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Evidence for 800 years of North Atlantic multi-decadal variability from a Puerto Rican speleothem

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ABSTRACT

The long-term behavior of the tropical Atlantic ocean/atmospheric system prior to the 20th century is not well characterized due to a lack of high-resolution proxy records to extend the short instrumental record. Here we present the first reconstruction of rainfall variability for the western tropical Atlantic that spans the past 8 centuries and is derived from the $\delta^{18}O$ of speleothem calcite. The $\delta^{18}O$ of speleothem calcite at this Puerto Rican location varies primarily in response to changes in the amount of summer-time precipitation. The speleothem documents multi-decadal to centennial length oscillations in $\delta^{18}O$ that point to large variations in rainfall that have not been manifest in the short instrumental period. Since AD 1850, variations in $\delta^{18}O$ have tracked shifts in the Atlantic Multidecadal Oscillation (AMO). We tentatively suggest that the speleothem $\delta^{18}O$-based rainfall record from Puerto Rico extends the history of the AMO to the 12th century.

1. Introduction

The tropical North Atlantic exhibits climatically complex ocean/atmosphere interactions that include local processes and localized responses to climate variability centered outside of the Caribbean itself (Chiang et al., 2002; Czaja et al., 2002; Xie and Carton, 2004). The trade winds modulate the seasonal cross-equatorial sea surface temperature (SST) gradient and influence the location and the intensity of the Atlantic Intertropical Convergence Zone (ITCZ). The tropical Atlantic SSTs vary in response to forcing centered in the tropical Pacific (El Niño/Southern Oscillation (ENSO) phenomenon), the North Atlantic (North Atlantic Oscillation), NAO, as well as from, the Atlantic Multi-decadal Oscillation (AMO, Knight et al., 2006). The AMO is a term coined by Kerr (2000) to refer to the spatially coherent, slow (multidecadal) variation of North Atlantic SSTs. An early description of this pattern of SST variability appears in Folland et al. (1986) in connection with the publication of their comprehensive atlas of global SST variability and their interest in the causes of the 1970s drought in the Sahel region. Kushnir (1994) examined the relationship between the SST pattern and atmospheric circulation variability and showed that it is different than the ocean–atmosphere relationship associated with interannual variability in the North Atlantic Basin. Schlesinger and Ramankutty (1994) argued for an influence of the AMO on Northern Hemisphere temperatures. The latter study also showed that as far as can be discerned from the relatively short observational record, the AMO “oscillates” with a period of ~70 years and amplitude of 0.4 °C. Later, Enfield and Mestas-Nuñez (1999) showed that the AMO emerges as the first rotated EOF of non-ENSO global SST. Coupled ocean–atmosphere model experiments reproduce multidecadal climate modes with patterns similar to that of the AMO (Delworth et al., 1993; Delworth and Mann, 2000; Knight et al., 2006; Timmermann et al., 1998), which suggests that it can arise from internal ocean dynamics. The AMO related ocean–atmosphere pattern suggested that ocean dynamics are primarily responsible for the SST changes, a hypothesis that was supported at that time by the modeling study of Delworth et al. (1993) in which oscillations with an ~50 year

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period in the AMOC was investigated. Different physical mechanisms have been suggested to explain their existence. Most involve variations of the large scale AMOC and its poleward oceanic heat transport.

The AMO can have an influence on hydroclimates throughout Atlantic Basin (Enfield et al., 2001; Folland et al., 1986; Folland et al., 2001; Goldenberg et al., 2001; Knight et al., 2006; Kushnir et al., 2010; Seager et al., 2009; Sutton and Hodson 2007; Zhang and Delworth, 2005; Zhang and Delworth 2006). It is this coupling between the AMO and hydroclimate variability in the western tropical Pacific that prompted the current investigation to evaluate whether the AMO-style variability has been a persistent behavior prior to the short instrumental period.

Paleoclimate reconstructions of the AMO are few. Gray et al. (2004) reconstructed a history of the AMO since 1567 AD from tree ring records from the North Atlantic. Their reconstructed SSTs suggest that the AMO is indeed an inherent pattern of natural recurrent variability within the Atlantic and that it can exhibit a broad range of periods of oscillation. Denton and Broecker (2008) suggested that the history of the AMO during the past few millennia could be traced from observing the advance and retreat of glaciers in the Swiss Alps. These paleo-reconstructions suggest that the low-frequency SST pattern is not a signature of a true "oscillation" and should better be referred to as the Atlantic Multidecadal Variability (AMV).

Notwithstanding evidence for an AMO-style pattern of variability within the North Atlantic, there has been a debate about the stationarity of an AMO influence on tropical Atlantic temperatures beyond the past century. Goldenberg et al. (2001) argued for persistence of a multi-decadal SST variability that was attributed to the AMO. On the other hand, Mann and Emanuel (2006) suggested that anthropogenic forcing from greenhouse gasses and aerosols has been partly responsible for the observed multi-decadal pattern of SST change in the tropical Atlantic. This may imply that an AMO-mode of variability may not have been a primary mode of variability prior to the 20th century. However, Ting et al. (2009) as well as Knight (2009) argue that the AMO signal is discernible in the tropical Atlantic separately from anthropogenic forcing and more prominently in the early 20th century (1930s) than in recent decades.

Even less certain is whether the AMO persisted over entire late Holocene. Based on a relatively high-resolution record of SSTs derived from a sediment core from the Sargasso Sea, Keigwin (1996) argued that North Atlantic SST warming and cooling (respectively) occur during the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). Denton and Broecker (2008) presented a similar argument, based on numerous lines of evidence (sea ice extent, alpine glacier, ocean sediment, radio carbon) from the North Atlantic, Europe and North America. Clearly, a reconstruction of the AMO over several centuries would contribute greatly to our understanding of its characteristics and impact. Because instrumental observations show only two full cycles of the AMO, extending the AMO record further back in time would help to determine its low frequency characteristics.

Set in the northern Caribbean, the island of Puerto Rico is well situated for reconstructions of western tropical Atlantic hydroclimate variability in response to SST variability that may arise from an AMO influence (Kilbourne et al., 2008). This is because SSTs in this region correlate with regional SST variability, which are in turn associated with hemispheric-scale temperature variability at the centers of action summarized above.

On a seasonal time scale, changes in western tropical Atlantic SSTs influence rainfall across the region and this influence can extend to landmasses from tropical South America to Central America and as far as West Africa (Bell and Chelliah, 2006; Enfield 1996; Giannini et al., 2001; Sutton and Hodson, 2007; Vimont and Kossin, 2007). Moreover, tropical Atlantic hydrologic variability affects the conveyance of moisture from the Atlantic basin to the Pacific basin, which is a key factor in the thermohaline circulation (Lohmann and Lorenz, 2000; Zaucker and Broecker, 1992). Variations in water vapor transport can be triggered by Atlantic and Pacific SST anomalies and affect the surface salinity budget of the Atlantic and may be linked to changes in the AMOC (Latif et al., 2000; Schmittner et al., 2000). The tropical North Atlantic region itself is one of the locations where climate models project large future changes in the hydrological cycle, displaying a significant drying over the Caribbean area and Central America (Neelin et al., 2006). Also projected is a possible increase in tropical Atlantic storm intensity as the climate warms (Emanuel, 2005; Knutson et al., 2010). A better understanding of the natural modes of tropical Atlantic climate variability on various time scales is a key to efforts to derive more accurate predictions of how the region's climate will change in response to added radiative forcing. Our understanding of long-term natural climate variability within the tropical Atlantic and in the region surrounding Puerto Rico has been hampered by an inadequate database of well-dated tropical climate records, particularly for the period prior to the 17th century (Jansen et al., 2007). Here we present $\delta^{18}O$ data derived from speleothem calcite that was collected from a deep cave located in central Puerto Rico. The $\delta^{18}O$ of speleothem calcite at this location is primarily controlled by changes in the isotopic variability of rainwater. The oxygen isotope composition of rain water varies in response to changes in both sea surface and atmospheric temperature variability, which govern the isotopic fractionations between liquid and vapor water. These influences are superseded over Puerto Rico however, by the larger isotope fractionation that accompanies the distillation of rainwater from clouds, the so-called rainfall 'amount effect' (e.g. Bowen and Revenaugh, 2003) (Fig. 2). The $\delta^{18}O$ of speleothem calcite precipitated at constant temperature deep within the cave is a sensitive recorder of varying rainfall amount that accumulated in the overlying aquifer in Puerto Rico. We present a speleothem $\delta^{18}O$ record from Puerto Rico spanning the past 8 centuries that exhibits a recurrent pattern of multi-decadal to centennial scale variability that is interpreted to reflect shifts in amount of rainfall.

2. Materials and methods

In June 2006, we collected a speleothem from Perdida Cave (Fig. 1), in an isolated forest west of the town of Utuado (18°N, 67°W) in central Puerto Rico. The cave has formed in karst on the Oligocene limestone of the Lares Formation at 350–400 m a.s.l. (Miller, 2009). The sampling site was a chamber 360 m from the nearest entrance and 50 m below the surface, at the end of a series of restrictions and cul-de-sacs that limit human visitors, temperature variation, and air exchange. The cave is located in a local groundwater system, and the chamber lies well above the level of modern floods, which eliminates inaccuracies in dating due to possible initial detrital ^{230}Th. The stalagmite chosen for the present study, PDR-1, (Fig. 1) was active and growing at the time of collection, and was columnar to ensure it was a product of a single drip source. A data logger was placed in the chamber to monitor temperature and humidity for a period of 4 months (June–September).

The temperature within the chamber remained constant over the monitoring period at 22 °C. Humidity remained 100% over the monitoring period, likely stabilized by active drips throughout the isolated chamber. A glass plate was also placed at the collection site of the PDR-1 speleothem, beneath the active drip and left in place between June and October of 2006. After retrieval the calcite precipitated on the glass plate was removed for oxygen isotopic analysis.

PDR-1 was sawn lengthwise along its axis; the top layer we estimate to be 2005 AD, the year prior to collection. Samples were obtained from a polished slab section of the PDR-1 speleothem for ^{230}Th dating. Samples used for ^{230}Th dating were collected with a hand-held dental drill. We obtained seven ^{230}Th dates, all in stratigraphic order, with a magnetic sector inductively-coupled plasma mass spectrometer at the University of Minnesota, Isotope Laboratory. Chemical separation procedures followed those described in Edwards et al. (1987). We