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Ocean-atmosphere interactions as drivers of mid-to-late Holocene rapid climate changes: Evidence from high-resolution stalagmite records at DeSoto Caverns, Southeast USA

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ABSTRACT

Oxygen and carbon isotope time-series derived from an actively growing aragonitic stalagmite in DeSoto Caverns exhibit with unusual clarity rapid hydroclimate changes in the mid-to-late Holocene. Data consist of 1884 $\delta^{18}O$ and $\delta^{13}C$ determinations whose chronology is anchored on 35 $^{230}Th/^{234}U$ absolute dates in the interval 6.0–1.1 cal ka BP. Exceptional ^{18}O and ^{13}C-enrichments centered at 4.8 ± 0.14 cal ka BP likely represent the imprints of a severe drought. Isotope cycles from 4.7 to 1.3 cal ka BP, exhibit a dominant periodicity of 68 ± 4 yrs. A gradual cooling trend of ~0.6 °C/10^3 yrs is attributed to a declining seasonal contrast in insolation. The synchronicity of the mega-drought in the Southeast US with the (1) termination of the African Humid Period; (ii) abrupt reduction of the North Atlantic Deep Water production, and (iii) rapid sea-ice expansion in the polar regions of both Hemispheres testifies to the global extent and rapidity of the "5 ka" event and points to the North Atlantic Deep Water variability as the likely controlling factor. The multidecadal cycles are consistent with alternating dry and wet summers occurring during a long-term switch in the seasonal rainfall amount dominance from winter to summer. The periodic summer droughts in the Southeast US support climate models that predict profound hydroclimate changes in the late Holocene governed by the Atlantic Multidecadal Oscillation. The relatively short and rapid hydroclimate phase transitions documented in this study introduce a complication in the correlation of late Holocene drought events that had significant societal impacts.

1. Introduction

Whereas the climate of the mid-to-late Holocene appears relatively stable when viewed in the context of the large, rapid swings of the last deglaciation, a number of significant abrupt hydroclimate events have been documented in the time interval between 5 ka (1 ka = 1000 yrs) to present. The most dramatic and most intriguing abrupt climate events are two that occurred at or near the mid-Holocene. The first, named the "5 ka" event, occurred at the transition from the relatively warm Hypsithermal to the relatively cool Neoglacial (H/N transition) and its extent is considered global (Davis and Thompson, 2006; Hodell et al., 2001; Keigwin, 1996; Thompson et al., 2006). The other occurred during the early part of the late Holocene, the "4.2 ka" event but its global extent, expression and whether it represents a single or multiple events are subject to debate (Booth et al., 2005; Finné et al., 2011).

Two aspects of the prominent 5 ka and 4.2 ka climate shifts are particularly controversial: (i) their timing and duration, and (ii) the controlling factors of the hydroclimate shifts (Arz et al., 2006; Bar-Matthews and Ayalon, 2011; Booth et al., 2005; Cullen et al., 2000; Davis and Thompson, 2006; Dixit et al., 2014; Drysdale et al., 2006; Yang et al., 2015).

The precise timing and duration of the 5 ka and 4.2 ka events are equivocal because most dates are either based on the radiocarbon time scale using reservoir corrections with large uncertainties (Arz et al., 2006; Cullen et al., 2000; Dixit et al., 2014; Russell and Johnson, 2005) and/or questionable correlations (Gasse, 2000). Exceptional are speleothem archives from caves in Corchia, Italy (Drysdale et al., 2006), Soreq, Israel (Bar-Matthews and Ayalon, 2011), and Mawmluh, Northeast India (Berkelhammer et al., 2012) whose age models were derived from absolute U/Th dates.

The factors controlling multi-centuries climate variability at sub-Milankovitch timescales are poorly constrained (Wanner et al., 2008). A number of studies proposed solar variability as a possible

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forcing mechanism (Bond et al., 2001; Wanner et al., 2008) while others implicate the Atlantic Multidecadal Oscillation (AMO; Knudsen et al., 2011), a northward shift of the Westerlies (Zanchetta et al., 2014), or El-Niño-Southern Oscillation (ENSO) variability (Booth et al., 2005; Donders et al., 2005).

Here we report the results of a stalagmite investigation (DSSG-5) from DeSoto Caverns in the Inner Gulf Coast (IGC), Southeast US (SEUS) (Fig. 1 A) spanning the time interval from 6.0 to 1.1 cal ka BP (calendar kilo-anum Before Present, where present is 1950 CE). The stalagmite, whose chronology is anchored on 35 precise ^{230}Th/^{234}U absolute dates, yields stable oxygen and carbon isotope time-series at interannual resolution of 2–8 yrs that exhibit with unusual clarity the climate changes that occurred during mid-to-late Holocene. The geographic location of the cave in the IGC offers unusual opportunities to study hydroclimate variability around the mid-to-late Holocene time interval for the following reasons: (i) it is located at the southern limit of the winter polar jet-stream; (ii) it receives moisture predominantly from the Gulf of Mexico (GoM) that occupies a central position in the Atlantic Warm Pool (AWP), the second largest oceanic warm pool on Earth (Wang and Enfield, 2001); (iii) GoM is a significant source of moisture fueling the North American rainfall at present and its moisture-controlling role likely extended back in the Holocene and beyond, and (iv) global atmospheric circulation patterns, such as ENSO and the Bermuda High (BH), govern the interannual δ^{18}O isotope trends discerned in the water cycle compartments (Lambert and Aharon, 2010). This study provides detailed climate proxy records whose chronology is well constrained, and assesses the dominant drivers of climate variability in mid-to-late Holocene in the SEUS where high-resolution continental paleo-climate records, such as those from speleothems, are notably lacking.

2. Study site and regional climate

DeSoto Caverns (86°16′36″ W, 33°18′26″ N) is located on the outskirts of Childersburg, AL in the IGC and is separated from its major moisture source in the GoM by 365 km of low elevation coastal plains (Fig. 1, inset). Details of the cave geomorphology can be found in Lambert and Aharon (2010, 2011) and will not be repeated here. Pristine fossil and active speleothems within the cave consist primarily of metastable aragonite (Lambert and Aharon, 2010, 2011).

The study area experiences a mean annual air temperature of 17.2 °C and an average annual rainfall total of 1338 ± 70 mm (1σ Standard Error of the Mean (SEM), n = 10) based on our rainfall gauge data over the period 2005–2015 (Table 1). The question of seasonality will turn to be important in the proxy climate data interpretation and therefore warrants further attention.

Present climate is typified by a moderate seasonality with average monthly air temperatures ranging from ~7 °C in January to ~27 °C in July while average monthly rainfall ranges from ~80 mm in October to ~150 mm in March (Lambert and Aharon, 2010). The fraction of winter precipitation is greater than the summer precipitation (fw > fs) by a factor of 1.3 (fw = 0.56 ± 0.08; fs = 0.44 ± 0.08, 1σ SEM, n = 10).

Rainfall occurs throughout the year by two distinct modes. In winter, the collision of opposing cold and warm air masses often results in rain-producing storm systems that are carried west to east by the polar jet-stream (Baigorria et al., 2007). In contrast, summer rainfall is typically derived by convection-style thunderstorms whose frequency is impacted by the east-west position of the BH pressure cell (Li et al., 2011). Ten years (2005–2015) of weekly rainfall isotope measurements (Table 1) yield a seasonal δ^{18}O contrast of 1.1‰ (based on weighted monthly means) between a mean winter rainfall value of −5.1 ± 0.3 (‰ V-SMOW) and a mean summer rainfall value of −4.0 ± 0.2 (‰ V-SMOW) (1σ SEM, n = 10). Exceptional are rainfalls associated with tropical storms that yield anomalous ^{18}O-depletions down to −8.3‰ (e.g., five severe tropical storms encountered in the summer of 2005) and interannual ^{18}O-enrichment trends of up to 1‰ associated with regional droughts (e.g., drought of 2006–2007; Lambert and Aharon, 2010).

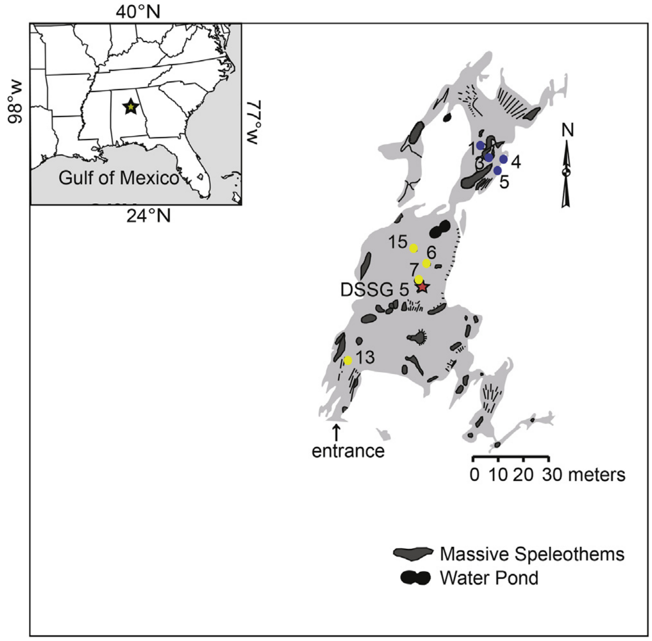

Fig. 1. Inset: Map of the Southeast US (SEUS) and the Inner Gulf Coast (IGC) showing the location of DeSoto Caverns (solid star). Plan-view map of DeSoto Caverns (modified from Lambert and Aharon, 2010) showing the location of the DSSG-5 stalagmite (red star) in the front chamber of the cave. Blue dots mark the location of drips studied by Lambert and Aharon (2010, 2011) in the back chamber of the cave. Yellow dots mark the location of drips in the front chamber whose isotope chemistry is discussed in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Monthly monitoring of DeSoto Caverns air parameters (i.e., temperature, humidity), dripwater flow-rates, stable isotopes and elemental chemistry occurred during two time intervals. Five dripwater sites were monitored in the back-chamber of the cave (Fig. 1, cave map) over a three-year period (2005–2008) with the results being reported by Lambert and Aharon (2010, 2011). Four dripwater sites were subsequently monitored in this study over a two-year period (2012–2013) in the cave front-chamber above and immediately adjacent to the DSSG-5 stalagmite (Fig. 1, cave map). The complete results of the second monitoring phase are the subject of a separate manuscript (in prep.) and only measurements relevant to this study are summarized in Table 1.

3. Methods

An actively growing stalagmite, located in the center of the cave front-chamber, was cored along the growth axis (core dimensions: 75 cm long, 4 cm diameter) without causing permanent damage to the whole formation (DSSG-5, Fig. 2 A). The uppermost 40 mm of the stalagmite contains several hiatuses reported by Aharon et al. (2012) and therefore the paleoclimate reconstruction in this study focuses on the stalagmite interval below 40 mm. X-ray diffraction analysis coupled with petrographic observations (see later) reveal that the DSSG-5 stalagmite consists predominantly of aragonite. Its dominance is attributed to the relative high Mg^{2+} concentrations in the drips (Mg/Ca >1.1 mol/mol) exceeding the