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*Southeastern United States Hydroclimate During Holocene Abrupt Climate Events: Evidence From New Stalagmite Isotopic Records From Alabama*

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# Paleoceanography and Paleoclimatology®

## RESEARCH ARTICLE

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### Key Points:

- Precipitation amount in the southeastern US likely increased during the Younger Dryas, the 8.2 ka and Little Ice Age abrupt cooling events
- High precipitation during these events likely reflected enhancement of spring and summer precipitation
- Atlantic Meridional Overturning Circulation shutdown could potentially help mitigate regional drought in the southeastern United States in the future

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Southeastern United States Hydroclimate During Holocene Abrupt Climate Events: Evidence From New Stalagmite Isotopic Records From Alabama

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**Abstract** We present new high-resolution absolute-dated stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  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-weighted  $\delta^{18}\text{O}$  composition exists on interannual timescales, driven mostly by an amount effect during summer and spring seasons. Based on a novel quantitative interpretation of modern rainfall isotopic data, stalagmite  $\delta^{18}\text{O}$  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 an interval of 500 yr coeval with the Younger Dryas and during the 8.2 ka and Little Ice Age abrupt cooling events. High precipitation during these events reflects enhancement of spring and summer precipitation by 90% combined, relative to today's conditions, 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. 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 to have occurred in other tropical and subtropical regions. The dynamical link between AMOC shutdown and precipitation variability in the SE US remains to be examined.

**Plain Language Summary** We present a paleoclimate record from Alabama, United States, interpreted to reflect precipitation variability over the last 12 thousand years. This record suggests that precipitation in the southeastern United States (SE US) increased during rapid cooling events in the North Atlantic associated with the Younger Dryas, 8.2 ka and Little Ice Age events. We suggest that regional precipitation variability during these climatic events was linked to shifts in North Atlantic deep ocean formation. The implication of our study for the future is that if North Atlantic deep water formation slows down as a result of global warming, as suggested by recent observations and model simulations, the SE US region may experience a tendency to wetter conditions, particularly during the summer time.

## 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 & Bentley, 2018).

**Writing – original draft:** Martín Medina-Elizalde  
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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 & Brady, 2010; Vellinga & 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 & 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 (12.9–11.7 ka; Rasmussen et al., 2014), the 8.2 ka (Alley & Ágústssdóttir, 2005) and the Little Ice Age (LIA, CE 1400–1900; Matthes, 1939) cooling events are hypothesized to be associated with AMOC slowdown/shutdown (Aguiar et al., 2021; Alley & Ágústssdóttir, 2005; Broecker et al., 1989; Thomas et al., 2007; Wagner et al., 2013), 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 & 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 & 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 & Brady, 2010).

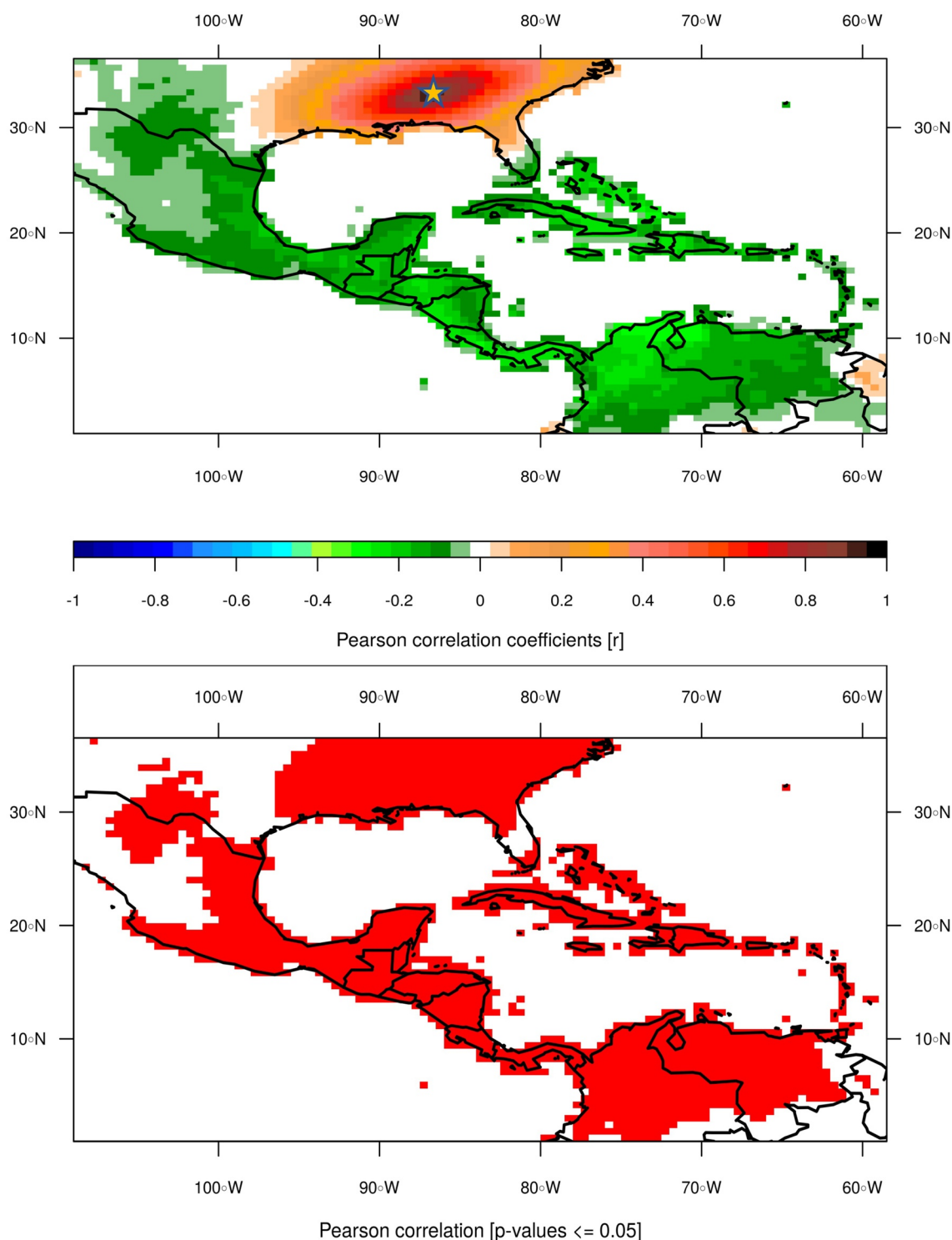
Stalagmite  $\delta^{18}\text{O}$  records from the North Atlantic offer a unique opportunity to reconstruct the long-term history of precipitation variability from interannual to millennial timescales in low and mid-latitudes (Aharon & Dhungana, 2017; Medina-Elizalde et al., 2017). Currently, there 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  $\sim 1$  ka BP (Aharon & 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  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  time series from the SE US that span the last  $\sim 12.2$  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 ( $PP_{nda}$ , 34 cm long) from an isolated cave chamber within War Eagle (WE) cave located in Jackson County, Alabama (Figure 1 and Figure S1 in Supporting Information S1). This cave is located on private property and is only accessible for half a year, when hunting season is



**Figure 1.** Spatio-temporal correlation analysis of annual precipitation (monthly values from 1901 to 2013 and with a spatial coverage of  $0.5^\circ$  latitude by  $0.5^\circ$  longitude) at the location ( $34^\circ 31'N$ ,  $86^\circ 11'W$ ) (War Eagle Cave, Alabama). Location of War Eagle Cave indicated with light yellow 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 (R-Core Team, 2013).

off. WE cave has only one entrance requiring a 41 m 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., 34.6736°N, 86.0536°W). Precipitation shows almost no seasonality, with the lowest monthly rainfall amount typically observed in the month of October and the highest in December (Figure S2 in Supporting Information S1). Monthly temperature variations range from the lowest in January (4°C) to the highest in July (26°C; [ncdc.noaa.gov](https://www.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 from Tuscaloosa, Alabama, 2005–2015; Dhungana & Aharon, 2019; Lambert & Aharon, 2010).

Spatial correlation analyses of the instrumental record of monthly precipitation (from 1901 to 2013) across the SE US, Caribbean and Gulf of Mexico (GOM) 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 (Figure 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 (Bai-gorria 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 GOM and North Atlantic into this region (Keim, 1996). The subtropical North Atlantic ocean, the Mexican Caribbean and the GOM 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 data sets 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  $PP_{nda}$  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 ( $\delta^{18}O = -5.9\text{‰}$ ) 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 GOM (Lases-Hernández et al., 2020).

## 2.4. Chronology

The  $PP_{nda}$  stalagmite time scale was determined with 22 U/Th dates (Table S1 and Figure S3 in Supporting Information S1), following the methods by Cheng et al. (2013). Calcite powders weighing 50–130 mg were combined with a calibrated  $^{229}\text{Th}$ - $^{233}\text{U}$ - $^{236}\text{U}$  tracer solution, dissolved, and purified through iron co-precipitation and anion exchange columns based on the methods of Edwards et al. (1987). U-Th isotopic measurements were conducted on a Nu Plasma II-ES multi-collector inductively coupled plasma mass spectrometer 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  $\pm 15$  to  $\pm 110$  yr with a mean of  $\pm 40$  yr. Only one date has an uncertainty of  $\pm 110$  yr and the remaining 16 dates have uncertainties lower than  $\pm 70$  yr, across the 12 ka record.

U-Th dates indicate that  $PP_{nda}$  stalagmite grew over three different 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  $\sim 2$  ka growth interruption, the stalagmite resumed growth once again 2.6 ka BP and stopped growing 310 yr BP (years BP are relative to CE 1950). These two hiatuses are visually distinctive as a shift in color, fabric and vertical growth orientation (Figures S1 and S4 in Supporting Information S1). Importantly, the stalagmite spans 500 yr of the YD event and the full 8.2 ka and LIA events. We developed the chronology of these sections based on piecewise-linear models to account for nonlinearity in stalagmite growth (Figure S3 in Supporting Information S1).

## 2.5. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ Time Series

The  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  data was obtained at the Paleoclimate and Stable Isotope Laboratory 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  $\mu\text{m}$  (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 yr) reproducibility for reference standard IAEA-603 is 0.09‰ and 0.07‰ for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , respectively. Reproducibility of  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  (average standard deviation for each sample of the  $PP_{nda}$  data set) were 0.06‰ for both.

# 3. Results and Discussion

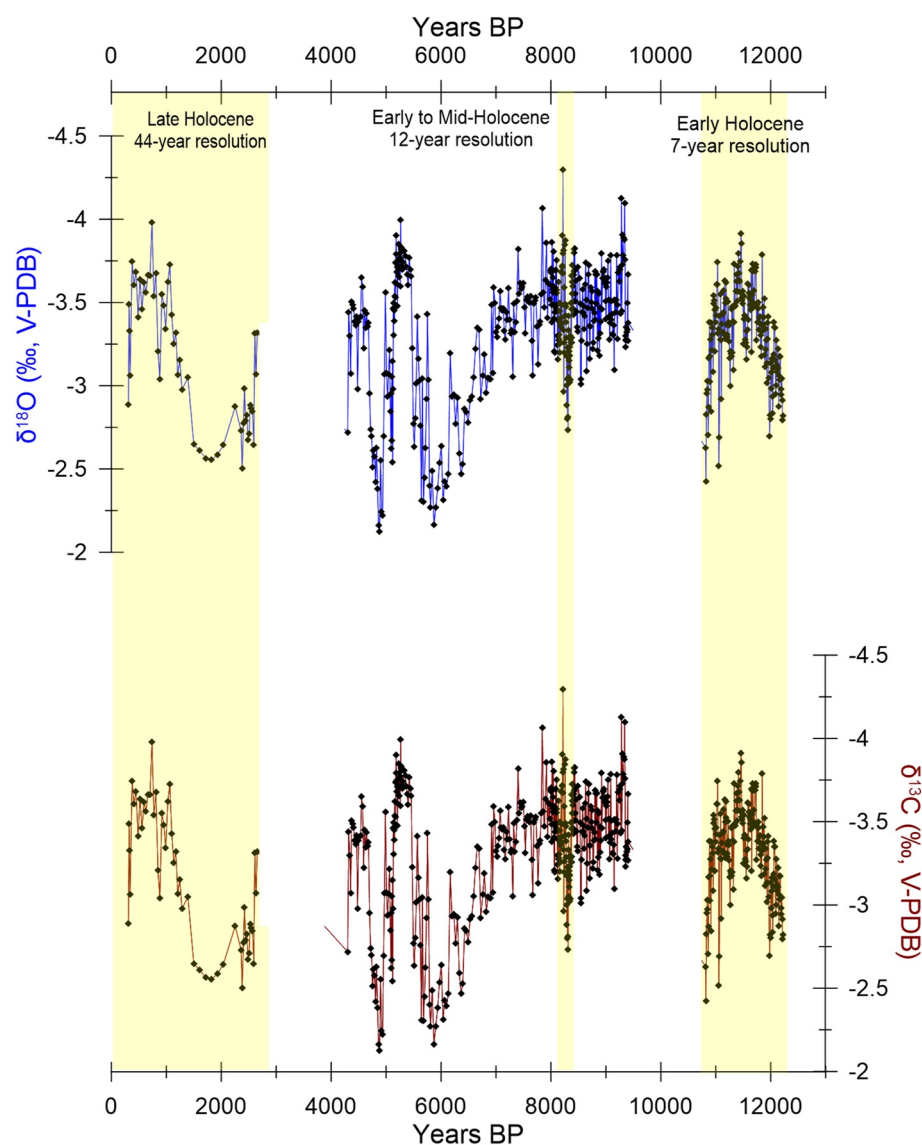
The  $PP_{nda}$  stalagmite long-term average  $\delta^{18}\text{O}$  composition is  $-3.3\text{‰}$ , with a range from  $-4.3\text{‰}$  to  $-2.1\text{‰}$ . The most negative isotopic values occur over the intervals 11.8–11, 9.4–8, and 0.5–1 ka BP and the most positive over the intervals 6.5–5.5 and 10.8–11 ka BP (Figure 2). We focus this section on the climate interpretation of four separate windows of the  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  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  $PP_{nda}$  stalagmite  $\delta^{13}\text{C}$  series in support of hydroclimate inferences from the  $\delta^{18}\text{O}$  record.

## 3.1. Precipitation $\delta^{18}\text{O}$ 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 isotope-enabled models 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), on the other hand, suggest the existence of an amount effect on interannual timescales by examining two years of rainfall isotopic data.

We examined a 5 yr record (January 2005–December 2008 and 2012–2013) of precipitation amount and  $\delta^{18}\text{O}$  (Dhungana & Aharon, 2019; Lambert & Aharon, 2010) 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  $\delta^{18}\text{O}$  (Figures S5 and S6 in Supporting Information S1 and Table S3).

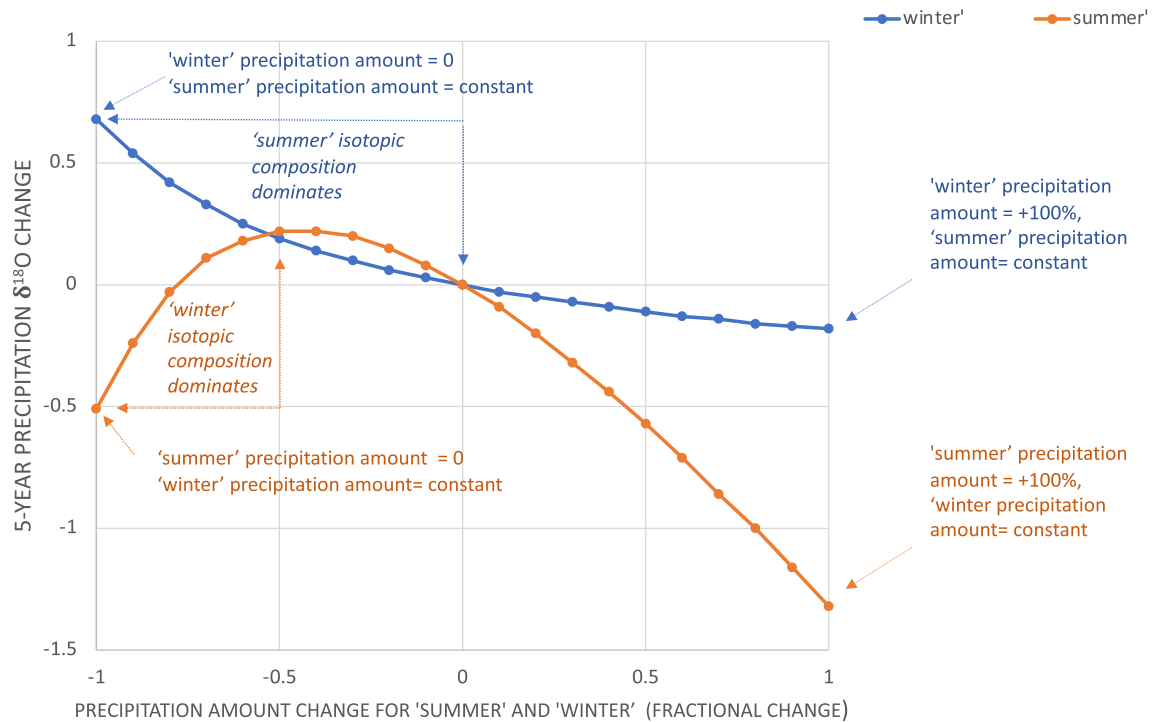




**Figure 2.** Stalagmite  $PP_{nda}$   $\delta^{18}O$  and  $\delta^{13}C$  records spanning the last 12.2 ka. Vertical colored bars indicate relevant time intervals discussed in the manuscript. The time resolution of these records is from 7 to 44 yr, decreasing as time progresses from the Early to the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

Examination of this precipitation amount ( $P$ ) and precipitation  $\delta^{18}O$  ( $\delta P$ ) record reveals the existence of an interannual relationship between  $\delta P$  and  $\Delta P$  with a slope  $\delta P/\Delta P = -0.0013\text{‰}$  per mm;  $r^2 = 0.39$ ; Figure S5 in Supporting Information S1). 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”). In this study, we interpret stalagmite  $\delta^{18}O$  variability to reflect quantitative shifts in the relative contributions of “winter” and “summer” precipitation amount, applying a novel approach of examining the instrumental data of precipitation amount and  $\delta^{18}O$ . This is to our knowledge the first speleothem paleoclimate study that examines interannual variability in rainfall amount and  $\delta^{18}O$  in all four climatological seasons, using instrumental data, in order to develop an interpretative framework under which to interpret stalagmite  $\delta^{18}O$  variability quantitatively in a subtropical region.

An observation from the instrumental record from Alabama relevant to support hydroclimate interpretations of stalagmite  $\delta^{18}O$  is that “winter” precipitation shows low interannual  $\delta^{18}O$  variability, the highest occurrence



**Figure 3.** Plot illustrating the change in the 5 yr average  $\delta^{18}\text{O}$  composition of rainfall resulting from shifting the amount of precipitation during spring and summer (“summer”, see main text for definition), and fall and winter (“winter”, see main text), relative to modern conditions (Table S3). Summer (June, July, and August); Fall (September, October, and November); Winter (December, January, and February); Spring (March, April, and May). 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 5 yr average  $\delta^{18}\text{O}$  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 5 yr average  $\delta^{18}\text{O}$  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 5 yr average  $\delta^{18}\text{O}$  composition of rainfall, because of the inverse relationship between precipitation amount and precipitation  $\delta^{18}\text{O}$  during the summer and spring. This occurs up to the point when the decline of “summer” precipitation amount is such, that “winter” precipitation amount and its distinctive negative isotopic composition begin to dominate (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  $0.22\text{‰}$  associated with a 50% precipitation amount reduction. A larger decrease in “summer” precipitation amount no longer increases the isotopic composition of rainfall, because of the reason mentioned above. On the other hand, because there is no relationship between precipitation amount and precipitation  $\delta^{18}\text{O}$  during “winter” and there is an amount effect during summer and spring, an increase in “winter” precipitation has a much modest effect that an increase in “summer” precipitation amount on the 5 yr average rainfall  $\delta^{18}\text{O}$  composition. A doubling in the amount of “winter” precipitation is expected to decrease the 5 yr average  $\delta^{18}\text{O}$  composition of rainfall by  $0.18\text{‰}$ , whereas a doubling in “summer” precipitation amount would decrease it by  $1.4\text{‰}$ .

of depleted  $\delta^{18}\text{O}$  values of all seasons, and no amount effect on interannual timescales. An amount effect on interannual timescales is observed only during the summer and spring seasons (Figure S6 in Supporting Information S1). In order to interpret  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  variability, we thus examine the effect of shifting the amount of precipitation during “summer”, relative to modern conditions, on the 5 yr average  $\delta^{18}\text{O}$  composition of rainfall, while maintaining “winter” precipitation amount constant, and vice versa, the effect of shifts in “winter” precipitation on rainfall  $\delta^{18}\text{O}$  while keeping “summer” precipitation constant (Figure 3 and Table S3). We explore 5 yr rainfall isotopic shifts because this time resolution is relevant to that of the  $PP_{nda}$  stalagmite isotopic records (i.e., 7–44 yr) and because this is the length of the instrumental record that is currently publicly available (Figure 2).

We point out that isotope-enabled models covering the SE US and that consider the specific boundary conditions associated with the YD, 8.2 ka and LIA events, are not currently available. We acknowledge the relevance of these type of models (e.g., *IsoGSM* or *ECHAM-5*) to help inform of potential shifts in the relative contribution of moisture sources that could affect our interpretation of stalagmite  $\delta^{18}\text{O}$ . At this point, our study assumes that no significant shifts in moisture sources relative to today occurred at the time of the climate events examined. Results from global circulation model hosing experiments that incorporate isotope tracers, notably suggest that precipitation  $\delta^{18}\text{O}$  would have remained practically unchanged in the SE US relative to unforced conditions, thus



offering some support to this assumption, particularly for those events such as the YD where freshwater forcing is considered to be the dominant driving forcing (LeGrande et al., 2006).

The developed framework we present in Table S3 and illustrated in Figure 3 provides three main observations relevant to the hydroclimate interpretation of stalagmite  $\delta^{18}\text{O}$ : (a) a large increase in “winter” precipitation amount does not produce *per se* a negative annual precipitation  $\delta^{18}\text{O}$  shift, but only via dilution of isotopically enriched “summer” precipitation (Figure 3). A doubling of “winter” precipitation amount, for instance, would only shift the 5 yr average  $\delta^{18}\text{O}$  composition of rainfall by  $-0.18\text{‰}$  while maintaining “summer” precipitation unchanged (Figure 3). (b) Peak negative 5 yr 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 (Figure S6 in Supporting Information S1). Doubling of “summer” precipitation amount would shift the 5 yr average rainfall  $\delta^{18}\text{O}$  by  $-1.3 \pm 0.5\text{‰}$  (uncertainty reflects amount effect slope uncertainty; see Figure S6 in Supporting Information S1), while doubling “winter” precipitation amount would only shift it by  $-0.18\text{‰}$ , as mentioned above (Figure 3). (c) Maximum positive 5 yr rainfall isotopic shifts can only be attained by decreasing both “winter” and “summer” precipitation. Decreasing “summer” precipitation amount alone would produce a maximum positive shift of  $\sim +0.22 \pm 0.1\text{‰}$  when precipitation is reduced by 50%. A larger “summer” precipitation reduction than this, would start shifting rainfall  $\delta^{18}\text{O}$  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, would produce a 5 yr average positive rainfall isotopic shift of  $+0.68\text{‰}$  (Figure 3). This shift corresponds to the difference between the 5 yr average annual amount-weighted  $\delta^{18}\text{O}$  composition of rainfall (including all seasons) versus the 5 yr average “summer” amount-weighted  $\delta^{18}\text{O}$  composition of rainfall.

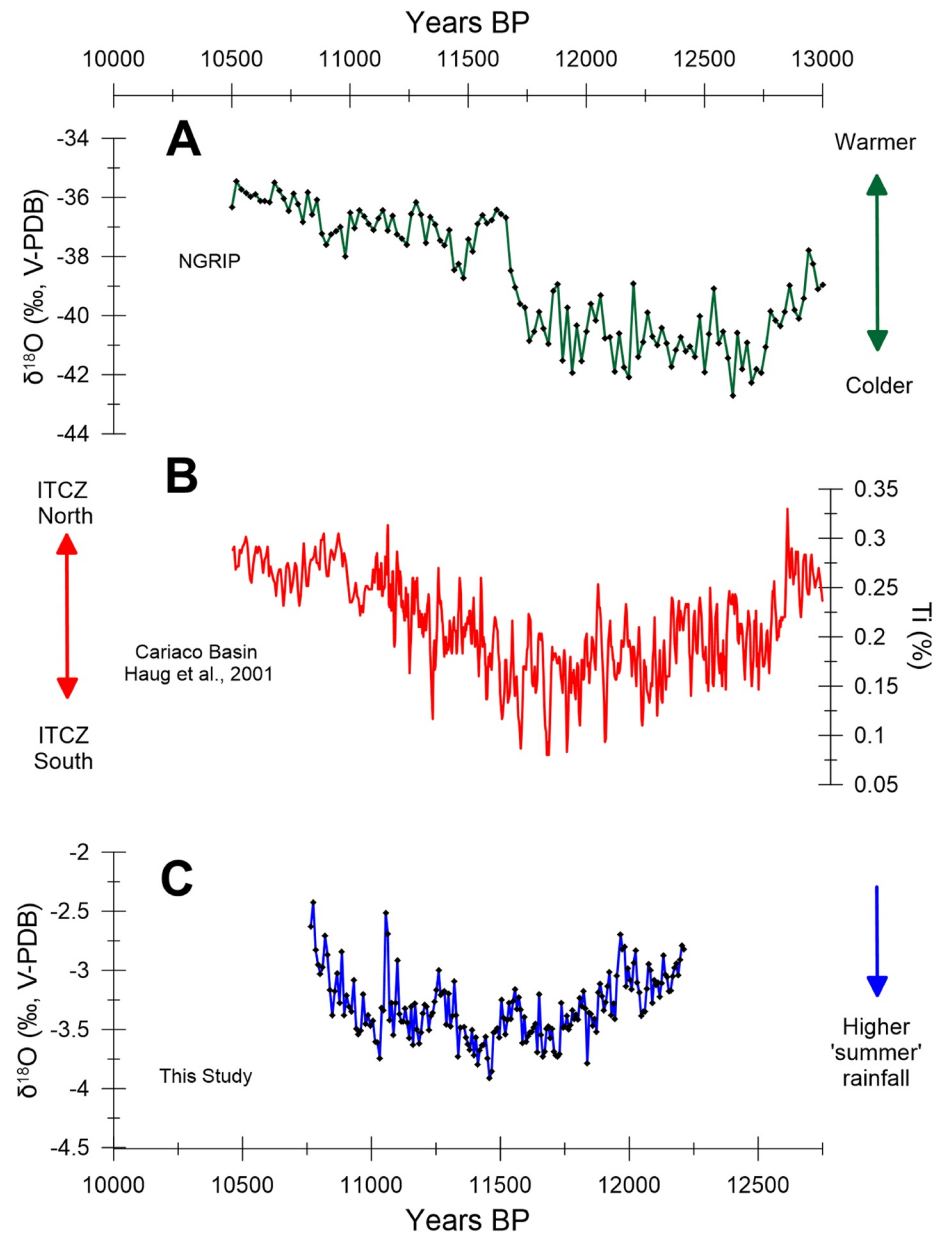
### 3.2. Expected Equilibrium Stalagmite $\delta^{18}\text{O}$ Values

A necessary condition to interpret the oxygen isotopic composition of stalagmite calcite as a record of precipitation  $\delta^{18}\text{O}$  variability is that calcite  $\delta^{18}\text{O}$  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 ( $14.7^\circ\text{C}$ ) and range of annual amount-weighted  $\delta^{18}\text{O}$  composition of rainfall (i.e.,  $-5.5\text{‰}$  to  $-3.9\text{‰}$ ; Table S3) would have a  $\delta^{18}\text{O}$  composition ranging from  $-6.6\text{‰}$  to  $-2.9\text{‰}$  in agreement with the  $PP_{nda}$  stalagmite isotopic composition (Table S4). Supported by these results, in addition to the observed cave environmental conditions (relative humidity  $\sim 100\%$  and stable temperature), we suggest that  $PP_{nda}$  stalagmite calcite was precipitated near isotopic equilibrium conditions and likely faithfully records precipitation  $\delta^{18}\text{O}$  variability (Table S4). We note that  $PP_{nda}$  stalagmite does not have distinctive short-term laminations to successfully produce a conventional Hendy Test *sensu* ref (Dorale & Liu, 2009).

### 3.3. Younger Dryas and 8.2 ka Cooling Events

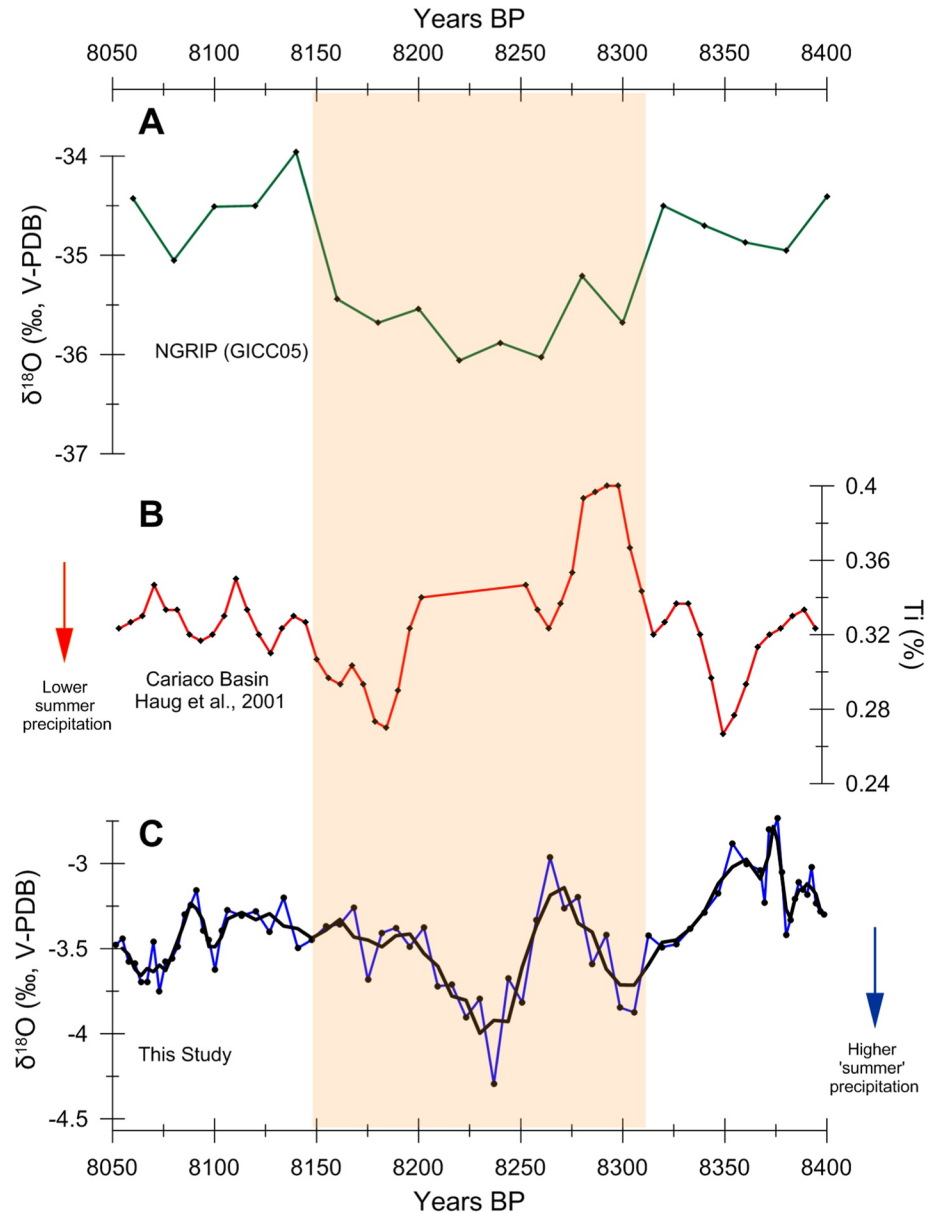
Figures 4 and 5 place the  $PP_{nda}$  stalagmite-precipitation  $\delta^{18}\text{O}$  record in the context of high-latitude climate variability during the YD and 8.2 ka cooling events. Stalagmite  $\delta^{18}\text{O}$  values become progressively more negative during the evolution of these two events by about  $\sim -1.2\text{‰}$ . The observed relationship between precipitation  $\delta^{18}\text{O}$  and precipitation amount observed today on interannual timescales suggests that such negative shift in stalagmite  $\delta^{18}\text{O}$  reflects persistent increases in precipitation amount in the SE US during the peak of these events (Figure S5 in Supporting Information S1). We acknowledge that the negative stalagmite  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$ . As pointed out before, however, global circulation model hosting experiments with isotope tracers suggest that precipitation  $\delta^{18}\text{O}$  would have remained practically unchanged in the SE US during these events (LeGrande et al., 2006). We cave air cooling during these events, on the other hand, would have increased calcite  $\delta^{18}\text{O}$  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 (Figure 3) suggests that the stalagmite isotopic shift of  $\sim -1.2\text{‰}$  can be explained by an average of 90% increase of “summer” precipitation relative to today's conditions (range 75%–130% based on the amount effect uncertainty, Figure S3 in Supporting Information S1). As mentioned previously, an increase in “winter” precipitation by 100% would only shift rainfall  $\delta^{18}\text{O}$  by  $-0.18\text{‰}$  (while maintaining “summer” precipitation amount constant). The possibility that “winter” precipitation declined



**Figure 4.** Blow up comparing the NGRIP ice core  $\delta^{18}\text{O}$  record (panel A; Rasmussen et al., 2006), the  $\text{Ti}\%$  record from the Cariaco Basin, offshore Venezuela (panel B; Haug et al., 2001) and the  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  record (panel C, this study) over the Younger Dryas event (12.9–11.8 ka; Rasmussen et al., 2006). Note that the speleothem isotopic record does not span the full length of the YD event, but only 500 yr of it. 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  $\sim 200$  yr, in order to accommodate a dating uncertainty in the layer counting of young ice of  $\pm 120$  yr in the NGRIP ice core record (Rasmussen et al., 2006) and in the stalagmite  $\delta^{18}\text{O}$  record  $\sim 12$  ka BP of  $\pm 70$  yr (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  $PP_{nda}$  stalagmite record.

at the time cannot be discarded because such a large increase in the influence of “summer” precipitation would be expected to 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  $\delta^{18}\text{O}$  by  $-0.1\text{‰}$  when “summer” precipitation increases by 90% (Table S3). We point out that a decrease of “summer” precipitation to zero while maintaining “winter” precipitation unchanged would decrease rainfall  $\delta^{18}\text{O}$  only by a maximum of  $-0.55\text{‰}$  and thus would fail to explain the observed stalagmite isotopic change of  $-1.2\text{‰}$ . An increase in “summer” precipitation is thus necessary to explain observations. We note that the suggested increase in “summer” precipitation by 90% yields



**Figure 5.** Blow up comparing the NGRIP ice core  $\delta^{18}\text{O}$  record (panel A; Rasmussen et al., 2006), the  $\text{Ti}\%$  record from the Cariaco Basin, offshore Venezuela (panel B) and the  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  record (panel C, this study) over the 8.2 ka cooling event.

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 (Figure S6 in Supporting Information S1). Lastly, we observe that stalagmite hiatuses at 10.8, 4.3, and 0.3 ka BP occurred when the stalagmite  $\delta^{18}\text{O}$  composition had positive trends, suggesting that these hiatuses were associated with drops of precipitation and rainwater infiltration. This inference is also supported by an increasing  $PP_{nda}$  stalagmite  $\delta^{13}\text{C}$  compositions at these times, which likely reflect enhanced Prior Calcite Precipitation and/or a reduction in the contribution of soil carbon to drip water dissolved inorganic carbon (Fairchild & Baker, 2012; see Section 3.6).

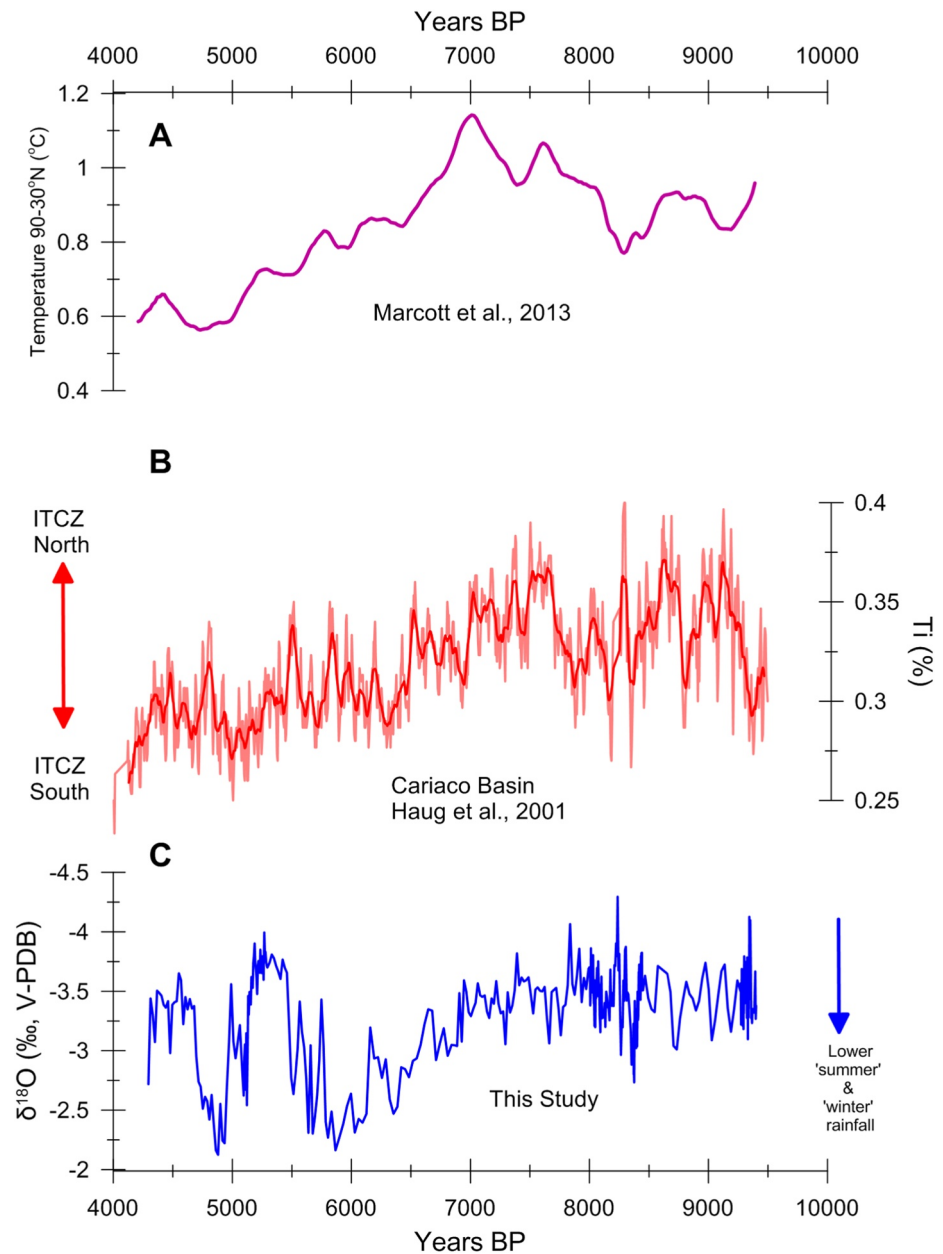
The YD and 8.2 ka events were associated with AMOC slowdown, North Atlantic cooling, a southward displacement of the ITCZ (or weakening of associated convection during boreal summer), and precipitation reductions in the NH low latitudes as suggested by climate model hosing experiments (Dahl et al., 2005; LeGrande et al., 2006; Otto-Bliesner & Brady, 2010; Vellinga & Wood, 2002) and paleoclimate records (Lea et al., 2003; Peterson &

Haug, 2006). A southward displacement of the ITCZ during the YD and 8.2 ka events is suggested by the Cariaco Basin Ti% sediment record from offshore Venezuela and from its antiphase relationship with hydroclimate records from south America (Peterson & Haug, 2006; Figures 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 & Brady, 2010; Stouffer et al., 2006; Vellinga & 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 & Brady, 2010; Vellinga & Wood, 2002). This ocean “cold tongue” is flanked to the west by mild or slightly cooler surface temperatures in the western North Atlantic mid-latitudes and GOM 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 SE US. On the other hand, during the YD, a planktonic foraminifer *Globigerinoides ruber* (pink) Mg-SST record from Orca Basin, located in the northern GOM, suggests a 1.5°C increase in summer SSTs and enhanced temperature seasonality, particularly from 12.4 to ~11.8 ka BP (Williams et al., 2010). In contrast, another *G. ruber* (white variety) Mg-SST record from the western margin of the Florida Straits (site KNR166-2-26JPC), suggests that SSTs were 1°C colder during the YD and they increased progressively across this event (Schmidt & Lynch-Stieglitz, 2011). This SST divergence suggested by *G. ruber* pink and white varieties during the YD likely reflects that they live preferentially during the summer and winter, respectively (see Williams et al., 2010, for a discussion).

Increased local precipitation in the SE US during the YD would be favored by warmer ocean conditions in the GOM and western North Atlantic, particularly in the summer, and/or by coeval enhancement of meridional and zonal temperature gradients in the North Atlantic and GOM. This is supported by various model experiments of freshwater perturbation to AMOC, which simulate enhanced precipitation in the SE US coeval with precipitation reduction in the tropical Atlantic, and enhanced meridional and zonal air temperature gradients, in agreement with observations (LeGrande et al., 2006; Renssen et al., 2002; Vellinga & Wood, 2002; Figures 4 and 5). Hydroclimate inferences for the SE US during the YD and 8.2 ka events have potential implications for the inferred position and strength of the North Atlantic subtropical high-pressure (NASH) system at the time. Significant summer precipitation enhancement in the SE US during these events would be consistent with a westward movement of the NASH western ridge toward the American continent and with intensification of its center as suggested by modern observations (Li et al., 2012, 2013). Western displacement of the NADH western ridge could also result in enhanced evaporation in the GOM at the time which would increase ocean salinity, in agreement with foraminiferal  $\delta^{18}\text{O}$  and SST records spanning the YD (Schmidt & Lynch-Stieglitz, 2011).

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 GOM, 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 AMOC slowdown/shutdown. This pattern is consistent with evidence from the instrumental record that indicates an antiphase relationship between precipitation in the SE US and the broader Caribbean on seasonal and interannual timescales (Figure 1 and Figure S7 in Supporting Information S1). Lastly, climate model predictions for the SE region by the end of this century under the IPCC RCP 8.5 scenario suggest that moisture and precipitation are reduced in the SE US under warmer atmospheric conditions (Heidari et al., 2020).



**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  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  record (panel C, this study) spanning the transition from the Early to the mid-Holocene. Darker continuous lines represent 7-point moving averages.

### 3.4. Early to Mid-Holocene Climate Variability

The  $PP_{nda}$  stalagmite suggests a long-term  $+1\text{‰}$  isotopic shift occurring from  $\sim 7.5$  to  $\sim 5.5$  ka (Figure 6). A decline in “summer” precipitation alone would not explain this large positive isotopic shift, because it would increase  $\delta^{18}\text{O}$  by  $+0.2\text{‰}$  maximum, when precipitation amount decreases by 50% (Figure 3). As mentioned previously, a decrease of “summer” precipitation amount beyond this level would no longer increase annual precipitation  $\delta^{18}\text{O}$  because the depleted isotopic composition of “winter” rainfall becomes dominant after this threshold (Figure 3). An additional 80% 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 as pointed out before the maximum isotopic shift when “winter” precipitation becomes zero is  $+0.68\text{‰}$ , therefore it would still be insufficient to explain the mid-Holocene stalagmite



shift (Figure 3). The precipitation decline from  $\sim 7$  to  $\sim 6$  ka suggested by the  $PP_{nda}$  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 & 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, 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; Figure 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). Faunal assemblage records from the GOM indicate increased transport of Caribbean waters into the Gulf and warmer than present winter sea surface temperatures during the early Holocene (Kennett et al., 1985; Poore et al., 2003). 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).

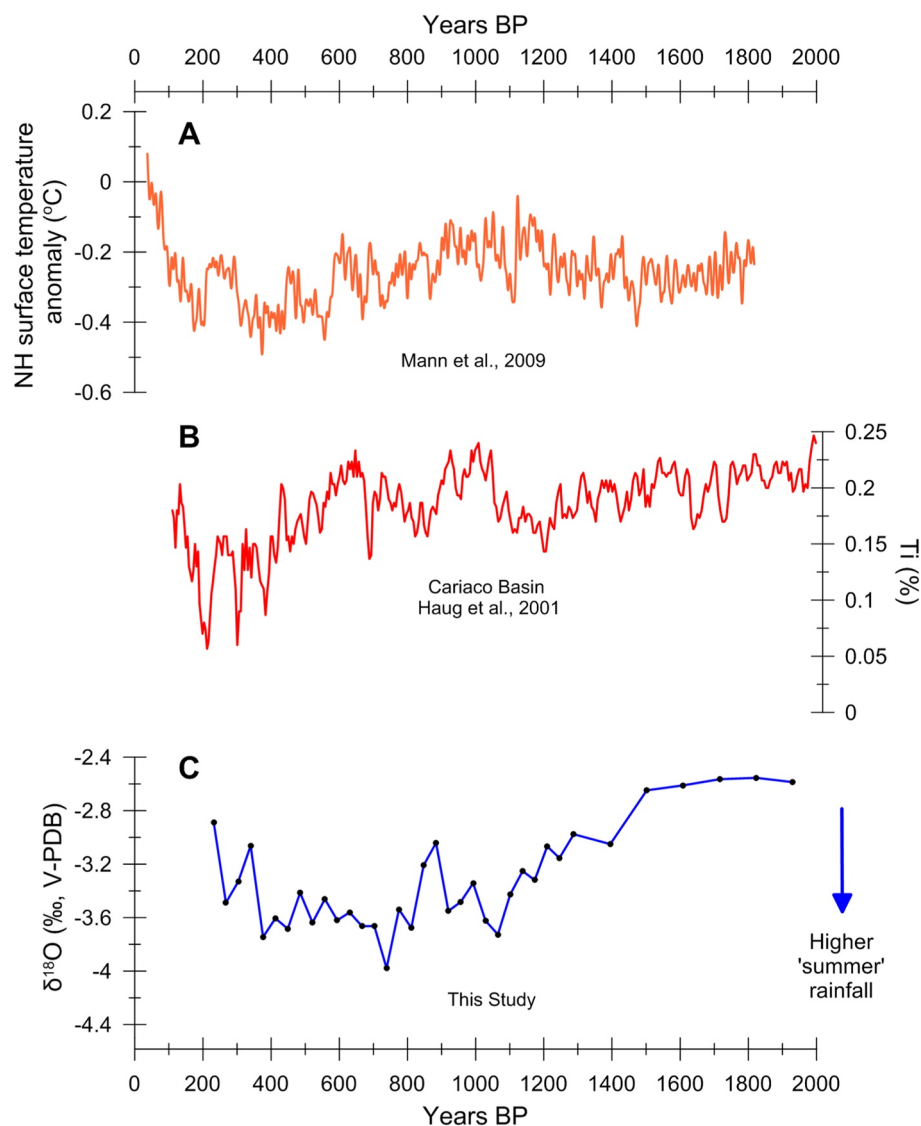
The drying trend suggested by the  $PP_{nda}$  stalagmite is interrupted by two climate excursions between 6 and 4.5 ka BP indicated by prominent negative isotopic excursions (Figure 2 and Figure S8 in Supporting Information S1). These inferred climate excursions are also represented, although more subtly, by the stalagmite  $\delta^{18}\text{O}$  record from DeSoto Caverns, Alabama, that spans the interval between  $\sim 6$  ka and 1 ka BP (Aharon & Dhungana, 2017; Figure S8 in Supporting Information S1). 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; Figure 5). Isotopic excursions are also observed in the  $PP_{nda}$  stalagmite  $\delta^{13}\text{C}$  record, offering further evidence of a local hydrological change at the time (Figure 2). We lastly note that these climate excursions are not suggested by two stalagmite  $\delta^{18}\text{O}$  records from West Central Florida: that is, the stalagmite BC01–17, spanning the interval between 6.5 and 4.5 ka BP (Pollock et al., 2016), and the stalagmite BRC03–03, spanning the interval between  $\sim 5$  and 4 ka BP (Beynen et al., 2017). These two additional stalagmite records from the southeastern US indicate that more stable hydroclimate occurred in West Central Florida while rapid climate swings were occurring further west in Northern Alabama. We propose that the Alabama speleothems' isotopic excursions probably record an amplified regional hydrological response to North Atlantic climate conditions perhaps reflecting that dynamical processes (*sensu* Li et al., 2013), 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 terrestrial precipitation recycling (Dominguez et al., 2006), with enhanced depletion of its oxygen isotopic composition, 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).

### 3.5. Late-Holocene Climate Variability

During the transition from the Medieval Climate Anomaly time interval to the LIA (Mann et al., 2009), the  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  record shows a negative isotopic shift from 1.2 to 0.4 ka BP of  $\sim -0.8\text{‰}$  (Figure 7). This stalagmite negative isotopic excursion coincides with the LIA interval (Mann et al., 2009); the Holocene's coldest period in the North Atlantic (Marcott et al., 2013) and the driest in the Caribbean (Higuera-Gundy et al., 1999; Hodel et al., 1991; Peterson & Haug, 2006). Similar to our previous interpretation concerning the YD and 8.2 ka events, we suggest that this negative isotopic excursion reflects an increase in “summer” precipitation. We note that tree ring records from the eastern SE US spanning the last 1,000 yr (Stahle & Cleaveland, 1992) do not suggest a long-term shift in spring precipitation during the LIA interval. We thus infer that the long-term stalagmite isotopic shift associated with the LIA may only reflect precipitation changes during the summer season.

Although the evidence provided by the  $PP_{nda}$  stalagmite  $\delta^{18}\text{O}$  record during the YD and LIA suggest a consistent relationship between low latitude hydroclimate change and high latitude North Atlantic cooling (Keigwin & Boyle, 2000; Lund et al., 2006), we note that the inference of a similar magnitude increase in precipitation during these two events is surprising in light of evidence that the magnitude of freshwater forcing to North Atlantic cooling and AMOC slowdown was significantly lower during the LIA relative to the YD. The latter as suggested by North Atlantic deep sea sediment  $^{231}\text{Pa}/^{230}\text{Th}$  records (McManus et al., 2004), a recent reconstruction of AMOC strength (Rahmstorf et al., 2015) and transient model simulations (Moreno-Chamarro et al., 2015). Thus,





**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  $PP_{nda}$  stalagmite  $\delta^{18}O$  record (panel C, this study) spanning the late Holocene. The mean resolution of the stalagmite record over this time interval is 44 yr.

hydroclimate variability in the SE US during the LIA was perhaps not solely related to AMOC slowdown. Additional factors such as increasing Arctic sea ice export (Moreno-Chamarro et al., 2015), a negative phase shift of the Atlantic multidecadal variability, and a weakening of the North Atlantic subpolar gyre (Lapointe & Bradley, 2021) were likely sufficient to produce the observed North Atlantic cooling during the LIA, which in turn produced the enhanced hydroclimate response at the time suggested by this study.

### 3.6. Stalagmite Carbon Isotopes

Across the full length of the  $PP_{nda}$  stalagmite, and during the prominent climate events highlighted above, the stalagmite  $\delta^{13}C$  record mimics the  $\delta^{18}O$  record (Figure 2). We note that most of the stalagmite  $\delta^{13}C$  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 & Baker, 2012). Hydrological shifts affecting vegetation type, density, and/or soil microbial productivity are, therefore, unlikely to dominate the  $\delta^{13}C$  signal and the observed covariance between stalagmite  $\delta^{13}C$  and  $\delta^{18}O$ . We therefore conclude that covariance

between stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  reflects shifts in karst hydrology whereby wetter conditions would favor faster infiltration, decreased  $\text{pCO}_2$  degassing and reduced prior calcite precipitation, ultimately producing lower  $\delta^{13}\text{C}$  values from a bedrock-dominated carbon baseline (Fairchild & Baker, 2012).

#### 4. Conclusion

We produced high-resolution stalagmite  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records of hydroclimate from Alabama spanning the last 12 ka, extending the existing regional paleoclimate record to the early Holocene. Spatial correlation analysis using the instrumental record of precipitation amount indicate that hydroclimate variability in Alabama is coherent with the broader SE US. We interpret the stalagmite  $\delta^{18}\text{O}$  record to reflect the relationship between rainfall amount and  $\delta^{18}\text{O}$  that is observed today on interannual timescales and shifts in the relative contributions of precipitation, over the different seasons, to the annual budget. The stalagmite  $\delta^{13}\text{C}$  record reflects variability in prior calcite precipitation and a bedrock-dominated carbon source. Based on this interpretation of stalagmite isotopic records, we find a consistent hydrological response during the YD, 8.2ka and LIA, whereby the SE US becomes wetter as a result of an increase in summer precipitation. We find a close connection between hydroclimate variability in the SE US, North Atlantic high latitude climate variability and Caribbean/GOM 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 LIA 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.  $PP_{nda}$  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 Hemisphere, 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. Our study suggests that similar to how AMOC shutdown could counteract anthropogenic global warming in the coming centuries by inducing global cooling (Drijfhout, 2015), it could also mitigate future aridification in the SE US by enhancing precipitation. The dynamical link between AMOC shutdown and precipitation variability in the SE US remains, however, to be examined further by future studies, including those with regional model simulations.

#### Data Availability Statement

The new  $PP_{nda}$  stalagmite carbon and oxygen isotopic data presented in this study in Figure 2 is available in its associated Supporting Information (Tables S1 and S2) and at the NOAA National Centers for Environmental Information websites: (<https://www.ncei.noaa.gov/access/paleo-search/study/35213>) and (<https://www.ncei.noaa.gov/pub/data/paleo/speleothem/northamerica/usa/alabama/war-eagle2022iso.txt>). Modern precipitation data used is available at (<https://psl.noaa.gov/data/gridded/data.gpcp.html>). Rainfall isotopic data represented in Figure 3, Figures S5, and S6 in Supporting Information S1, collected at the University of Tuscaloosa, United States, from January 2005 to December 2008, is available in the IAEA GNIP database (<https://www.iaea.org/services/networks/gnip>).

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