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Changing amounts and sources of moisture in the U.S. southwest since the Last Glacial Maximum in response to global climate change

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ABSTRACT

The U.S. southwest has a limited water supply and is predicted to become drier in the 21st century. An improved understanding of factors controlling moisture sources and availability is aided by reconstruction of past responses to global climate change. New stable isotope and growth-rate records for a central Texas speleothem indicate a strong influence of Gulf of Mexico (GoM) moisture and increased precipitation from 15.5 to 13.5 ka, which includes the majority of the Bølling–Allerød warming (BA: 14.7–12.9 ka). Coeval speleothem records from 900 and 1200 km to the west allow reconstruction of regional moisture sources and atmospheric circulation. The combined isotope and growth-rate time series indicates 1) increased GoM moisture input during the majority of the BA, producing greater precipitation in Texas and New Mexico; and 2) a retreat of GoM moisture during Younger Dryas cooling (12.9–11.5 ka), reducing precipitation. These results portray how late-Pleistocene atmospheric circulation and moisture distribution in this region responded to global changes, providing information to improve models of future climate.

1. Introduction

The effect of future climatic changes on water availability in the subtropics is a substantial concern for a large segment of the world's population (Solomon et al., 2007). The highly populated U.S. southwest is particularly susceptible to droughts (Seager, 2007), as evinced by the record-setting drought that began in 2011 (Hylton, 2011). Using climate proxies to understand the regional response of effective precipitation to changes in hemispheric and global climate change of the past may provide guidance for future planning, development, and water management.

The U.S. southwest (broadly defined, e.g., Seager et al., 2007) extends from the Edwards Plateau (in central Texas) in the east to the Pacific coast in the west. The area covers four physiographic regions: the Interior Plains, the Rocky Mountain System, the Intermontane Plateaus, and the Pacific Mountain System. The Chihuahuan and Sonoran deserts, situated in the longitudinal center of the U.S. southwest (mostly within southern Arizona and New Mexico), are two prominent arid lands, whose larger portions extend further south into Mexico. The source regions of the moisture transferred to these arid regions vary seasonally, with an increasing contribution of Gulf of Mexico (GoM) moisture to summer precipitation, and winter precipitation mostly Pacific-sourced (Gulf of California, Fig. 1, e.g., Asmerom et al., 2010; Pape et al., 2010; Wagner et al., 2010). Precipitation from these two source regions has different oxygen isotopic compositions ($\delta^{18}O$ values). This leads to a strong correlation between moisture source and isotopic composition (Strong et al., 2007). New Mexico precipitation is seasonal, with a strong summer monsoon pattern in annual rainfall and drier than average summers typically following wetter winters (Stahle et al., 2009). The isotopic composition of semi-arid to subtropical central Texas precipitation is consistent with a GoM source (Pape et al., 2010) and shows strong seasonal autocorrelation. Summer precipitation amount is dependent on soil moisture conditions that are controlled by winter precipitation (Myoung and Nielsen-Gammon, 2010).

Speleothem $\delta^{18}O$ values, which likely reflect the precipitation $\delta^{18}O$ at the time of calcite deposition, provide a means

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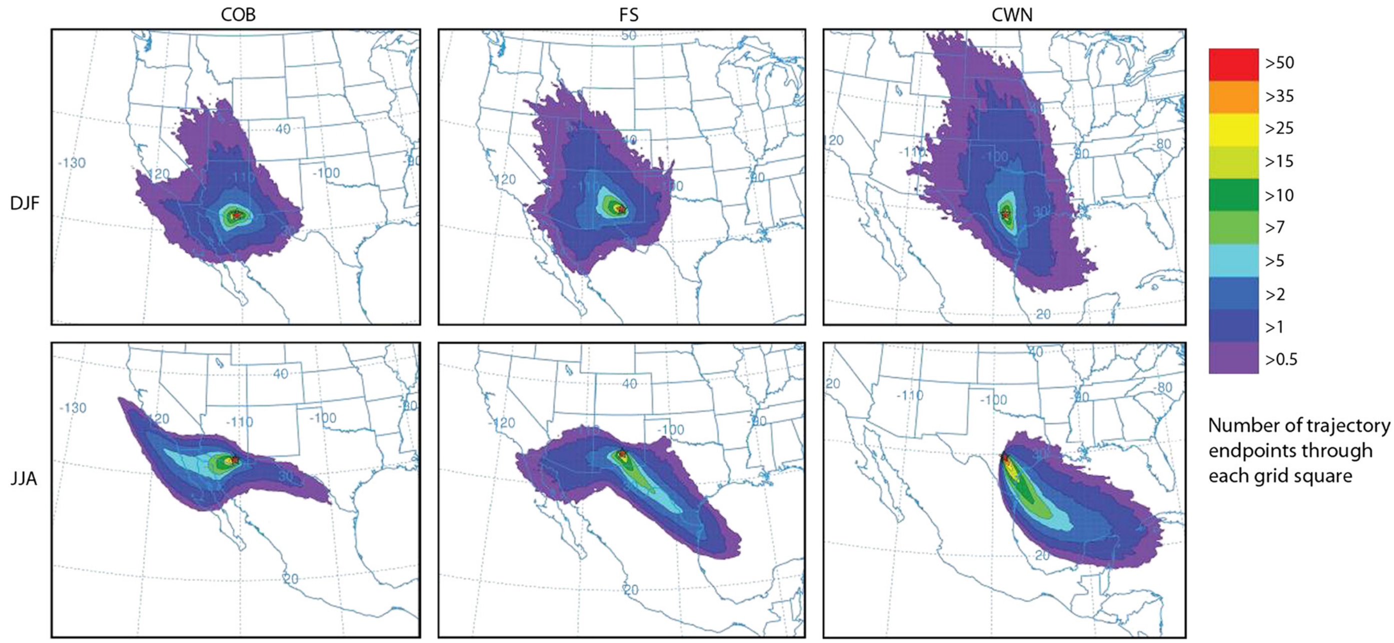

Fig. 1. Frequency of air mass trajectories for December–January–February (DJF) and June–July–August (JJA) at the locations of the three U.S. southwest caves: Cave Without a Name (CWN, Texas); Fort Stanton (FS, New Mexico); Cave of the Bells (COB, Arizona). Frequencies are plotted as percentages of all trajectories passing through a given grid square over the thirty year period from 1980 to 2009 (inclusive). In this period, CWN site received ∼28% of annual precipitation in JJA and 17% in DJF (NCDC, station ID: 410902). For FS, 46% and 25% of annual precipitation occurred in JJA and DJF respectively (station ID: 291440). For COB site, 48% and 13% of annual precipitation occur in JJA and DJF respectively (station ID: 27593).

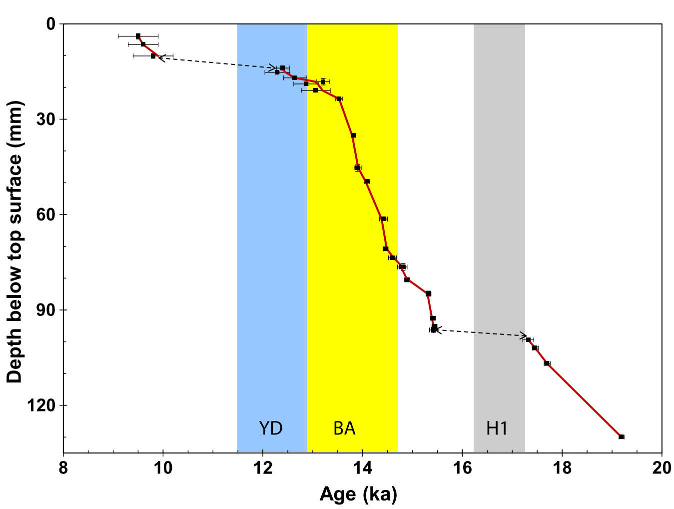

Fig. 2. CWN-4 age model. Data are from Table S1. Solid black squares are the corrected ages with 2σ uncertainties. Solid red line is age model using assigned ages (Table S1). Vertical error bars are determined based on the thickness of the dated layers (may be too small to see) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

for assessing climatic conditions prior to the instrumental record. Speleothem $\delta^{13}C$ values also may serve as secondary indicators of surficial and in-cave processes that carry paleoclimate information. This study presents a new $\delta^{18}O$ and $\delta^{13}C$ time series and twenty-one new U-series ages (Fig. 2; supplementary material, Table S1) for speleothem CWN-4 from a central Texas cave. Integrated analysis of changes in the growth rate and stable isotope records for the period from the Last Glacial Maximum (LGM) to the beginning of the Holocene, which includes the Bølling–Allerød warming (BA, 14.7–12.9 ka) and Younger Dryas cooling (YD, 12.9–11.5 ka), and comparison with speleothem isotope records from elsewhere in the region elucidate controls on precipitation in the U.S. southwest from central Texas to Arizona.

2. Methods and samples

CWN-4 is from *Cave Without a Name* (CWN, 29°53.11′N; 98° 37.25′W, Fig. 1) near Boerne, Texas. The cavern is located on the eastern Edwards Plateau, and formed within the lower Cretaceous Glen Rose Limestone. The stalagmite is ∼50 cm in length, and comprised of translucent calcite that is coarsely crystalline with a columnar fabric. Previous geochronological study of the sample indicates growth from 38.5 to ∼9.6 ka (Musgrove et al., 2001). The top portion (174 mm in length), which is used in this study, grew from ∼29 ka to 9.6 ka. Possible hiatuses occur at depths (from top of the sample) of 13, 99, 131, 144, and 205 mm (Fig. S1).

2.1. Determination of moisture sources and seasonality in the U.S. southwest

To track moisture sources, back trajectories of particle movements were created for 72 h periods using the registered version of the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model (Draxler and Hess, 1998). The model was run for CWN and two additional cave sites in New Mexico (FS: Fort Stanton Cave) and Arizona (COB: Cave of the Bells), for which speleothem records (Asmerom et al., 2010; Wagner et al., 2010) are compared with CWN-4. Backwards trajectories tracking air masses over the previous 72 h were generated every six hours for thirty years from January 1, 1980 to December 31, 2009 using NCAR/NCEP reanalysis data. A total of 43,832 trajectories were created for each site, which were grouped by season (DJF, MAM, JJA, and SON) and processed using a batch file script to create a trajectory frequency plot for each season.

The plotted trajectory frequencies were compared with the percentage contributions of seasonal (DJF and JJA) precipitation. Precipitation data are from National Weather Service Cooperative stations at Boerne, Texas (COOP ID: 410902); Santa Rita, Arizona (COOP ID: 27593); and Capitan, New Mexico (COOP ID: 291440).

2.2. U-series geochronology and speleothem growth rate

U-series chronology was obtained for samples collected from two faces (I and II, supplementary material, Fig. S1) of CWN-4. This study includes eight ages from a previous study (Musgrove et al., 2001), and twenty-one new ages (Fig. 2, supplementary material, Fig. S1, Table S1).

Samples for U-series analyses were drilled by hand using a dental drill, or by a Merchantek Microdrill (New Wave Research, Fremont, CA) along growth layers in a laminar flow hood at the University of Texas at Austin (UT). About 200–700 mg of powder for each sample was prepared in a class 100 clean lab at UT or in a clean lab at the University of Minnesota–Twin Cities (UMN) as described by Musgrove et al. (2001). Isotope ratios were measured on a Thermo–Finnigan Triton TIMS (UT) or a Neptune ICP-MS (UMN). Ages were calculated using published half-lives (Cheng et al., 2009) and corrected for detrital thorium assuming an initial ^{230}Th/^{232}Th ratio of 4.4 ± 2.2 ppm. The eight ages reported in the prior study of CWN-4 (Musgrove et al., 2001) were re-calculated using these parameters.

An age model (Fig. 2) was constructed by linear interpolation between measured ages. Where this resulted in an apparent age reversal, the age of the horizon was shifted (assigned ages, Table S1) within the stated uncertainty (2σ) to create a monotonic trend. Consideration was given to minimize abrupt changes in growth rate and to make the assigned age as close to the measured age as possible. Growth rates were calculated as the ratio of the distance between the middle-depth of the two consecutive dated layers and the age difference represented by the two dates. The growth rate plot ends at the youngest dated layer. This differs from a previous study of CWN-4, which assumed a modern age at the top (Musgrove et al., 2001). Note that despite possible hiatuses (Fig. S1), above 131 mm, there are more than two U/Th ages between every two possible hiatuses, allowing more reliable estimates of the growth rates for the top 131 mm than those below.

2.3. Stable isotope analyses

For stable isotope analyses, 896 calcite powder samples were collected along the approximate central growth axis of CWN-4 using a Super-tech Taig-3000 Micromill (Fig. S1). To resolve decadal variations, the top 800 samples were milled at a 200 μm step along an 800 μm-wide track with an 800 μm depth after removal of the surface 100–200 μm. The base 96 samples were milled at a 100 μm step with the same track width and depth. Of the samples collected, 568 were analyzed. This includes most of the top 800 samples and all 96 samples from the base (see supplementary material for analysis strategy).

The age of each CWN-4 calcite sample milled for stable isotope analysis was determined based on the sample's distance from the closest dated layer and the calculated growth rate for the sampling location. A StalAge (Scholz and Hoffmann, 2011) model was also constructed, which delivers essentially the same results as the simpler linear interpolation age model for the period of interest from 16 ka forward.

Stable isotope analyses were carried out using the modified method of McCrea (1950) on a Thermo-Finnigan MAT 253 attached to a Kiel IV carbonate device at the University of Texas at Austin. Seventy one NBS-19 standards were run with CWN-4 samples and have an average value for δ^{18}O of $-2.20 \pm 0.12(2\sigma)$‰ and for δ^{13}C of $1.95 \pm 0.04(2\sigma)$‰ (V-PDB). Twenty four Estremoz standards were run with an average value for δ^{18}O of $-5.95 \pm 0.14(2\sigma)$‰ and for δ^{13}C of $1.63 \pm 0.06(2\sigma)$‰ (V-PDB).

3. Results

3.1. HYSPLIT back trajectories

Cool season trajectories (DJF, Fig. 1) show greater influence of Pacific moisture at all sites; warm season (JJA) trajectories include more easterly flow (Fig. 1). For CWN and FS, these easterly pathways originate over the GoM, while air masses are unable to reach COB from the GoM within the 72 h used in the model runs. The COB site shows strong influence of Pacific moisture throughout the year, but also includes an easterly component during summer months. The CWN site moisture appears to originate consistently from the GoM, with possibly some recycled moisture from the continental interior. The FS site has a greater mix between the two source regions, with GoM contributions occurring exclusively during warm months.

3.2. Stable isotopes

CWN-4 calcite has relatively invariable δ^{18}O values ranging from −3.8 to −2.1‰ (average: −3.2‰, Fig. 3) from the LGM to the beginning of the BA. At glacial Termination I (∼14.7 ka, Fig. 3), δ^{18}O values declined abruptly by ∼1.5‰ in ∼200 yr, followed by an additional 0.5‰ decrease during the BA. The transition to the YD is characterized by a relatively abrupt 2‰ rise, essentially returning to glacial δ^{18}O values. In the early Holocene, δ^{18}O values were slightly more negative (∼1‰).

The CWN-4 record shows strong correspondence with the GoM seawater δ^{18}O time series from the Orca Basin (Fig. 3, Flower et al., 2004; Williams et al., 2012). Both records show large negative shifts at the onset of Termination I (Fig. 3), and reached their lowest values during the BA (∼13.3 ka). Both records then shifted to more positive values across the BA/YD boundary and reached pre-Termination I values during the YD (∼12.6 ka). This is followed by ∼1‰ more negative values in both records in the early Holocene.

The δ^{13}C values range from −7.5 to −3.3‰ (Table S2, Fig. 3). There is an overall weak correlation between δ^{13}C and δ^{18}O ($r^2 = 0.20$, $p < 0.0001$, Fig. S2). However, within each individual time period associated with paleoclimatic variability (e.g., LGM to Termination I, BA, YD and onward), there is no correlation (Fig. S2).

3.3. Growth rate

CWN-4 speleothem growth rates varied between 3 and 87 μm/yr (Fig. 4) for the three continuous growth periods separated by hiatuses. From the LGM to 15.5 ka, growth rates were ∼20 μm/yr. From 15.5 ka, the growth rate rapidly increased (with some fluctuation) to 87 μm/yr within 1 ky. The growth rate remained mostly high for most of the BA before slowing (3–21 μm/yr) from 13.5 ka to the YD (11.5 ka). The growth rate remained low (∼19 μm/yr overall) above the hiatus for the early Holocene until the record ends at 9.6 ka. The notably faster growth and more negative δ^{18}O values during the BA are the main features of the CWN record.

4. Discussion

4.1. Controls and implications of the CWN-4 isotope and growth-rate records

The CWN-4 δ^{18}O record is similar to seawater δ^{18}O records from the Orca Basin in the northwest GoM in both the timing and magnitude of events (Fig. 3, Flower et al., 2004; Williams et al., 2012). The ∼2–3‰ decline in GoM seawater δ^{18}O values beginning at ∼16 ka has been attributed to an influx of low δ^{18}O glacial meltwater (Flower et al., 2004), which shut off once the Laurentide

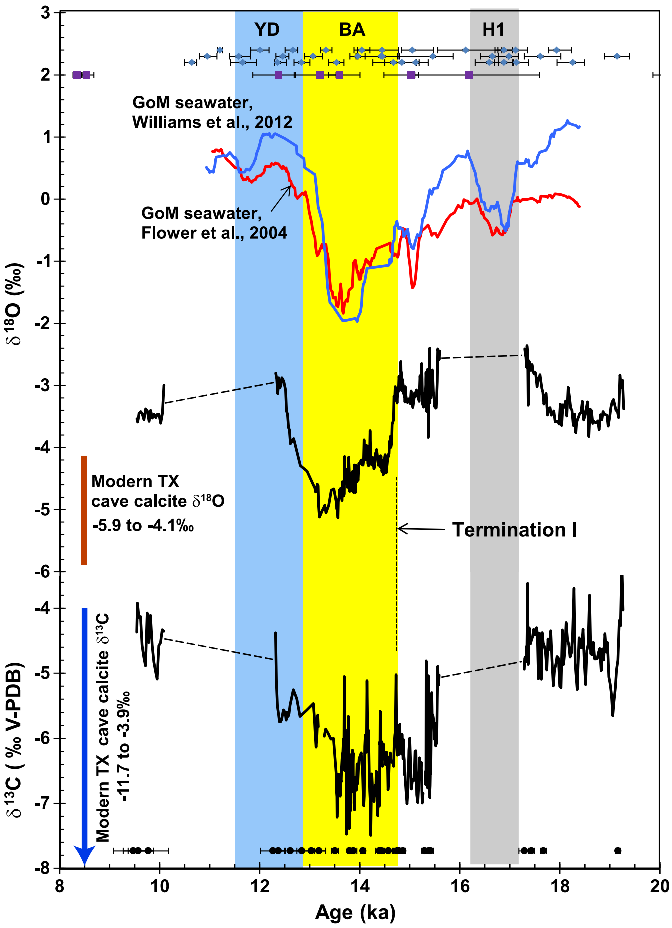

Fig. 3. Comparison of CWN-4 speleothem δ^{13}C and δ^{18}O, and Gulf of Mexico (GoM) seawater δ^{18}O records. The GoM seawater records are from the Orca Basin (red and blue solid line). Similarities between the speleothem (V-PDB, black line) and GoM seawater records (V-SMOW) indicate a predominant control of GoM moisture on central Texas precipitation. The timing of the Termination I, the Bølling–Allerød (BA), Younger Dryas (YD), and Heinrich events 1 (H1, e.g., Hemming, 2004) are included for reference. Age control of the seawater records is plotted at the top of the figure, while corrected U-series ages for CWN-4 are located below the δ^{13}C time series. Dash lines represent possible hiatuses in speleothem growth. Also plotted is the range of modern cave calcite δ^{18}O values (−5.9 to −4.1‰, from Inner Space Cavern and Natural Bridge Caverns, Feng et al., 2012) and δ^{13}C values (−11.7 to −3.9‰, from Inner Space Cavern, unpublished data). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

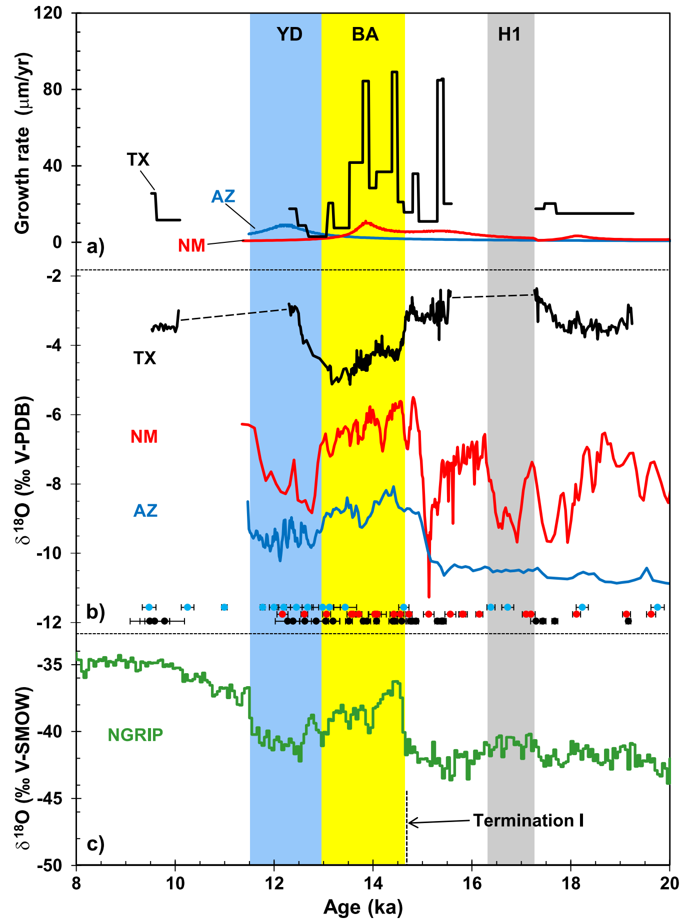

Fig. 4. Comparison of Texas, New Mexico, and Arizona speleothem δ^{18}O and growth-rate records. Time series are: a) speleothem growth rates (μm/yr) for Texas (CWN-4; black), New Mexico (FS-2; red), and Arizona (COB-01-02; blue); b) speleothem calcite δ^{18}O time series (V-PDB) and associated U-series ages (with 2σ error bars, colors correspond to the δ^{18}O time series) for Texas (black), New Mexico (red) and Arizona (blue); and c) North Greenland Ice Core Project (NGRIP) ice core δ^{18}O (V-SMOW, green line, Andersen et al., 2004) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ice sheet retreated beyond the Mississippi River drainage divide at ∼13 ka (Tarasov and Peltier, 2005), causing seawater δ^{18}O values to rebound. A similar link between speleothem δ^{18}O and regional seawater composition has previously been shown (Bar-Matthews et al., 2003; Badertscher et al., 2011) in the East Mediterranean and Black Sea regions. The correspondence between the GoM and CWN-4 δ^{18}O records indicates that CWN received moisture predominantly from the part of the GoM that was most affected by glacial outflow, as not all GoM seawater δ^{18}O records show the same magnitude and timing of the depletion event (Aharon, 2006; Nürnberg et al., 2008). Thus, the CWN-4 δ^{18}O record appears to predominantly reflect changes in the GoM moisture source δ^{18}O values, rather than reflecting meteorological processes resulting from changing temperature, seasonality, or amount of precipitation.

The inferred dominance of a GoM moisture source at CWN is supported by several lines of evidence. This inference is consistent with modern precipitation in central Texas (Fig. 1, Pape et al., 2010). Although Pacific moisture, with ∼10‰ more negative δ^{18}O values (Hoy and Gross, 1982; Yapp, 1985), occasionally contributes to modern local precipitation (Pape et al., 2010), it does not appear to have left a notable signal in the CWN-4 δ^{18}O record. This is likely due to GoM-sourced precipitation dominating the moisture budget in the area (Fig. 1). Modern central Texas precipitation δ^{18}O values show no correlation with temperature (Pape et al., 2010). Precipitation amount significantly impacts δ^{18}O values only at monthly mean temperatures above 26.9 °C, when it is less likely to contribute to recharge (Pape et al., 2010). A temporal decrease in δ^{18}O of rainfall in Texas during the BA alternatively could have been driven by an increase in tropical cyclone activity facilitated by warm GoM SSTs. Such cyclones produce precipitation with significantly lower than usual δ^{18}O values (e.g., Lawrence and Gedzelman, 1996; Pape et al., 2010). However, from ∼16.2 to 11.8 ka, spanning the BA, summer SSTs show little to no change (Williams et al., 2012), suggesting that increased cyclone activity driven by higher SSTs is not the cause. Additionally, monitoring in central Texas caves from 1999 to 2014 shows no discernible changes in drip water or calcite δ^{18}O values despite variations in cyclone frequency and intensity, and annual rainfall ranging from ∼40 to 130 cm (Pape et al., 2010; Feng et al., 2012, 2014).

Other factors that might influence CWN-4 isotopic values include kinetic effects (Hendy, 1971; Mickler et al., 2004, 2006; Feng et al., 2012) and/or seasonal growth biases (Banner et al., 2007). The seasonally biased growth observed in Texas caves (Banner et al., 2007) is unlikely to be responsible for the observed shifts in the isotopic time series, because most drip waters have residence times of greater than a year (Pape et al., 2010).

The impacts of kinetic effects on speleothem $\delta^{18}O$ values differ significantly depending on the cause (e.g., Hendy, 1971; Mickler et al., 2004, 2006; Feng et al., 2012). Commonly proposed causes include surface layer trapping, water evaporation and rapid CO_2 degassing. Surface layer trapping can lead to a −0.8‰ shift for every ten-fold increase in calcite deposition rate (Feng et al., 2012). It cannot, however, account for the magnitude (−2‰) of the variation in the isotope record. Water evaporation increases both water and calcite $\delta^{18}O$ values; if this were responsible for the variations in the CWN-4 time series, calcite deposited outside the BA would be in disequilibrium. However, CWN-4 $\delta^{18}O$ values for non-BA time periods averaged −3.1‰ (±1‰) V-PDB, in equilibrium with a drip water (and rainfall) composition of ∼−2.9‰ V-SMOW. Assuming interglacial seawater $\delta^{18}O$ being ∼1‰ lower than glacial period seawater (e.g., Schrag et al., 2002), this value is consistent with modern regional rainfall from GoM moisture (−7 to −2‰, Pape et al., 2010), and agrees with the hypothesis that the CWN-4 $\delta^{18}O$ record reflects the composition of GoM moisture. Furthermore, 14 years of modern drip water $\delta^{18}O$ and cave meteorological monitoring at multiple sites in several central Texas caves show no evidence of significant evaporation (Banner et al., 2007; Feng et al., 2012, 2014). Monitoring studies show that slow growth at these sites produces calcite closer to $\delta^{18}O$ equilibrium than faster growth (Feng et al., 2012), the opposite pattern to the hypothesis that significant evaporative enrichment occurs under slow calcite growth.

Elevated $\delta^{13}C$ values in speleothem calcite, compared to values in equilibrium with CO_2 sourced from C_3-dominated vegetation, may imply the influence of C_4 vegetation or kinetic effects on $\delta^{13}C$ values. However, significant ^{13}C enrichments have also been accounted for by CO_2 degassing in the vadose zone above caves (e.g., Frisia et al., 2011; Lambert and Aharon, 2011) and in central Texas (Guilfoyle, 2006). This alternative control on $\delta^{13}C$, however, does not affect speleothem $\delta^{18}O$ values significantly due to buffering effects of a much larger oxygen reservoir in the drip water ($O:C \geq 10^3$). In fact, given more time for isotopic buffering, the slower calcite growth during the non-BA period enables values closer to $\delta^{18}O$ equilibrium. The lack of significant correlation between $\delta^{13}C$ and $\delta^{18}O$ values also supports the hypothesis (Fig. S2) that controlling factors for the two isotopes are not the same. Furthermore, recent studies of the modern CO_2 cycle in caves in this region shows that CO_2 transport to the caves is preferentially sourced from deeply rooted plants in the soil zone, providing another line of evidence for the decoupling of oxygen and carbon isotopes (Breecker et al., 2012). Therefore, the speleothem $\delta^{13}C$ and $\delta^{18}O$ values are not necessarily affected by the same factors or affected to the same extents; disequilibrium of one isotope does not indicate disequilibrium of the other.

A lack of kinetic effects is also evidenced by the invariability of $\delta^{18}O$ values from multiple transects across the same growth layer (see "Parallel track tests" in the supplementary material). In all, changes in GoM seawater composition represent the most likely control on the CWN-4 speleothem $\delta^{18}O$ time series.

The more negative $\delta^{13}C$ values for the period of 15.5 to 13.5 ka (mostly within the BA) suggest a shorter residence time for drip water along a flow path (e.g., Guilfoyle, 2006; Frisia et al., 2011; Lambert and Aharon, 2011). Therefore the CWN-4 $\delta^{13}C$ record is consistent with a wetter BA and drier YD in central Texas. There is a slight mismatch in timing, as the inferred wetter conditions started before the beginning of the BA. Accounting for age uncertainties in the two records, this suggests that changes in U.S. southwest rainfall patterns precede the temperature change shown by the Greenland ice core record by 700 ± 200 yr (2σ, using the GICC05 chronology of Svensson et al., 2008, Table S1).

The growth-rate history of CWN-4 provides significant information regarding the amount of moisture transferred to central Texas for the period of 19–9 ka. Temporal changes in speleothem growth rates of samples from multiple central Texas caves, including CWN, Inner Space Cavern and Double Decker Cave, track each other well (Musgrove et al., 2001). This correspondence indicates a regional climatic control. Changes in effective precipitation are considered the most likely cause (Musgrove et al., 2001). Furthermore, in arid to semi-arid climates, low soil-moisture limits soil CO_2 production, and thus Ca^{2+} concentration in the drip-water supply to the cave (Emmerich, 2003; Mielnick et al., 2005). Multi-year monitoring studies at Natural Bridge Caverns and Inner Space Cavern in central Texas indicate a drip-rate control on calcite growth rate at inter-annual timescales (Banner et al., 2007), despite the substantial seasonal impact of CO_2 ventilation on growth rate. Given the timescales considered in this study, drip rates, and correspondingly, moisture budget, provide a more reasonable explanation for changes in CWN-4 growth rate than changes in CO_2 ventilation. While faster speleothem growth could be caused by the effects of warmer temperatures on the retrograde solubility of calcite, a kinetic growth-rate model (Romanov et al., 2008) suggests that an increase in mean annual temperature from 18 to 21 °C (maximum warmth during the BA in U.S. southwest, Liu et al., 2009) would increase growth rates by only 25%, whereas the growth rate of CWN-4 and other Texas speleothems (Musgrove et al., 2001) quadrupled during the BA from ∼20 to 87 μm/yr (Fig. 4).

If effective precipitation is the primary control, then the growth-rate history of CWN-4 is consistent with the CWN-4 $\delta^{13}C$ record that suggests an increase in effective precipitation during the warmer period of 15.5 to 13.5 ka (preceding but mostly within BA) and a reduction during the cooler YD. This inference, coupled with the $\delta^{18}O$ data, suggests stronger advection of GoM moisture into central Texas from 15.5 to 13.5 ka, including the majority of the BA.

4.2. Regional speleothem $\delta^{18}O$ gradient from Texas to New Mexico and Arizona

Comparison of coeval speleothem records from the U.S. southwest from FS, New Mexico (sample FS-2, Asmerom et al., 2010) and COB, Arizona (sample COB-01-02, Wagner et al., 2010) help to assess the extent of the inferred changes in GoM moisture advection. All three caves are located at a similar latitude; CWN is 1200 km east of COB, and 900 km east of FS (Fig. 1). Together, these three caves cover a large portion of the U.S. southwest and enable a comparison of $\delta^{18}O$ and growth-rate records that may reflect changes in regional precipitation under variably warmer and cooler climate regimes since the LGM. A similar regional, multi-speleothem $\delta^{18}O$ approach has been used in Europe (McDermott et al., 2011) and the Asian monsoon region (Hu et al., 2008) to provide broader-scale regional insights that were not possible from individual records.

The Arizona $\delta^{18}O$ time series (COB-01-02) contains a gradual, ∼1‰ positive shift from the LGM to Termination I, followed by a ∼3‰ abrupt, positive shift entering the BA (Fig. 4). The $\delta^{18}O$ values remained high throughout the BA, then dropped slightly (<1‰) across the BA/YD boundary. The $\delta^{18}O$ values increased by ∼1.5‰ after the YD, when the record ends. Due to the strong influence of Pacific moisture at COB, especially in winter, the time series is interpreted as mainly an indicator of winter moisture amount in the area, whereby a drier BA resulted in more positive $\delta^{18}O$ values, and a wetter YD produced more negative $\delta^{18}O$ values (Wagner et al., 2010). The New Mexico $\delta^{18}O$ time

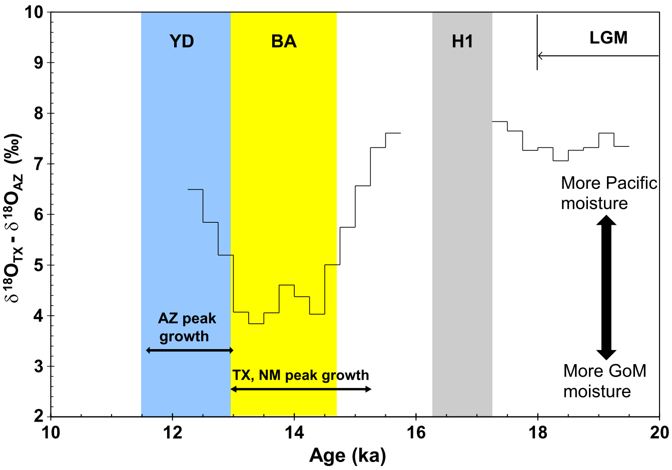

Fig. 5. Time series of the regional speleothem $\delta^{18}O$ gradient, constructed using differences between CWN-4 and COB-01-02 averaged $\delta^{18}O$ values for 250-yr intervals. Temporal variations in the gradient are interpreted to reflect the changing balance between Pacific and GoM moisture sources. The reduced gradient during the period 15.5 to 13 ka indicates enhanced GoM moisture transfer to these regions.

series (FS-2) shows high-frequency, millennium-scale oscillations throughout the entire record, which was interpreted as changing moisture compositions, mostly due to changes in the contribution of Pacific moisture (Asmerom et al., 2010). Nonetheless, abrupt positive changes in $\delta^{18}O$ values, similar to those in the COB-01-02 record, can be observed at Termination I, while a marked decrease is present at the BA/YD boundary. Both the Arizona and New Mexico studies note the strong seasonality associated with the GoM and Pacific moisture sources, with cool season precipitation derived from the Pacific source. Both studies propose a drier BA and a wetter YD based on the $\delta^{18}O$ results due to the timing of recharge in the modern system.

The conclusion of a drier BA, however, might contradict the growth-rate records of the respective samples from COB and FS, which showed higher growth rate during the BA; this would be consistent with wetter BA conditions. Synthesis of these two records with the CWN-4 $\delta^{18}O$ time series allows re-examination of the existing data in a regional framework. This may improve understanding of the complex dynamics governing moisture source, seasonality, and effective precipitation in this part of the U.S. southwest.

Speleothem $\delta^{18}O$ values depend on precipitation $\delta^{18}O$ values. Therefore, changes in the relative contributions of Pacific and GoM moisture can be evaluated by determining a regional speleothem $\delta^{18}O$ gradient for the common continuous growth period of the three samples. The differences between coeval CWN-4 and COB-01-02 speleothem $\delta^{18}O$ records (in ∼250-yr intervals) are used here to represent this regional speleothem $\delta^{18}O$ gradient (Fig. 5). Because speleothem $\delta^{18}O$ values are related to drip water and long-term averaged effective precipitation $\delta^{18}O$ values by a temperature-dependent fractionation factor (Coplen, 2007), past precipitation $\delta^{18}O$ gradients can be inferred from the speleothem gradients. The reported cave temperature at COB is ∼19.8 °C (Wagner et al., 2010). There is no multi-year temperature record available at CWN; mean annual temperature for a nearby cave (Natural Bridge Caverns, 35 km to the SE) is 22 °C (Feng et al., 2012). Adopting a calcite–water fractionation relationship of ∼ −0.2‰/°C (Coplen, 2007), the difference in the caves' temperatures would make the observed speleothem $\delta^{18}O$ gradient ∼0.4‰ smaller than the precipitation gradient. Although the temperatures of both CWN and COB likely varied in the past, the differences probably remained similar. Therefore, changes in the speleothem $\delta^{18}O$ gradient should directly reflect changes in the precipitation $\delta^{18}O$ gradient.

For the entire common growth period, CWN-4 had more positive $\delta^{18}O$ values than FS-2, which in turn were more positive than COB-01-02 (Fig. 4). This yields a positive E–W $\delta^{18}O$ gradient for the entire record that varies from 3.8 to 8‰ (Fig. 5). The modern precipitation gradient is 3‰ (weighted mean annual $\delta^{18}O$ of modern precipitation is −4.4‰ in central Texas and −7.4‰ in Tucson, Arizona, Pape et al., 2010; Wagner et al., 2010). Despite suggestions of continentality effects (Pape et al., 2010), a single moisture source rain-out process and associated isotopic distillation effects do not manifest themselves substantially in the precipitation $\delta^{18}O$ values in the region. In fact, longitude is a poor predictor of precipitation $\delta^{18}O$ values for the region as a whole (Lechler and Niemi, 2011), likely due to the impacts of multiple moisture sources and advection pathways. Studies of central Texas (Pape et al., 2010) and Arizona (Wagner et al., 2010) precipitation support this interpretation as both have similar $\delta^{18}O$ values of −7 to −2‰ for summer precipitation, while winter precipitation ranges from −12 to −8‰ at both locations. Furthermore, continentality effects, when present, likely did not change significantly in the study period and thus would have negligible impact on changes in the speleothem $\delta^{18}O$ gradients. Additionally, an isotope study of modern precipitation in areas near Tucson, Arizona shows no evidence of an amount effect over the 32-yr length of the record, despite decadal-scale changes in climate (Eastoe and Dettman, 2013). This is similar to the lack of an amount effect in a modern monitoring study in central Texas when temperature is below 26.9 °C (Pape et al., 2010). The differences in precipitation $\delta^{18}O$ values across the U.S. southwest are thus interpreted to reflect changes in the proportional mixing of low-$\delta^{18}O$ Pacific moisture in the west, and high-$\delta^{18}O$ GoM moisture in the east (Hoy and Gross, 1982; Yapp, 1985). Seasonality is a fundamental aspect of this variability, owing to a more southern position of the westerly jet stream during the winter months, which enhances transport of Pacific moisture. The $\delta^{18}O$ record from FS, geographically located between COB and CWN, generally shows much larger variations than either the COB-01-02 or CWN-4 records throughout the time series. These relatively large $\delta^{18}O$ oscillations in the FS record are consistent with variations of proportional mixing from the two distinct moisture sources. All of the inferences discussed here regarding moisture sources are consistent with the modern circulation patterns shown in Fig. 1.

Quantitatively, assuming that Texas speleothem $\delta^{18}O$ is dominantly influenced by GoM moisture as seen in the CWN-4 $\delta^{18}O$ record:

$$\delta^{18}O_{TX} = \delta^{18}O_{s,GoM,TX} \tag{1}$$

Here, $\delta^{18}O_{s,GoM,TX}$ is the speleothem $\delta^{18}O$ value in equilibrium with precipitation at CWN from a GoM source. According to mass balance, the COB speleothem $\delta^{18}O$ values can be expressed as:

$$\delta^{18}O_{AZ} = \delta^{18}O_{s,GoM,AZ} + f_P(\delta^{18}O_{s,P,AZ} - \delta^{18}O_{s,GoM,AZ}) \tag{2}$$

$\delta^{18}O_{s,P,AZ}$ and $\delta^{18}O_{s,GoM,AZ}$ are speleothem values in equilibrium with precipitation at COB from Pacific and GoM sources respectively, with f_P denoting the fraction of Pacific-sourced moisture.

Values of $\delta^{18}O_{s,GoM,TX}$ and $\delta^{18}O_{s,GoM,AZ}$ are related since both are for speleothems grown from GoM-sourced precipitation (in Texas and Arizona respectively), which has a similar isotopic composition at both sites (Pape et al., 2010; Wagner et al., 2010). The two values would not be the same, however, due to differences in mean annual temperature between CWN and COB. As temperature differences between sites are expected to be fairly constant with time, the difference between $\delta^{18}O_{s,GoM,TX}$ and $\delta^{18}O_{s,GoM,AZ}$ can be approximated by a constant "*m*":

$$\delta^{18}O_{s,GoM,TX} = \delta^{18}O_{s,GoM,AZ} + m \quad (3)$$

The Texas–Arizona $\delta^{18}O$ gradient can be subsequently expressed as:

$$\begin{aligned}\Delta^{18}O_{TX\text{-}AZ} &= \delta^{18}O_{s,GoM,TX} - \delta^{18}O_{AZ} \\ &= f_P(\delta^{18}O_{s,GoM,AZ} - \delta^{18}O_{s,P,AZ}) + m \end{aligned} \quad (4)$$

If the value of $\delta^{18}O_{s,GoM,AZ} - \delta^{18}O_{s,P,AZ}$ is constant, which is achieved when the difference in precipitation $\delta^{18}O$ between GoM and Pacific sources remains unchanged, a reduced gradient would correspond to a decreased fraction of Pacific moisture, and an increased fraction of GoM moisture.

Temperature is not considered a likely control on the $\Delta^{18}O_{TX\text{-}AZ}$ values, as regional climate models constrain temperature change over the study period to 0–3 °C (Liu et al., 2009), which potentially explains <1‰ of the variability in the $\delta^{18}O$ time series (Rozanski et al., 1993; Coplen, 2007). Temperature is an even smaller factor when considering changes in the regional precipitation $\delta^{18}O$ gradient, as temperature differences between CWN and COB likely remained the same.

The magnitude of the overall regional speleothem $\delta^{18}O$ gradient ranged from ∼3.8 to ∼8‰, with notable variation since the LGM (Fig. 5). A $\Delta^{18}O_{TX\text{-}AZ}$ value of $\sim 7.6 \pm 0.4$‰ existed until 15.5 ka. This value and its apparent stability are consistent with CWN and COB receiving precipitation from distinct moisture sources. After the Heinrich Event 1, the gradient decreased ∼3.5‰ in less than 1 ky and reached a minimum during the BA. A smaller gradient persisted throughout the BA. This gradient is similar to the modern value, which suggests increased importance of GoM moisture for the region from central Texas to Arizona since the BA period. However, the similar gradient does not necessarily suggest similar annual precipitation amounts.

4.3. Changes of moisture transfer into U.S. southwest from the LGM to Holocene

The $\delta^{18}O_{s,GoM,AZ} - \delta^{18}O_{s,P,AZ}$ values ($\delta^{18}O$ difference of COB speleothem grown from GoM and Pacific-sourced precipitation) fell by ∼2‰ during the BA, therefore the implication of a reduced gradient ($\Delta^{18}O_{TX\text{-}AZ}$ values, Fig. 5, Eq. (4)) needs further discussion. Detailed examination reveals that the reduced gradient during the BA is largely a result of a positive shift of COB-01-02 $\delta^{18}O$ values from −10.5 to −8.5‰, similar to a concurrent positive shift for FS-2 $\delta^{18}O$ values. These are consistent with an increased influence of a higher-$\delta^{18}O$ moisture source, likely the GoM. Although the meltwater pulse would have lowered the $\delta^{18}O$ of GoM moisture (Fig. 3), the depletion was ≤3‰ (Flower et al., 2004; Williams et al., 2012) and likely did not shift GoM moisture to values more negative than Pacific moisture. The overall decreasing trend in GoM seawater, CWN-4, FS-2 and COB-01-02 $\delta^{18}O$ values from 15 to 13 ka (Fig. 4) lends further insight into the impact of GoM moisture in three speleothem isotope records. This correspondence suggests that during the relatively warm BA, GoM moisture penetrated beyond central Texas and into New Mexico and Arizona. Increased growth rates in all three speleothem samples during this period (FS-2 and CWN-4 reached peak growth, Fig. 4) further suggest an increase in overall effective precipitation across these regions. The similar trends in growth rates of FS-2 and CWN-4 also lend credence to the hypotheses of a regional control on growth rates for these speleothems.

The inference of a wetter period for Texas and New Mexico from 15.5 to 13.5 ka includes the majority of the BA. This is based on correspondence of speleothem growth rates and moisture abundance, and differs from the interpretation of a drier BA based on FS-2 $\delta^{13}C$ and $\delta^{234}U$ records, and growth interval records from nearby Carlsbad Caverns (Polyak et al., 2012; Asmerom et al., 2013). The FS-2 $\delta^{13}C$ record shows generally opposite variations to its $\delta^{18}O$ time series from 20 to 12 ka, and has more negative values during 17–13.5 ka than the periods before or after (Polyak et al., 2012). These studies interpreted changes in $\delta^{13}C$ values as a combination of kinetic effects and changes in vegetation, which indicate a drier BA. We agree in part that these changes could be due to a kinetic effect. However, as discussed above, it is likely that wetter conditions lead to less CO_2 degassing from drip water and more negative $\delta^{13}C$ values during the majority of the BA. It is worth noting that $\delta^{13}C$ and $\delta^{18}O$ are not correlated in the FS-2 record, which demonstrates that they are controlled by different factors. Although Polyak et al. (2012) interpreted a drier BA from Carlsbad Caverns speleothem growth records, the wetter period from their shelf-stone chronology extends to 13.2 ka (Polyak et al., 2012) with associated age uncertainties of 200–400 yr. Therefore, it is possible that most of the BA, if not the entire BA, at Carlsbad Caverns was relatively wet, followed by rapid drying crossing the BA/YD boundary. This interpretation would be consistent with the findings of the current study. The increase in COB-01-02 growth rate during the BA is small (Fig. 4), possibly due to a greater sensitivity to Pacific moisture, or indicating the limit and boundary of GoM moisture expansion.

In contrast to the BA, the YD appears to have been a time of greater Pacific-sourced winter precipitation and a retreat of GoM moisture. The regional $\delta^{18}O$ gradient increased by ∼3‰ across the BA/YD transition (Fig. 5) and the growth rate of COB-01-02 peaked (Fig. 4). This is consistent with an increase in Pacific moisture and emphasizes the importance of winter, Pacific-sourced precipitation for recharge at COB (Wagner et al., 2010). The negative shifts in the New Mexico and Arizona $\delta^{18}O$ records (Fig. 4) may represent a temporary retreat of GoM moisture during the YD when decreasing temperatures pushed the polar jet stream farther south (e.g., Lu et al., 2007; Archer and Caldeira, 2008). While the altered path of the jet stream appears to have produced greater precipitation in Arizona, that does not appear to be the case for New Mexico or Texas. CWN-4 and FS-2 growth rates declined during the YD (Fig. 4), suggesting that either 1) overall effective precipitation declined at these sites, which may be a result of Pacific moisture not extending substantially east of Arizona; or 2) during the relatively cooler late Pleistocene, regional recharge may not have been as dependent on winter precipitation as it is today.

The CWN-4 speleothem had limited growth during the early Holocene, while FS-2 and COB-01-02 have virtually no record in the Holocene (Asmerom et al., 2010; Wagner et al., 2010). Therefore, changes in moisture sources cannot be assessed after the YD (∼9 ka). It can be speculated that after the final retreat of the Laurentide ice sheet, speleothem growth rates slowed dramatically at all sites (Fig. 4), consistent with a decrease in the amount of effective precipitation. This is supported by other studies in the region (Toomey et al., 1993; Musgrove et al., 2001). Compared to Holocene speleothems (with growth dated from 7 to 1.5 ka) from central Texas ($\delta^{18}O$: −4.9 to −3.6‰, Wong et al., 2012), the CWN-4 $\delta^{18}O$ values are, on average, ∼1‰ more positive. CWN-4 $\delta^{18}O$ values, on average, are also 1–2‰ more positive than those of modern calcite deposited on artificial substrates in nearby Natural Bridge Caverns and Inner Space Cavern (Feng et al., 2012). Together, these central Texas speleothems and modern cave calcite reveal a 1–2‰ shift to lower values from the LGM to the Holocene. This is consistent with the impact of reduced ice volume on seawater $\delta^{18}O$ values in the Holocene.

Changes in speleothem growth rate across the region reveal the complex nature of moisture availability in the U.S. southwest from central Texas to Arizona. The region did not respond consistently to changing climate during the BA and YD. While Arizona precipitation appears to have been greater during the YD, the data also points to a BA that was wetter than commonly assumed. Texas and New Mexico were likely substantially wetter during the BA than during the LGM or YD. The stable isotope evidence from FS-2 suggests that this increased moisture was primarily GoM-sourced summer precipitation. This result emphasizes that the BA climate was substantially different from the modern setting, where recharge is mainly dependent on winter precipitation. Nonetheless, the reduced modern precipitation $\delta^{18}O$ gradient (∼3‰) seems to suggest that GoM moisture reaches into Arizona. The cessation of growth at all three sites shortly after the YD further suggests that Holocene circulation patterns were quite different than those of the late Pleistocene. The absence of the Laurentide ice sheet in the Holocene likely played a role in generating these differences.

4.4. Comparison with other proxy records of the U.S. southwest

A comprehensive picture of changing moisture conditions in the U.S. southwest remains elusive. Existing proxy records are sparse and contain substantial chronological and geologic uncertainties. Interpretations of proxy records often appear in conflict with each other in the precise timing and magnitude of change. Given those challenges, we attempt to place our record with its interpretation into the broader context of previous work. Despite some apparent conflicts with previous interpretations, the original data sets do not contradict our interpretation.

This and previous work in New Mexico (Polyak et al., 2004) and Texas caves (Musgrove et al., 2001; Banner et al., 2007) supports interpreting speleothem growth rates as a proxy for moisture availability in this region. There is also strong evidence from Holocene speleothems in New Mexico (Asmerom et al., 2013) for moisture control on growth rates. Theoretical models of speleothem growth (Dreybrodt, 2005) also link growth rates to moisture delivery in arid to semi-arid regions.

An inferred wetter condition for the majority of the BA from speleothem records is, at first glance, inconsistent with previous studies set throughout the U.S. southwest. Other paleoclimate proxies for moisture amount, although rarely available due to lack of preservation, may help corroborate the speleothem growth-rate records. Available proxies include tree-ring data, which extend back to ∼1 ka (Cook et al., 2004), paleolake shorelines, and packrat middens. Regional aridity has led to desiccation of pluvial lakes, causing oxidation of sediments and loss of potential climate information. The age control on shoreline deposits is less precise than speleothem records due to uncertainties in reservoir corrections and ^{14}C calibration during the YD. Packrat midden data have fewer complications, but tend to provide only snapshots of time, rather than a continuous record.

Lake Estancia in New Mexico (34.6°N, 105.6°W) achieved a high stand of ∼40 m above the present elevation dated to ∼16.6 ka (13.4 ka ^{14}C), with a secondary high stand of +25 m at ∼14.7 ka (12.5 ka ^{14}C, Allen and Anderson, 2000). These reported ages include substantial uncertainty (Broecker and Putnam, 2012; Zimmerman et al., 2012). Thus, the +25 m lake level could have occurred during the BA, consistent with the FS-2 peak growth rate at 13.8 ka. The earlier and larger high-stands in the Estancia record may also correspond to intervals of higher growth in FS-2, although the exact timing is not clear due to uncertainties in age control, and the magnitude does not scale clearly between the two sites. Many of these episodes of faster growth in FS-2 also correspond to more positive $\delta^{18}O$ values (Fig. 4), which supports the conclusion that greater GoM-sourced summer precipitation could have increased the overall moisture balance. A deflation event at Estancia (interpreted as drier conditions) is inferred for a time period of 11 ka ^{14}C BP, immediately prior to the onset of the YD (Anderson et al., 2002). As the timing of this deflation event depends on the ages of the bracketing high-stands, this event could have occurred within the YD.

In Arizona, COB-01-02 growth rates show a maximum at ∼12.2 ka, placing it clearly within the YD. Ballenger et al. (2011) noted that there was no conclusive evidence for a lake high-stand in the U.S. southwest during the YD. A dated shoreline from pluvial Lake Cochise (Willcox Playa, 32.13°N, 109.85°W), however, does support a high stand with a minimum age of ∼10 ka (8.9 ka ^{14}C), which suggests that it could have occurred during the YD (Street-Perrott et al., 1989; Waters, 1989). The different timing between high stands at Cochise and Estancia further emphasizes the heterogeneity of the region and large uncertainties in ^{14}C dating. Haynes (2008) also noted widespread deposition of black mats during the YD in the San Pedro Valley of southeastern Arizona, consistent with a higher water table. The black mats, which are typically spring deposits, provide a more direct comparison to speleothem growth rates, as both systems would respond to changes in groundwater recharge and are less influenced by surface runoff. Pluvial lake levels, while dependent on recharge, were more directly affected by evapotranspiration. Large summer rainfall events could saturate the root zone, allowing a greater proportion to infiltrate and contribute to groundwater recharge. The increases in lake levels from these same events would not likely be sustained for a sufficiently long period to yield a datable shoreline. These results, while not definitive, indicate that regional proxy records might not directly contradict an interpretation of faster growth rates in COB-01-02 as a proxy for increased effective precipitation and in fact might support this conclusion.

4.5. Changes in seasonal balance of moisture and its implications

GoM moisture in the region contributes primarily to summer precipitation, while winter precipitation is mostly Pacific-sourced (Fig. 1). At FS, ∼68% of modern annual precipitation occurs during the warmer months, and is associated with the GoM, while Pacific-sourced cool season precipitation accounts for ∼32% (Asmerom et al., 2010). Modern winter precipitation, however, is more likely to contribute to groundwater recharge due to reduced evapotranspiration. The concurrent increases in speleothem growth rates at FS and CWN, and the $\delta^{18}O$ increase at FS during the BA suggest that an increase in GoM-sourced summer precipitation produced an increase in effective precipitation in these areas during the BA, highlighting the differences with modern climate.

Inferred changes in the seasonal balance of precipitation could notably impact regional ecosystems. Summer and winter annuals appear to negatively influence each other's germination success (Guo and Brown, 1997). Flowering events in several desert plant species in the northern Sonoran desert are triggered by the timing of precipitation (Bowers and Dimmitt, 1994). Summer precipitation in the Chihuahuan desert is used more efficiently by C_4 grasses than shrub plants (Reynolds et al., 2000). Increased precipitation, particularly in the summer, has been shown to increase both absolute and relative abundance of C_4 grasses in the region (Epstein et al., 1997). Even in Arizona, summer-flowering C_4 plants were reasonably abundant from ∼16 to 12 ka (Holmgren et al., 2006), consistent with an increase in summer precipitation and roughly corresponding to the timing of the decreased $\delta^{18}O$ gradient. Packrat midden data indicate that vegetation dependent on summer precipitation disappeared across the U.S. southwest during the transition from the BA to the YD (Holmgren et al., 2003).

During the YD, packrat midden data indicate that spring-flowering annuals were more prevalent in southern Arizona at ∼11 ka, due to wetter-than-present winters (Bowers, 2005), consistent with the observed increase in the $\delta^{18}O$ gradient and our interpretation. A greater prevalence of spring flowers would impact pollinator communities and other trophic levels. The potential for such ecological changes in the highly sensitive U.S. southwest may provide additional context for the collapse of the Clovis culture that occurred near the onset of the YD (Ballenger et al., 2011).

Stable isotopic evidence from Clovis-aged mammoth tusks collected from southeast Arizona suggests a diet that included a high proportion of C_4 plants, particularly during the summer months (Metcalfe et al., 2011). This contrasts with LGM-era mammoths, which showed a greater reliance on C_3 species. The tusk data also shows no evidence of a major drought, but instead is consistent with increased summer moisture, in agreement with the $\delta^{18}O$ data from COB-01-02.

5. Conclusions

Changes in the speleothem $\delta^{18}O$ gradient across a large part of the U.S. southwest indicate variability in the relative contributions of Pacific and GoM moisture, while growth-rate histories provide evidence of changes in the amount of effective precipitation. From the LGM to the early Holocene, precipitation at CWN in central Texas was predominantly controlled by GoM moisture. Similarly, the COB record (Arizona) prior to 15.5 ka indicates predominantly Pacific-sourced moisture. In contrast, the entire record of FS-2 (New Mexico) and the post-15.5 ka record of COB reflect varying contributions of Pacific and GoM moisture. During the warm period of 15.5 to 13.5 ka (mostly within the BA), a shrinking Laurentide ice sheet and a northward shift of the polar jet stream apparently brought more GoM moisture in the summer to a large part of the U.S. southwest, producing an overall increase in precipitation from central Texas to New Mexico and Arizona, and a decrease in the $\delta^{18}O$ gradient. This effect may not extend significantly beyond Arizona. During the subsequent cooling of the YD, southward movement of the polar jet stream caused GoM moisture to retreat and the $\delta^{18}O$ gradient to increase by allowing greater advection of Pacific moisture into Arizona.

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Appendix A. Supplementary material

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