Holocene hydroclimate in the Southeastern United States during abrupt climate events: evidence from new speleothem isotopic records from Alabama


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Abstract

We present new high-resolution absolute-dated stalagmite δ18O and δ13C records from Alabama, southeastern United States (SE US), spanning the last 12 thousand years (ka). A local relationship between annual rainfall amount and its amount-weighed δ18O composition exists on interannual timescales, driven mostly by an amount effect during summer and spring seasons, and by an isotopically depleted composition of fall and winter precipitation. Based on a novel interpretation of modern rainfall isotopic data, stalagmite δ18O variability is interpreted to reflect the relative contribution of summer and spring precipitation combined relative to combined fall and winter precipitation. Precipitation amount in the SE US increases during the Younger Dryas, the 8.2 ka and Little Ice Age abrupt cooling events. High precipitation during these events reflects enhancement of spring and summer precipitation while the contribution of fall and winter rainfall remained unchanged or decreased slightly. Results from this study support model simulation results that suggest increased precipitation in the SE US during Atlantic Meridional Overturning Circulation (AMOC) slowdown/shutdown (LeGrande et al., 2006; Renssen et al., 2002; Vellinga and Wood, 2002). In association with Northern Hemisphere mid-latitude cooling
from the Early to mid-Holocene, annual precipitation in the SE US decreases, a pattern distinctive from that observed during abrupt cooling events related to AMOC shifts. Long-term hydroclimate change in the SE US is likely sensitive to summer insolation reduction as inferred for other tropical and subtropical regions. This study has implications for our understanding of the sensitivity of subtropical hydroclimate to factors both internal and external to the climate system in a warmer climate.

1. Introduction

The evolution of human societies and ecosystems are intimately related to the degree of climate stability over time at a regional scale (IPBES, 2019; Ipcc, 2014). The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) estimates that within the next three decades 1 million species are threatened with extinction, and it highlights temperature and hydroclimate change as chief driving factors (IPBES, 2019). Large uncertainty remains, however, regarding our understanding of past hydroclimate variability and its underlying drivers, and therefore also, in our capacity to predict the future. Considerable disagreement among state-of-the-art climate model predictions of precipitation for the end of this century underlines the need to better understand the drivers of hydroclimate variability to help improve the climate forecast (Anandhi and Bentley, 2018).

A potential driver of abrupt hydroclimate change relates to climate reorganizations associated with slowdown or complete shutdown of the Atlantic Meridional Overturning Circulation (AMOC). This circulation system is thought to be a key tipping point of the Earth’s climate system and seems to already be responding to increasing anthropogenic climate forcings (Collins et al., 2019). The potential impacts of AMOC shifts on Northern Hemisphere hydroclimate remain unclear, however. The historical hydroclimate record remains too short and
fragmented to help validate long-term climate model simulations. Thus, model studies rely on
the few existing paleoclimate records to assess their performance simulating climate change
triggered by abrupt ocean circulation changes (Dahl et al., 2005; Otto-Bliesner and Brady, 2010;
Vellinga and Wood, 2002).

Hydroclimate variability in the Southeastern United States (SE US) over the Holocene
remains poorly understood and model predictions for the end of this century are highly variable,
ranging from regional changes of -30 to +35% (Anandhi and Bentley, 2018). The possibility that
SE US hydroclimate could respond to abrupt climate change resulting from AMOC shifts exists
but remains to be examined with empirical observations.

The YD (12.8-11.8 ka) (Rasmussen et al., 2006), the 8.2 ka (Thomas et al., 2007) and the
Little Ice Age (LIA, C.E. 1400-1900) (Matthes, 1939) cooling events are hypothesized to be in
association with AMOC slowdown/shutdown (Broecker et al., 1989), and they provide a testbed
to examine subtropical hydroclimate responses to ocean thermohaline circulation shifts.
Paleoclimate and model results support the hypothesis that thermohaline circulation changes
triggered the YD and 8.2 ka cooling events (Bard et al., 2000; Lea et al., 2003; LeGrande et al.,
2006; Peterson and Haug, 2006; Renssen et al., 2002), and were associated with the LIA (Lund
et al., 2006). The extent to which these climate oscillations propagated beyond the North Atlantic
high-latitudes and affected subtropical hydroclimate, particularly within the SE US, remains
poorly known.

There are currently very few paleoclimate records from the SE US that cover the critical time
intervals during which ocean thermohaline circulation shifts have been recorded. Available
paleoenvironmental records for this region (Goman and Leigh, 2004; Grimm et al., 1993)
suggest a pattern of Holocene hydroclimate that does not seem to agree with observations from
the North Atlantic over these critical intervals (Grimm et al., 2006). Furthermore, climate model-
hosing experiments produce hydroclimate results for the North Atlantic region that are model
dependent and strongly contingent upon the duration, magnitude and location of freshwater
forcing (Collins et al., 2019; Otto-Bliesner and Brady, 2010).

Stalagmite δ18O records from the North Atlantic offer a unique opportunity to reconstruct the
long-term history of precipitation variability from interannual to millennial timescales in low and
mid-latitudes (Aharon and Dhungana, 2017; Medina-Elizalde et al., 2017). Currently, there are
only two stalagmite high-resolution climate records available from the SE US region covering
the Holocene time interval; one from Alabama spanning from 6 ka to ~1 ka BP (Aharon and
Dhungana, 2017) and another from West-Central Florida, spanning from 6.6 ka to 4.6 ka BP
(Pollock et al., 2016). These high-resolution records reveal novel information about decadal and
multidecadal hydroclimate variability in the SE US but do not span the critical YD, 8.2 ka, and
LIA cooling intervals to enable assessing the regional impact of ocean thermohaline shifts.

In this study we present a hydroclimate record based on stalagmite δ18O and δ13C timeseries
from the SE US that span the last ~12 ka and allow us to examine subtropical climate responses
to high-latitude climate change forced by thermohaline circulation shifts. There is an interest in
determining the actual geographical extent of the YD, 8.2 ka and LIA events beyond the circum-
North Atlantic region, especially if climate proxy records representing these events are to be
used in helping validate models of thermohaline circulation shifts, in the context of potential
changes in deep water formation during the Anthropocene (Collins et al., 2019).
2. Methods

2.1. Study Area

In 2017 we retrieved an inactive stalagmite specimen (34 cm long) named War Eagle (WE) from an isolated cave chamber within War Eagle (WE) cave located in Jackson County, Alabama (Fig. 1 and Fig. S1). This cave is located on private property and is only accessible for half a year, when hunting season is off. WE cave has only one entrance requiring a 41m rappel. The cave is hosted within the Bangor Limestone and the thickness of the epikarst where the stalagmite was found is estimated to be between 30 and 35 m. The soil on the cave’s exterior surface is scarce and the topography is categorized as stony colluvial, rockland limestone, and rockland sandstone (United States Department of Agriculture).

2.2. Local and regional climatology

Mean annual precipitation in the locality of WE Cave is 1,446 mm and mean annual temperature is 15°C (1981-2010, NOAA’s weather station in Scottsboro, AL., 34.6736N, 86.0536W). Precipitation shows almost no seasonality, with the lowest monthly rainfall amount typically observed in the month of October and the highest in December (Fig. S2). Monthly temperature variations range from the lowest in January (4°C) to the highest in July (26°C) (ncdc.noaa.gov). Alabama like many other locations in the interior southeast has nearly the same amount of precipitation in the warm season as in the cool season. Regional winter precipitation amount comprises the largest portion of the annual budget (29%), followed by spring and summer (~25% each) and lastly fall (~20%) (data from 2005 to 2015). Despite these long-term averages, in recent years summer precipitation has often been greater than other seasons (data

Spatial correlation analyses of the instrumental record of monthly precipitation (from 1901 to 2013) across the SE US, Caribbean and Gulf of Mexico regions relative to the precipitation record from Alabama, suggest coherent in-phase variability within much of the SE US, and a weak anticorrelation with precipitation variability in the broader Caribbean region (Fig. 1). Anticorrelation reflects the underlying climate dynamics driving seasonal precipitation variability in these regions. Minor precipitation seasonality characterizes the SE US, whereas monsoonal-style seasonality is typical in the broader Caribbean (Karmalkar et al., 2011). End of 21st century climate projections suggest contrasting climate responses of these regions as radiative forcing from greenhouse gases increases (Collins et al., 2013).

The spatial and temporal pattern of summer precipitation in the SE US is influenced by convective systems (Baigorria et al., 2007), synoptic-scale systems such as tropical cyclones, and large-scale circulation changes (e.g. (Li et al., 2013) and references therein). During the spring and winter seasons mid-latitude cyclones advect moisture from the Gulf of Mexico and North Atlantic into this region (Keim, 1996). The subtropical North Atlantic ocean, the Mexican Caribbean and the Gulf of Mexico regions represent the main source of year-round moisture for precipitation in large areas of the continental US and particularly of the SE US (Gimeno et al., 2012). Li et al., (2013), examining multiple reanalysis datasets find that the North Atlantic Subtropical High western ridge position is a primary regulator of interannual variation of moisture transport to the SE US and that dynamical processes (atmospheric circulation) are the main control on interannual variations in precipitation.
2.3. Cave Monitoring

WE cave monitoring was established in order to better understand cave environmental conditions, particularly temperature and relative humidity; both factors affect the isotopic fractionation between drip water and stalagmite calcite. Two ONSET-HOBO instruments were placed inside the chamber where the WE stalagmite was retrieved, from October 2018 to October 2019. Monitoring results indicate WE cave remained at or near saturation conditions (RH 100%) and was thermally stable year-round with a constant temperature of 14.7°C, thus very close to local mean surface air temperature. These conditions favor isotopic equilibrium between calcite and drip water. Observed cave air thermal stability indicates that it is in thermal equilibrium with outside air temperature and thus responds to persistent air surface temperature change and not seasonal variability. We collected water at one drip site over the course of one year (i.e. from October 2018 to October 2019). Two six-month cumulative water samples yielded the same isotopic values ($\delta^{18}O = -5.9\%$) similar to the amount-weighted $\delta^{18}O$ composition of rainfall typically observed in Tuscaloosa (more details below). This indicates that drip water integrates several months and likely more than one year of precipitation amount and that surface and cave evaporative processes are not expected to significantly alter drip water $\delta^{18}O$, similar to what it is observed in a cave in the Yucatan Peninsula, across the Gulf of Mexico (Lases-Hernández et al., 2019).

2.4. Chronology

The WE stalagmite time scale was determined with 22 U/Th dates (Table S1 and Fig. S3), following the methods by (Cheng et al., 2013). Calcite powders weighing 50 to 130 mg were combined with a calibrated $^{229}$Th-$^{233}$U-$^{236}$U tracer solution, dissolved, and purified through iron
co-precipitation and anion exchange columns based on the methods of Edwards et al (1987) (Edwards et al., 1987). U-Th isotopic measurements were conducted on a Nu Plasma II-ES multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at the Massachusetts Institute of Technology. Analyses were conducted in static mode, with the minor isotopes ($^{234}\text{U}$ and $^{230}\text{Th}$) measured on a secondary electron multiplier, and all other isotopes measured on Faraday cups. U analyses were bracketed by analyses of standard CRM112a, and Th analyses were bracketed by an in-house $^{229}\text{Th}$-$^{230}\text{Th}$-$^{232}\text{Th}$ standard. All dates are corrected for instrument background, tailing, mass bias, SEM yield, contributions from impurities in the spike, and chemistry blanks using an offline data reduction procedure. All errors of isotopic data and dates given are two standard deviations. Age uncertainties ranged from ±15 to ±110 years with a mean of ±40 years. Only one date has an uncertainty of ±110 years and the remaining 16 dates have uncertainties lower than ±70 years, across the 12 ka record.

U-Th dates indicate that WE stalagmite grew over three time intervals separated by two hiatuses. The stalagmite began to grow 12.2 ka BP and stopped growing at 10.8 ka BP. After an interruption of over 1 ka, the stalagmite resumed growth 9.4 ka BP and stopped growing 4.3 ka BP. Finally, after a ~2 ka growth interruption, the stalagmite resumed growth once again 2.6 ka BP and stopped growing 300 years BP (years BP are relative to C.E. 1950). These two hiatuses are visually distinctive as a shift in color, fabric and vertical growth orientation (Fig. S1 & S4). Importantly, the stalagmite spans the intervals of interest corresponding to the YD and 8.2 ka cooling events and the LIA. We developed the chronology of these sections based on piecewise-linear models to account for non-linearity in stalagmite growth (Fig. S3).
2.5. $\delta^{18}O$ & $\delta^{13}C$ Time Series

The $\delta^{18}O$ and $\delta^{13}C$ data was obtained at the Paleoclimate and Stable Isotope Laboratory (PSI) in the Department of Geosciences at Auburn University, Alabama. Along the main growth axis, 688 calcite powder micro samples were drilled at a sampling resolution of 500 µm (Table S2). The carbon and oxygen isotopic composition of calcite powders were analyzed with a Thermo Scientific Delta V Plus Isotope Ratio Mass Spectrometer interfaced with a Thermo Gasbench II. Long-term (3-year) reproducibility for reference standard IAEA-603 is 0.09‰ and 0.07‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively. Reproducibility of $\delta^{18}O$ and $\delta^{13}C$ (average standard deviation for each sample of the WE data-set) were 0.06‰ for both.

3. Results and Discussion

The WE stalagmite long-term average $\delta^{18}O$ composition is -3.3 ‰, with a range from -4.3‰ to -2.1 ‰. The most negative isotopic values occur over the intervals 11.8-11ka BP, 9.4-8 ka BP and 0.5-1 ka BP and the most positive over the intervals 6.5-5.5 ka BP and 10.8-11 ka BP (Fig. 2). We focus this section on the climate interpretation of four separate windows of the WE stalagmite $\delta^{18}O$ record, which span the YD and 8.2 ka cooling events, the Early to Mid-Holocene and the Late Holocene. We provide a final discussion on the WE stalagmite $\delta^{13}C$ series in support of hydroclimate inferences from the $\delta^{18}O$ record.

3.1. Precipitation $\delta^{18}O$ variability and the amount effect

The amount effect is well documented within tropical to subtropical regions (Rozanski et al., 1993) but has not been well documented within the SE US, although modeling data with isotope tracers suggest its existence in the southernmost extension of this region (Vuille et al., 2003).
Relevant studies by Dhungana and Aharon (2019) and Lambert and Aharon (2010) suggested the existence of an amount effect on interannual timescales by examining a couple of years of rainfall isotopic data.

We examined a 10-year record (2005-2015) of precipitation amount and $\delta^{18}$O data produced by the University of Alabama (Dhungana and Aharon, 2019; Lambert and Aharon, 2010; McKay and Lambert, 2015) in order to investigate the existence of an amount effect on seasonal and interannual time scales and the impact of shifts in seasonality on precipitation amount and annual precipitation $\delta^{18}$O (Fig. S5 and Table S3).

Examination of decadal precipitation amount ($P$) and precipitation $\delta^{18}$O ($\delta P$) data (2005-2015), reveals the existence of an interannual relationship between $\delta P$ and $\Delta P$ with a slope $\delta P/\Delta P = -0.0017$ ‰ per mm ($r=0.34$) (Fig. S5A). Removal of three “anomalous” years suggests a much stronger relationship ($\delta P/\Delta P = -0.003$ ‰ per mm) ($r=0.92$) (Fig. S5B). The observed relationship between precipitation $\delta^{18}$O and precipitation amount on interannual timescales is the result of an amount effect observed during the summer and spring seasons (hereafter jointly referred to as ‘summer’) combined with the distinctive depleted isotopic contribution of fall and winter precipitation (hereafter referred to as ‘winter’). Although instrumental observations support interpretation of interannual stalagmite $\delta^{18}$O variability in terms of precipitation amount change, the observed variability of the slope $\delta P/\Delta P$ (i.e. Fig. S5A versus S5B) is significant enough to introduce uncertainty in quantitative precipitation estimates determined sensu Medina-Elizalde and Rohling (2012). In this study, we interpret stalagmite $\delta^{18}$O variability to reflect precipitation amount qualitatively, although we examine the shift in ‘winter’ and ‘summer’ precipitation amount using the instrumental data necessary to explain stalagmite $\delta^{18}$O variability.
An observation from the instrumental record relevant to support hydroclimate interpretations of stalagmite $\delta^{18}O$, is that ‘winter’ precipitation shows low interannual $\delta^{18}O$ variability, the highest frequency of depleted $\delta^{18}O$ values, and no amount effect on interannual timescales. An amount effect on interannual timescales is particularly observed during the summer and spring seasons (Fig. S6). In order to interpret WE stalagmite $\delta^{18}O$ variability, we examine the effect of shifting the amount of precipitation during ‘summer’, relative to modern conditions, on the decadal average $\delta^{18}O$ composition of rainfall, while maintaining ‘winter’ precipitation amount constant, and vice versa, the effect of shifts in ‘winter’ precipitation on rainfall $\delta^{18}O$ while keeping ‘summer’ precipitation constant (Fig. 3 and Table S3). We explore decadal rainfall isotopic shifts because this time resolution is relevant to that of the WE stalagmite isotopic records (i.e. 7-44 years) (Fig. 2).

This analysis provides three main observations relevant to the hydroclimate interpretation of stalagmite $\delta^{18}O$: (i) a large increase in ‘winter’ precipitation amount does not produce per se a negative annual precipitation $\delta^{18}O$ shift, but only via dilution of isotopically enriched ‘summer’ precipitation (Fig. 3). A doubling of ‘winter’ precipitation amount, for instance, would only shift the decadal average $\delta^{18}O$ composition of rainfall by -0.24‰ when maintaining ‘summer’ precipitation unchanged (Fig. 3). (ii) Peak negative decadal isotopic shifts can only be attained if ‘summer’ precipitation increases. This is the result of the amount effect observed during the summer and spring seasons (Fig. S6). Doubling of ‘summer’ precipitation amount would shift decadal average rainfall $\delta^{18}O$ by -1.4‰, while doubling ‘winter’ precipitation amount would only shift it by -0.24‰, as mentioned above (Fig. 3). (iii) Maximum positive decadal rainfall isotopic shifts can only be attained by decreasing both ‘winter’ and ‘summer’ precipitation. Decreasing ‘summer’ precipitation amount alone can produce a maximum positive shift of
~+0.21‰ when precipitation is reduced by 48%. A larger ‘summer’ precipitation reduction starts shifting rainfall δ¹⁸O in the opposite direction, by enhancing the influence of isotopically depleted ‘winter’ rainfall on the annual isotopic budget. Maximum decline of ‘winter’ precipitation to zero, produces a decadal averaged positive rainfall isotopic shift of +0.85‰ (Fig. 3). This shift corresponds to the difference between the decadal averaged annual amount-weighed δ¹⁸O composition of rainfall (including all seasons) versus the decadal averaged ‘summer’ amount-weighed δ¹⁸O composition of rainfall.

3.2. Expected equilibrium stalagmite δ¹⁸O values

A necessary condition to interpret the oxygen isotopic composition of stalagmite calcite as a record of precipitation δ¹⁸O variability is that calcite δ¹⁸O is precipitated under isotopic equilibrium conditions. Results from calculations using empirical isotopic equilibrium equations indicate calcite precipitated at or near equilibrium under the observed cave air temperature (14.7°C) and range of annual amount-weighted δ¹⁸O composition of rainfall (i.e. -5.9 ‰ to -3.9 ‰) would have a δ¹⁸O composition ranging from -6.6 ‰ to -2.9 ‰ in agreement with the WE stalagmite isotopic composition (Table S4). Supported by these results, in addition to the observed cave environmental conditions (relative humidity ~100% and stable temperature), we suggest that stalagmite WE calcite was precipitated near isotopic equilibrium conditions and likely faithfully records precipitation δ¹⁸O variability (Table S4). We note finally that WE stalagmite does not have distinctive temporal laminations to produce a conventional Hendy Test.
3.3. Younger Dryas and 8.2 ka cooling events

Figures 4 and 5 place the WE stalagmite-precipitation $\delta^{18}O$ record in the context of high-latitude climate variability during the YD and 8.2 ka cooling events. Stalagmite $\delta^{18}O$ values become progressively more negative during the evolution of these two events by about $\sim 1.2\%$. The observed relationship between precipitation $\delta^{18}O$ and precipitation amount observed today on interannual timescales suggests that such negative shift in stalagmite $\delta^{18}O$ reflects persistent increases in precipitation amount in the SE US during the peak of these events (Fig. S5). We acknowledge that the negative stalagmite $\delta^{18}O$ shift observed during the YD and 8.2 ka events could reflect regional atmospheric cooling via the same-sign relationship between water condensation temperature and precipitation $\delta^{18}O$. Global circulation model hosing experiments with isotope tracers suggest, however, that precipitation $\delta^{18}O$ would have remained practically unchanged in the SE US (LeGrande et al., 2006). WE cave air cooling during these events, on the other hand, would have increased calcite $\delta^{18}O$ not decrease it, due to thermodynamic isotopic fractionation between drip water and calcite, probably counterbalancing positive rainfall isotopic shifts driven by atmospheric cooling.

The sensitivity test we applied using the instrumental data (Fig. 3) suggests that the stalagmite isotopic shift of $\sim 1.2\%$ can be explained by a 90% increase of ‘summer’ precipitation relative to today’s conditions. As mentioned previously, an increase in ‘winter’ precipitation by 100% would only shift rainfall $\delta^{18}O$ by -0.2‰ (while maintaining ‘summer’ precipitation amount constant). We cannot discard that ‘winter’ precipitation declined at the time, because such a large increase in the influence of ‘summer’ precipitation would mask the isotopic signal of declining ‘winter’ rainfall amount. As an example, a coeval decrease of ‘winter’ precipitation amount by 100% would only shift rainfall $\delta^{18}O$ by -0.1‰ when ‘summer’
precipitation increases 90% (Table S3). We point out that a decrease of ‘summer’ precipitation to zero while maintaining ‘winter’ precipitation unchanged would decrease rainfall $\delta^{18}O$ only by a maximum of -0.7‰ and thus would fail to explain the observed stalagmite isotopic change of -1.2‰. An increase in ‘summer’ precipitation is thus necessary to explain observations. We lastly note that the suggested increase in ‘summer’ precipitation by 90% yields an increase in annual precipitation, even when winter precipitation amount is reduced by as much as 90%; in agreement with inferences based on the observed amount effect on interannual timescales (Fig. S6).

The YD and 8.2 ka events were associated with AMOC slowdown, North Atlantic cooling, a southward displacement of the ITCZ, and precipitation reductions in the NH low latitudes as suggested by climate model hosing experiments (Dahl et al., 2005; LeGrande et al., 2006; Otto-Bliesner and Brady, 2010; Vellinga and Wood, 2002) and paleoclimate records (Lea et al., 2003; Peterson and Haug, 2006). A southward displacement of the ITCZ during the YD and 8.2 ka events in particular is suggested by the Cariaco Basin Ti% sediment record from offshore Venezuela and from its antiphase relationship with hydroclimate records from south America (Peterson and Haug, 2006) (Figs. 4 and 5). A southward displacement of the ITCZ due to AMOC slowdown is also supported by climate model simulations and expected to result from atmospheric circulation changes associated with significant tropical cooling (Otto-Bliesner and Brady, 2010; Stouffer et al., 2006; Vellinga and Wood, 2002).

Model simulations of AMOC slowdown/shutdown feature a ‘cold tongue’ of surface temperatures that extends from the North Atlantic high-latitudes through the eastern North Atlantic sector down to the tropical region (Otto-Bliesner and Brady, 2010; Vellinga and Wood, 2002). This ocean ‘cold tongue’ is flanked by mild or warmer surface temperatures in the
western North Atlantic mid-latitude and Gulf of Mexico regions, the main sources of moisture into the SE US region (Gimeno et al., 2012; Li et al., 2013). Additional model hosing experiments that address shifts in seasonality (LeGrande et al., 2006; Renssen et al., 2002), suggest that AMOC slowdown decreases winter surface temperatures while summer temperatures remain unchanged or increase in the Gulf of Mexico and SE US. Warmer ocean conditions in the Gulf of Mexico and western North Atlantic, particularly in the summer, coeval with stronger meridional and zonal temperature gradients in the North Atlantic would be conducive to increasing local precipitation in the SE US. Enhanced precipitation in the SE US is actually supported by various model experiments of freshwater perturbation to AMOC that at the same time simulate coeval precipitation reduction in the tropical Atlantic (LeGrande et al., 2006; Renssen et al., 2002; Vellinga and Wood, 2002), in agreement with observations (Fig. 4 and 5).

We acknowledge that these observations have potential implications for the inferred position and strength of the North Atlantic subtropical high pressure system during these climate events that deserve a deeper exploration beyond the scope of this study.

The results from this study suggesting the SE US was wet when the North Atlantic was cold and the tropics experienced negative precipitation anomalies agree with independent paleoclimate evidence based on pollen and plant macrofossil records from Lake Tulane, Florida. These records spanning the last 60 ka suggest that Florida was wet and warm during Heinrich events, including the YD, and during the stadial intervals of Dansgaard-Oeschger events (Grimm et al., 2006). Grimm et al., (2006) suggest that a reduction in North Atlantic deep water formation decreased the northward ocean heat transport and retained warmth in the subtropical Atlantic and Gulf of Mexico, essentially producing a polar-subtropical seesaw. Paleoclimate evidence both supporting and opposing the seesaw pattern exists from the Caribbean, as
described in detail by Grimm et al. (2006). Regardless of the mechanism ultimately enhancing summer precipitation in the SE US, model simulations and paleoclimate records provide evidence of an antiphase climate relationship between the SE US and the eastern subtropical North Atlantic and southern Caribbean, during events of AMOC slowdown/shutdown. We note that the instrumental record indicates an antiphase relationship between precipitation in the SE US and the broader Caribbean on interannual timescales (Fig. 1) and during the summer season (Fig. S7).

359 3.5. Early to Mid-Holocene Climate Variability

The WE stalagmite suggests a long-term +1‰ isotopic shift occurring from ~7.5 ka to ~5.5 ka (Fig. 6). A decline in ‘summer’ precipitation alone would not explain this large positive isotopic shift, because it would increase δ^{18}O by +0.2‰ maximum, when precipitation amount decreases by 49% (Fig. 3). As mentioned previously, a decrease of ‘summer’ precipitation amount beyond this level would no longer increase annual precipitation δ^{18}O because the depleted isotopic composition of ‘winter’ rainfall becomes dominant after this threshold (Fig. 3). An additional 75% decline of ‘winter’ precipitation amount would be needed to explain the Mid-Holocene stalagmite positive isotopic shift. We note that ‘summer’ precipitation must have declined together with ‘winter’ precipitation, because the maximum isotopic shift when ‘winter’ precipitation becomes zero is 0.8‰, therefore it would still be insufficient to explain the mid-Holocene stalagmite shift (Fig. 3). The precipitation decline from ~7 to ~6 ka suggested by the WE stalagmite is consistent with pollen records from wetlands in the SE US that suggest a decline over this time of high-diversity taxa indicative of moist soils (Goman and Leigh, 2004). In addition, a hydroclimate transition from wet to dry conditions at the time is also suggested by
a decrease in the abundance of *Pinus* inferred from pollen records from lake Tulane, Florida

(Grimm et al., 1993; Grimm et al., 2006).

Inferred climate evolution from the Early Holocene (9-7 ka BP) to the mid-Holocene (6-5 ka BP) in the SE US coincides with boreal summer insolation reduction, North Atlantic cooling (Marcott et al., 2013; Renssen et al., 2005; Wanner et al., 2011), decrease rainfall in the Caribbean (Haug et al., 2001) and weakening of Northern Hemisphere monsoon intensity (Fleitmann et al., 2007) (Fig. 6). Evidence of mid-Holocene precipitation reduction is also provided by paleoclimate records from Cuba (Fensterer et al., 2013), and from the central and northwestern US (Shin et al., 2006). Lastly, Early Holocene precipitation maxima in the SE US coeval with Northern Hemisphere warm conditions is consistent with projected hydroclimate change in the region by the end of this century resulting from anthropogenic warming (Collins et al., 2013).

The drying trend suggested by the WE stalagmite is interrupted by two climate reversals between 6 and 4.5 ka BP indicated by prominent negative isotopic excursions (Fig. 2 and Fig. S8). These inferred climate reversals are also represented, although more subtlety, by the stalagmite $\delta^{18}O$ record from DeSoto Caverns, Alabama, that spans the interval between ~6 ka and 1 ka BP (Aharon and Dhungana, 2017) (Fig. S8). Similar but more subtle hydroclimate cycles are shown by paleoclimate records from the Caribbean which are coeval with North Atlantic temperature variability (Haug et al., 2001; Marcott et al., 2013)(Fig. 5). Isotopic reversals are observed in the WE stalagmite $\delta^{13}C$ record, also suggesting a local hydrological change at the time (Fig. 2). We propose that the speleothem isotopic records from Alabama probably record an amplified regional hydrological response to North Atlantic climate conditions perhaps reflecting that dynamical processes became progressively less influential in controlling
moisture sources into the SE US from the early to the mid-Holocene. During this time, the region
began to experience an increase in precipitation recycling from precipitation of terrestrial origin
(Dominguez et al., 2006) that became more important as oceanic sources of moisture became
less dominant as the North Atlantic cooled (Gimeno et al., 2012; Li et al., 2013).

3.6. Late-Holocene Climate Variability

During the transition from the Medieval Climate Anomaly time interval to the Little Ice
Age (Mann et al., 2009), WE stalagmite $\delta^{18}O$ shows a negative isotopic shift from 1.2 to 0.4 ka
BP of $-0.8\%$ (Fig. 7). The stalagmite negative isotopic excursion coincides with the LIA
interval (Mann et al., 2009); arguably the Holocene’s coldest period in the North Atlantic
(Marcott et al., 2013) and the driest in the Caribbean (Higuera-Gundey et al., 1999; Hodell et al.,
1991; Peterson and Haug, 2006). Similar to our interpretation concerning the YD and 8.2 ka
events, we suggest this negative isotopic excursion reflects an increase in ‘summer’ precipitation.
Tree ring records from the eastern SE US spanning the last 1000 years (Stahle and Cleaveland,
1992) do not suggest a long-term shift in spring precipitation during the LIA interval. Thus, the
long-term stalagmite isotopic shift associated with the LIA is likely to reflect mostly summer
precipitation changes during this time. Climate variability in the SE US across the YD, 8.2 ka,
and LIA events support a connection with AMOC shifts (Keigwin and Boyle, 2000; Lund et al.,
2006); in the case of the LIA, perhaps reflecting ocean-atmospheric feedbacks to forcing from
volcanic sulfur emissions and total solar irradiance at the time (Andres and Peltier, 2016; Free
and Robock, 1999).
3.7. Stalagmite Carbon Isotopes

Across the full length of the WE stalagmite, and during the prominent climate events highlighted above, the stalagmite δ¹³C record mimics the oxygen isotope record (Fig. 2). The carbon isotope response across these events suggests hydrological shifts affecting vegetation type, density, and/or soil microbial productivity. We note that most of the stalagmite δ¹³C record have values that suggest a strong dominance of carbon of bedrock origin with positive isotopic compositions and only minor contributions of carbon from vegetation dominated by C4 plants (Fairchild and Baker, 2012). We therefore conclude that stalagmite calcite covariance between δ¹⁸O and δ¹³C probably reflects shifts in karst hydrology whereby wetter conditions would favor faster infiltration, decreased pCO₂ degassing and reduced prior calcite precipitation, ultimately producing lower δ¹³C values from a bedrock-dominated carbon baseline (Fairchild and Baker, 2012).

4. Conclusion

We produced high-resolution stalagmite δ¹⁸O and δ¹³C records of hydroclimate from Alabama spanning the last 12 ka, extending the existing regional paleoclimate record to the early Holocene. Hydroclimate in Alabama is linked to the broader Southeastern United States (SE US) as suggested by spatial correlation analysis using the instrumental record of precipitation amount. We interpret the stalagmite isotope records to reflect: (i) an amount effect observed on interannual timescales, and; (ii) shifts in the relative contribution of changes in spring-summer versus fall-winter rainfall amount. We find a close connection between hydroclimate variability in the SE US, North Atlantic high latitude climate variability and Caribbean/Gulf of Mexico hydroclimate. A consistent picture emerges whereby spring-summer precipitation in the SE US
increases during events of high latitude cooling associated with Atlantic Meridional Circulation slowdown/shutdown, such as during the Younger Dryas, 8.2 ka and Little Ice Age cooling events. Speleothem evidence of hydroclimate change is supported by pollen records from Florida and shows consistency with climate model studies of AMOC slowdown/shutdown. WE speleothem isotopic records suggest that annual precipitation decreased in the SE US across the climate transition from the early Holocene (‘Holocene Climate Optimum’) to the late Holocene (the ‘Neoglacial’) in the Northern Hemispher, generally attributed to external orbital forcing. Results from this study have implications for our understanding of the sensitivity of subtropical North Atlantic hydroclimate to abrupt melting of the Greenland ice sheet and its influence on AMOC in a future dominated by increasing greenhouse gases.

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Figure Captions

Figure 1. Spatio-temporal correlation analysis of precipitation (monthly values from 1901 to 2013 and with a spatial coverage of 0.5° latitude by 0.5° longitude) at the location (34°31’N, 86°11’W) (War Eagle Cave, Alabama). Location of War Eagle Cave indicated with light blue star. The precipitation data set comes from the GPCC Global Precipitation Climatology Centre
and is available from https://psl.noaa.gov/data/gridded/data.gpcc.html. The map was created using the R software.

Figure 2. Stalagmite War Eagle (WE) $\delta^{18}$O and $\delta^{13}$C records spanning the last 12.2 ka. Vertical colored bars indicate relevant time intervals discussed in the manuscript. The time resolution of these records is from 7 to 44 years, decreasing as time progresses from the Early to the Late Holocene.

Figure 3. Plot illustrating the change in the decadal average $\delta^{18}$O composition of rainfall resulting from shifting the amount of precipitation during spring and summer labelled as ‘summer’, and fall and winter, labeled as ‘winter’, relative to modern conditions. The X axis represents the fractional change in precipitation amount from modern conditions; 1 = 100% increase or a doubling of precipitation amount, and -1 = 100% decline in precipitation amount. *Blue line* represents the expected decadal average $\delta^{18}$O composition shift from changing the amount of precipitation during ‘winter’ from -100% (no precipitation) to plus 100% (doubling) while keeping ‘summer’ precipitation amount constant. *Dark orange line*, represents the expected decadal average $\delta^{18}$O composition shift from changing the amount of precipitation during ‘summer’ keeping ‘winter’ precipitation amount constant. These calculations include the amount effect relationship during the summer and spring seasons observed today. A decrease in ‘summer’ precipitation increases the decadal average $\delta^{18}$O composition of rainfall, because of the inverse relationship between precipitation amount and precipitation $\delta^{18}$O during the summer and spring, up to the point when the decline of ‘summer’ precipitation amount and its relatively positive isotopic composition “enhances” the influence of the depleted isotopic
composition that characterizes ‘winter’ precipitation (shown in plot section as “‘winter’ isotopic composition dominates”). The maximum positive isotopic shift produced from a reduction in ‘summer’ precipitation amount per se, keeping ‘winter’ precipitation constant, is 0.21‰ associated with a 40% precipitation amount reduction. A larger decrease in ‘summer’ precipitation amount no longer increases the isotopic composition of rainfall, because as mentioned above the depleted isotopic composition of winter begins to dominate. On the other hand, because there is no relationship between precipitation amount and precipitation δ¹⁸O during ‘winter’ and there is an amount effect during summer, an increase in ‘winter’ precipitation has a much modest effect that an increase in ‘summer’ precipitation amount on rainfall δ¹⁸O. A doubling in the amount of ‘winter’ precipitation is expected to decrease the decadal average δ¹⁸O composition of rainfall by 0.24‰, whereas a doubling in ‘summer’ precipitation amount would decrease the δ¹⁸O of rainfall by 1.4‰.

Figure 4. Blow up comparing the NGRIP ice core δ¹⁸O record (panel A) (Rasmussen et al., 2006), the Ti% record from the Cariaco Basin, offshore Venezuela (panel B) (Haug et al., 2001) and the WE stalagmite δ¹⁸O record (panel C, this study) over the Younger Dryas time interval. Note that top X-axis representing panels A and B and the bottom X-axis representing panel C, are shifted relative to each other with a maximum offset of ~200 yrs, in order to accommodate a dating uncertainty in the layer counting of young ice of ±120 yrs in the NGRIP ice core record (Rasmussen et al., 2006) and in the stalagmite δ¹⁸O record ~12 ka BP of ± 70 yrs (Table S1). Top X-scale corresponds to that of the records presented on panels A and B and the bottom X-scale corresponds to the WE stalagmite record.
Figure 5. Blow up comparing the NGRIP ice core δ¹⁸O record (panel A) (Rasmussen et al., 2006), the Ti% record from the Cariaco Basin, offshore Venezuela (panel B) and the WE stalagmite δ¹⁸O record (panel C, this study) over the 8.2 ka cooling event.

Figure 6. Blow up comparing a North Atlantic sea surface temperature reconstruction (panel A) (Marcott et al., 2013), the Cariaco Basin Ti% record (panel B) (Haug et al., 2001) and the WE stalagmite δ¹⁸O record (panel C, this study) spanning the transition from the Early to the Mid-Holocene. Darker continuous lines represent 7-point moving averages.

Figure 7. Blow up comparing a Northern Hemisphere surface temperature record (panel A) (Mann et al., 2009), the Cariaco Basin Ti% record (panel B) (Haug et al., 2001) and the WE stalagmite δ¹⁸O record (panel C, this study) spanning the late Holocene. The mean resolution of the stalagmite record over this time interval is 44 yrs.

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Figure 1.
Figure 2
DECADAL PRECIPITATION \\
18O CHANGE

PRECIPITATION AMOUNT CHANGE FOR 'SUMMER' AND 'WINTER' (FRACTIONAL CHANGE)

'winter' precipitation amount = 0
'summer' precipitation amount = constant

'summer' precipitation amount = 0
'winter' precipitation amount = constant

'summer' isotopic composition dominates
'winter' isotopic composition dominates

'winter' precipitation amount = +100%,
'summer' precipitation amount = constant

'summer' precipitation amount = +100%,
'winter' precipitation amount = constant

Figure 3
Figure 5

A. NGRIP (GICC05)

B. Cariaco Basin Haug et al., 2001

C. This Study

Lower summer precipitation

Higher 'summer' precipitation
Figure 6

A

Temperature 90-30°N (°C)

Marcott et al., 2013

B

ITCZ North

ITCZ South

Cariaco Basin
Haug et al., 2001

C

δ¹⁸O (‰, V-PDB)

Lower 'summer' & 'winter' rainfall

This Study

Years BP

Years BP
Figure 7

Panel A: NH surface temperature anomaly (°C) from Mann et al., 2009.

Panel B: δ¹⁸O (%o, V-PDB) from Cariaco Basin data by Haug et al., 2001.

Panel C: δ¹⁸O (%o, V-PDB) from This Study, indicating higher 'summer' rainfall.

Years BP