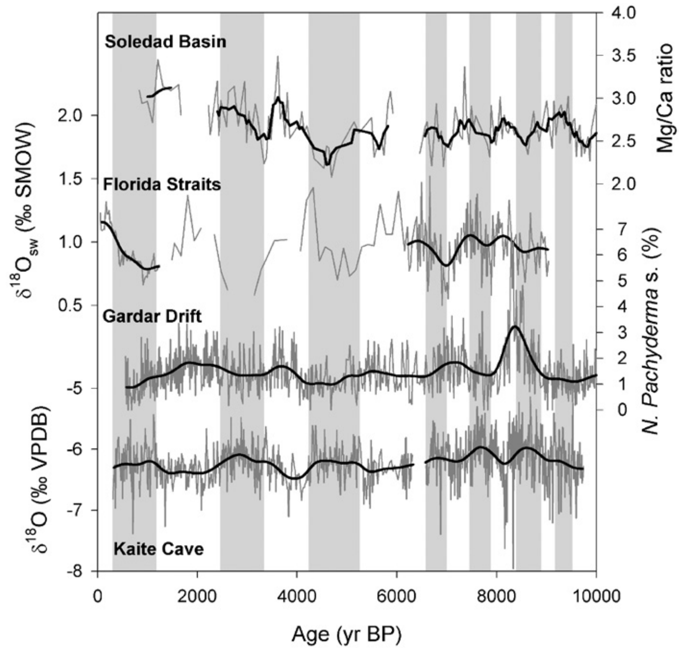

Figure 1. Comparison of the Kaite Cave (northern Iberian Peninsula) $\delta^{18}O$ record with ocean core records along the Gulf Stream–North Atlantic Current. Millennial oscillations of the 3 time series are highlighted by a Gaussian smoothing curve of 1450 yr (bold lines). Vertical gray boxes indicate periods with less negative $\delta^{18}O$ values in the Kaite record resulting from reduced recycling over the Iberian Peninsula, warmer temperature over the subpolar site of Gardar Drift indicated by the reduction of the foraminifera *Neogloboquadrina pachyderma* (s.), and attenuated trade winds over Florida Straits causing less positive sea-surface $\delta^{18}O$ composition ($\delta^{18}O_{sw}$) as a result of southward migration of the Inter Tropical Convergence Zone. Age models of ocean records were tuned within radiocarbon and reservoir effect uncertainties. Comparison with original chronologies is provided in Figure DR9 (see footnote 1). VPDB—Vienna Peedee belemnite; SMOW—standard mean ocean water.

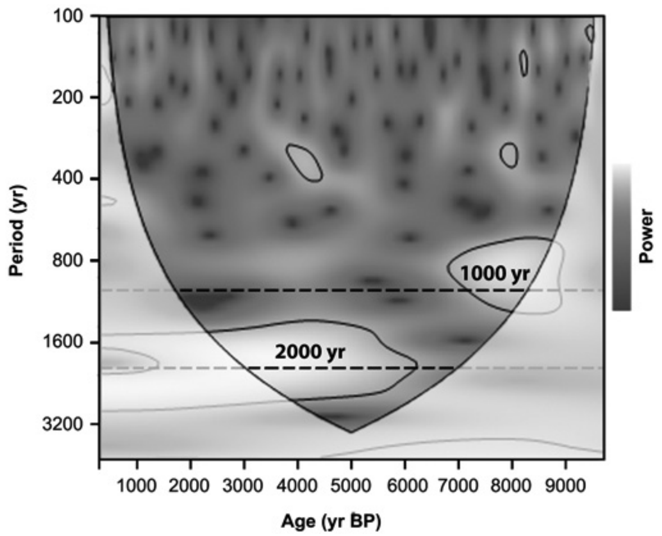

Figure 2. Wavelet analysis of $\delta^{18}O$ record from Kaite Cave (northern Iberian Peninsula). The confidence level at 95% is depicted with black lines, and areas beyond the cone of influence are shaded. Note that the pacing of millennial oscillations changes between the early and middle Holocene. Periods at 1000 and 2000 yr are indicated by discontinuous horizontal lines.

for numerous paleoclimate records around the globe (Debret et al., 2009; Fletcher et al., 2013).

The $\delta^{18}O$ signal from Kaite Cave speleothems records the interannual variability of the $\delta^{18}O$ composition of precipitation ($\delta^{18}O_p$) over the cave (Domínguez-Villar et al., 2008), and therefore the speleothem $\delta^{18}O$ signal records changes in the hydrological cycle. The amount of precipitation does not control the record of $\delta^{18}O$ variability beyond decadal time scales (Domínguez-Villar et al., 2009), and changes in precipitation moisture sources can dominate the low-frequency variability. The ratio of regional recycled precipitation (i.e., the proportion of the total precipitation that originates within the Iberian Peninsula, according to the modeled moisture sources, in relation to all other sources) is the most significant moisture source affecting the $\delta^{18}O_p$ from the Iberian Peninsula (Krklec and Domínguez-Villar, 2014). Therefore, we hypothesize that the ratio of recycled precipitation in the Iberian Peninsula is the dominant control on the millennial oscillations in the Kaite Cave $\delta^{18}O$ record (see the Data Repository for further details).

We found significant correlations between pressure fields over the North Atlantic and the ratio of recycled precipitation in the Iberian Peninsula on a monthly time scale (Fig. DR4). The mechanism that justifies this connection in the Iberian Peninsula is the variable role of local and mesoscale convective systems (Rios-Entenza et al., 2014). Significant correlation is also found between pressure fields and $\delta^{18}O_p$, establishing a link between $\delta^{18}O_p$ and atmospheric dynamics in the North Atlantic (Fig. DR4). The spatial distribution of areas significantly correlated describes an east-west dipole over the North Atlantic, with a pole around Newfoundland and the other pole around Scotia. This dipole differs notably from the north-south dipole associated with the North Atlantic Oscillation (NAO) and likely represents additional variability of pressure fields in the North Atlantic not captured by the NAO index (Wang et al., 2012). The zonal displacement of the pressure cells in the North Atlantic is responsible for the nonstationary relationship between precipitation and the NAO index (Vicente-Serrano and López-Moreno, 2008), supporting the relevance of these east-west displacements of the pressure cells to properly characterize the variability of the pressure fields in the North Atlantic affecting the climate system. In agreement with these observations, the $\delta^{18}O$ record from Kaite Cave shows no similarity with millennial reconstructions of the NAO (Fig. DR5). Therefore, the correlation between pressure fields in the North Atlantic and the $\delta^{18}O_p$/recycled precipitation ratio in the Iberian Peninsula establish a link between the climate system and our speleothem record not related to the NAO index. We therefore interpret the millennial $\delta^{18}O$ anomalies in Kaite Cave as a proxy of zonal displacement of the pressure fields over the North Atlantic (e.g., westward shift of the pressure fields relates to less negative $\delta^{18}O$ values).

Comparison with North Atlantic Paleoclimate Records

Several ocean records along the Gulf Stream–North Atlantic Current show persistent millennial oscillations similar to those found in the Kaite Cave $\delta^{18}O$ record (Ellison et al., 2006; Lund and Curry, 2006; Schmidt et al., 2012). In Figure 1, we compare the cave $\delta^{18}O$ record with ocean core records from the Florida Straits, south of Florida (USA), and Gardar Drift, south of Iceland. The variability of the reconstructed $\delta^{18}O$ composition of seawater ($\delta^{18}O_{sw}$) in the Straits of Florida is related to the evaporation/precipitation ratio at the surface of the ocean that is controlled by the strength and latitudinal position of the trade winds (Lund and Curry, 2006; Schmidt et al., 2012). At Gardar Drift, the relative abundance of the foraminifera *Neogloboquadrina pachyderma* (s.), typical of polar regions, responds to variations in the sea-surface temperature (SST) (Ellison et al., 2006). We found that both ocean records are statistically correlated with our cave $\delta^{18}O$ record (Table DR2). Every millennial Kaite Cave $\delta^{18}O$ anomaly is found in both ocean core records, and the mechanism linking the climate of these regions is well known. The atmospheric dynamics over the tropical North Atlantic affect the salinity of the ocean in the Florida

Straits (Lund and Curry, 2006; Schmidt et al., 2012). This anomaly is transferred to higher latitudes by the Gulf Stream–North Atlantic Current and affects the position of the subpolar front (Joyce et al., 2000) affecting the SST at Gardar Drift (Ellison et al., 2006). Pressure fields in the North Atlantic are controlled by SST in the region (Joyce et al., 2000), which eventually influences the percentage of recycled precipitation and the $\delta^{18}O_p$ in the Iberian Peninsula, in turn affecting continental archives such as Kaite speleothems.

Comparison with Pacific Paleoclimate Records

In the western offshore of Baja California (Mexico), the Soledad Basin is located in the subtropical eastern Pacific, and variations of its SST depend on the El Niño–Southern Oscillation (ENSO) (Marchitto et al., 2010). Persistent anomalies of ocean dynamics in the Florida Straits during the early Holocene are synchronous with SST changes in the Soledad Basin (Schmidt et al., 2012). The Kaite Cave $\delta^{18}O$ record for this period has a significant correlation with the Soledad Basin record (Fig. 3; Table DR2). This is not surprising, because the impact of the ENSO system on climate is recorded beyond tropical regions, including the Iberian Peninsula (López-Parages and Rodríguez-Fonseca, 2012). During the middle and late Holocene El Niño events become more frequent. At this time, Laguna Pallcacocha, in Ecuador, records millennial-scale oscillations related to ENSO (Moy et al., 2002) synchronous with those recorded in the Kaite Cave $\delta^{18}O$ record. Thus, persistent ocean anomalies that affected the Gulf Stream-North Atlantic Current were also synchronous with changes in tropical and subtropical waters from the eastern Pacific later in the Holocene. The mechanism responsible for transferring tropical North Atlantic variability to the Pacific basin across Central America is an atmospheric bridge (Oppo et al., 2007).

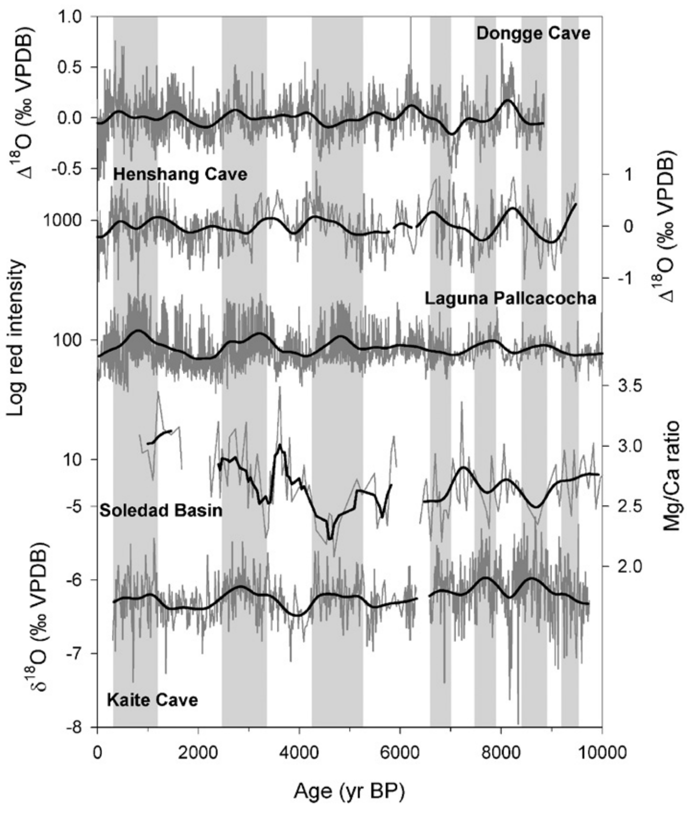

Figure 3. Comparison of the Kaite Cave (northern Iberian Peninsula) $\delta^{18}O$ record with paleoclimate records from the Pacific region. Millennial oscillations of the 3 time series are highlighted by a Gaussian smoothing curve of 1450 yr (bold lines). Vertical gray boxes are described in Figure 1. Mg/Ca in the Soledad Basin has a direct relationship with sea-surface temperature (SST). The intensity of the red color in the sediments of Laguna Pallcacocha (vertical axis of the graph) results from erosive episodes in its basin triggered by El Niño events. The $\delta^{18}O$ proxy from Henshang and Dongge Caves represents changes in the hydrological cycle affecting the East Asian monsoon. The age model of the ocean record was tuned within radiocarbon and reservoir effect uncertainties. Comparison with original chronologies is provided in Figure DR9 (see footnote 1). VPDB—Vienna Peedee belemnite.

During the early Holocene, the millennial oscillations of the hydrological cycle recorded in the $\delta^{18}O$ signal of Chinese speleothems (Wang et al., 2005; Hu et al., 2008) are highly correlated with records from the Soledad Basin, Laguna Pallcacocha, and the North Atlantic sites discussed here (Table DR2). The common forcing that linked the synchronous climate changes of all these sites weakened its influence after 7500 yr B.P., resulting in the variability of eastern Asian records being independent or recording a limited impact from the dynamics on the North Atlantic. Chinese speleothems have shown a clear response to changes in the northern North Atlantic (Wang et al., 2005). The mechanism of this teleconnection is the persistent change in sea-ice cover over the high latitudes of the Northern Hemisphere that affects the regional atmosphere temperature, and progressively the Pacific SST from northern to tropical latitudes, until it affects the atmospheric dynamics of the Inter Tropical Convergence Zone, and consequently the monsoon in East Asia (Chiang and Bitz, 2005). Sea-ice cover conditions similar to modern conditions were established between 8000 and 7000 yr B.P. (Fahl and Stein, 2012), causing other controls of the East Asian monsoon to dominate its variability. Thus, although continents at both sides of the Pacific are influenced by ENSO, the hydrological cycle of the western Pacific has little response to persistent anomalies in North Atlantic records unless major modifications of sea-ice cover in the northern North Atlantic are involved.

Source Regions of Climate Variability

Persistent and major sea-surface salinity changes caused by sea-ice or glacier melting in the northern North Atlantic affect the tropical North Atlantic by the transfer of these ocean anomalies throughout the subpolar and subtropical gyres. During the Holocene, this mechanism affected the SST variability in locations offshore from western Europe (Bond et al., 2001; Cacho et al., 2001) and western Africa (deMenocal et al., 2000) and finally the ocean dynamics in the Straits of Florida (Schmidt et al., 2012). However, the SST of the subpolar North Atlantic is also affected by the potential vorticity of the Gulf Stream–North Atlantic Current that has a coupled ocean-atmosphere response (Joyce et al., 2000), and depends greatly on the ocean dynamics in the tropical North Atlantic (Lund et al., 2006). During the Holocene, this alternative mechanism transferred the persistent anomalies from the tropical North Atlantic to the subtropical and subpolar North Atlantic (Lund and Curry, 2006; Schmidt et al., 2012). Thus, records affected by the variability of the Gulf Stream–North Atlantic Current show significant correlations at millennial time scales independent of the source region and the mechanism that caused the anomaly. The millennial oscillations that originated in the northern North Atlantic are characterized by a periodicity of ~1000 yr, and the triggering factor has been related to insolation variability (Marchitto et al., 2010; Schmidt et al., 2012). However, the drastic weakening or disconnection of millennial climate anomalies between eastern Asia and the North Atlantic and east Pacific regions supports a decreased impact of the ocean dynamics on the high latitudes of the North Atlantic in the global climate system (Debret et al., 2009). Millennial climate changes during the middle and late Holocene have a periodicity of ~2000 yr. The triggering factor of these persistent anomalies is related to the internal dynamics of the coupled ocean-atmospheric system in the tropics instead of insolation variability (Moy et al., 2002; Koutavas et al., 2002). Thus, the change in frequency of the millennial oscillations through the Holocene results from two different triggers of climate anomalies (Debret et al., 2009; Fletcher et al., 2013).

CONCLUSIONS

We propose that millennial climate oscillations recorded during the Holocene along wide regions of the globe are triggered by persistent climate anomalies that originated in two alternative source regions, the northern North Atlantic and the tropical North Atlantic. During the early Holocene, persistent anomalies in the northern North Atlantic dominated the millennial climate variability, while the glaciers and sea-ice cover of this region had large volumetric changes controlled by insolation variability. Thus, the periodicity of millennial oscillations during this period was ~1000 yr, in agreement with insolation spectra (Marchitto et al., 2010). However, after deglaciation was completed, the northern North Atlantic reduced its control on the global climate, and the tropical North Atlantic, the variability of which depends on the ocean-atmosphere dynamics in the tropics, dominated the millennial climate oscillations during the middle and late Holocene with a periodicity of ~2000 yr. The extension of the teleconnections that originated from these two alternative climate mechanisms differs, with the common variability affecting eastern Asia only when climate changes are triggered by persistent anomalies in the northern North Atlantic. Thus, we suggest that the frequency change of the millennial oscillations after the early Holocene resulted from these different mechanisms governing climate variability; this implies that there were alternative source regions affecting the climate system. Therefore, persistent anomalies that originate in the tropical North Atlantic, and not only in the northern North Atlantic, cause millennial oscillations of the climate system in wide regions of the planet.

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