Mid-Holocene Speleothem Climate Proxy Records from Florida and Belize

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Mid-Holocene Speleothem Climate Proxy Records from Florida and Belize

by

Anna L. Pollock

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy School of Geoscience College of Arts and Sciences University of South Florida

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Date of Approval: April 9, 2015

Keywords: North Atlantic Subtropical High (NASH), Intertropical Convergence Zone (ITCZ), precipitation, paleoclimate

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DEDICATION

To my parents, Peter and Elizabeth, for instilling in me the importance of higher education; to my husband, D.J., for encouraging me and supporting me throughout this endeavor; to my brothers, for pursuing higher education before me; and to my children, Samuel and Eliza, for whom I hope to set an example so that they may pursue knowledge and education.
ACKNOWLEDGMENTS

Specials thank my advisor, Phil van Beynen, for taking me on as a Research Assistant, reading excessive drafts, and being so patient as I slowly moved forward with my dissertation. My committee have been invaluable on this journey. Thank you to: Kristine DeLong, who spent a great deal of time answering my questions, and sharing her vast knowledge of time series analysis and paleoclimatology; Jonathan Wynn for teaching me about stable isotopes, running the mass spec and really taking a lot of time to go through revisions to greatly improve my work; and to Bob Brinkmann and Phil Reeder for taking the time to do all the things associated with being a committee member, even after leaving USF.

I would also like to acknowledge all of the following people that in some way contributed to this dissertation: Jason Polk, for collecting initial samples and figuring out how to use the micromill; Victor Polyak and Yemane Asmerom, for teaching me about U-series dating, and the use of their lab; Zac Atlas, for stable isotope/mass spec help; Ethan Goddard, for running stable isotopes; Michael Niedzielski for map creation; several undergrads that helped collect the thousands of stable isotope samples; and last, but not least, Johannah Kovarik for putting up with me in the lab and listening when I had far too much to say.

This research was funded by National Science Foundation Grant Number 0823476.
# TABLE OF CONTENTS

List of Tables iii

List of Figures iv

Abstract v

## Chapter 1: Introduction and Background
  1.1 Introduction 1
  1.2 Research objectives 2
  1.3 Organization of the dissertation 3
  1.4 References 4

## Chapter 2: A Mid-Holocene Paleoprecipitation Record from Belize 5
  2.1 Abstract 5
  2.2 Introduction 6
    2.2.1 Study area 9
    2.2.2 Regional climate setting 10
  2.3 Materials and methods 11
    2.3.1 Stable isotope analysis 11
    2.3.2 Chronology 13
    2.3.3 Spectral analysis 14
    2.3.4 Comparison of mid-Holocene to present 14
  2.4 Results and discussion 15
    2.4.1 Isotopic equilibrium 15
    2.4.2 Stable isotope ratios 17
    2.4.3 Age model 19
    2.4.4 Autocorrelation and variance of the oxygen isotope record 21
    2.4.5 Spectral analysis 21
    2.4.6 Mid-Holocene vs. modern precipitation 23
    2.4.7 Oscillatory variability in precipitation 26
  2.5 Conclusions 27
  2.6 References 27

## Chapter 3: A Speleothem Based Paleoprecipitation Record for West Central Florida 34
  3.1 Abstract 34
  3.2 Introduction 35
  3.3 Regional setting 37
  3.4 Materials and methods 38
3.4.1 Speleothem collection
3.4.2 $^{234}\text{U} - ^{230}\text{Th}$ dating
3.4.3 Stable isotopic analysis
3.4.4 Time series analysis
3.4.5 Comparison of mid-Holocene to late-Holocene

3.5 Results and discussion
3.5.1 Uranium-series dating
3.5.2 Stable isotope records
   3.5.2.1 Isotopic equilibrium
   3.5.2.2 Stable isotope interpretation
3.5.3 Change in mid-Holocene precipitation: Comparison to present
3.5.4 Multi-decadal and centennial changes in mid-Holocene precipitation

3.6 Conclusions
3.7 References

Chapter 4: Investigation of Climate Teleconnections between Central America and Subtropical North America
4.1 Abstract
4.2 Introduction
4.3 Regional setting
   4.3.1 Belize
   4.3.2 Florida
4.4 Previous research
   4.4.1 Belize: CH04-02
   4.4.2 Florida: BC01-07
4.5 Florida and Belize comparison
   4.5.1 Methods
   4.5.2 Results and discussion
4.6 Conclusion
4.7 References

Chapter 5: Conclusions
5.1 Purpose and objectives
5.2 Conclusions
5.3 Future research
5.4 References
LIST OF TABLES

Table 2.1  CH 04-02 U/Th dating results  20
Table 2.2  CH04-03 U/Th dating results  20
Table 3.1  BC01-07 U/Th dating results  43
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Location of Chen Ha Cave, Belize</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Tests for isotopic equilibrium for CH04-02</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>Oxygen (top-black) and carbon (bottom-grey) isotopic variations of CH04-02</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>U-Th derived age model</td>
<td>19</td>
</tr>
<tr>
<td>2.5</td>
<td>Spectra analysis results</td>
<td>22</td>
</tr>
<tr>
<td>3.1</td>
<td>Location of Brown’s Cave, West Central Florida</td>
<td>38</td>
</tr>
<tr>
<td>3.2</td>
<td>Uranium-series dating model with analytical uncertainties (2σ)</td>
<td>42</td>
</tr>
<tr>
<td>3.3</td>
<td>Tests for isotopic equilibrium conditions during calcite deposition</td>
<td>44</td>
</tr>
<tr>
<td>3.4</td>
<td>The $\delta^{18}$O$_c$ (top) and $\delta^{13}$C$_c$ (bottom) variations from BC01-07</td>
<td>46</td>
</tr>
<tr>
<td>3.5</td>
<td>Comparison between oxygen isotope records from (left) late-Holocene speleothems from Brooksville Ridge Cave (BRC) (blue line) and Briar’s Cave (black dotted line) and (right) low resolution mid-Holocene speleothem records from BC01-07 (dashed line) and BRC03-03 (solid line) from West-Central Florida</td>
<td>48</td>
</tr>
<tr>
<td>3.6</td>
<td>Results from time series analysis of the $\delta^{18}$O$_c$ variations from BC01-07</td>
<td>50</td>
</tr>
<tr>
<td>4.1</td>
<td>Precipitation reconstructions for BC01-07 from Brown’s Cave, West-Central Florida (blue) and CH04-02 from Chen Ha, Vaca Plateau, Belize (green) from $\delta^{18}$O values</td>
<td>62</td>
</tr>
<tr>
<td>4.2</td>
<td>Cross wavelet transform (top) and wavelet coherency (bottom) of aligned CH04-02 and BC01-07</td>
<td>66</td>
</tr>
<tr>
<td>4.3</td>
<td>Map of precipitation (mm) data for the mid-Holocene from terrestrial proxy records compared to modern in Central America, Mexico and the southern United States</td>
<td>68</td>
</tr>
</tbody>
</table>
ABSTRACT

As global temperatures rise due to anthropogenic climate change, water resources, thus economies, are threatened. A geologically recent period of increased temperatures is the mid-Holocene and an investigation of its climate may allow for a better understanding of future precipitation and changes to regional water resources. The regions of interest are tropical Northern Central America and subtropical North America with Belize and Florida representing each climate zone. By reconstructing mid-Holocene climate in Florida and Belize, I hope to provide a better understanding of how increased temperatures and a reduced latitudinal temperature gradient impacts both precipitation patterns and variability. Today, drivers of changes in precipitation include climate systems such as the Atlantic Multidecadal Variability (AMV), North Atlantic Oscillation (NAO), and the Intertropical Convergence Zone (ITCZ). Therefore, it is imperative to determine their latitudinal influences during the mid-Holocene and consequently their potential impact on water resources in the near future.

Speleothems from Chen Ha Cave, Vaca Plateau, Belize and Brown’s Cave, West Central Florida, provided high-resolution (sub-annual to decadal) oxygen and carbon stable isotope data that allowed for a detailed investigation of mid-Holocene climate. The speleothems were sampled along the growth axis of a cross-section for oxygen and carbon isotopic analysis. $^{234}$U-$^{230}$Th dating was used to create a chronology for each record and determine the time step between each isotope sample. Time series analysis with variations of Fourier transforms, including Lomb-Scargle, wavelet analysis, and multi-taper method, was used to extract periodicities for each oxygen isotope record. To determine which atmospheric-oceanic modes
influenced mid-Holocene precipitation, the speleothem periodicities were compared to those of known periodicities of atmospheric-oceanic modes, such as the AMV and NAO. Finally, the Florida and Belize records were assessed for coherency using cross wavelet analysis.

The Floridian speleothem recorded less precipitation compared to present levels due to a westward expansion and intensification of the North Atlantic Subtropical High (NASH) with a quasi-persistent but less influential AMV. Relative to today, the mid-Holocene in Belize was slightly wetter which I suggest is a result of a more northerly ITCZ and an intensification of the NASH that increased the strength of the Caribbean Lower Level Jet (CLLJ). The Seuss solar cycle was also significant in Belize, contributing 7.2% of the precipitation variability. Wavelet coherency assessment reveal very little connectivity between the Florida and Belize speleothem reconstructions, potentially due to the blocking influence of the ITCZ. Comparison to other records from the mid-Holocene supports the hypothesis of an intensified NASH and more northerly ITCZ.

A future increase in precipitation in Belize may lead to increased soil erosion, the need for crop adaptation, and risk to the population of low lying areas, such as Belize City. In Florida, reduced precipitation may result in a decrease in agricultural output and threats to the state’s freshwater supply.
CHAPTER 1:
INTRODUCTION AND BACKGROUND

1.1 Introduction

With steadily rising global temperatures and potential widespread water shortages (Intergovernmental Panel on Climate Change - IPCC, 2013) it is imperative to be able to predict future change. Although it is widely accepted that anthropogenic activities are responsible for the current warming trend (IPCC, 2013), it is essential to examine warming within the context of natural climate variability and its forcing mechanisms. Such an investigation requires the use of paleoclimate proxies, indirect measures of past climates, including ice cores, tree rings, speleothems and corals, which allow the investigation of pre-industrial (natural) climate change.

The 2013 IPCC report predicts a future scenario that is similar to that of the mid-Holocene pertaining to the latitudinal temperature gradient and enhanced warmth in the high latitudes (Dorale et al., 1992; Koc and Jansen, 1994; Korhola et al., 2000; Rosen et al., 2001; Solovieva et al., 2005). Therefore, climatic conditions and forces during the mid-Holocene may potentially predict future conditions. The IPCC report calls for future catastrophic changes in the tropical and subtropical water resources (IPCC, 2013), thus, based on the similarities between the mid-Holocene and future latitudinal temperature gradient, knowledge of precipitation change during the mid-Holocene would be useful. The focus of this dissertation is to reconstruct mid-Holocene precipitation variability using speleothems from Belize and Florida.
1.2 Research objectives

The investigation of mid-Holocene climates of Florida and Belize must consider the forcing mechanisms behind any changes. These include various teleconnections such as the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Variability (AMV), and the migration of both the Intertropical Convergence Zone (ITCZ) and the North Atlantic Subtropical High (NASH). Using high resolution stable isotope records (~annual) and U-series dating of speleothems collected from Florida and Belize, I aim to determine the contribution of these forcing mechanisms to precipitation variability during the mid-Holocene.

Therefore, my research questions are:

1) How did the increased global temperatures during the mid-Holocene effect teleconnections and climate variability?

2) How does precipitation during the mid-Holocene in Florida and Belize compare to present?

3) How do these reconstructions compare to each other and other proxy data from these two regions?

My research objectives are:

1) To identify the stable isotope variability during the mid-Holocene in Florida and Belize.

2) To identify the drivers of variability with the stable isotope records and determine if they represent oscillations in NAO, AMV, or other climate drivers.

3) To determine how the presence or absence of these climate drivers explains the regional changes in the long term precipitation.
1.3 Organization of the dissertation

The following three chapters of this dissertation are written as stand-alone articles that will be submitted to journals for publication; therefore, each chapter contains the background and introductory information necessary to understand each topic. While each chapter is independent, they all address the central question of what drives mid-Holocene precipitation variability for Florida and Belize.

In Chapter 2: A Mid-Holocene Paleoprecipitation Record from Belize, I present a high-resolution (sub-annual to bi-annual) speleothem-derived oxygen and carbon isotope record of precipitation for the mid-Holocene (~4.7 to 6.9 ka) from Chen Ha Cave, Vaca Plateau, Belize. I compared my mid-Holocene precipitation proxy to a late-Holocene record to determine how the mid-Holocene climate differed from modern conditions. Time-series analysis allowed for an investigation into the drivers of mid-Holocene variability. This chapter includes a discussion on the influence of the ITCZ and AMV.

Chapter 3: A Speleothem Based Paleoprecipitation Record from West Central Florida provides a similar investigation into mid-Holocene climate as Chapter 2, but for Brown’s Cave in West-Central Florida. Nearby speleothem-based oxygen isotope records from the mid- and late-Holocene allowed for robust comparisons between the two time periods. Time series analysis provided information into the drivers of climate variability during the mid-Holocene. This chapter includes a discussion on the influence of the NASH, AMV and NAO.

Chapter 4: Investigation of Climatic Teleconnections between Central America and Subtropical North America integrates the oxygen isotope records from Chapters 2 and 3 to paint a picture of regional climate during the mid-Holocene. I compared the Chen Ha and Brown’s Cave records through cross-wavelet transform and wavelet coherence to determine periodicities
that influenced both locations. Previous paleoclimate data compilations from Ruter et al. (2004) and Bartlein et al. (2011), combined with my new records, allowed for the creation of a map of point data representing proxy records of mid-Holocene precipitation compared to present across the southern United States, Mexico, and northern Central America. This chapter includes discussion on the ITCZ and NASH.

Chapter 5: Conclusion presents an overview of the findings of the preceding chapters and the potential for future research.

1.4 References


Intergovernmental Panel on Climate Change (IPCC), 2013. Climate change 2013 – The physical science basis. Cambridge UP: Cambridge.


CHAPTER 2:
A MID-HOLOCENE PALEOPRECIPITATION RECORD FROM BELIZE

2.1 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 I 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. I 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 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. The North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Variability (AMV; also known as the Atlantic Multidecadal Oscillation (AMO)) are considered important drivers of precipitation variability for modern Belize; however, time series analyses of the oxygen isotope record found no evidence of periodicities of
the AMV and the NAO. The only significant periodicity band is centered on 225–250 years/cycle, which is within the upper range of the Suess solar cycle.

2.2 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). Mid-Holocene temperature changes are similar to that predicted by the IPCC due to anthropogenic climate change (IPCC, 2013). The mid-Holocene was a period of enhanced warming, particularly in the high northern hemisphere latitudes (e.g., Dorale et al., 1992; Koc and Jansen, 1994; Korhola et al., 2000; Rosen et al., 2001; Solovieva et al., 2005). 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 in 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 report of Metcalfe et al. (2009) presents the most recent study with evidence of a moist and relatively stable climate in the New River Lagoon, Belize for 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.

In order to understand mid-Holocene precipitation in Central America, a proxy that is sensitive to changes in rainfall is necessary; variations in the oxygen isotopic ratio ($\delta^{18}$O) within tropical speleothems meet this criterion. $\delta^{18}$O is reported in delta notation (Eq. 1.1) where the ratio of $^{18}$O to $^{16}$O is reported relative to a standard

$$\delta = \left( \frac{R_x - R_{STD}}{R_{STD}} \right) \times 1000 \quad \text{Eq 1.1}$$

Where $R_x$ and $R_{STD}$ are the isotope ratios (less abundant/more abundant) of the sample (x) and the standard (STD), respectively. The $\delta^{18}$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 $\delta^{18}$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; therefore, towards the higher end of the range it is possible to sample the speleothem calcite at annual or sub-annual resolution (McDermott, 2004). Such high temporal resolutions allow for seasonally resolved reconstructions of past precipitation.

Interpretation of the carbon isotopic ratio ($\delta^{13}C$; ratio of $^{13}C/^{12}C$) variability in tropical speleothems is more complex. Fluctuating $\delta^{13}C$ 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$_2$ (pCO$_2$), plant productivity, rates of CO$_2$ degassing, and various other factors can play a role shifting speleothem $\delta^{13}C$ values (Yonge et al., 1985; Fairchild et al., 2006).

Here I 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.

I consider the following questions:

1) How does the magnitude and variability of mid-Holocene precipitation compare to modern precipitation?

2) If differences are apparent, what atmospheric-oceanic mechanisms could drive this change?
My research objectives are:

1) To determine stable isotopic variability in a speleothem that formed during the mid-Holocene;
2) To compare mid-Holocene precipitation to the present; and
3) To assess possible drivers of mid-Holocene precipitation amount and variability.

2.2.1 Study area

![Map showing the location of Chen Ha Cave, Belize. A) Precipitation in Belize is a result of moisture transport from the Caribbean Sea via Central 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 examined in this study (CH04-02) was collected from Chen Ha Cave located on the Vaca Plateau (17°N, 89°W, 550 masl; Fig. 2.1) in the Mayan Lowlands of southwestern Belize by Philip van Beynen in 2004. 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.,
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 CO$_2$ levels within the cave. Other caves with similar depth within the study area have relative humidity between 93 to 95% (Webster et al., 2007). CH04-02 was chosen because it was towards the back of the cave and was very large (~1 m tall). 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.

### 2.2.2 Regional climate setting

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).

The climate of the Vaca Plateau is controlled by the influences from the Pacific Ocean and the Caribbean Sea, with the Caribbean being more influential due to the predominant easterly wind direction. The Intertropical Convergence Zone (ITCZ) and NASH both influence
the climate of Belize (Fig. 2.1) (Haug et al., 2003; Hodell et al., 2005; Gamble and Curtis, 2008; Cook and Vizy, 2010). During the boreal summer, the ITCZ’s northward movement brings precipitation to Belize, and conditions are drier during the winter when the ITCZ migrates south (Haug et al., 2003; Hodell et al., 2005). The NASH influences 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 Nino 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).

2.3 Materials and methods

2.3.1 Stable isotope analysis

For CH04-02, I sampled the speleothem for isotopic analysis ($\delta^{18}O$ and $\delta^{13}C$) along the c-axis at 200 μm intervals, and for CH04-03, I 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 Peedee Belemnite (VPDB) with a precision of 0.10‰ (2σ) for δ¹⁸O and 0.07‰ (2σ) for δ¹³C.

To properly understand the stable isotope records, I 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 δ¹⁸O values and comparing the δ¹⁸O and δ¹³C values (Hendy, 1971). In the absence of kinetic fractionation or evaporation, δ¹⁸O values should remain constant along a growth layer, and δ¹⁸O and δ¹³C 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, I investigated correlation between the δ¹⁸O and δ¹³C values along the growth axis of the speleothem and the replication of δ¹⁸O 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. I performed an autocorrelation on the entirety of the oxygen isotope record, as well as the segments between
each of the dates. I calculated the variance of each segment to determine if there was any
relationship between variance and resolution.

2.3.2 Chronology

Using prior thermal ionization mass spectrometry (TIMS) uranium-thorium (U-Th) dates
for CH04-02, I 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. I 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
$^{236}\text{U}$, $^{233}\text{U}$, and $^{229}\text{Th}$, 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, I 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, I
also used multiple Monte Carlo simulations in which one date was removed, a technique known
as bootstrapping.
2.3.3 Spectral analysis

The isotopic samples extracted from CH04-02 have c-axis increments of 200 μm; therefore, I converted the record to the time domain for further interpretation. Using the results from high resolution U-Th dating, I defined the age model for CH04-02. Before spectral analysis, I removed the mean and detrended the δ¹⁸O time series. I used two spectral analysis methods with Fourier transforms to assess periodicities in the δ¹⁸O record: the Multi-Taper Method (MTM) (Thomson, 1982; Ghil et al., 2002) and wavelet analysis (Torrence and Campo, 1998; Grinsted et al., 2004). I 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).

2.3.4 Comparison of mid-Holocene to present

To compare the amount of precipitation between the mid-Holocene and modern, I compared the δ¹⁸O record of CH04-02 to the modern speleothem δ¹⁸O record from Macal Chasm on the Vaca Plateau (Webster et al., 2007). Additionally, I 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.
2.4 Results and Discussion

2.4.1 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 calcite is deposited under isotopic equilibrium conditions. The Hendy test reveals a visually evident trend between the $\delta^{18}$O and $\delta^{13}$C values along each sampled layer and variability within $\delta^{18}$O values with distance from the apex of the stalagmite (Fig. 2.2a-d). Therefore, this speleothem fails the Hendy Test; however, the Hendy 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 $\delta^{18}$O and $\delta^{13}$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 2.2e). However, the highlighted values in Figure 2.2e represent less than 2% of the total number of the isotopic samples. If these values are removed, the $r^2$ value drops to 0.09 ($p<0.0001$) thereby suggesting that 98% of the speleothem was deposited under equilibrium conditions, although there may be a small subset of samples that were not. The covariance may also be a result of environmental factors that impact $\delta^{18}$O and $\delta^{13}$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 $\delta^{18}$O and $\delta^{13}$C values in the speleothem. The final test for equilibrium is similar $\delta^{18}$O values and coeval variability of CH04-03 and CH04-02 (Fig. 2.2f). 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, I compared the two speleothems at the same sampling resolution by averaging the CH04-02 values. The $\delta^{18}$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 2.2f).

Overall, while there is some evidence of kinetic fractionation during the deposition of CH04-02,

**Figure 2.2:** Tests for isotopic equilibrium for CH04-02. a) Hendy test: a and b) correlation of $\delta^{18}$O and $\delta^{13}$C along a single growth layer; c and d) $\delta^{18}$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.
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.

**2.4.2 Stable isotope ratios**

The $\delta^{18}O$ values of CH04-02 have a mean of $-5.0\% _{\text{oo}} \pm 0.6\% _{\text{oo}}$ ($1\sigma$, n=1573), and a range of 4.2‰ and the $\delta^{13}C$ values have a mean of $-11.3\% _{\text{oo}} \pm 0.8\% _{\text{oo}}$ ($1\sigma$, n=1573) and a range of 5.3‰ (Fig. 2.3). The main controls on speleothem $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ of precipitation to my study area, and the precipitation data for that station indicates that precipitation $\delta^{18}O$ 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 $\delta^{18}O$ value of precipitation (Dansgaard, 1964). Similarly, Medina-Elizalde et al. (2010) determined that precipitation $\delta^{18}O$ values for their Yucatan study site were controlled by the amount affect. Chen Ha cave is located in the same climate regime as both the Veracruz IAEA station and the Yucatan peninsula; therefore, I assume that the $\delta^{18}O$ values for CH04-02 are largely controlled by precipitation via the amount effect.

The main control on speleothem $\delta^{13}C$ variability is the $\delta^{13}C$ 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
Figure 2.3: Oxygen (top-black) and carbon (bottom-grey) isotopic variations of CH04-02. Dashed lines represent average values.

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 C₃ plants (humid climate) to vegetation adapted to arid conditions (C₄ plants). An alternate explanation proposed by the study of Webster et al. (2007) is that abrupt changes in speleothem δ¹³C for the Vaca Plateau (same as my study site) are a result of the fluctuating partial pressure of the CO₂ (pCO₂) in the soil above the cave. Those authors concluded that during drier periods, there was a decrease in soil pCO₂ because of decreased plant productivity, leading to the lower δ¹³C values in speleothem calcite. This is because dripwater with higher pCO₂ can dissolve and hold more carbonates, leading to a faster rate of degassing and a higher δ¹³C value in the speleothem (Webster et al., 2007). A range of –6 to –13.5‰ in their late-Holocene speleothem δ¹³C values is similar to the range of –8 to –13‰ and –9 to –12‰ observed in CH04-02 and CH04-03, respectively. Consequently, I agree with their interpretation that the main control on variability in speleothem δ¹³C values are driven by changes in the moisture content of the soil above the cave.
2.4.3 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 2.1). 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 in considered (Fig. 2.4 and Table 2.1).

Figure 2.4: U-Th derived age model. Errors bars are 2 sigma (Table 2.1).

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*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 2.1); therefore, it may lead to larger time step uncertainties. The resulting average Δt from
Table 2.1: CH04-02 U/Th dating results

<table>
<thead>
<tr>
<th>Distance from top (mm)</th>
<th>$^{238}$U (p/pg)</th>
<th>$^{232}$Th (pg/g)</th>
<th>$^{230}$Th/$^{232}$Th (activity)</th>
<th>$^{230}$Th/$^{238}$U (activity)</th>
<th>$\delta^{234}$U$_i$</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>540</td>
<td>58.7±0.2</td>
<td>6394±46</td>
<td>3.0±0.1</td>
<td>0.1080±0.0023</td>
<td>240.0±3.2</td>
<td>4706±2586</td>
</tr>
<tr>
<td>570</td>
<td>63.0±0.2</td>
<td>2074±20</td>
<td>6.4±0.1</td>
<td>0.0691±0.0010</td>
<td>221.0±1.7</td>
<td>4777±791</td>
</tr>
<tr>
<td>595</td>
<td>71.5±0.2</td>
<td>1682±49</td>
<td>8.7±0.4</td>
<td>0.0667±0.0020</td>
<td>223.3±2.7</td>
<td>4985±590</td>
</tr>
<tr>
<td>620</td>
<td>84.6±0.2</td>
<td>1013±52</td>
<td>16.9±1.0</td>
<td>0.0661±0.0018</td>
<td>234.2±2.3</td>
<td>5432±328</td>
</tr>
<tr>
<td>660</td>
<td>56.3±0.2</td>
<td>569±50</td>
<td>21.2±2.1</td>
<td>0.0701±0.0030</td>
<td>301.8±3.5</td>
<td>5585±350</td>
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<tr>
<td>690</td>
<td>70.8±0.2</td>
<td>1076±43</td>
<td>14.7±0.7</td>
<td>0.0729±0.0020</td>
<td>271.7±2.5</td>
<td>5741±393</td>
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<tr>
<td>725</td>
<td>63.9±0.2</td>
<td>1209±41</td>
<td>12.7±0.5</td>
<td>0.0789±0.0021</td>
<td>286.9±2.5</td>
<td>6039±466</td>
</tr>
<tr>
<td>750</td>
<td>66.4±0.2</td>
<td>1523±46</td>
<td>11.2±0.5</td>
<td>0.0838±0.0023</td>
<td>267.6±2.8</td>
<td>6396±567</td>
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<tr>
<td>780</td>
<td>74.2±0.2</td>
<td>292±38</td>
<td>62.8±8.2</td>
<td>0.0808±0.0016</td>
<td>293.5±2.0</td>
<td>6846±166</td>
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<tr>
<td>820</td>
<td>124.2±0.3</td>
<td>1829±28</td>
<td>17.3±0.3</td>
<td>0.0831±0.0008</td>
<td>248.2±1.1</td>
<td>6823±350</td>
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<tr>
<td>835</td>
<td>88.2±0.2</td>
<td>3469±45</td>
<td>7.6±0.2</td>
<td>0.0973±0.0018</td>
<td>257.8±2.0</td>
<td>6936±926</td>
</tr>
</tbody>
</table>

Table 2.2: CH04-03 U/Th dating results

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

The Monte-Carlo simulation using all U-Th ages was 1.605 ± 0.813 years/sample (2σ). The results of the bootstrapping (Δt = 1.645 ± 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 (Δt = 1.605 years/sample) is used to assign dates to each stable isotope sample for spectral analysis.
2.4.4 Autocorrelation and variance of the oxygen isotope record

After creating the age model, further analysis of the δ¹⁸O values reveals insights on the controls of δ¹⁸O 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 δ¹⁸O 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 δ¹⁸O 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 was expected because subannual precipitation records would generally show more variability than a 1-4 year sampling resolution that would have an averaging effect thus less variance. 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.

2.4.5 Spectral analysis

Spectral analysis of the mid-Holocene δ¹⁸O precipitation reconstruction revealed significant periodicities (95% confidence level) centered on 225–250 years/cycle and 21 years/cycle periodicity bands (Fig. 2.5). MTM and wavelet analysis were performed on the δ¹⁸O 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. I interpolated the data to a Δt of 3.2 years/sample, which accounts for 2 standard
Figure 2.5: Spectral analysis results. Top) MTM spectrum of detrended $\delta^{18}O$ values from CH04-02. 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). Bottom) Wavelet spectrum of the detrended $\delta^{18}O$ 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.
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.

The wavelet analysis of CH04-02 (Fig. 2.5) reveals the time intervals when periodicities have significant concentrations of spectral power. The ~225-250 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. 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 δ¹³C for ~21 years/cycle at 5.9 ka that coincides with the results of the oxygen isotope wavelet analysis.

2.4.6 Mid-Holocene vs modern precipitation

Based on my conclusion that the speleothem δ¹⁸O values are indicative of precipitation amount, I assessed how the mid-Holocene precipitation differed from that of the present. The tip of the late-Holocene stalagmite from a nearby cave (2 km) reported by the study of Webster et al. (2007) has a δ¹⁸O value of −4.3‰. 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 δ¹⁸O 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 my 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 δ18O value of –4.80 ± 0.75‰ (1σ) for Tzabnah record, the variability of δ18O 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 δ18O. 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 (Metcalfe 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. My 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.

Further contributing to increased precipitation was the intensification and westward expansion of the NASH (Bartlein et al., 1998; Shuman et al., 2002; Hardt et al., 2010). A strengthening of the NASH during the mid-Holocene strengthened the CLLJ, thereby reducing convection in the Caribbean Sea (Giannini et al., 2000; Wang, 2007; Whyte et al., 2008) but increasing the advection of moist air to the Maya Mountains and increasing precipitation in northern Central America (Cook and Vizy, 2010). Every boreal summer the intensification of the NASH is accompanied by the northward migration of the ITCZ (Giannini et al., 2000). Consequently, my discussion of the impact of the ITCZ migration on mid-Holocene precipitation complements the idea of NASH intensification.
2.4.7 Oscillatory variability in precipitation

The 225-250 year oscillation found in the $\delta^{18}$O record of CH04-02 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), which govern the intensity of the NASH (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 Suess solar cycles identified by the spectral analysis of the CH04-02 $\delta^{18}$O data (225-250 year oscillation) demonstrate the overarching control of solar variability as the driving force of precipitation variability in North Central America during the mid-Holocene.

No significant periodicities in the range of that observed for the North Atlantic Oscillation (NAO) or Atlantic Multidecadal Variability (AMV) are present in the $\delta^{18}$O record despite the fact that this record has the resolution to resolve decadal periodicities if present. It is unlikely that the impact of the AMV or NAO on Belizean precipitation during the mid-Holocene can be entirely discounted. There are several possible explanations for their absence: they influence winter precipitation, which may be masked by the stronger summer signal, or their effects may be diminished by the influence of the ITCZ over Belize, which is to the south of Belize today. My 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
America. Their conclusion, derived from analysis of the Lake Chichancanab record from the Yucatan, Mexico (Hodell et al., 2001), was based on the entirety of that low-resolution record. My spectral analysis of the mid-Holocene portion of the Lake Chichancanab record cannot reveal significant periodicities within the band of the AMV or NAO.

2.5 Conclusions

My analysis of mid-Holocene precipitation variability for the north of Central America as derived from a ~annually resolved mid-Holocene speleothem record suggests a slight increase in and more stability in precipitation levels than present. I 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 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 (225-250 years) thereby highlighting the importance of solar irradiance in driving climate change on centennial time scales. My data indicate that the AMV and NAO cycles do not have a significant impact on the precipitation in northeastern region of Central America during the mid-Holocene.

2.6 References


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CHAPTER 3:
A SPELEOTHEM BASED PALEOPRECIPITATION RECORD FOR WEST-CENTRAL FLORIDA

3.1 Abstract

The economic future of Florida is dependent on adapting to climate change. In order to better understand what changes in climate are in our future, we can look back to the mid-Holocene, which is a geologically recent period of higher than modern global temperatures. A high resolution (biannual-subannual) speleothem paleoprecipitation record from West-Central Florida allows for a detailed investigation into mid-Holocene climate. Oxygen isotopic analysis of a U-Th dated speleothem from west-central Florida resulted in a subannual to biannual oxygen isotope ratio record for the mid-Holocene. The speleothem $\delta^{18}O$ values vary from $-2.5$ to $-5.0\%o$, with a mean value of $-3.6 \pm 0.3\%o$ ($1\sigma$, $n=1476$) and no trend. A comparison of the mid-Holocene record to modern speleothem isotopic records revealed that during the mid-Holocene West-Central Florida was drier than present. The westward shift of the North Atlantic Subtropical High over Florida, due to increased insolation, led to reduced summer precipitation. Time series analysis of the Brown’s Cave oxygen isotopic record revealed that the North Atlantic Oscillation (NAO) did not influence precipitation variability in West-Central Florida during the mid-Holocene; however, a lower intensity Atlantic Multidecadal Variability (AMV) may have been quasi-persistent during this period.
3.2 Introduction

Understanding future changes in precipitation due to climate change is critical to maintaining Florida’s economy (National Climate Assessment, 2015). Changes in precipitation could be devastating to Florida’s 47,500 farms that export $4 billion in products annually including citrus, sugar, beef, and strawberries (Florida Department of Agriculture and Consumer Services, 2015). Increased global temperatures during the mid-Holocene (e.g., Dorale et al., 1992; Koc and Jansen, 1994; Korhola et al., 2000; Rosen et al., 2001; Solovieva et al., 2005) are similar to what is predicted for the future by the Intergovernmental Panel on Climate Change (IPCC, 2013). Since temperature influences precipitation, increased temperatures have the potential to significantly change precipitation patterns. Therefore, understanding mechanisms that drove precipitation in the mid-Holocene for Florida will help predict the future of water resources for the state.

Annual variability in precipitation in Florida is largely a result of the interaction between several climatic phenomena. The North Atlantic Subtropical High (NASH) is a high pressure system over the North Atlantic (Li et al., 2011). Atlantic Multidecadal Variability (AMV) is defined as alternating warm-cool phases in the North Atlantic sea surface temperature every ~30 years (Kerr, 2000; Enfield et al., 2001; Kelly and Gore, 2008). North Atlantic Oscillation (NAO) is defined by shifts in sea level pressure differences between the NASH and Icelandic subpolar low on interannual to ~24 years time scales (Loewe, 1966; Rogers and van Loon, 1979; Trenberth and Paolini, 1980; Zhang and Delworth, 2006). The mid-latitudes, where the NASH, AMV, and NAO originate, experienced higher temperatures than present during the mid-Holocene because of increased solar insolation (Mayewski et al., 2004). The similarity between what is known about the climate of the mid-Holocene and changes predicted by the IPCC
suggest that a study of the mid-Holocene precipitation in Florida may yield information on the intensity and teleconnective properties of these climate modes.

A detailed investigation into mid-Holocene precipitation in Florida requires a high resolution climate proxy. While several high resolution proxies exist, such as tree rings, coral and ice cores (e.g., Thompson et al., 1985; Gagan et al., 1998; Briffa, 2000), speleothems are one of the few high-resolution proxies that are available in Florida for reconstructing climate. They form when water saturated with calcium carbonate (CaCO$_3$) enters a cave with lower partial pressure of CO$_2$ relative to the soil, which causes the degassing of CO$_2$ out of the drip water and the precipitation of calcite (Holland et al., 1964; Schwarcz, 1986; Fairchild et al., 2006). The variations of the stable isotopic ratios of oxygen ($\delta^{18}$O, where $\delta = ((R_x - R_{STD})/ R_{STD}) * 1000$ and $R_x$ and $R_{STD}$ are the isotope ratios ($^{18}$O/$^{16}$O) of the sample and the standard, respectively) and carbon ($\delta^{13}$C—relative ratio of $^{13}$C/$^{12}$C) in speleothem calcite are related to environmental conditions at time of deposition (Burns et al., 2002; Lachniet et al., 2004; McDermott, 2004). Thus, speleothems are a useful proxy for regional paleoclimatic change (Broecker at al., 1960; Dansgaard, 1964; Craig, 1965; Burns et al., 2002; Lachniet et al., 2004; McDermott, 2004). Speleothems with high deposition rates coupled with millimeter scale sampling can provide insights into seasonal climate variability (Collcutt, 1979; McDermott, 2004).

Here I present a high-resolution (~annual) speleothem-based precipitation reconstruction for the mid-Holocene (4.9–6.5 ka) from West-Central Florida.

I consider the following questions:

1) How does the magnitude of mid-Holocene precipitation compare to modern precipitation?
2) If differences are apparent, what atmospheric-oceanic mechanisms could drive this change?

The objectives of this study are to:

1) Assess changes in precipitation during the mid-Holocene;
2) Determine what periodicities are present and what they represent; and
3) Compare mid-Holocene precipitation reconstruction to late-Holocene speleothem
\(\delta^{18}O_c\) records to discern differences between the mid-Holocene and modern conditions.

3.3 Regional Setting

Brown’s Cave lies within the Brooksville ridge in West-Central Florida (Fig. 3.1). The area is composed of soft, white, highly permeable fossil-rich Eocene Ocala limestone and the topographic highs contain highly eroded, pale-orange Oligocene Suwannee Limestone (Hoestine and Lane, 1991; Florea et al., 2003; Florea, 2006). The limestone is intermittently overlain and confined by the Hawthorne Formation, although this is non-existent or thin in the highly karstified and cave-rich portions of the Brooksville Ridge (Hoestine and Lane, 1991; Florea et al., 2003). Caves in the Brooksville Ridge formed at several consistent elevations related to the changes in sea level and the water table and have NW-SE or NE-SW orientation (Florea, 2006). In Brown’s Cave, rapid infiltration into the limestone results in active drip sites within the cave. Poor air exchange between the cave and the surface due to a narrow entrance results in relative humidity consistently above 95% within the cave (Polk, 2009).

Nearby average annual air temperature is 21.3°C and mean monthly temperatures vary by ±6.2°C (Southeast Regional Climate Center, 2014). Afternoon relative humidity varies from 52 to 64% (Southeast Regional Climate Center, 2014). West-Central Florida receives ~1355 mm of
rainfall per year, with 60% of the annual precipitation occurring during the warm season between May and October (Southeast Regional Climate Center, 2014). Local convective thunderstorms account for ~74% of warm season precipitation and during the cool season continental frontal systems dominate bringing light to moderate showers (Weatherspark, 2014).

![Figure 3.1](image)

**Figure 3.1:** Location of Brown’s Cave, West-Central Florida. A) The Atlantic Ocean with approximation location of climate influences on Florida (Base map courtesy of the National Park Service) B) Location of Brown’s Cave in Citrus County and Brooksville Ridge Cave in Hernando County, West-Central Florida, both caves on the Brooksville Ridge. Exact locations are not provided in order to protect the caves.

### 3.4 Materials and methods

#### 3.4.1 Speleothem collection

An ~200 mm long speleothem (BC01-07) from Brown’s Cave was collected from the back of the cave, ~15 m from the single, narrow cave entrance in 2001. The stalagmite was selected due to active calcite deposition with very little visible detritus. BC01-07 has dense translucent columnar calcite with clear laminations and several hiatuses at its base. The speleothem was analyzed above these hiatuses to avoid disruptions to the record.
3.4.2 $^{234}\text{U}-^{230}\text{Th}$ dating

Calcite powders (~100–300 μg) were milled from nine clearly visible bands in the speleothem using a hand-held Dremel tool with a 0.24 mm diameter carbide-tipped dental bur. Uranium-thorium series ($^{234}\text{U}-^{230}\text{Th}$) dating was performed on the nine calcite samples collected from BC01-07 at the Radiogenic Isotope Laboratory, University of New Mexico. The samples were dissolved in nitric acid then spiked with $^{229}\text{Th}$-$^{233}\text{U}$-$^{236}\text{U}$ and the Th and U were separated using anion resin columns (Asmerom et al., 2010). Isotopic compositions of the U and Th fractions were measured with a Thermo Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS). Analytical errors were based on initial $^{230}\text{Th}/^{232}\text{Th}$ values of 4.4 ± 2.2 ppm, 2σ.

3.4.3 Stable isotopic analysis

Samples for stable isotopic ratio analysis were micromilled from BC01-07 along the c-axis of the speleothem at 100 μm intervals. The $\delta^{18}\text{O}_c$ and $\delta^{13}\text{C}_c$ of these samples were measured using an isotope ratio mass spectrometer (IRMS) located in the College of Marine Science at the University of South Florida. Approximately 50 μg of speleothem calcite was dissolved in anhydrous phosphoric acid at 70°C for stable isotopic analysis using a ThermoFinnigan DeltaPlus XL IRMS. The analytical precision of $\delta^{18}\text{O}$ is ±0.06‰ (1σ) and for $\delta^{13}\text{C}$ is ±0.03‰ (1σ); all values are reported relative to Vienna PeeDee Belemnite (VPDB).

Isotopic equilibrium fractionation occurs when the isotopic movement between two phases is influenced by the bond strengths of the different isotopes (Hendy, 1971). Heavier isotopes form higher energy bonds, therefore, they will be drawn towards the phase with the stronger bond (Hendy, 1971). Kinetic fractionation occurs when processes such as diffusion
drive the movement between phases; for example, if CO₂ rapidly degasses during speleothem formation then kinetic fractionation occurs because the CO₂ is quickly removed from the solution and isotopic equilibrium cannot be maintained between the remaining aqueous CO₂ and bicarbonate ions (Hendy, 1971). To investigate the assumption that BC01-07 was deposited under isotopic equilibrium conditions, I conducted three tests: the Hendy Test, a test for correlation between δ¹⁸O and δ¹³C values down profile of the speleothem, and a test for coeval variance of δ¹⁸O values of two speleothems from the same region. The Hendy Test investigates the relationship between δ¹⁸O and δ¹³C values and variation in δ¹⁸O values along a single growth layer (Hendy, 1971). The theory is that under isotopic equilibrium, there will be no simultaneous enrichment of ¹⁸O and ¹³C because it is assumed that calcite δ¹⁸O is influenced by climate (precipitation and temperature) and δ¹³C is controlled by soil organic matter composition (Hendy, 1971; Dorale and Liu, 2009). Secondly, assuming that there is no kinetic fractionation or evaporation, δ¹⁸O values along a single growth layer will remain constant from the apex down the flanks (Hendy, 1971; Dorale and Liu, 2009). The test for coeval variance of δ¹⁸O values of two speleothems from the same regions presumes that it is highly unlikely that two speleothems that are spatially separate would be deposited under the same kinetic or evaporative conditions; thus, replication of the record in two speleothems suggests that isotopic equilibrium occurred during deposition (Dorale and Liu, 2009).

3.4.4 Time series analysis

Time-series analysis was used to detect any significant periodicities present in the stable isotopic records. Using the results from the U-Th dating, I defined the age model and converted the stable isotopic records to the time domain. Three different time-series analysis methods were
used: Lomb-Scargle Fourier Transform (LSFT) using Spectrum software (Schultz and Stattegger, 1997) (Lomb, 1976; Scargle, 1982; Scargle, 1989), Multi-Taper Method (MTM; tapers=3, smoothing=5) using k-Spectra Lite software (Ghil et al., 2002)(Thomson, 1982) and wavelet spectrum (Morlet mother wavelet; using MatLab code from Grinsted et al., 2004) (Torrence and Campo, 1998). Prior to this analysis, the mean was removed and the records were detrended, if a trend was present. Each analysis method has different assumptions and time-frequency transforms thus using three methods allows for greater confidence in determining significant periodicities than from an individual method. For example, MTM and wavelet analysis require constant temporal spacing; therefore, the speleothem records were interpolated to a constant time interval, whereas the LSFT can be performed on a time series with uneven time intervals thus interpolation is not necessary. To assess the influence of interpolating to a constant time interval for the MTM and wavelet spectrum, a Monte Carlo simulation of the dating model (n = 10,000 assuming a Gaussian probability distribution function) was used to compare various possible time steps and chronologies that vary within U-Th dating uncertainties. Significance was assessed at the 95% confidence interval (CI) assuming a red-noise background modeled as an auto-regressive lag-1 (AR(1)) process for MTM, LSFT, and wavelet analyses (Schultz and Stattegger, 1997; Torrence and Campo, 1998; Ghil et al., 2002).

3.4.5 Comparison of mid-Holocene to late-Holocene

To determine how the mid-Holocene precipitation may differ from the present, I compared two late-Holocene speleothem records, one from Brooksville Ridge Cave (BRC) located 1.5 km south of Brown’s Cave and another 50 km north (Briar Cave) with two mid-Holocene stalagmites, BC01-07 and BRC03-03. Modern day precipitation rate varies little
between these areas, with BC and BRC annual average total is 1355 mm compared to 1375 mm at Briar’s Cave (Southeast Regional Climate Center, 2014).

3.5 Results and discussion

3.5.1 Uranium series dating

The U-Th dates for BC01-07 yield ages from ~4.8 to 6.5 ka spanning close to 2 kyr in the mid-Holocene (Table 3.1, Fig. 3.2). The nine dates are in chronological order and have errors less than 2.5% due to low detrital thorium concentrations. A 4th order polynomial age model provided the best fit (r = 0.99) to create the chronology for the stable isotopic records. Based on this age model, the sampling resolution is approximately annual.

Figure 3.2: Uranium-series chronology with analytical uncertainties (2σ). The polynomial fit is within dating uncertainties (years=5.4x10^6(mm from top)^4 − 1.2x10^3(mm from top)^3 + 0.1(mm from top)^2 + 6.9(mm from top) + 4.6x10^3 (Table 3.1)). The top ~1 mm is suggested to be modern and was excluded.
**Table 3.1**: BC01-07 U/Th dating results

<table>
<thead>
<tr>
<th>Distance from top (mm)</th>
<th>$^{238}$U (pg/g)</th>
<th>$^{232}$Th (pg/g)</th>
<th>$^{230}$Th/$^{232}$Th (activity)</th>
<th>$^{230}$Th/$^{238}$U (activity)</th>
<th>$\delta^{234}$U$_i$</th>
<th>Corrected age</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>386.8±0.9</td>
<td>886.7±26.3</td>
<td>59.9±1.8</td>
<td>0.0449±0.0004</td>
<td>12.3±0.8</td>
<td>4824±80</td>
</tr>
<tr>
<td>33</td>
<td>418.7±1.0</td>
<td>412.0±30.9</td>
<td>138.5±10.4</td>
<td>0.0446±0.0003</td>
<td>12.2±0.8</td>
<td>4864±47</td>
</tr>
<tr>
<td>55</td>
<td>361.6±0.9</td>
<td>227.8±43.2</td>
<td>231.3±44.0</td>
<td>0.0477±0.0005</td>
<td>9.6±1.2</td>
<td>5248±64</td>
</tr>
<tr>
<td>73</td>
<td>586.6±1.5</td>
<td>166.5±41.4</td>
<td>524.1±130.5</td>
<td>0.0487±0.0004</td>
<td>8.4±0.9</td>
<td>5388±46</td>
</tr>
<tr>
<td>94</td>
<td>565.6±1.4</td>
<td>461.5±42.6</td>
<td>189.0±17.5</td>
<td>0.0505±0.0004</td>
<td>8.8±0.9</td>
<td>5555±51</td>
</tr>
<tr>
<td>103</td>
<td>688.1±1.7</td>
<td>510.2±33.4</td>
<td>211.3±13.9</td>
<td>0.0513±0.0003</td>
<td>8.8±0.8</td>
<td>5654±42</td>
</tr>
<tr>
<td>115</td>
<td>699.7±1.7</td>
<td>2410.7±32.5</td>
<td>48.9±0.7</td>
<td>0.0551±0.0004</td>
<td>9.2±0.7</td>
<td>5934±108</td>
</tr>
<tr>
<td>133</td>
<td>1026.1±2.5</td>
<td>5969.4±30.5</td>
<td>30.9±0.2</td>
<td>0.0587±0.0003</td>
<td>9.8±0.6</td>
<td>6207±170</td>
</tr>
<tr>
<td>147</td>
<td>926.7±2.2</td>
<td>1259.7±43.7</td>
<td>131.6±4.7</td>
<td>0.0585±0.0005</td>
<td>0.4±0.7</td>
<td>6504±65</td>
</tr>
</tbody>
</table>

### 3.5.2 Stable isotope records

#### 3.5.2.1 Isotopic equilibrium

Several tests were undertaken to determine if the speleothem’s oxygen and carbon isotopes were deposited under isotopic equilibrium conditions. The Hendy Test was performed on two growth layers and resulted in high correlation between $\delta^{18}$O and $\delta^{13}$C ($r=0.88$, $n=7$, $p=0.005$; $r=0.84$, $n=10$, $p=0.0005$) and variability within $\delta^{18}$O values along both layers tested (Fig. 3.3a-d). These results suggest that isotopic equilibrium did not occur during speleothem deposition. However, there are several weaknesses of the Hendy Test that complicate the interpretation (Dorale and Liu, 2009). The assumption that $\delta^{18}$O values are reflective of climate and $\delta^{13}$C values are reflective of soil organic matter composition thus they should not co-vary is “highly unlikely” (Dorale and Liu, 2009). Changes in temperature or precipitation that lead to changes in $\delta^{18}$O values may also influence vegetation composition and productivity, which in turn changes organic matter composition, and speleothem $\delta^{13}$C values (Dorale and Liu, 2009). Secondly, the calcite down the apex of the speleothem may be deposited under isotopic equilibrium conditions, with kinetic factors effecting the flanks (Dorale and Liu, 2009). Such a scenario would result in variability within the $\delta^{18}$O values along a single layer, suggesting that
the speleothem is unusable for paleoclimate reconstruction, even though isotopic equilibrium occurred down the growth axis (Dorale and Liu, 2009). There is no significant correlation ($r=-0.007, n=3048; p=0.795$) between the $\delta^{18}O$ and $\delta^{13}C$ values down the growth axis (Fig. 3.3e).

**Figure 3.3**: Tests for isotopic equilibrium conditions during calcite deposition. (a-d) The Hendy Test: a and b) correlation of $\delta^{18}O$ and $\delta^{13}C$ along a single growth layer; c and d) $\delta^{18}O$ values by distance from the apex along a single growth layer; e) correlation between $\delta^{18}O$ and $\delta^{13}C$ values down the axis of the speleothem and f) the coeval variance of $\delta^{18}O$ values of BC01-07 and BRC03-03, speleothems from the same region.
The lack of correlation suggests that isotopic equilibrium conditions existed during deposition. The final test is replication. With only the one speleothem from Brown’s Cave, I tested for coeval variance with a speleothem (BRC03-03) from Brooksville Ridge Cave (1.5 km from Brown’s Cave) that grew during a contemporaneous interval (4.8–5.0 ka). A preliminary study of BC01-07 was undertaken at a similar resolution to BRC03-03, thereby allowing me to carry out a direct comparison using the 200 years of each speleothem that are contemporary. The close match \(r=0.764, n=22; p=0.004\) between these segments in the two speleothems provides evidence for isotopic equilibrium (Fig. 3.3f). Even though there are only 8-10 isotopic ratio determinations for each speleothem, this shows a trend towards isotopic equilibrium for the overlapping portion of the speleothems as it is unlikely that two speleothems from different caves would show similar isotopic signals if kinetic fractionation was a factor (Dorale and Liu, 2009). Overall, despite the results of the Hendy Test, further evidence suggests that isotopic equilibrium occurred during the deposition of BC01-07; however, kinetic fractionation cannot entirely be discounted.

3.5.2.2 Stable isotope interpretation

The \(\delta^{18}O\) values from BC01-07 vary from \(-2.5\) to \(-5.0\)‰, with a mean value of \(-3.6 \pm 0.3\)‰ (1σ, n=1476) with no trend (Fig. 3.4). Calcite \(\delta^{18}O\) values are controlled by temperature dependent fractionation for calcite and water of \(-0.20\)‰/°C (Kim and O’Neil, 1997) and the isotopic composition of precipitation (Fleitmann et al., 2003; Asmerom et al., 2007; Lachniet et al., 2007; van Beynen et al., 2007; Baker et al., 2010). For temperature to be solely responsible for the \(\delta^{18}O\) variability, cave temperature would have to vary \(\sim12.5\)°C. Above ground temperatures have a mean seasonal range of \(\sim12\)°C (Southeast Regional Climate Center, 2014), but the cave temperature is representative of the average annual above ground temperature, so
such a large range in cave temperature seasonally is implausible. Consequently, cave temperature is not the dominant driver of speleothem $\delta^{18}O_c$ variability. However, amount effect in precipitation has been found to be an important control of precipitation $\delta^{18}O$ in this region (Polk et al., 2012); therefore, I infer that speleothem $\delta^{18}O_c$ is largely controlled by precipitation amount.

**Figure 3.4:** The $\delta^{18}O_c$ (top) and $\delta^{13}C_c$ (bottom) variations from BC01-07.

Given that speleothem $\delta^{18}O_c$ is largely controlled by precipitation amount, it is necessary to determine if the $\delta^{18}O_c$ values are recording annual or seasonal variability. As expected, an increase in sampling resolution (from lower resolutions to annual and subannual) results in an increase in the variance of the speleothem $\delta^{18}O$ values and precipitation. Additionally, autocorrelation is 0.76 and 0.66 for lag of one and two years between $\delta^{18}O$ samples, respectively, suggesting that there is some dependence from one sample to the next or year to year for annually resolved samples from mixing within the soil or bedrock above the cave. Based on this evidence, I concluded that the $\delta^{18}O_c$ values are representative of average annual precipitation.
amount in the annual or lower resolutions, but in the segments where sampling resolution increases to subannual (~4.8 and 5.4-5.5 ka), seasonal precipitation variation is evident.

The δ\(^{13}\)C\(_c\) values in BC01-07 vary from –6.8 to –10.6‰ with a mean of –8.8 ± 0.7‰ (1σ, n=1476) (Fig. 3.4). Changes in the proportion of C\(_3\) to C\(_4\) plants are often determined to be the main driver of δ\(^{13}\)C\(_c\) variability (Dorale et al., 1992; Fairchild et al., 2006). For example, Dorale et al. (1992) found that in Iowa, during wet, cool conditions, δ\(^{13}\)C\(_c\) values were more negative, which is reflective of C\(_3\) vegetation, and during hot, dry conditions, δ\(^{13}\)C\(_c\) values were less negative, suggesting a shift towards C\(_4\) pathways. However, this is not always the case. Van Beynen et al. (2008) investigated the relationship between strontium and δ\(^{13}\)C\(_c\) in Briar’s Cave, Florida, and found an inverse relationship between strontium and δ\(^{13}\)C\(_c\), which is indicative of changes in soil productivity. When plant productivity is high, the enhanced root respiration produces more CO\(_2\), which in turn increases carbonic acid production. This leads to an increase in solubility of strontium from the soil or bedrock, and more negative δ\(^{13}\)C\(_c\) values in speleothem calcite (Hellstrom and McCulloch, 2000; van Beynen et al, 2008). Precipitation amount and evaporation of soil water also influence the δ\(^{13}\)C\(_c\) values in speleothem calcite, complicating the interpretation of the shifts in the δ\(^{13}\)C\(_c\) values. A lack of correlation (r=–0.007, n=3048; p=0.795) between the δ\(^{13}\)C\(_c\) and the δ\(^{18}\)O\(_c\) values (Fig. 3.3e), suggests that the carbon isotopes do not record similar changes in the paleoenvironment caused by changes in precipitation. For example, the prolonged period of more negative carbon isotope values from 6.2 to 6.4 ka have no corresponding shift in the δ\(^{18}\)O\(_c\) record. Consequently, the interpretation of the carbon isotope record remains unclear.
3.5.3 Change in mid-Holocene precipitation: Comparison to present

The $\delta^{18}O_c$ values of the two modern speleothems (BRC and Briar’s Cave) average $-4.5 \pm 0.2\%$ (1σ, n=457). BRC was sampled at a resolution of ~1.2 years/sample and resolution of the Briar’s Cave record was ~2-6 years/sample. I compare this to the averages of the mid-Holocene record of BC01-07 and BRC03-03 (Fig. 3.5), which have respective $\delta^{18}O_c$ values of $-3.6 \pm 0.3\%$ (1σ, n=1476) and $-3.6 \pm 0.3\%$ (1σ, n=13). Considering the amount effect as the main control of speleothem $\delta^{18}O_c$, the most likely explanation for the difference between the mid-Holocene and late-Holocene speleothem isotopic values is a drier mid-Holocene.

Figure 3.5: Comparison between oxygen isotope records from (left) late-Holocene speleothems from Brooksville Ridge Cave (BRC) (blue line) and Briar’s Cave (black dotted line) and (right) low resolution mid-Holocene speleothem records from BC01-07 (dashed line) and BRC03-03 (solid line) from West-Central Florida. The difference between the isotopic values of the mid-Holocene compared to the late-Holocene suggests that the mid-Holocene was drier than the late-Holocene.

A westward shift of the NASH may be responsible for the reduced precipitation in the mid-Holocene. Several studies have suggested that during the mid-Holocene the NASH
intensified (Bartlein et al., 1998; Shuman et al., 2002; Hardt et al., 2010). This led to the westward shift and expansion of the NASH and its increasing influence on summertime precipitation in the southeastern United States (SE USA) (Li et al., 2011). Higher pressure leads to reduced precipitation, and the seasonal north-south migration of a more intense and westward NASH directly influences SE USA precipitation (Li et al., 2011). When the westward shifted NASH moves further north, the high pressure is over Florida leading to reduced precipitation. Conversely, when it is further south and east, winds from the western edge of NASH bring precipitation from the Gulf of Mexico to Florida. A more northerly mid-Holocene ITCZ (Fleitmann et al., 2003; Knudsen et al., 2011) coincides with a comparable latitudinal shift in the NASH reducing precipitation in Florida.

### 3.5.4 Multi-decadal and centennial changes in mid-Holocene precipitation

I used several time-series analysis methods to assess significance of periodicities present in the speleothem $\delta^{18}O_c$ record. The LSFT analysis results in significant (95% CI) periodicities at ~55–60 years/cycle (Fig. 3.6). A Monte Carlo simulation to determine a constant time step, within dating uncertainty, for the stable isotopic samples resulted in optimal time step of 1.27 years/sample, which was used for MTM and wavelet analysis. The MTM spectrum has significant periodicities (95% CI) at 54–69 years/cycle (Fig. 3.6b) that contain 4.73% of the variance in the reconstruction, more than any of the other significant periodicities. The wavelet spectrum reveals several short (<100 years) time intervals during the mid-Holocene with significant concentrations (95%) in spectral power in the 50–70 years/cycle band, particularly between 4.7–4.8 ka and 5.5–6.0 ka (Fig. 3.6a and 3.6c). These significance bands are within the periodicity of the AMV. There is high power, albeit not significant to the 95% level, throughout
Figure 3.6: Results from time series analysis of the δ¹⁸Oc variations from BC01-07. A) Lomb Scargle Fourier transform. Lines represent 90% and 95% confidence intervals (CI). B) Variance preserving MTM spectrum (tapers = 3 and smoothing = 5), where the area under the spectral line represents the true variance. Green line represents the 95% (green) CI assessed assuming an AR(1) red noise model (Ghil et al., 2002). C) Wavelet spectrum determined using a Morlet mother wavelet. The area under the thick black curve is the cone of influence, which is interpreted with caution. Thin black contour lines enclosing time-periodicity regions with significant concentrations of spectral power (95% CI) assuming a first-order autoregressive (AR(1)) model (Torrence and Campo, 1998).
much of the wavelet analysis spectrum in the range of the AMV. Since the wavelet analysis only shows significant power in a few short intervals, it is possible that a small number of individual events or a low amplitude oscillation are responsible for the significance seen in the LSFT and MTM results (DeLong et al., 2009). I suggest that AMV may be present during the mid-Holocene, but it is weak and quasi-persistent. The AMV influences winter precipitation, but the dominance of summer precipitation in the study area may overshadow any changes in winter precipitation due to AMV variability.

My analysis revealed other non-AMV frequencies (Fig. 3.6). Both LSFT and wavelet analysis show a significant oscillation of ~35 years. The wavelet analysis shows this frequency to be only significant for short intervals, suggesting that it may be simply a result of several large, discrete events.

3.6 Conclusions

My reconstruction of mid-Holocene precipitation derived from the Brown’s δ¹⁸O record suggests that Florida was drier than present during the mid-Holocene. This is most likely a result of the intensification and westward expansion of the NASH. The well-documented northward migration of the ITCZ during the mid-Holocene (Fleitmann et al., 2003; Knudsen et al., 2011) is associated with a similar shift in the NASH thereby reducing precipitation in Florida. Time series analysis of the δ¹⁸O c record suggests that multidecadal variability was a contributor to oxygen isotopic ratio variance during the mid-Holocene; however, the AMV appears to be in a weakened state and quasi-persistent throughout the period. This finding of quasi-persistence is in agreement with that of Knudsen et al. (2011). The potential for reduced precipitation in Florida in the
coming years requires serious consideration of water conservation measures in order to maintain the state’s economy.

3.7 References


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CHAPTER 4:
INVESTIGATION OF CLIMATIC TELECONNECTIONS BETWEEN CENTRAL AMERICA AND SUBTROPICAL NORTH AMERICA

4.1 Abstract

Anthropogenic climate change may result in critical water resource issues for tropical and subtropical regions. Determining precipitation variability in northern hemisphere tropical and subtropical North America during the mid-Holocene may help improve our understanding of how increasing temperatures will influence future precipitation for the region. High-resolution speleothem δ¹⁸O records from the mid-Holocene in West Central Florida and the Vaca Plateau, Belize allow for the investigation of precipitation of these lower latitudes during a geologically recent period of higher temperatures in the high northern latitudes compared to those of the late 20th century. I found that Florida was drier than present and influenced by a low intensity, quasi persistent Atlantic Multidecadal Variability (AMV) while a wetter Belize showed no evidence of any periodic oceanic-atmospheric climate modes. Wavelet coherence and cross wavelet transform show little connectivity between the two locations, although this may be a result of dating uncertainties. Overall, I suggest that these conditions are a result of the intensification and westward expansion of the North Atlantic Subtropical High (NASH), leading to drier conditions in Florida and increased rainfall in Belize. Such an intensification leads to a more northerly Intertropical Convergence Zone (ITCZ) bringing more rainfall to Belize and preventing the
AMV from impacting Belize, resulting in the lack of coherency between Florida and Belize. Other paleoprecipitation records with lower resolution for each region supports these findings.

4.2 Introduction

The mid-Holocene was a period of warmer than present temperatures in the high northern latitudes (Thompson et al., 1995; Korhola et al., 2000; Solovieva et al., 2005) while the tropics and subtropics were comparatively cooler (Rimbu et al., 2003; Giry et al., 2012). This temperature differential produced a weak latitudinal temperature gradient (LTG) similar to that predicted by the 2013 Intergovernmental Panel on Climate Change (IPCC) report for the 21st century (IPCC, 2013). As a consequence of a change in the LTG, one would expect some change in the influence of teleconnections between these regions. Determining whether and to what extent these teleconnections change during the mid-Holocene may be informative as to what could be expected in the coming decades. However, few mid-Holocene paleoclimate studies, especially with high temporal resolution, exist to allow such investigation for northern hemisphere tropical and subtropical North America.

Atmospheric-oceanic teleconnections originating in the North Atlantic influence regional climates well beyond their latitudinal/longitudinal locations (Lamb and Peppler, 1987; Hurrell and van Loon, 1997; Kerr, 2000; Enfield et al., 2001; Visbeck et al., 2001); yet how their hemispheric reach varies with a weaker LTG is poorly understood. Here I suggest that by reconstructing the climates of American tropical and subtropical regions during the mid-Holocene it is possible to determine the extent of teleconnective influence for a period analogous to that of the coming decades. In order to collect the necessary data, I created two high resolution (~annual) mid-Holocene speleothem climate proxy records from subtropical North America.
(West Central Florida - BC01-07) and the northern tropics of Central America (Vaca Plateau, Belize - CH04-02). Tropical and subtropical speleothems record changes in precipitation (through their calcite $\delta^{18}O$ values) through the amount effect with higher amounts of rainfall correspond to lower $\delta^{18}O$ values (Burns et al., 2002; Lachniet et al., 2004; Lachniet, 2009). The high deposition rates of speleothems provide the possibility of reconstructing annual-resolved records of paleo-precipitation (Lachniet et al., 2004; McDermott, 2004). Through the combination of my paleo-precipitation reconstructions, I can investigate regional precipitation variability. My research question is:

During the mid-Holocene, how did increased temperatures compared to present influence the latitudinal influence of teleconnections?

To answer this question, my research objective are:

1) Determine what, if any, periodicities are evident in both reconstructions that correspond to known teleconnections; and

2) Determine the spatial influences of these teleconnections and if shifts occur, what may be the driving forces of those changes.

4.3 Regional setting

Changes in modern day precipitation for the tropical and subtropical regions of Northern Hemisphere America are largely driven by oceanic-atmospheric variability derived from both the Pacific and Atlantic Oceans (Klein et al., 1999; Enfield et al., 2001; Mestas-Nunez and Enfield, 2001; Taylor et al., 2002; Knudsen et al., 2011). The easterly trade winds direct moisture into the low latitudes from the Atlantic Ocean, and their strength varies due to the influence of the North Atlantic Subtropical High (NASH) as well as teleconnections such as the North Atlantic
Oscillation (NAO), Atlantic Multidecadal Variability (AMV), and El Niño Southern Oscillation (ENSO). Consequently, these systems affect precipitation amount in the tropical and subtropical regions of Central and North America (Klein et al., 1999; Taylor et al., 2002; Knudsen et al., 2011).

4.3.1 Belize

Ninety percent of annual total precipitation on the Vaca Plateau of Belize occurs between June and September, largely a result of the north-south migration of the Intertropical Convergence Zone (ITCZ) (Belize National Meteorological Service, 2014). Changes in the Caribbean Low Level Jet (CLLJ) – a manifestation of the easterly trade winds – influence both long term and annual precipitation variability (Marshall et al., 2001; Wang 2007). The easterlies are partly controlled by the sea level pressure in the Caribbean region, which in turn is influenced by the NASH (Gamble and Curtis, 2008; Cook and Vizy, 2010). Belize can be considered representative of the American tropics due to the known modern influences on precipitation. While smaller, local effects can influence precipitation, larger systems, such as the CLLJ and ITCZ, also control precipitation; therefore, I can infer that precipitation variability in Belize during the mid-Holocene would be influenced by variability in these systems.

4.3.2 Florida

A prominent wet season for West Central Florida occurs between May and October and accounts for ~60% of annual rainfall (Southeast Regional Climate Center, 2014). The summer precipitation is locally driven by the converging sea breezes from the Gulf of Mexico and the Atlantic producing daily thunderstorm activity. Dry season precipitation is mainly due to frontal
systems whose frequency is often controlled by AMV and ENSO variability (Enfield et al., 2001; Mestas-Nunez and Enfield, 2001). The changing influences of these teleconnections recorded in my paleoprecipitation records for this latitude (Hagemeyer, 2006; van Beynen et al, 2007; Kelly and Gore, 2008) for the mid-Holocene are representative of regional climate variability.

4.4 Previous research

Mid-Holocene precipitation reconstructions for both Florida and Belize were created using the oxygen stable isotope composition of speleothem calcite and uranium series dating (Chapter 2; Chapter 3). As is standard in the speleothem reconstructions of paleoclimates, I undertook various tests that determined that while kinetic factors cannot be entirely ruled out, isotopic equilibrium was likely during calcite deposition: Hence, my interpretation of the speleothem records as reliable surrogates of paleoprecipitation is valid (Chapter 2; Chapter 3).

4.4.1 Belize: CH04-02

The CH04-02 record consists of 1089 stable isotope samples that span ~4.6 to 6.5 ka (Fig. 4.1). Sampling resolution varies from sub-annual to ~3.5 years/sample. The $\delta^{18}O$ values vary from $-3.3$ to $-7.0\%$ with a mean of $-4.9\% \pm 0.6\%$ (1σ, n=1089). When compared to a nearby modern speleothem record (Webster et al., 2007), the mid-Holocene in Belize was determined to be wetter, yet precipitation was less variable than the present. Enhanced precipitation in Central America has previously been attributed to a northward migration of the ITCZ (Harrison et al., 2003; Ruter et al., 2004; Shin et al., 2006; Metcalfe et al., 2009) as well as the intensification of the NASH (Cook and Vizy, 2010). My finding suggests that the ITCZ was positioned over Belize during the mid-Holocene for longer periods each year producing more
precipitation and a reduced migratory band led to more stable precipitation patterns. This more
northerly ITCZ would have blocked the influence of teleconnections such as the AMV. In
addition, the intensification of the NASH strengthens the CLLJ, bringing more moisture into the
eastern side of the Central American isthmus (Cook and Vizy, 2010). Time series analysis of the
CH04-02 $\delta^{18}O$ record does not show any significant cycles in the frequency bands of any known
teleconnections, such as the AMV or NAO.

![Figure 4.1](image-url)

**Figure 4.1**: Precipitation reconstructions for BC01-07 from Brown’s Cave, West-Central Florida
(blue) and CH04-02 from Chen Ha, Vaca Plateau, Belize (green) from $\delta^{18}O$ values. Note: wetter
conditions are more negative but each record does not necessarily correspond to each other in the
amount of precipitation, this will vary by site.

### 4.4.2 Florida: BC01-07

The BC01-07 record consists of 1360 stable isotope samples from ~4.6 to 6.5 ka, with an
average annual resolution (Fig. 4.1). The $\delta^{18}O$ values vary from $-2.5$ to $-5.0\%$, with a mean
value of $-3.6 \pm 0.3\%$ (1σ, n=1360). A comparison of my reconstruction to a nearby similarly
resolved late-Holocene speleothem record (Polk, 2009) shows that the mid-Holocene for West-
Central Florida was drier than the present. The decrease in precipitation is most likely a result of the intensification and westward expansion of the NASH over Florida (Li et al., 2011), which would result in reduced summertime precipitation. Time series analyses of the BC01-07 record revealed the presence of a potentially low intensity and quasi-persistent AMV-like band during the mid-Holocene. Although time series analyses revealed other significant centennial scale periodicities (95%), none contribute more than 0.2% of the total variance in my record.

4.5 Florida and Belize comparison

4.5.1 Methods

Comparing the records from Florida and Belize allows for an investigation into the regional teleconnective influences that may have controlled precipitation in the area during the mid-Holocene. To compare the periodicities found in the Belize and Florida records, I used cross wavelet transform and wavelet coherency analyses (Torrence and Campo, 1998)(Grinsted et al., 2004). Cross wavelet transform determines periods in time of common high power in each time series. Wavelet coherence shows time intervals where the wavelets co-vary, although each signal does not necessarily possess high power. When used in conjunction, these two methods can determine any similarities in periodicities between the records. Unfortunately, the large dating errors, particularly in CH04-02 make comparing the records difficult. Although the time step in each record was determined to be accurate (Chapter 2; Chapter 3), there may be error in the actual dates that the records are tied to. Therefore, in addition to performing the cross wavelet transform and wavelet coherency analysis on the original oxygen isotope records from BC01-07 and CH04-02, I also aligned the records to each other, and ran the analyses. To align the records, I used a Butterworth filter to remove frequencies higher than 200 years, and used cross
correlation to determine the lag that results in the highest correlation of the records. I then
adjusted the dates on the CH04-02 record so that the records aligned at the highest correlation.
Following the alignment, each unfiltered record was detrended, normalized, and interpolated to
the same time step of 1.65 years.

To determine whether my paleoprecipitation records match other regional mid-Holocene
proxies of paleoclimates, I used the compilations of Ruter et al. (2004) and Bartlein et al. (2011).
Ruter et al. (2004) compiled 36 published records from the Americas between the equator and
30°N, which encompass the latitudes of my records, and ran models to replicate the mid-
Holocene climate conditions. Bartlein et al. (2011) synthesized global pollen and plant
macrofossil records. The data from Ruter et al. (2004) and Bartlein et al. (2011) were compiled
into a map, which I will use to investigate the teleconnections’ influences on the region’s
paleoclimates during the mid-Holocene.

4.5.2 Results and discussion

The comparison of oxygen isotope composition records from West-Central Florida and
Belize has some interesting results (Fig. 4.1). CH04-02 had lower average δ¹⁸O values than
BC01-07, with a wider range (Fig. 4.1), despite the finding of increased stability in Belize. The
oxygen isotopic values of these locations cannot be directly compared to determine which
location was wetter or drier, and the range of each record does not necessarily point to which
location had more precipitation variability. Direct comparison of the actual values and ranges
would be meaningless as these locations have different precipitation source water, yearly
distributions, and cave geology, all that will influence the speleothem δ¹⁸O values.
Modern-day Belize receives approximately 90% of its precipitation during the warm summers and has a wide range of precipitation $\delta^{18}$O values throughout the year: average July precipitation $\delta^{18}$O values are between $\sim-4.0$ to $-5.9\%o$ whereas the January values are between $\sim-0.1$ to $2.0\%o$ (waterisotopes.org). Modern-day Florida receives $\sim$60% of its precipitation during the summer, and precipitation $\delta^{18}$O values are $\sim-3.9$ to $-2.0\%o$ in July and $\sim-1.9$ to $0\%o$ in January (waterisotopes.org). With an increase in ITCZ precipitation during the warmer months, Belize’s average annual precipitation oxygen isotope composition would be more negative. For Florida, a decrease in summer precipitation would reduce its overall contribution to yearly precipitation and therefore shift the isotopic values of the mid-Holocene to less negative values.

The aligned cross wavelet transform and wavelet coherency (Fig. 4.2) show some areas of significance (95%) in the multi-decadal periodicities, and the results were similar to the analyses of the un-aligned records. Since the periods of significance only cover short time intervals, they are likely a result of several short, highly correlated events and not a consistent shared periodicity. The lack of coherence in the high frequencies ($\sim$annual) is expected, even within the aligned records, because finding coherence at annual to sub-annual periodicities requires perfectly aligned time series.

The lack of coherence between Florida and Belize highlights the absence of AMV in Belize because even if it had only a minor climate impact during the mid-Holocene, it would be present in the wavelet coherency. While some of the absence of large periods of high power may be a result of dating errors, the low correlation between the Florida and Belize records shows a change in the teleconnective influences of the mid-Holocene compared to today.
Figure 4.2: Cross wavelet transform (top) and wavelet coherency (bottom) of aligned CH04-02 and BC01-07 (Grinsted et al., 2004). Heavy black line and shaded area is the cone of influence, which is interpreted with caution. 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, 1998).

Based on these results, I posit a quasi-persistent, low intensity AMV during the mid-Holocene, which influenced precipitation in Florida but not Belize. Several studies have shown that there was a more northerly ITCZ during the mid-Holocene (Harrison et al., 2003; Ruter et
al., 2004; Shin et al., 2006; Metcalfe et al., 2009); therefore, I suggest the northward movement of the ITCZ over Belize would block the AMV. A more northerly ITCZ is also responsible for the increased precipitation in Belize (Metcalfe et al., 2009). The increased intensity and westward shift of the NASH during the mid-Holocene (Bartlein et al., 1998; Shuman et al., 2002; Hardt et al., 2010) brought drier conditions to Florida, and enhanced the CLLJ bringing more precipitation to Belize.

In order to test the above scenario regarding the changes in the influences of the major climate controls in the American tropics and subtropics, I used data compiled by Ruter et al. (2004) and Bartlein et al. (2011) for precipitation proxy records from the two latitudinal zones. Ruter et al. (2004) and Bartlein et al. (2011) determined if each proxy record showed the mid-Holocene to be wetter or drier than present. By mapping the location of each record and indicating if it was wetter or drier than present, it is possible to see the regional differences between mid-Holocene and modern precipitation amount (Fig. 4.3). This depiction confirms my observation that most of Central America, including Belize, experienced increased levels of summer precipitation because of a more northerly ITCZ. The northern migration of the ITCZ is also responsible for drier conditions in northern South America, because it is over northern South America for less time each year, thus, less precipitation. Most of the proxy records for the southeastern USA show a drier mid-Holocene thereby agreeing with my interpretation of the climate conditions at the time. Modern decreases in precipitation are related to the expansion of high atmospheric pressure systems in the region. Consequently, the westward expansion of NASH due to increased boreal solar irradiance during the mid-Holocene explains the decrease in precipitation in Florida for this period.
Figure 4.3: Map of precipitation (mm) data for the mid-Holocene from terrestrial proxy records compared to modern in Central America, Mexico and the southern United States. The red star indicates the location of BC01-07, which was drier than present, and the blue star indicates the location of CH04-02, which was wetter than present (data from Ruter et al., 2004 and Bartlein et al., 2011, map created by Michael Niedzielski).

Even though the compilation of these proxy records shows relatively consistent precipitation patterns (i.e., all show that Belize was wetter during the mid-Holocene), the models used by Ruter et al. (2004) were unable to accurately replicate the mid-Holocene precipitation. All of the models showed that Florida was drier, in agreement with the proxy records, however, the models also showed Belize to be drier than or the same as the present, which disagrees with the proxy records. Such a finding underscores the difficulty in modeling and predicting climate and the need for in depth paleoclimate studies.
4.6 Conclusion

The comparison of paleoprecipitation records from West Central Florida and Belize allow for the investigation of changing Northern Hemisphere teleconnections during the mid-Holocene. Individually, I determined that 1) Florida was drier largely due to the westward expansion of the NASH; and 2) Belize was wetter due to the northward migration of the ITCZ and the westward expansion of the NASH, which strengthened the CLLJ thereby bringing more precipitation to Belize. The lack of large areas of significance in the cross wavelet transform and wavelet coherency analysis underscores the lack of connectivity between Florida and Belize. The combined influences of the intensification and westward expansion of the NASH and a northward migration of the ITCZ may have prevented any common teleconnections between the two locations. Given these conclusions, it is imperative that policy makers in both Belize and Florida take steps to consider the consequences of future precipitation change.

4.7 References


Intergovernmental Panel on Climate Change (IPCC), 2013. Climate change 2013 – The physical science basis. Cambridge UP: Cambridge.


CHAPTER 5: CONCLUSIONS

5.1 Purpose and objectives

The purpose of the research presented in this dissertation was to investigate the climate of Florida and Belize during the mid-Holocene using speleothems as a climate proxy. The mid-Holocene was selected as it was a geologically recent period of higher average global temperatures (Dorale et al., 1992; Koc and Jansen, 1994; Briffa, 2000; Korhola et al., 2000; Rosen et al., 2001; Solovieva et al., 2005), similar to what we may experience in the near future due to anthropogenic climate change. Florida and Belize were chosen because subtropical and tropical northern hemisphere America is lacking in high resolution climate data from the mid-Holocene, yet changing global climate will potentially have devastating impacts on precipitation. A better understanding of how precipitation, and thus, water availability may change has the potential to help plan for the future to avoid catastrophic water supply issues.

The initial focus was determining what periodicities were present in speleothem stable isotope records to better understand how teleconnections, such as the Atlantic Multidecadal Variability (AMV) and North Atlantic Oscillation (NAO) impacted each location, and then the region as a whole. However, as the project progressed, it became evident that these periodicities were not major contributors to mid-Holocene precipitation, so the focus morphed towards different explanations for precipitation patterns within the records.
In order to investigate the mid-Holocene climate, I used speleothem oxygen and carbon isotope records from Brown’s Cave, West Central Florida and Chen Ha Cave, Vaca Plateau, Belize. Specifically, I looked at:

1) stable isotope variability during the mid-Holocene in Florida and Belize.
2) how the precipitation during the mid-Holocene in Florida and Belize relates to the climate that is seen in these locations today.
3) how the climate change during the mid-Holocene influenced teleconnections and climate variability.

5.2 Conclusions

Chapter 2 discusses the stable isotope record from the Chen Ha Cave, Belize speleothem (CH04-02). The focus was the $\delta^{18}O$, which was determined to be a record of precipitation variability, as are most tropical speleothems (Lachniet, 2009; Webster et al., 2007). Today, Belize’s precipitation variability is a result of the position of the Intertropical Convergence Zone (ITCZ), the North Atlantic Subtropical High (NASH) through the Caribbean Lower Level Jet (CLLJ), as well as the North Atlantic Oscillation (NAO), El Nino Southern Oscillation (ENSO) and Atlantic Multidecadal Variability (AMV) (Hastenrath, 1976; Giannini et al., 2001; Jury et al., 2007; Mestas-Nunez et al., 2007; Gamble and Curtis, 2008; Fritz et al., 2011; Knudsen et al., 2011). Through comparison to a modern speleothem from Tzabnah Cave on the Yucatan Peninsula (Medina-Elizalde et al., 2010), it was determined that Belize was slightly wetter than present, and the comparison to a speleothem from nearby Macal Chasm (Webster et al., 2007) indicated that Belize’s precipitation amount was less variable during the mid-Holocene. Time series analysis of CH04-02 indicated that periodicities of the AMV and NAO were not present,
but the Seuss solar cycle (~200-250 years) was present in the record. Overall, I found that Belize’s increased precipitation was a result of a more northerly ITCZ, which was over Belize for a longer period each year, bringing more precipitation and the expansion of the NASH which strengthened the CLLJ, again bringing more precipitation to the area.

Chapter 3 is a similar investigation into the precipitation of West-Central Florida using a ~annual speleothem (BC01-07) $\delta^{18}$O record from Brown’s Cave on the Brooksville Ridge. Oxygen isotope variability was determined to be reflective of the amount effect. Florida’s modern precipitation is influenced by the NASH, AMV, NAO and ENSO (Ropelewski and Halpert, 1986; Enfield et al., 2001; Hagemeyer, 2006; van Beynen et al., 2007). I compared the mid-Holocene record of BC01-07 to two modern speleothems from Brooksville Ridge and Briar’s Caves, and determined that the mid-Holocene was drier than present in West-Central Florida. Robust time series analysis revealed that the AMV was the only teleconnection influencing mid-Holocene precipitation, although it was low intensity and quasi-persistent throughout the mid-Holocene. The drier conditions during the mid-Holocene are a result of the westward expansion of the NASH which was also further north due to the northward migration of the ITCZ. This shifted the high pressure system over Florida resulting in reduced summer time precipitation.

The comparison of both records to each other, as well as the addition of records compiled by Ruter et al. (2004) and Bartlein et al. (2011), is discussed in Chapter 4. Cross wavelet transform and wavelet coherency suggest reduced connectivity between the study sites during the mid-Holocene although this may be a result of dating error. Models have not successfully been able to replicate the conditions derived from mid-Holocene paleoprecipitation records for the region (Ruter et al., 2004); however, the drier conditions for Florida and the wetter conditions for
Belize during the mid-Holocene are replicated by other climate proxies from each location. The compilation of my records and the compilations of Ruter et al. (2004) and Bartlein et al. (2011) support the conclusion that precipitation changes were a result of a more northerly ITCZ and the expansion of the NASH. The lack of coherency between Florida and Belize is potentially a result of the ITCZ over Belize blocking teleconnections, particularly the AMV, that influence Florida’s precipitation.

Overall, these findings suggest that with a reduced latitudinal temperature gradient in the future, the influence of teleconnections that currently affect precipitation patterns in West-Central Florida and Belize may be reduced, especially in Belize. This may have major impacts on the economies of these locations.

If Belize sees a modern increase in precipitation, agriculture and the stability of the population may be at risk. Agriculture accounts for ~12% of Belize’s gross domestic product (AQUASTAT, 2014), and an increase in precipitation will have overall negative results for the country’s agricultural sector. Over 38% (1600 km²) of Belize’s agricultural area is on steep, erosion-prone slopes that already receive high amounts of precipitation (Simpson, 2009). Any increase in rainfall will only accentuate the soil erosion in these uplands. In addition, much of the lowland soils have high clay content (Simpson, 2009), thus, increased precipitation will lead to a higher occurrence of waterlogged soils. A marginal increase in precipitation may be beneficial for agriculture; however, a greater increase may lead to soil erosion and necessitate crop adaptation. Both of these factors will lead to more runoff and higher sediment loads in the rivers which would negatively impact tourism that relies heavily on the nation’s coastal areas. Additionally, flooding is a major risk in low-lying Belize City and both urban and rural areas
lack sufficient flood protection to safeguard the country against the potential increase in precipitation (Global Facility for Disaster Reduction and Recovery, 2010).

Reduced precipitation in Florida is potentially catastrophic, in part due to the economy and freshwater supplies. Agriculture in Florida is a $4 billion/year industry (Florida Department of Agriculture and Consumer Services, 2015) and population growth is also a major driver of the state’s economy. As precipitation decreases, the cost of producing crops will increase and flow of new residents to Florida may decline, negatively impacting the economy and food availability (National Resource Defense Council, 2001). Sea level rise, a widely accepted response to increasing global temperatures, will lead to greater salt-water intrusion into Florida’s karst aquifer, contaminating the state’s supply of freshwater (NRDC, 2001). Less precipitation will also reduce aquifer recharge, adding stress to both agriculture and population growth as the freshwater supply will be vulnerable. To counter this decrease, the state will have to invest in desalinization plants and build new reservoirs, potentially costing billions of dollars.

5.3 Future research

Although this research adds vital high-resolution stable isotope records to the paleoclimate library, it opens the door to further research. Two high resolution speleothem records are not sufficient to completely understand what was happening during the mid-Holocene in tropical and subtropical northern Hemisphere America. The lack of other high resolution records from Belize, Florida, or the entire region that span the ~2 kyr of the mid-Holocene makes it difficult to properly determine the behavior of systems such as the NAO and AMV. More high resolution, millennial and longer records will also aid in the refinement of
reconstructive climate models that can better re-create mid-Holocene conditions, and in turn better predict what may happen in the near future as temperatures rise.

5.4 References

AQUASTAT, 2014. Belize. UN Food and Agriculture Organization.


