1 **A MID-HOLOCENE PALEOPRECIPITATION RECORD FROM BELIZE**

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Abstract

Understanding past climate may contribute to a better understanding of future climate change, allowing for adaptations to changing water resources. High latitude paleoclimate reconstructions reveal a warmer northern hemisphere during the mid-Holocene, yet paleoclimate records from tropical Central America are lacking, especially seasonally-resolved reconstructions needed to resolve seasonal shifts. Here we reconstruct mid-Holocene precipitation using high-resolution (sub-annual to biannual) stable isotope ratios (oxygen and carbon) extracted from a speleothem recovered from Belize to investigate the frequency and magnitude of precipitation variability. We found a slight increase in precipitation during the mid-Holocene in Belize with less variability compared to the present. This increase is due to the expansion of the North Atlantic Subtropical High (NASH), which strengthens the Caribbean Lower Level Jet, enhancing westward advection of atmospheric moisture to Belize. The decrease in precipitation variability is related to a northward movement of the Intertropical Convergence Zone (ITCZ) placing Belize within the bounds of the ITCZ for a longer period each year. Time series analysis reveals periodicities of 200-250 years which correspond to the Suess solar cycle. The additional periods of ~100 and ~50 years also have origins in solar irradiance. The North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Variability (AMV; also known as the Atlantic Multidecadal Oscillation (AMO)), long recognized as important drivers of precipitation variability in the region, are present but only at the 90% significance level. We posit that the reduced influence of the NAO and AMV is due to the northerly migration of the ITCZ.

Keywords: Paleoclimate; Speleothem; Belize, Central America

1. Introduction

The recent report by the Intergovernmental Panel on Climate Change (IPCC) highlighted Central America as a region highly likely to experience precipitation changes in the coming decades due to greenhouse gas warming (IPCC, 2013). The Mid-Holocene was a period of enhanced warming in the high northern hemisphere (e.g., Dorale et al., 1992; Koc and Jansen, 1994; Korhola et al., 2000; Rosen et al., 2001; Solovieva et al., 2005) with temperature changes similar to those predicted by the IPCC due to anthropogenic climate change (IPCC, 2013). The larger increase in temperature in the Polar Regions compared to the tropics results in a decreased latitudinal temperature gradient. An increase in boreal solar irradiance during the mid-Holocene produced a summer enhancement of the North Atlantic Subtropical High (NASH) (Bartlein et al., 1998; Shuman et al., 2002; Hardt et al., 2010) and a similar situation presently exists (Mayewski et al., 2004; Li et al., 2011; Li et al., 2012). The NASH is an area of high pressure centered on Bermuda that influences precipitation in North and Central America (Zishka and Smith, 1980). An investigation into mid-Holocene precipitation variability for northern Central America would provide insight into the precipitation response to increased temperatures and decreased latitudinal temperature gradient. This investigation will allow for better predictions of future precipitation so that governments are able to prepare for potential water supply and management issues.

Paleoclimate studies have investigated the late-Holocene in Central America (e.g., Covich and Stuiver, 1974; Leyden et al., 1994; Hodell et al., 1995; Rosenmeier et al., 2002) but very few studies exist for the mid-Holocene period (e.g., Covich and Stuiver, 1974; Leyden et al., 1994; Hodell et al., 1995; Metcalfe et al., 2009). Of the latter period, all are based exclusively on lacustrine sediments, predominantly from the Yucatan peninsula, with most showing

increased precipitation during the mid-Holocene. The study of Hodell et al. (1995) found evidence for higher lake levels during the mid-Holocene than the present in their Lake Chichancanab, Mexico sediment record. Similar evidence is present in sediment cores from Lake Quexil, Guatemala (Leyden et al., 1994) and Lake Coba on the Yucatan Peninsula (Whitmore et al., 1996). The mid-Holocene sediment core records from Lake Salpetén and Lake Petén Itzá in Guatemala reveal evidence for increased surface and groundwater flow (Rosenmeier et al., 2002). The evidence of Metcalfe et al. (2009) shows a moist and relatively stable climate in the New River Lagoon, Belize from the early Holocene to 5.6 ka. The limitations of these lake reconstructions is their lower resolution (centennial to decadal) and limited number of dates to constrain their chronologies.

To understand what drives mid-Holocene precipitation variability in Central America requires a temporally high resolution proxy that is sensitive to changes in rainfall; variations in the oxygen isotopic ratio ($\delta^{18}\text{O}$) within tropical speleothems meet this criterion. The ability to accurately date speleothems using ICPMS and sample calcite at the micron resolution allows the production of paleoclimate records that can be subjected to time series analyses with statistical confidence. Such analyses can provide insights into which of the various teleconnections, each with its own periodicities, may be the drivers of this precipitation variability.

The $\delta^{18}\text{O}$ in speleothems are controlled by cave temperature and the isotopic composition of the drip waters derived from surface precipitation (Fleitmann et al., 2003; Lachniet et al., 2004; Asmerom et al., 2007; van Beynen et al., 2007; Lachniet and Patterson, 2009; Baker et al., 2010). In the tropics, relatively low speleothem $\delta^{18}\text{O}$ values are indicative of more precipitation and vice versa, via the amount effect (Lachniet, 2009; Shah et al., 2013). Speleothem growth rates vary between 0.01 – 1.00 mm/year with the highest value giving calcite samples at annual

or sub-annual resolution (McDermott, 2004). This resolution allows for seasonally resolved reconstructions of past precipitation.

Interpretation of the carbon isotopic ratio ($\delta^{13}\text{C}$; ratio of $^{13}\text{C}/^{12}\text{C}$) variability in tropical speleothems is more complex. Fluctuating $\delta^{13}\text{C}$ values may represent changes in carbon fixation in photosynthesis pathways (C_3 vs C_4 plants) related to water stress adaptations in vegetation (Yonge et al., 1985; Fairchild et al., 2006). Variability in the partial pressure of soil CO_2 ($p\text{CO}_2$), plant productivity, rates of CO_2 degassing, and various other factors can play a role shifting speleothem $\delta^{13}\text{C}$ values (Yonge et al., 1985; Fairchild et al., 2006).

Here we present a high-resolution (sub-annual to biannual) speleothem record of mid-Holocene precipitation for the western Maya Mountains of Belize. This location is considered representative of broad precipitation patterns in northern Central America based on the understanding of modern regional climate influences (Jury et al., 2007; Gamble and Curtis, 2008; Cook and Vizy, 2010; Karmalkar et al., 2011). The sub-annual to biannual resolution of this Belizean Maya Mountains reconstruction provides the most detailed paleoprecipitation reconstruction to date for the mid-Holocene.

Our main questions are how the magnitude and variability of mid-Holocene precipitation compares to that of modern precipitation and if differences are apparent, what atmospheric-oceanic mechanisms could drive this change? To address these questions, our research objectives are to: 1) determine stable isotopic variability in a speleothem that formed during the mid-Holocene; 2) compare mid-Holocene precipitation to the present; and 3) assess possible drivers of mid-Holocene precipitation amount and variability.

2. Site description

The climate of our study site, which lies on the Vaca Plateau of Belize, is controlled by both the Pacific Ocean and the Caribbean Sea, the latter being more influential due to the dominant easterly trade winds. The Intertropical Convergence Zone (ITCZ) and NASH both influence the climate of Belize (Fig. 1) (Haug et al., 2003; Hodell et al, 2005; Gamble and Curtis, 2008; Cook and Vizy, 2010). During the boreal summer, the ITCZ's northward migration brings precipitation to Belize and the opposite occurs during the winter (Haug et al., 2003; Hodell et al, 2005). The NASH impacts tropical American precipitation via the Caribbean Low-Level Jet (CLLJ), which is a regional manifestation of the easterly trade winds (Gamble and Curtis, 2008; Cook and Vizy, 2010). Summer expansion and intensification of the NASH strengthens the CLLJ (Gamble and Curtis, 2008; Fritz et al., 2011). This leads to decreased precipitation in the eastern Caribbean due to an increase in moisture flux divergence and increased precipitation and lower level jet convergence in the western Caribbean and coastal Central America (Gamble and Curtis, 2008; Fritz et al., 2011).

In addition to the influence of NASH and the CLLJ, interactions between the low latitude Pacific and Atlantic Oceans contribute to the Central American climate. Jury et al. (2007) found a stronger influence of El Niño Southern Oscillation (ENSO) in the western Caribbean while the influence of the North Atlantic Oscillation (NAO) is more evident in the southeastern Caribbean. Decadal variability in North Atlantic SSTs, termed Atlantic Multidecadal Variability (AMV) (originally coined the Atlantic Multidecadal Oscillation (AMO)) (Enfield et al., 2001), impacts seasonal precipitation with warm phases generating more winter precipitation in the western Caribbean and Central America and vice versa (Knudsen et al., 2011).

Our study site (Chen Ha Cave) lies within the Cayo District of Belize and the closest

weather station is ~50 km away at Spanish Lookout. The average annual temperature is 26°C (average monthly temperatures varies from 21 to 31°C) with wet summers and dry winters (Belize National Meteorological Service, 2014). The orographic effect of the Maya Mountains leads to precipitation in excess of 3800 mm/year on the windward side compared to the leeward side where the study area receives 1500 mm/year (Belize National Meteorological Service, 2014).

Fig. 1. Location of Chen Ha Cave, Belize. **A)** Precipitation in Belize is a result of moisture transport from the Caribbean Sea via Caribbean Low Level Jet (CLLJ) and the Intertropical Convergence Zone (ITCZ) **B)** Approximate location of Chen Ha Cave in Belize (Base map derived from NASA).

The speleothem used in this study (CH04-02) was collected in 2004 from Chen Ha Cave located on the Vaca Plateau (17°N, 89°W, 550 masl; Fig. 1) in the Mayan Lowlands of southwestern Belize. A second speleothem, CH04-03, was collected from the same cave to compare with CH04-02. The Vaca Plateau is comprised of Cretaceous Campur limestone, which

is highly karstified and heavily brecciated (Reeder et al., 1996). The recharge on the Northern Vaca Plateau is entirely autogenic and thin soils permit rapid infiltration of precipitation (Reeder et al., 1996; Webster et al., 2007). The Vaca Plateau has insufficient rainfall for its forests to be classified as tropical rainforest and is considered tropical moist broadleaf forest (Douglas et al., 2012).

Chen Ha Cave has a narrow vertical shaft 55 m deep that terminates in a horizontal chamber measuring 20 m by 7 m with a height that varies from 1 to 7 m. Constrictions in the shaft reduce the exchange of air between the cave and the surface, leading to high humidity and elevated CO₂ levels within the cave. Other caves with similar depth within the study area have relative humidity of 93 to 95% (Webster et al., 2007). CH04-02 was chosen for its size (~1m in length) and location in the far reaches of the cave. Very few of the stalactites within the chamber were actively dripping at the time of collection; therefore, it is assumed that the hydrologic connection with the surface has diminished since the mid-Holocene.

3 Materials and methods

3.1 Stable isotope analysis

For CH04-02, we sampled the speleothem for isotopic analysis ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) along the c-axis at 200 μm intervals, and for CH04-03, we sampled at intervals of ~5 mm. Approximately 200 μg of each sample was dissolved in anhydrous phosphoric acid prior to determining isotopic ratios using a Thermo Fisher Scientific (Finnigan) Delta V 3 keV Isotope Ratio Mass Spectrometer at the University of South Florida. Analytical precision was determined using an internal standard calibrated to NBS-18 and NBS-19 and isotopic ratios are reported relative to

Vienna Pee Dee Belemnite (VPDB) with a precision of 0.10‰ (2σ) for $\delta^{18}\text{O}$ and 0.07‰ (2σ) for $\delta^{13}\text{C}$.

To properly understand the stable isotope records, we tested for isotopic equilibrium conditions during deposition. Isotopic equilibrium occurs when the isotopic movement between two phases is influenced by the bond strengths of the different isotopes (Hendy, 1971). There are several tests for isotopic equilibrium. The Hendy Test involves sampling along a single growth layer, and investigating the $\delta^{18}\text{O}$ values and comparing the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (Hendy, 1971). In the absence of kinetic fractionation or evaporation, $\delta^{18}\text{O}$ values should remain constant along a growth layer, and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ should not co-vary because different environmental controls influence the carbon and oxygen isotopic composition of speleothems (Hendy, 1971; Dorale and Liu, 2009). In addition to the Hendy Test, we investigated correlation between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values along the growth axis of the speleothem and the replication of $\delta^{18}\text{O}$ values of two speleothems from the same cave. The replication test assumes that it is highly unlikely that two speleothems from the same cave would show the same signal if kinetic factors were influencing the isotopic composition of the speleothem (Dorale and Liu, 2009).

An investigation of the autocorrelation and variance of the oxygen isotope record allows for a better understanding of the controls on the oxygen isotope values. We performed an autocorrelation on the entirety of the oxygen isotope record, as well as the segments between each of the dates. We calculated the variance of each segment to determine if there was any relationship between variance and resolution.

3.2 Chronology

Using prior thermal ionization mass spectrometry (TIMS) uranium-thorium (U-Th) dates

for CH04-02, we had an initial U-Th chronology for this stalagmite allowing for the selection of a portion that spanned the mid-Holocene (540–835 mm from the top). From this portion of CH04-02, a higher resolution (11 dates) U-series chronology was established by extracting 50 to 150 mg of calcite powder using a hand-held Dremel tool equipped with a 0.5 mm dental bur. We sampled a second speleothem from Chen Ha Cave (CH04-03) to create a U-series chronology to compare to CH04-02. Each calcite powder sample was dissolved in nitric acid and spiked with a solution of ^{236}U , ^{233}U , and ^{229}Th , dried and then re-dissolved in nitric acid. The Th and U isotopes were separated using anion resin columns and the resulting solutions were analyzed on a Thermo Neptune Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) in the Radiogenic Isotope Laboratory at the University of New Mexico. The U-Th dating methods are described by the study of Asmerom et al. (2010).

Large dating errors because of low uranium and high detrital thorium warranted further analysis to ensure that the dating model is accurate. In order to determine an appropriate time step and to account for large errors, we used a Monte Carlo simulation ($n = 10,000$) assuming a Gaussian probability distribution function for the analytical uncertainty to assess the influence of large analytical error. To ensure that a single date does not significantly alter the age model, we also used multiple Monte Carlo simulations in which one date was removed, a technique known as bootstrapping.

3.3 Spectral analysis

The isotopic samples extracted from CH04-02 have c-axis increments of 200 μm ; therefore, we converted the record to the time domain for further interpretation. Using the results from high resolution U-Th dating, we defined the age model for CH04-02. Before spectral analysis, we removed the mean and detrended the $\delta^{18}\text{O}$ time series. We used two spectral

analysis methods with Fourier transforms to assess periodicities in the $\delta^{18}\text{O}$ record: the Multi-Taper Method (MTM) (Thomson, 1982; Ghil et al., 2002) and wavelet analysis (Torrence and Campo, 1998; Grinsted et al., 2004). We used three tapers with five band smoothing for the MTM analysis, and a morlet wavelet for wavelet analysis. Significance was assessed at the 95% confidence interval assuming a red-noise background modeled as an auto regressive lag-1 (AR(1)) process for MTM and wavelet analysis (Ghil et al., 2002; Grinsted et al., 2004; Torrence and Campo, 1998).

3.4 Comparison of mid-Holocene to present

To compare the amount of precipitation between the mid-Holocene and today, we compared the $\delta^{18}\text{O}$ record of CH04-02 to the modern speleothem $\delta^{18}\text{O}$ record from Macal Chasm on the Vaca Plateau (Webster et al., 2007). Additionally, we used the late-Holocene speleothem record of Medina-Elizalde et al. (2010) from Tzabnah Cave on the Yucatan Peninsula to compare mid- and late-Holocene precipitation variability.

4 Results and Discussion

4.1 Isotopic equilibrium

The environmental conditions around CH04-02 were conducive to isotopic equilibrium, due to the high CO_2 levels and the location of the speleothem far from the narrow cave entrance. The speleothem deposition for CH04-02 ceased ~ 1.0 ka, so it is not possible to conduct a drip water study to determine if modern calcite is deposited under isotopic equilibrium conditions. The Hendy test reveals a visually evident trend between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values along each sampled layer and variability within $\delta^{18}\text{O}$ values with distance from the apex of the stalagmite

(Fig. 2a-d). Therefore, this speleothem fails the Hendy Test; however, this test does have inherent weaknesses, such as the possibility that evaporation can occur at the flanks but not down the c-axis and the possibility that environmental conditions similarly influence $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (Dorale and Liu, 2009).

For the second test, there is a weak statistically significant relationship ($r^2=0.14$, $n=3046$, $p=0.0001$) between oxygen and carbon isotope composition along the growth axis of CH04-02 (Fig 2e). However, a common problem with regression analyses is that a small number of points can produce what appears to be significant correlations. As Figure 2e illustrates, the removal of less than 2% of the total number of the isotopic samples (highlighted) drops the r^2 value to 0.09 ($p<0.0001$) thereby suggesting that 98% of the speleothem was deposited under isotopic equilibrium conditions. The covariance may also be a result of environmental factors that impact $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in a similar way and not disequilibrium. For example, drier conditions lead to a higher proportion of ^{18}O in precipitation and more ^{13}C in the soil due to a shift towards C_4 vegetation; this leads to higher $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in the speleothem.

The final test for equilibrium is similar $\delta^{18}\text{O}$ values and coeval variability of CH04-03 and CH04-02 (Fig. 2f). Although CH04-03 was dated to the same interval as CH04-02, only low-resolution sampling at 5 mm intervals is available at this time. Therefore, we compared the two speleothems at the same sampling resolution by averaging the CH04-02 values. The $\delta^{18}\text{O}$ values of CH04-02 and CH04-03 have an r value of 0.42 ($p=0.0142$, $n=80$), indicating that there is co-variability despite dating uncertainties (Figure 2f). Overall, while there is some evidence of kinetic fractionation during the deposition of CH04-02, most of the speleothem was deposited under isotopic equilibrium conditions. The evidence of periodic kinetic fractionation, most likely

a result of evaporation, does not invalidate the paleoclimate record, but is important to recognize in the interpretation of the record.

Fig. 2. Tests for isotopic equilibrium for CH04-02. a) Hendy test: a and b) correlation of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ along a single growth layer; c and d) $\delta^{18}\text{O}$ values by distance from the apex along a single growth layer e) coeval distribution of isotopic values along the growth axis of the speleothem; and f) comparison between two speleothems from Chen Ha Cave, CH04-03 (solid line) and CH04-02 (dashed line). CH04-02 values were averaged to compare to the lower resolution CH04-03; therefore, CH04-03 displays discrete values which can be higher, whereas CH04-02 are an average over time, thus eliminating higher values.

A common method of testing for equilibrium deposition is to measure the isotopic composition of the modern speleothem calcite, its feed-waters and surface precipitation (Burns et

al. 2002; Fischer and Treble 2008; Medina-Elizalde et al. 2010). Equilibrium deposition is assumed when these have very similar isotopic values. Unfortunately, CH04-02 was not actively growing when collected, nor were there any actively dripping stalagmites within the cave, therefore such a study was unfeasible.

4.2 Stable isotope ratios

The $\delta^{18}\text{O}$ values of CH04-02 have a mean of $-5.0\text{‰} \pm 0.6\text{‰}$ (1σ , $n=1573$), and a range of 4.2‰ and the $\delta^{13}\text{C}$ values have a mean of $-11.3\text{‰} \pm 0.8\text{‰}$ (1σ , $n=1573$) and a range of 5.3‰ (Fig. 3). The main controls on speleothem $\delta^{18}\text{O}$ values are cave temperature and precipitation (Fleitmann et al., 2003; Asmerom et al., 2007; Lachniet et al., 2007; van Beynen et al., 2007; van Beynen et al., 2008; Baker et al., 2010). Speleothem $\delta^{18}\text{O}$ records from the tropics of Central America have been found to have recorded past precipitation amount (Lachniet et al., 2004; Webster et al., 2007; Shah et al., 2013). Veracruz, Mexico is the closest International Atomic Energy Agency (IAEA) recording station for $\delta^{18}\text{O}$ of precipitation to the study area, and the precipitation data for that station indicates that precipitation $\delta^{18}\text{O}$ values are largely controlled by the amount effect (Vuille et al., 2003). The amount effect is the inverse correlation relationship between the amount of precipitation and the $\delta^{18}\text{O}$ value of precipitation (Dansgaard, 1964). Similarly, Medina-Elizalde et al. (2010) determined that precipitation $\delta^{18}\text{O}$ values for their Yucatan study site were controlled by the amount affect. Chen Ha Cave falls within the same climate regime as both the Veracruz IAEA station and the Yucatan peninsula; therefore, we assume that the $\delta^{18}\text{O}$ values for CH04-02 are largely controlled by precipitation via the amount effect.

The main control on speleothem $\delta^{13}\text{C}$ variability is the $\delta^{13}\text{C}$ of surface soil, which is largely a result of the type of surface vegetation, C_3 or C_4 plants (Yonge et al., 1985; Fairchild et

Fig. 3. Oxygen (top-black) and carbon (bottom-grey) isotopic variations of CH04-02. The trend lines are a third-order polynomial fit.

al., 2006; van Beynen et al., 2007). With the current knowledge of mid-Holocene climate in Central America from pollen records (Covich and Stuiver, 1974; Leyden et al., 1994; Hodell et al., 1995), it is highly unlikely that there was a rapid shift from C_3 plants (humid climate) to vegetation adapted to arid conditions (C_4 plants). An alternate explanation proposed by the study of Webster et al. (2007) is that abrupt changes in speleothem $\delta^{13}C$ for the Vaca Plateau (same study site) are a result of the fluctuating partial pressure of the CO_2 (pCO_2) in the soil above the cave. They concluded that during drier periods, there was a decrease in soil pCO_2 because of decreased plant productivity, leading to the lower $\delta^{13}C$ values in speleothem calcite. A range of –6 to –13.5‰ in their late-Holocene speleothem $\delta^{13}C$ values is similar to the range of –8 to –13‰ and –9 to –12‰ observed in CH04-02 and CH04-03, respectively. Consequently, we agree with

their interpretation that the main control on variability in speleothem $\delta^{13}\text{C}$ values are driven by changes in the moisture content of the soil above the cave.

4.3 Age model

The 11 U-series CH04-02 ages capture a depositional period of ~2,230 years, from ~4.7 to 6.9 ka (Table 1). The stalagmite has low uranium concentrations and elevated detrital thorium levels resulting in analytical errors (2σ) on the order of hundreds of years except for the youngest date. The ages are in chronological order with the exception of the sample at 780 mm from the top of the stalagmite, yet that date is in chronological order when dating error is considered (Fig. 4 and Table 1).

Fig. 4. U-Th derived age model. Errors bars are 2 sigma (Table 1).

Linear interpolation between each of the dates, excluding the reversal at 780 mm, led to resolution that varied from 0.47 years/sample to 3.57 years/sample. These raw dates were used for autocorrelation and variance calculations. All dates were used for determining the age model for time series analysis. Assuming constant deposition, the best-fit linear model of the U-Th dates (age (years) = $8.118 \times \text{distance from top (mm)} + 244.7$) for the isotopic samples (sampling interval = 200 μm) results in a time step (Δt) of 1.615 years/sample (8.075 years/mm). The error of the U-Th age for the sample at 540 mm is an order of magnitude larger than the other samples

(Table 1); therefore, it may lead to larger time step uncertainties. The resulting average Δt from

Table 1: CH04-02 U/Th dating results

Distance from top (mm)	^{238}U (p/pg)	^{232}Th (pg/g)	$^{230}\text{Th}/^{232}\text{Th}$ (activity)	$^{230}\text{Th}/^{238}\text{U}$ (activity)	$\delta^{234}\text{U}_i$	Age
540	58.7 $\pm$ 0.2	6394 $\pm$ 46	3.0 $\pm$ 0.1	0.1080 $\pm$ 0.0023	240.0 $\pm$ 3.2	4706 $\pm$ 2586
570	63.0 $\pm$ 0.2	2074 $\pm$ 20	6.4 $\pm$ 0.1	0.0691 $\pm$ 0.0010	221.0 $\pm$ 1.7	4777 $\pm$ 791
595	71.5 $\pm$ 0.2	1682 $\pm$ 49	8.7 $\pm$ 0.4	0.0667 $\pm$ 0.0020	223.7 $\pm$ 2.7	4985 $\pm$ 590
620	84.6 $\pm$ 0.2	1013 $\pm$ 52	16.9 $\pm$ 1.0	0.0661 $\pm$ 0.0018	234.2 $\pm$ 2.3	5432 $\pm$ 328
660	56.3 $\pm$ 0.2	569 $\pm$ 50	21.2 $\pm$ 2.1	0.0701 $\pm$ 0.0030	301.8 $\pm$ 3.5	5585 $\pm$ 350
690	70.8 $\pm$ 0.2	1076 $\pm$ 43	14.7 $\pm$ 0.7	0.0729 $\pm$ 0.0020	271.7 $\pm$ 2.5	5741 $\pm$ 393
725	63.9 $\pm$ 0.2	1209 $\pm$ 41	12.7 $\pm$ 0.5	0.0789 $\pm$ 0.0021	286.9 $\pm$ 2.5	6039 $\pm$ 466
750	66.4 $\pm$ 0.2	1523 $\pm$ 46	11.2 $\pm$ 0.5	0.0838 $\pm$ 0.0023	267.6 $\pm$ 2.8	6396 $\pm$ 567
780	74.2 $\pm$ 0.2	292 $\pm$ 38	62.8 $\pm$ 8.2	0.0808 $\pm$ 0.0016	293.5 $\pm$ 2.0	6846 $\pm$ 166
820	124.2 $\pm$ 0.3	1829 $\pm$ 28	17.3 $\pm$ 0.3	0.0831 $\pm$ 0.0008	248.2 $\pm$ 1.1	6823 $\pm$ 350
835	88.2 $\pm$ 0.2	3469 $\pm$ 45	7.6 $\pm$ 0.2	0.0973 $\pm$ 0.0018	257.8 $\pm$ 2.0	6936 $\pm$ 926

Table 2: CH04-03 U/Th dating results

Distance from top (mm)	^{238}U (p/pg)	^{232}Th (pg/g)	$^{230}\text{Th}/^{232}\text{Th}$ (activity)	$^{230}\text{Th}/^{238}\text{U}$ (activity)	$\delta^{234}\text{U}_i$	Age
15	80.9 $\pm$ 0.2	1948 $\pm$ 41	9.2 $\pm$ 0.3	0.0742 $\pm$ 0.0001	414.0 $\pm$ 2.1	4883 $\pm$ 510
53	72.5 $\pm$ 0.2	1526 $\pm$ 48	11.4 $\pm$ 0.4	0.0770 $\pm$ 0.0001	421.6 $\pm$ 2.3	5206 $\pm$ 428
70	67.1 $\pm$ 0.2	1612 $\pm$ 48	11.7 $\pm$ 0.4	0.0838 $\pm$ 0.0002	429.4 $\pm$ 2.5	5603 $\pm$ 515
90	65.3 $\pm$ 0.2	539 $\pm$ 37	29.1 $\pm$ 2.0	0.0772 $\pm$ 0.0001	427.6 $\pm$ 2.0	5718 $\pm$ 215
115	65.0 $\pm$ 0.2	2566 $\pm$ 46	7.3 $\pm$ 0.2	0.0999 $\pm$ 0.0002	433.0 $\pm$ 2.4	6261 $\pm$ 824
137	71.6 $\pm$ 0.2	3725 $\pm$ 48	6.2 $\pm$ 0.2	0.1050 $\pm$ 0.0002	435.7 $\pm$ 3.0	6151 $\pm$ 1070
160	78.2 $\pm$ 0.2	1208 $\pm$ 45	18.6 $\pm$ 0.8	0.0933 $\pm$ 0.0001	454.5 $\pm$ 2.2	6600 $\pm$ 337
180	80.4 $\pm$ 0.2	1619 $\pm$ 29	14.4 $\pm$ 0.3	0.0957 $\pm$ 0.0001	446.4 $\pm$ 1.6	6644 $\pm$ 415

the Monte-Carlo simulation using all U-Th ages was 1.605 ± 0.813 years/sample (2σ). The results of the bootstrapping ($\Delta t = 1.645 \pm 0.845$ years/sample, 2σ) suggest that the dating analytical errors, particularly in the 540 mm sample, do not greatly alter the determination of Δt .

The Monte Carlo simulation result ($\Delta t = 1.605$ years/sample) is used to assign dates to each stable isotope sample for spectral analysis.

The two dates for the top section of CH04-02 have large errors with 4706 ± 2581 and 4777 ± 2586 covering 71 years. Upon closer examination, there appears to be annual laminae between the two dated samples for this 30 mm section of the stalagmite. As demonstrated in Figure 5 the conservative count of 73 laminae confirms the chronological timespan for this upper section despite the larger dating errors. The occurrence of major hiatuses can also introduce large errors to the chronology. While there are changes in the color of the calcite in CH04-02 there are no apparent cessations in deposition.

Fig. 5. Annual laminae in upper section of CH04-02, highlighted by the vertical bars, confirming the dating timespan for the two U/Th ages. Upper scale is in millimeters. The channel below the scale is sampling track of the micromill which collected samples for stable isotopic analyses.

4.4 Autocorrelation and variance of the oxygen isotope record

After creating the age model, further analysis of the $\delta^{18}\text{O}$ values reveals insights on the controls of $\delta^{18}\text{O}$ in the speleothem calcite. Autocorrelation of the CH04-02 oxygen isotope record reveals that at a 1-sample lag the correlation is 0.73, and 0.60 at the 2-samples lag. This

suggests that there is homogenization of precipitation water within the bedrock and the $\delta^{18}\text{O}$ values are influenced by previous years' precipitation. Autocorrelation of each segment between dates reveals that there is not a strong relationship between autocorrelation and resolution.

A ten-point running variance of the raw $\delta^{18}\text{O}$ record reveals that the intervals of the record with the highest variance ($>0.4\%$) are the lower resolution intervals (>1 year). This is the opposite of what is expected because sub-annual precipitation records, capturing wet and dry seasons individually, would generally show more variability than a 1-4 year sampling resolution that would have an averaging effect. This finding suggests that during periods with less calcite deposition (lower resolution), there is less homogenization within the soils and bedrock, possibly due to less moisture retention in the soil, whereas during periods with more calcite deposition (higher resolution), there is more homogenization.

4.5 Spectral analysis

Spectral analysis of the mid-Holocene $\delta^{18}\text{O}$ precipitation reconstruction revealed significant periodicities (95% confidence level) centered on 225–250, 105–95, 50–45 and 21 years/cycle periodicity bands (Fig. 6). MTM and wavelet analysis were performed on the $\delta^{18}\text{O}$ values with a constant Δt determined from the Monte Carlo simulation (1.605 years/sample). An additional analysis was performed to assess the influence of the dating uncertainties on spectral analysis. We interpolated the data to a Δt of 3.2 years/sample, which accounts for 2 standard deviations of the simulation uncertainty, and re-performed spectral analyses. The same significant periodicity bands were found using both Δt , indicating that despite the U-Th age errors and uncertainties in determining Δt , the spectral analysis results for these significant frequencies are robust.

Fig. 6. Spectral analysis of the $\delta^{18}\text{O}$ record from CH04-02. Top) MTM spectrum of *detrended* $\delta^{18}\text{O}$ values: the number of tapers is 3 and resolution is 2. Gray bands denote significant ($p = 0.05$) periodicity bands assessed assuming an AR(1) red noise model (Ghil et al., 2002). The minor ticks marks are (left to right) given as frequency (periodicity): 0.001 (1000), 0.002 (500), 0.003 (333.33), 0.004 (250), 0.005 (200), 0.006 (166.67), 0.007 (142.85), 0.008 (125), 0.009 (111.11), 0.01 (100), and so on. Bottom) Wavelet spectrum of the detrended $\delta^{18}\text{O}$ variations from CH04-02 using a morlet mother wavelet. Thin black contour lines enclosing time-periodicity regions with significant concentrations of spectral power. Significance ($p = 0.05$) tested assuming a first-order autoregressive (AR(1)) model (Torrence and Campo, 2002). The shaded area is the cone of influence, which is interpreted with caution.

The wavelet analysis of CH04-02 (Fig. 6) reveals the time intervals when periodicities have significant concentrations of spectral power. The ~200-250 years/cycle periodicity has a significant concentration of spectral power from 5.4 to 5.9 ka and 6.4 to 7.2 ka in which the variance for this periodicity band modulates in strength with time. This periodicity band accounts

for ~7.2% of the variability in the record. Periodicity bands measured at 105-95 and 50-45 years do not appear to have significant spectral power ($p = 0.05$) with both containing ~1% of the record's variability. The 21-year cycle is significant at various anomalies that span ~20 years between 5.9 and 6.6 ka, indicating that these represent discrete events instead of a sustained oscillation. The 21-year cycle contains ~1.7% of the variability within the record. The results of the wavelet analysis and MTM of the carbon isotope record show no significant periodicities. However, the wavelet analysis does reveal one concentration of spectral power in the $\delta^{13}\text{C}$ for ~21 years/cycle at 5.9 ka that coincides with the results of the oxygen isotope wavelet analysis.

4.6 Mid-Holocene vs modern precipitation

Based on our conclusion that the CH04-02 $\delta^{18}\text{O}$ values are indicative of precipitation amount, we assessed how the mid-Holocene precipitation differed from present day. Webster et al. (2007) reported a modern calcite $\delta^{18}\text{O}$ value of -4.3‰ for a stalagmite in a nearby cave (2 km from Chen Ha Cave). The lower mean value of -5‰ for CH04-02 suggests that the mid-Holocene had slightly higher amounts of precipitation than the present. Although it is possible that the differences in speleothem $\delta^{18}\text{O}$ are the result of differences between the two caves (i.e., flow rate, rate of degassing, evaporation, etc.), the finding of a wetter mid-Holocene is supported by other lake and pollen studies (Leyden et al., 1994; Hodell et al., 1995; Metcalfe et al., 2009).

To test the variability of mid-Holocene precipitation requires a comparison of the mid-Holocene record with modern precipitation reconstructions from Central America. Few reconstructions with the temporal resolution of CH04-02 exist that allow for such comparisons. One such record is the late Holocene (1.5 ka to present) speleothem-based precipitation reconstruction reported by Medina-Elizalde et al. (2010) from Tzabnah Cave, Yucatan Peninsula,

Mexico (2.3 year average sampling resolution). With a mean $\delta^{18}\text{O}$ value of $-4.80 \pm 0.75\text{‰}$ (1σ) for Tzabnah record, the variability of $\delta^{18}\text{O}$ values of CH04-02 is comparatively smaller with a 1σ of 0.57‰. The difference in variance suggests that the mid-Holocene was climatically more stable than the late-Holocene despite the lower resolution of the modern record. The caveat to this finding is that these are different caves and speleothems whose individual characteristics may influence the variability. For example, the soil and bedrock above Chen Ha may have more of a reservoir effect leading to more homogenization and decreased variability within the speleothem $\delta^{18}\text{O}$. However, the finding of a decrease in climatic variability of the mid-Holocene relative to the late Holocene agrees with previous research (Metcalf et al., 2009; Knudsen et al., 2011) that suggest the mid-Holocene tropics were more climatically stable because of a more northerly ITCZ.

Previous studies have attributed enhanced precipitation for Central America during the mid-Holocene to the northward migration of the ITCZ (Harrison et al., 2003; Ruter et al., 2004; Shin et al., 2006; Metcalfe et al., 2009). The analysis of lacustrine sediments from northern Belize indicates that the mid-Holocene was wetter and more climatically stable as a result of this migration (Metcalf et al., 2009). These findings are confirmed by mid-Holocene paleoclimate models for this region of Central America (Harrison et al., 2003; Ruter et al., 2004; Shin et al., 2006). McGee et al. (2014) quantified the northward migration of the mean annual position of the ITCZ during the mid-Holocene as 0.3°N . This migration is potentially greater over land, such as Central America and less over the oceans due a difference in specific heat between land and water. As Belize lies within the northern bounds of the ITCZ's migration, any northward shift during the summer would place the ITCZ over Belize for a longer duration each year resulting in increased precipitation. Additionally, the climatic stability is indicative of a lack of

major shifts in the latitudinal location of the ITCZ during the mid-Holocene. Our record finds no evidence of a southerly transition in the ITCZ during the period which is in agreement with the mid-Holocene Lake Chichancanab record of the Yucatan (Hodell et al., 1995), the closest paleoclimate reconstruction to Chen Ha Cave.

Another contributing factor to increased precipitation for our region is the intensification and westward expansion of the NASH (Bartlein et al., 1998; Shuman et al., 2002; Hardt et al., 2010). A more intense mid-Holocene NASH strengthens the CLLJ and reduces convection in the Caribbean Sea (Giannini et al., 2000; Wang, 2007; Whyte et al., 2008) while enhancing the advection of moist air to the Maya Mountains thereby increasing precipitation in northern Central America (Cook and Vizy, 2010). The intensification of the NASH every boreal summer is accompanied by the northward migration of the ITCZ (Giannini et al., 2000). Consequently, both the ITCZ migration and the NASH intensification play complementary roles for enhancing mid-Holocene precipitation in Northern Central America.

4.7 Oscillatory variability in precipitation

Our spectral analyses extracted both centennial and multidecadal oscillation from the $\delta^{18}\text{O}$ record of CH04-02. The most prominent of these is the 200-250 year oscillation which falls within the upper limits of the oscillation band of the Suess cycle, a well-established solar cycle with a range of 200-260 years (Stocker and Mysak, 1992; Stuiver et al., 1998; von Rad et al., 1999; Wang et al., 1999; Agnihotri et al., 2002; Ogurtsov et al., 2002; Peristykh and Damon, 2003; Swindles et al., 2012). Insolation cycles with the periodicity of the Suess cycle drive changes in deep water formation and consequently the North Atlantic thermohaline circulation (THC). The THC governs the intensity of the NASH which we suggest has a major influence on

mid-Holocene precipitation in our study area (Cubasch et al., 1997; Weber et al., 2004). This cycle has been found in numerous mid-Holocene paleoclimate records such as Quelccaya Glacier accumulation rates (Stocker and Mysak, 1992), the laminated marine sediments in the Indian Ocean (von Rad et al., 1999), and peat bog records from northwest Europe (Swindles et al., 2012). The presence of the Suess solar cycle demonstrates the overarching control of solar variability as the driving force of precipitation variability in North Central America during the mid-Holocene.

Other oscillation bands revealed by the MTM analysis at the 95% significance level are 105-95, 50-45, 21 and 11 years (Fig. 6). The error on the stalagmite dates prevent any detailed discussion of the 21 and 11 year cycles although they correspond to the temporal periods of the Hale and Sunspot cycles respectively. The influence of the THC on precipitation variability is discussed above, but its impact is also evident in the ~100 yr oscillatory band which Knight et al. (2005) attributed to the variability in the strength of this oceanic circulation. The 50 year oscillation extracted from CH04-02 was also found in the Lake Chichancanab *Pyrgophorus coronatus* record (Hodell et al. 2001) in addition to a 200 year cycle. The authors posit that the changing evaporation/precipitation levels of this Yucatan Lake, as recorded by the gastropod $\delta^{18}\text{O}$ values, are driven by the 50 year solar cycle with the 200 year period being a combination of multiple 50 year cycles. The similarity between their and our $\delta^{18}\text{O}$ records (Fig. 7) show the indirect influence of solar irradiance on climate in Northern Central America. However, as these periods are not clearly apparent in the wavelet analysis, we can only tentatively attribute irradiance cyclicity as the main underlying driving mechanisms of precipitation variability.

No highly significant periodicities corresponding to the North Atlantic Oscillation (NAO) or Atlantic Multidecadal Variability (AMV) are present in the $\delta^{18}\text{O}$ record despite it having the

resolution to detect these teleconnections. It is unlikely that the impact of the AMV or NAO on
 Belizean precipitation during the mid-Holocene can be entirely discounted. The MTM analysis
 identifies an oscillatory band between 60-65 years albeit below the 90% significance level. There
 are several possible explanations for their low impact on the mid-Holocene precipitation
 variability: 1) as their influence is more prominent during the winter, their presence may be
 masked by the stronger summer monsoon providing most of the precipitation in the region; or 2)
 their impacts may be diminished by an atmospheric blocking effect of a more northerly mid-
 Holocene ITCZ compared to its modern southerly position. Our supposition regarding these
 oscillations disagrees with that of Knudsen et al. (2011) who found that the AMV was
 propagated throughout the Holocene in northern Central and South America. Their conclusion
 for Central America was derived from analysis of the Lake Chichancanab record from the
 Yucatan, Mexico (Hodell et al., 2001). However, our spectral analysis of the mid-Holocene
 portion of the Lake Chichancanab record cannot reveal significant periodicities within the band
 of the AMV or NAO.

Fig. 7. Lake Chichancanab $\delta^{18}\text{O}$ gastropod *Pyrgophorus coronatus* record (gray) from the
 Yucatan, Mexico (Hodell et al., 2001) and CH04-02. Lake Chichancanab is the geographically
 closet mid-Holocene paleoclimate record to our study area. Periods of disagreement can be
 attributed dating errors (CH04-02, 10 point running mean) and fewer dates (Lake Chichancanab).

5. Conclusions

Analysis of mid-Holocene precipitation variability for the north of Central America as derived from an ~annually resolved mid-Holocene speleothem record suggests a slight increase in and more stability in precipitation levels than present. We posit the cause of the increase in precipitation and greater stability is the combined influence of a more northerly ITCZ and a period of prolonged intensification of the NASH (Bartlein et al., 1998; Shuman et al., 2002; Hardt et al., 2010). A more intense NASH during the mid-Holocene would strengthen the CLLJ directing more moist air to the Maya Mountains thereby increasing precipitation (Cook and Vizy, 2010), and a more northerly ITCZ brings more precipitation and stability, as Belize remains consistently within the migration band for a longer period each year.

Both MTM and wavelet analyses reveal a significant spectral peak in the CH04-02 stable isotopic record with a periodicity within the Suess solar cycle (200-250 years) thereby highlighting the importance of solar irradiance in forcing climate change on centennial time scales. This solar influence can also be seen in the 50 year and 100 periodicities captured in CH04-02 and the nearby Lake Chichancanab (Hodell et al., 2001) isotopic record. The impact of solar irradiance could have been perpetuated by its influence on the location, intensity and strength of ITCZ, the NASH and the THC respectively, which are the main drivers of precipitation variability in northeastern region of Central America during the mid-Holocene. The northward migration of the ITCZ and the intensification of the NASH could have dampened the influence of the AMV and NAO during this interval.

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