Earth and Planetary Science Letters 298 (2010) 255–262

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

High resolution stalagmite climate record from the Yucatán Peninsula spanning the Maya terminal classic period

Martín Medina-Elizalde [a,*,1], Stephen J. Burns [a,2], David W. Lea [b,2], Yemane Asmerom [c,3], Lucien von Gunten [a,4], Victor Polyak [c,3], Mathias Vuille [d,5], Ambarish Karmalkar [a,6]

[a] Department of Geosciences, University of Massachusetts, Amherst, MA, USA
[b] Department of Earth Science, University of California Santa Barbara, CA, USA
[c] Department of Earth and Planetary Sciences, University of New Mexico, NM, USA
[d] Department of Atmospheric and Environmental Sciences, University at Albany, NY, USA

A R T I C L E I N F O

Article history:
Accepted 12 August 2010
Available online 21 August 2010

Editor: P. DeMenocal

Keywords:
stalagmite
stable isotopes
Maya
drought
rainfall
Yucatan

A B S T R A C T

The decline of the Classic Maya civilization was complex and geographically variable, and occurred over a ~150-year interval, known as the Terminal Classic Period (TCP, C.E. 800–950). Paleoclimate studies based on lake sediments from the Yucatán Peninsula lowlands suggested that drought prevailed during the TCP and was likely an important factor in the disintegration of the Classic Maya civilization. The lacustrine evidence for decades of severe drought in the Yucatán Peninsula, however, does not readily explain the long 150-year socio-political decline of the Classic Maya civilization. Here we present a new, absolute-dated, high-resolution stalagmite $\delta^{18}O$ record from the northwest Yucatán Peninsula that provides a much more detailed picture of climate variability during the last 1500 years. Direct calibration between stalagmite $\delta^{18}O$ and rainfall amount offers the first quantitative estimation of rainfall variability during the Terminal Classic Period. Our results show that eight severe droughts, lasting from 3 to 18 years, occurred during major depopulation events of Classic Maya city-states. During these droughts, rainfall was reduced by 52% to 36%. The number and short duration of the dry intervals help explain why the TCP collapse of the Mayan civilization occurred over 150 years.

Published by Elsevier B.V.

1. Introduction

In the beginning of the ninth century, the Maya Classic socio-political system characterized by kingdoms ruled by 'divine' kings, the *k'ul ajawob*, began to express the first symptoms of deterioration in the southern lowlands. By C.E. 909 the system of divine kingship had practically vanished in the southern lowland sites, after major depopulation in this region occurred (80–85% from its population peak) (Schele and Miller, 1986; Webster, 2002; Demarest et al., 2004). The Maya Classic socio-political system, however, persisted until ~C.E. 950 in the northwestern region of the Yucatán Peninsula, represented by the Puuc sites, such as the city-states of Uxmal and Oxkintok (Fig. 1). The lowland Maya population, which reached four million people by C.E. 800, plummeted to a few hundred thousand over the following 150 years (Culbert and Rice, 1990).

Previous studies have suggested that a "megadrought" lasting between 50 and 130 years, which extended across the Yucatán Peninsula, played a fundamental role in the socio-political events that led to the demise of the Classic Maya civilization (Hodell et al., 1995; Curtis et al., 1996; Gill, 2000). According to the megadrought hypothesis, the negative impacts of intense drought on the carrying capacity of the environment, food production, and human health, resulted in drastic depopulation, social unrest, warfare and, ultimately, the disintegration of the political system (Gill, 2000). As revealed by a wealth of archaeological evidence, however, the Classic Maya civilization declined over a 150-year period, and not abruptly, as would be expected if it had been significantly vulnerable to drought. Furthermore, the cultural history of the northern Puuc cities do not match environmental trends which imply that the lowlands were experiencing peak aridity during the time when regional population and monumental construction was growing rapidly (Carmean et al., 2004).

* Corresponding author. National Oceanography Centre, Southampton Waterfront Campus, European Way Southampton, Hampshire SO14 3ZH United Kingdom. Tel.: +44 23 805 96573.
E-mail address: mmedina@geo.umass.edu (M. Medina-Elizalde).

[1] MME designed and planned the research, conducted the oxygen isotope and U/Th dating analyses, participated in the field work and data interpretation, and prepared the manuscript.

[2] SJB and DWL helped planned the research, participated in the field work, data analysis, interpretation and writing.

[3] YA and VP helped developed the speleothem chronology.

[4] LvG helped creating the temperature correlation maps and participated in the statistical analysis, discussion and interpretation of the data.

[5] M.V. contributed his expertise to improving the climate/stable isotope relationship and its discussion in the manuscript.

[6] AK helped create manuscript figures and participated in the data analysis and interpretation.

0012-821X/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.epsl.2010.08.016

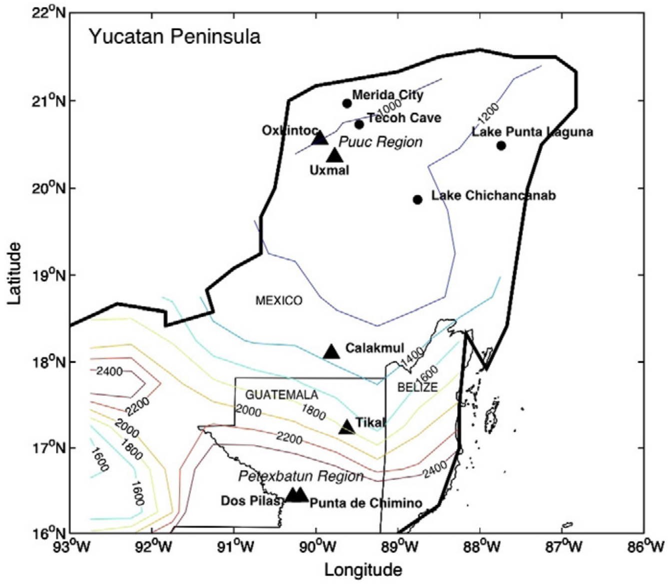

Fig. 1. Map of the Yucatán Peninsula and Maya lowlands including the countries of México, Belize and Guatemala. Color contours represent total annual precipitation isolines (mm/year). Terminal Classic Period Maya sites discussed in the study are indicated (black triangles). The location of Tzabnah cave in Tecoh, Yucatán (20° 45′N, 89° 28′W, 20 m above sea level), Lake Chichancanab (19° 52′N, 88° 46′W) and Lake Punta Laguna (20°38′N, 87°37′ W, 18 m above sea level) are also indicated (black circles).

Recent density records from sediment cores from Lake Chichancanab (Hodell et al., 2005a) suggest a more complex climate pattern than previous studies (Gunn et al., 1995; Hodell et al., 1995; Curtis et al., 1996) and indicate that, as opposed to a century-long drought during the Terminal Classic Period (C.E. 800–950), the north of the Yucatán Peninsula experienced four droughts with durations between 10 and 20 years. As pointed out by Hodell et al., (2005a) however, discrepancies between available lacustrine climate records have been cited as evidence that drought was not widespread during the TCP.

Searching for a unified and robust climate picture based on independent archives is fundamental in order to understand the role of climate in the Terminal Classic Period collapse and transformation of the Maya civilization. Here we present a new, absolute-dated, high-resolution stalagmite $\delta^{18}O$ record from the northwest Yucatán Peninsula that provides a much more detailed picture of climate variability during the last 1500 years and, particularly, over the Terminal Classic Period.

2. Methods

2.1. Speleothem collection and location

In the year 2004 we collected a 45 cm stalagmite specimen, named Chaac after the Maya god of rain, from cave "Tzabnah" in the village of Tecoh (20°43.83′N, 89°28.47′W, 20 m above sea level) (Fig 1, Supplementary Fig S1). Tecoh is located in the northwest Yucatán Peninsula only 30 km from the modern city of Mérida, the largest city in the Yucatán Peninsula today (~1 million people) and about 50 km northeast from the Maya Puuc region and the city of Uxmal (Fig. 1). The northwest Yucatán Peninsula region is semi-humid with mean annual precipitation of 1112 mm, 60–70% of which falls during the summer rainy season between June and October. Seasonal precipitation in the Yucatán Peninsula is determined by the movement of the ITCZ, the strength and movement of the Bermuda High and the easterly trade winds (Hastenrath, 1984). These factors give rise to two distinct wet and dry seasons. The northward movement of the ITCZ during boreal summer brings precipitation during the wet season that lasts from May to October. The wet season is punctuated by a relative decrease in precipitation in July and August resulting in bimodal annual cycle of precipitation (Magaña et al., 1999). The northern Yucatán Peninsula, where Tecoh is located, is characterized by a sharp meridional gradient in annual precipitation as a result of subsidence related to the descending branch of the Hadley Cell (Waliser et al., 1999).

2.2. Speleothem chronology

The speleothem time scale is based on 12 absolute U/Th dates (Supplementary Table S1). ^{234}U–^{230}Th dating was conducted at the Radiogenic Isotope Laboratory, the University of New Mexico. Calcite powders weighing from 0.06 to 0.15 mg were used for dating. The samples were spiked with a mixed ^{229}Th–^{233}U–^{236}U spike. U and Th were separated using conventional anion exchange chromatography. U and Th isotopes were measured using a Thermo Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) which was optimized for U-series analytical work as described by Asmerom et al. (2006). ^{234}U was measured on a secondary electron multiplier with high abundance filter, while the other isotopes of uranium were measured on Faraday cups with amplifiers that had mixed 10^{10}, 10^{11} and 10^{12} Ω resistors for $^{233}U$and ^{236}U, ^{235}U and ^{238}U respectively. Mass fractionation was monitored using the $^{236}U/^{233}U$ ratio, while SEM/Faraday gain was set using sample standard bracketing. A similar procedure was used for Th isotope measurements with ^{230}Th measured in the SEM and ^{229}Th and ^{232}Th measured in Faraday cups. The samples had very low uranium concentrations, most in the 200s of ppb (Supplementary Table S1). But many of them had very low ^{232}Th concentrations also (up to three orders of magnitude lower than U concentration), thus a number of the samples were very sensitive to initial $^{230}Th/^{232}Th$ corrections (e.g. samples YO4-CH17, YO4-CH18, YO4-CH3, YO4-CH19, YO4-CH21, YO4-CH22). We used an initial $^{230}Th/^{232}Th$ atomic ratio of $4.4\times10^{-6}\pm50\%$ determined from two three-dimensional isochrons that yielded values of $10.26\times10^{6}\pm1.1\times10^{6}$, and $0\pm14\times10^{6}$, and from a near-zero-aged calcite at the stalagmite's top. CRM145 U isotope standard was measured with the samples obtaining the conventionally accepted $\delta^{234}U$ value of $-36.5\pm0.5‰$ [35]. $\delta^{234}U=[[^{234}U/^{238}U_{sample}/^{234}U/^{238}U_{secular\ equilibrium}]-1]\times10^{3}$, where, $^{234}U/^{238}U_{secular\ equilibrium}=\lambda_{238}/\lambda_{234}$, $\lambda_{230}=9.1577\times10^{-6}\ year^{-1}$, $\lambda_{234}=2.8263\times10^{-6}\ year^{-1}$, $\lambda_{238}=1.55125\times10^{-10}\ year^{-1}$ (Cheng et al., 2000). U and Th procedural blanks were in the range of 5–10 pg and had little effect on ages.

We applied a polynomial and piecewise linear model and found a maximum age difference between these models of 31 years during the Medieval Climate Anomaly time interval. We developed the chronology based on the piecewise-linear model because it results in excellent agreement with an independent and well-dated stalagmite $\delta^{18}O$ record (errors <15 years) from subtropical China (Zhang et al., 2008) over the transition to the Medieval Climate Anomaly, when these two records display similar environmental trends (Supplementary Fig. S2). This model indicates that Chaac grew continuously from C.E. 478 to the year 2004, when Chaac was retrieved from the cave (Fig. 2). Parts of Chaac are distinctly laminated, including the interval covering the Terminal Classic Period. To test the age model in the critical interval defining the TCP we counted laminations and compared the results to the U/Th age model. The average number of laminations in the time interval between CE 918 and 820, which corresponds to 98 Th-years, is 85 ± 10 (Fig. 3). This test provides an independent confirmation of the U/Th age model. The U/Th date of C.E. 942 corresponding to the onset of the Medieval Climate Anomaly in Chaac is comparable to the age indicated by the well-dated (Th-dating errors ≤5 years) subtropical China stalagmite $\delta^{18}O$ record for this same event (Zhang et al., 2008) (Supplementary Fig. S2). This observation and the laminae counting suggest that the error in the absolute chronology in Chaac is no larger than ±10 years during the Terminal Classic Period.

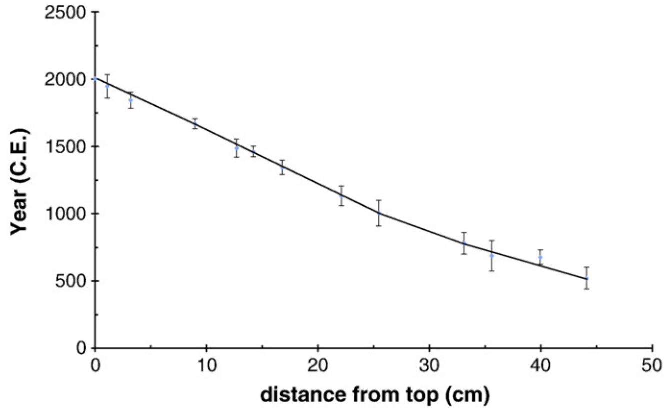

Fig. 2. Chaac ^{230}Th age model. The blue squares represent ^{230}Th ages with errors between 38 and 112 years (Supplementary Table S1). The chronology is based on a piece-linear model. Linear interpolation was performed between ^{230}Th dates in the following depth intervals (cm from the top): 44.1–33.1 [Year (C.E.) = −23.64 * distance (cm) + 1563], 33.1–25.45 [Year (C.E.) = −29.214 * distance (cm) + 1747.9], 25.45–8.95 [Year (C.E.) = −40.331 * distance (cm) + 2030.8], and 8.95-top [Year (C.E.) = −38.914 * distance + 2004].

2.3. Speleothem oxygen isotope data and interpretation

We determined stalagmite $\delta^{18}O$ from microsamples drilled along the stalagmite main growth axis at sampling resolutions between 0.2 and 0.5 mm. Our $\delta^{18}O$ record, spanning the last 1500 years, has an average resolution of 2.3 years but with annual resolution between C. E. 800 and 940 (Supplementary Table S1). The characteristics and physical conditions of Tzabnah cave, a Hendy test and isotopic equilibrium calculations (Sharp, 2007) suggest that Chaac's calcite was precipitated under or near equilibrium conditions and faithfully records rainfall $\delta^{18}O$ variability (Supplementary Fig. S3).

Instrumental records of precipitation amount and rainfall $\delta^{18}O$ from the nearest IAEA meteorological station to the Yucatán Peninsula, in addition to modelling studies, indicate that there is a clear amount effect on seasonal (Supplementary Fig. S4) and interannual time scales (Vuille et al., 2003). Even though seasonal variability in rainfall $\delta^{18}O$ also depends on the relative contribution of different moisture sources, today annual rainfall $\delta^{18}O$ (precipitation weighed) reflects mostly a single dominant tropical Atlantic/Caribbean source (Vuille et al., 2003). At this time we cannot assess if rainfall $\delta^{18}O$ has mostly reflected this same source in the past.

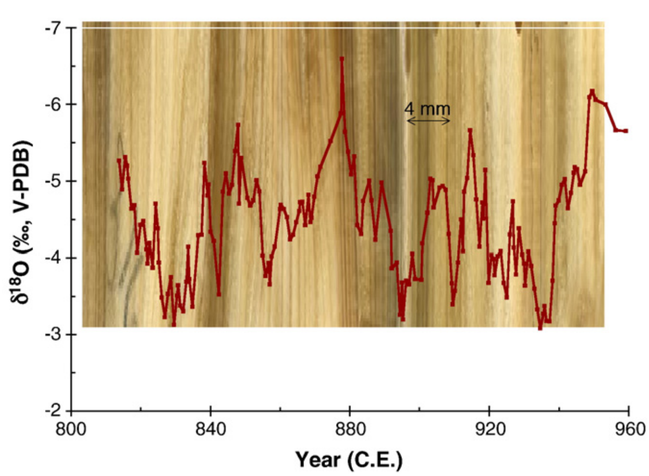

Fig. 3. Chaac center-of-growth cross-section showing distinct laminations during the Terminal Classic Period (TCP). A total of 85 ± 10 laminations were counted between the Th-dated interval 918–820 (98 years), strongly suggesting that these laminations are annual depositions. The error in lamination counts stems from the different number of laminations in the center of growth compared to the periphery along the same depth interval: often, a single layer observed in the center of growth appears as several bands away from the center. Superimposed on the stalagmite cross-section; the Chaac $\delta^{18}O$ record showing the TCP droughts. The nearest measured U–Th dates to the depth interval shown in this figure occur at C.E. 1004 and 780 (Table S1).

A calibration between Chaac $\delta^{18}O$ and the instrumental record of precipitation from a meteorological station in Mérida indicates a significant correlation between the two signals ($r = -0.62$, $P = 0.023$) with a slope of -176 mm‰$^{-1}$ increase in Chaac $\delta^{18}O$ (Fig. 4). The strength of the relationship between Chaac $\delta^{18}O$ and rainfall amount is similar to that observed between rainfall amount data from adjacent meteorological stations ($0.2 < r < 0.7$, $P < 0.01$). This calibration allows the first quantitative estimates of past precipitation changes before the instrumental record for this region. Cave temperature changes, which could also influence stalagmite $\delta^{18}O$, were likely small on interannual time scales (<0.5 °C or <0.13‰), as suggested by Northern Hemisphere temperature reconstructions (Mann and Jones, 2003). Correlation analysis using the instrumental record of precipitation from Tecoh cave and from other locations in México, Central and South America suggest a significant correlation between the precipitation history at this location and the southern Maya lowlands including the Yucatán Peninsula, Chiapas and Guatemala (Fig. 5). Thus, the Chaac $\delta^{18}O$ record is expected to reflect climate variability of a broad region of the Maya lowlands.

3. Results and discussion

The Chaac record has average $\delta^{18}O$ of −4.8‰, with a 2SD range from −3.4 to −6.4‰ over the last 1500 years, with significant variability at interannual, multi-decadal and centennial time scales (Fig. 6). Spectral analysis of the Chaac $\delta^{18}O$ record indicates significant periods at 200, 40, 24, 17, 12 and 8 years (CI = 95%) (Supplementary Fig. S5). The ~200-year dominant period closely corresponds to a 206-year cycle in radiogenic nuclide production (carbon-14 and beryllium-10), which is linked to variations in solar activity (Hodell et al., 2001). The Chaac $\delta^{18}O$ record reveals a ~12-year period which may correspond to the Schwabe sunspot cycle. Spectral analysis suggests that solar forcing played a role in driving precipitation changes in the Yucatán Peninsula over the past 1500 years. Mechanisms by which modest solar forcing produce strong hydrological responses in the Yucatán Peninsula have been explored by previous studies (Hodell et al., 2001; Shindell et al., 2006).

The Chaac $\delta^{18}O$ record indicates three distinctive time intervals of negative $\delta^{18}O$ anomalies which represent relatively wet conditions at 950–1250, 1490–1580, and 1760–1828 C.E. Taking our calibration between Chaac $\delta^{18}O$ and precipitation amount at face value (Fig. 4), we infer maximum annual precipitation values of 1150, 1200 and 1300 mm, for these three intervals respectively (Fig. 6). For comparison, today's mean annual precipitation at the Cave of Tecoh is ~1120 mm. The first of these intervals (950–1250) corresponds with the Medieval Climate Anomaly, whereas the last two intervals with positive Northern Hemisphere temperature anomalies within the Little Ice Age time interval (1350–1850, Mann and Jones, 2003). In addition, Chaac shows intervals of positive $\delta^{18}O$ anomalies during C.E. 501–518 (17 years), 527–539 (11 years), 658–668 (10 years) and 804–938 (~130 years), suggesting drops in precipitation between 52 and 36% with respect to today's mean annual precipitation. Chaac $\delta^{18}O$ record suggests that the droughts of the Terminal Classic Period were the most intense of the last 1500 years in the Yucatán Peninsula. Similar dry conditions at this time have been also documented in subtropical China (Zhang et al., 2008), Central and South America Hodell et al., 1995; Curtis et al., 1996; Haug et al., 2003; Rosenmeier et al., 2002) and tropical Africa (Holmes et al., 1999; Street-Perrott et al., 2000), suggesting large-scale ocean-atmospheric reorganizations at this time.

The dry interval recorded by the Chaac $\delta^{18}O$ record between 810 and 938, during the TCP, broadly coincides with arid conditions suggested by calcite $\delta^{18}O$ and sediment density records from Lakes

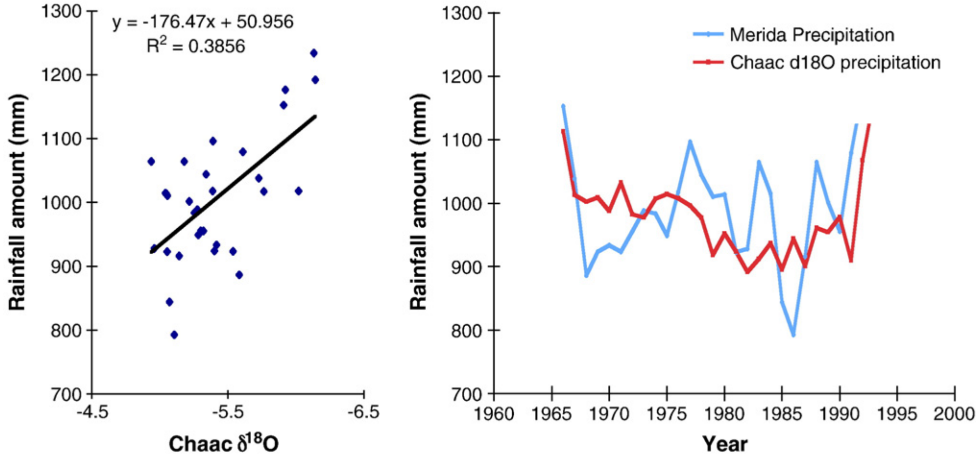

Fig. 4. Calibration between Chaac $\delta^{18}O$ and the instrumental precipitation record from Mérida (1966–1994, 3-year smoothed using triangular filtering). Cross-correlation analysis between Chaac $\delta^{18}O$ and the instrumental rainfall record suggests that maximum correlation occurs with a 6 years lag of Chaac $\delta^{18}O$ with respect to the instrumental record. This lag may reflect the combined effects of a long residence time of cave drips and uncertainty in the time scale. We used Pearson's product-moment correlation coefficients; *P* values were corrected for the loss of degrees of freedom according to the data smoothing. The correlation is significant ($r = -0.62$, $P = 0.023$) and suggests a slope of -176 mm‰$^{-1}$ (left). Reconstructed annual rainfall variability based on Chaac $\delta^{18}O$ and observed rainfall changes in Mérida from calibration period (right). The root mean square error of the calibration is equal to 81 mm/year.

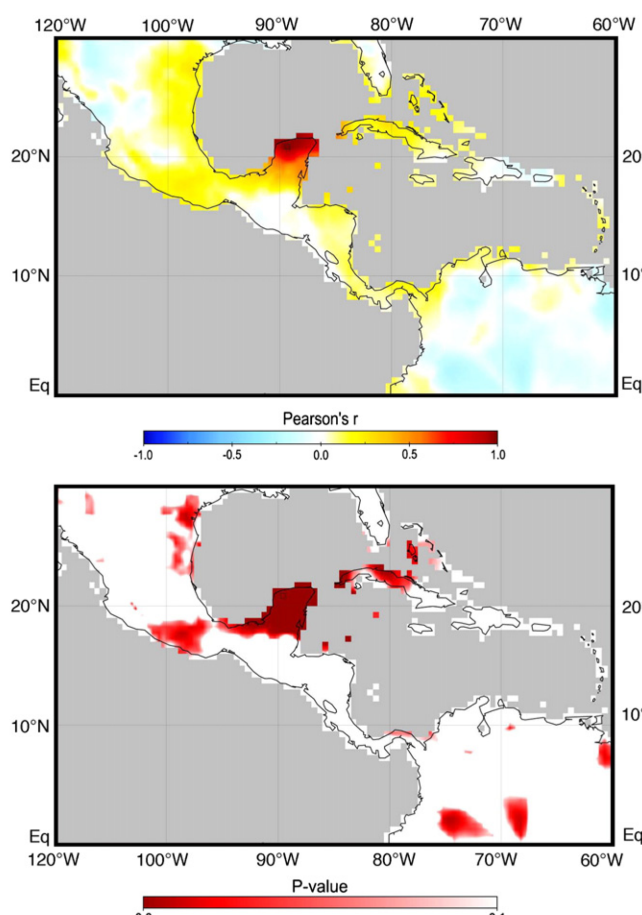

Fig. 5. Correlation field analysis (1901–2006) (Mitchell and Jones, 2005) showing that total annual precipitation at the location of Tecoh cave (20.75° N, 89.25° W) is highly correlated with annual precipitation over the entire Yucatán Peninsula. The map on the top shows the Spearman correlation-coefficient rho and the map below the corresponding *P* values (values <0.1 are colored in red). These maps also indicate that records from South America are not expected to be good predictors of climate in the Maya lowlands.

Chichancanab and Punta Laguna (Hodell et al., 1995, 2005a; Curtis et al., 1996) (Fig. 7). The evaporation/precipitation (E/P) $\delta^{18}O$ record from Lake Chichancanab (20-year resolution) suggests that the Yucatán Peninsula experienced a persistent arid interval lasting 130 years, from 830 to 950, whereas the Lake Punta Laguna E/P record (8-year resolution), suggests a 50-year drought, from 834 to 884 (Hodell et al., 1995; Curtis et al., 1996). The higher resolution density record from Lake Chichancanab (5 years resolution, Hodell et al., 2005a) implies four intervals of drought during the TCP peaking at 792, 808, 834 and 931, lasting 21, 10, 20 and 17 years, respectively. Chaac (1-year resolution), in contrast to these records, reveals a series of eight severe droughts between C.E. 800 and 950, having durations between 3 and 18 years (Figs. 6 and 7). Differences between these records likely relate to their resolution, chronology and responses to controlling climate factors.

Lake Chichancanab and Punta Laguna $\delta^{18}O$ records (Fig. 7C and D) reflect the balance between evaporative lake water loss and gains from precipitation, runoff and underground water inputs (Hodell et al., 1995; Curtis et al., 1996). The sediment density record from Chichancanab (Fig. 7B) (Hodell et al., 2005a) mostly reflects the amount of gypsum in the sediment, as controlled by lake depth and by the influence of evaporation/precipitation balance on gypsum saturation. These lacustrine records, in conjunction with the new Chaac $\delta^{18}O$ record, suggest that the Little Ice Age time interval (C.E.1350–1850) was not particularly dry, or even wet, in northern Yucatán Peninsula (Fig. 7). This pattern is also implied by records of available moisture ($\delta^{18}O$ and a luminescence) based on a stalagmite from the Macal Chasm cave in western Belize (Webster et al., 2007). In addition, pollen and diatom analyses on the sediment record from Lago Verde, in the region of Los Tuxtlas, México (18° 36′ 46″N; 95° 20′ 52″W), provide evidence that the deepest lake levels and densest tropical forest cover of the last two millennia were coeval with the Little Ice Age (Lozano-García et al., 2007). In contrast with these reconstructions, a dry Little Ice Age is implied by records from a sinkhole lake, Aguada X'Caamal, in the northwest Yucatán Peninsula, from high $\delta^{18}O$ values of ostracod and gastropod carbonates and the presence of the high-salinity tolerant foraminiferal species *Amonia becarii* during this time (Hodell et al., 2005b). The long-term shift to higher salinity and carbonate $\delta^{18}O$ values at Aguada X'Caamal beginning ~C.E. 1500, could be independent of climate and reflect, however, the basin's evolution from a more open (depleted

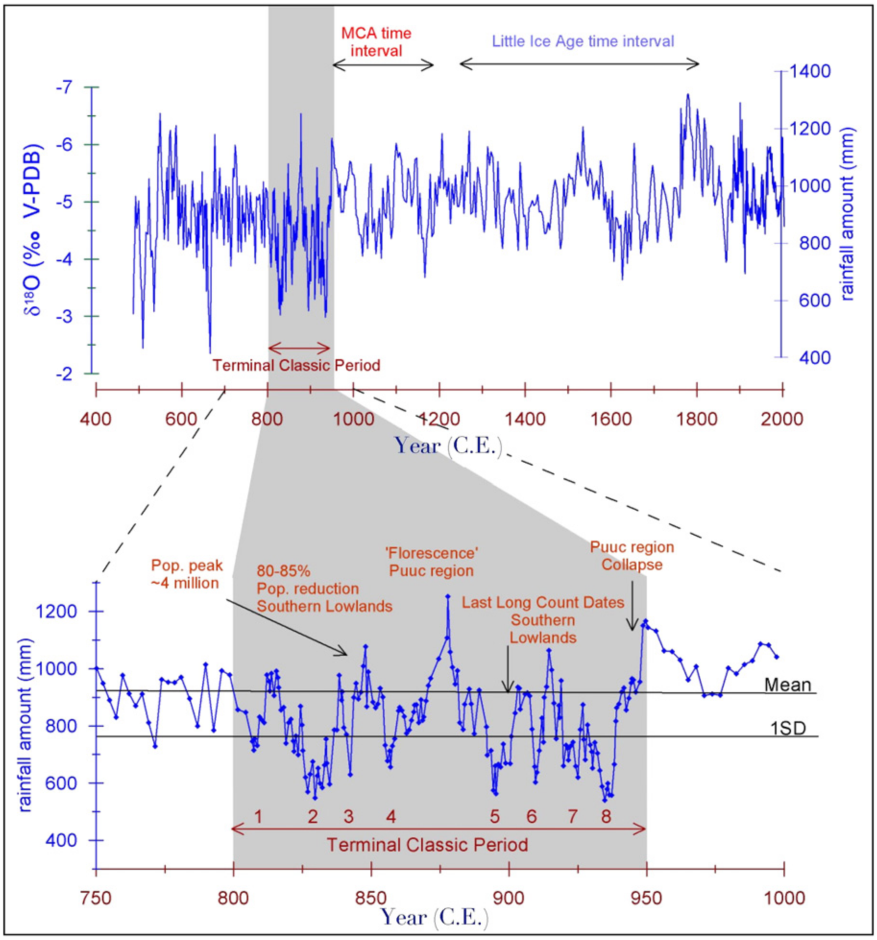

Fig. 6. Stalagmite (Chaac) δ^{18}O-derived precipitation record from the Yucatán Peninsula spanning the last 1500 years with an average resolution of 2.3 years (top). Chaac δ^{18}O was converted to precipitation amount applying the calibration equation: [precipitation (mm)] = −176.47(δ^{18}O_Chaac) − 50.956 (Fig. 4). The error of annual precipitation estimations is ±100 mm, including calibration and sample analytical reproducibility errors (±0.1‰). Blow up of Chaac δ^{18}O-derived precipitation changes over the Terminal Classic Period (below) showing a series of eight consecutive droughts from 800 to 950 C.E. The resolution of the record over the Terminal Classic Period is annual or higher. Precipitation reductions at this time were between 36 and 51% compared to today's mean annual average (1120 mm) in the region of Tecoh cave. Some relevant Terminal Classic Period political and demographic events are indicated.

groundwater δ^{18}O values) to closed system (enriched evaporative δ^{18}O values), in addition to enrichment of sinkhole water δ^{18}O from increased transpiration by emergent aquatic macrophytes (Hodell et al., 2005b).

The agreement among broadly distributed and independent climate records [i.e. Lakes Chichancanab, Punta Laguna and Lago Verde, and speleothems from Macal Chasm (Belize) and Tzabnah (Yucatán Peninsula)] suggests that a large portion of the Yucatán Peninsula and Gulf of Mexico's southern coast experienced relatively wet conditions during the Little Ice Age. The climate evolution recorded by these records contrasts with the sediment Ti percent record derived from the Cariaco Basin, Venezuela (Haug et al., 2001, 2003) interpreted to reflect precipitation changes in northern South America driven by latitudinal variations in the position of the intertropical convergence zone (ITCZ) during summer. The Cariaco Basin Ti record suggests that the driest interval of the last 1500 years in northern South America occurred during the Little Ice Age, which implies a more southern latitudinal position of the ITCZ during summer (Haug et al., 2001). This and other marked differences on centennial and decadal time scales between the Cariaco Basin Ti record and Yucatán Peninsula records (Supplementary Fig. S6), in addition to evidence from the instrumental record (Fig. 5), suggests that records from the Cariaco Basin are not a suitable climate analog for the Yucatán Peninsula, in contrast to previous inferences (Haug et al., 2003).

The eight intervals of peak aridity suggested by the Chaac record are centered at C.E. 806, 829, 842, 857, 895, 909, 921 and 935. The longest drought occurred in the beginning of the Terminal Classic Period between C.E. 819 and 836 (18 years). Chaac δ^{18}O implies precipitation drops between 36% and 52% from today's annual mean during the Terminal Classic Period (TCP) (Fig. 6). The TCP reduction in annual precipitation implied by Chaac is within projected rainfall reductions in the Yucatán Peninsula and Central America (30–50%) by the end of the 21st century under the IPCC AR4 A1B scenario (Christensen et al., 2007, Fig. 11.12).

The Chaac record indicates that moderately moist conditions (mean = 900 mm) persisted for 32 years from C.E. 858 to 890, after four droughts had already stricken the Yucatán Peninsula (Fig. 6). The agreement between two independent archives, Chaac and the density record from lake Chichancanab (Hodell et al., 2005a), particularly during the TCP, bring strong support for a more complex picture of climate variability of the Yucatán Peninsula than previously known (Gunn et al., 1995; Hodell et al., 1995; Curtis et al., 1996) (Fig. 7).

The first Late Classic Maya lowland sites to experience political disintegration and abandonment were those of the Petexbatún region, Guatemala (O'Mansky and Dunning, 2004) (Fig. 1). There is no evidence that the agricultural potential of this region was exhausted at the time when the sites began to collapse, contradicting the notion of drought as a major cause for the decline of Petexbatún sites (Emery, 1997, 2004; O'Mansky and Dunning, 2004; Wright, 2004). By the time

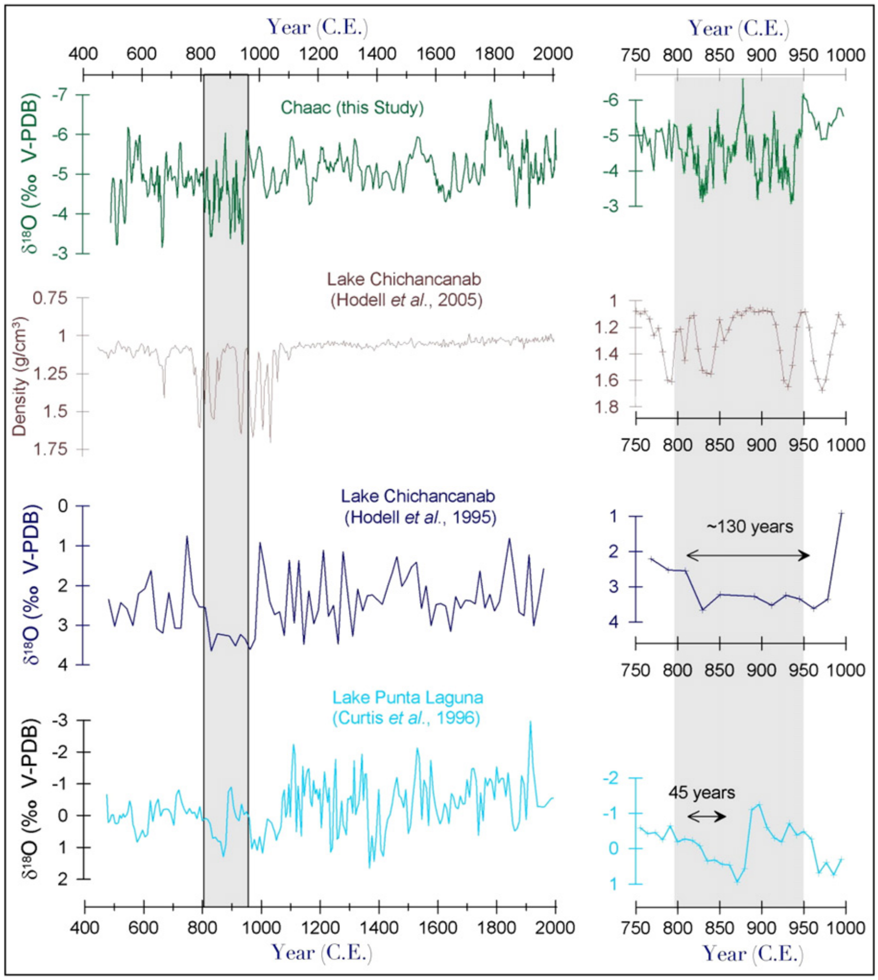

Fig. 7. Yucatán Peninsula climate records spanning the last 1500 years. Stalagmite Chaac $\delta^{18}O$ record of precipitation (A), Lake Chichancanab density record (B) (Hodell et al., 2005a), Lake Chichancanab gastropod *Pyrgophorus* sp. $\delta^{18}O$ record reflecting the evaporation/precipitation balance (C) (Hodell et al., 1995). Lake Punta Laguna ostracod *Cytheridella ilosvayi* $\delta^{18}O$ record, reflecting the evaporation/precipitation (D) (Curtis et al., 1996). Right panels; blow up of the terminal Classic Period corresponding to records on the left. The density, Chaac and lake Punta Laguna records indicate a wet interval between C.E. 870 and 900, coinciding with the revitalization of the Puuc region. The Chaac and density records indicate a shift towards more humid conditions after the Terminal Classic Period. Chaac provides additional evidence to available lacustrine records indicating that the Yucatán Peninsula was not particularly dry during the Little Ice Age time interval.

when the first drought suggested by the Chaac record struck the Yucatán Peninsula (C.E. 806), however, warfare had cornered the population of many Petexbatún sites to remote areas with very poor agricultural potential and highly vulnerable to drought (O'Mansky and Dunning, 2004). The nearly complete abandonment of most sites by C.E. 830 (O'Mansky, 2003; Dunning and Beach, 2004) coincides with the first two droughts recorded by the Chaac $\delta^{18}O$ record lasting 6 and 18 years and with precipitation reductions of 36 and 52%, respectively (Fig. 6). In light of these two droughts, it is not surprising that the last major population center in the Petexbatún was Punta de Chimino the best prepared to endure drought, with deep soils and access to abundant aquatic resources of Laguna Petexbatún (O'Mansky and Dunning, 2004) (Fig. 1).

The two largest Maya kingdoms by the eighth century, and long-term rivals, Calakmul and Tikal, experienced demographic and political crisis beginning in the ninth century (Demarest et al., 2004) (Fig. 1). With estimated populations at their ~C.E. 800 peak of about 1.5 million people each (including rural areas and subordinate sites), their population fell by 80–85% by C.E. 850 (Folan, 1988; Culbert et al., 1990; Turner, 1990). In contrast to the Petexbatún sites, there is no archaeological evidence that the fall of Tikal and Calakmul was linked to violence and warfare (Braswell et al., 2004; O'Mansky and Dunning, 2004; Valdes and Fahsen, 2004). Tikal maintained considerable hegemony over the central Petén region and the final abandonment of the city of Calakmul was sudden but orderly indicating that the inhabitants planned to return (Braswell et al., 2004; Valdes and Fahsen, 2004). A major factor in TCP demography at these two sites appears to be environmental degradation, produced by natural and human causes (Gunn et al., 1995; Braswell et al., 2004). The Chaac $\delta^{18}O$ record suggests that over the period of political disintegration and depopulation of these kingdoms (~C.E. 800 and 909) the Yucatán Peninsula experienced six droughts. The longest and most severe of these droughts lasted 18 years, with a maximum rainfall reduction of ~52% with respect to today's annual average (Fig. 6). The last carved monuments signalling the collapse of the Classic divine rulership of these kingdoms date to C.E. 889 and 909 (Braswell et al., 2004; Valdes and Fahsen, 2004), coinciding with the peak of the sixth major drought that affected the Yucatán Peninsula (Fig. 6).

While most Maya kingdoms and city-states were disintegrating in the southern lowlands, during the second half of the ninth century, the northern lowland cities, particularly in the Puuc region, were revitalized (Carmean et al., 2004) (Fig.1). This pattern represents a conundrum in light of the ‘megadrought’ hypothesis because the northern lowlands are the driest of the Yucatán Peninsula and therefore expected to be the most vulnerable to drought. Two independent paleoclimate archives, the Chaac $\delta^{18}O$ record and a density record from Lake Chichancanab (Hodell et al., 2005a), however, provide strong evidence that the revitalization in the Puuc region occurred during a moist interval, favorable for food production and the sustenance of a larger population (~C.E. 860–890 ± 20 years) (Fig. 7). Despite this revitalization of the Classic system in the Puuc region during a time of climatically favorable conditions for expansion, this 'bonanza' ended soon after when the Yucatán Peninsula was hit again by the last four major droughts of the TCP, centered at C.E. 895, 909, 921, 935 and having durations between 3 and 8 years. By 950 the Classic political system had practically vanished in the Puuc region as well, when most sites were rapidly abandoned or experienced depopulation (Carmean et al., 2004).

The Maya lowland population of around four million people by C.E. 800 plummeted to few hundred thousand over the following 150 years (Culbert and Rice, 1990). The evidence from the new record (Chaac) revealing that there was not a long drought during the Terminal Classic Period but a series of eight droughts with variable durations between 6 and 18 years, explains more convincingly the 150 years duration of the Terminal Classic Period. The humid intervals between these droughts allowed the civilization to momentarily 'catch its breath', such as during the florescence of the Puuc region, thus prolonging its demise.

4. Conclusions

The new, absolute-dated, high-resolution stalagmite δ^{18}O record (Chaac) from the northwest Yucatán Peninsula provides a much more detailed picture of climate variability than previous records, during the last 1500 years. A direct calibration between stalagmite δ^{18}O and rainfall amount suggests that eight severe droughts occurred in the Yucatán Peninsula lowlands during the Terminal Classic Period (TCP). In contrast, previous Yucatán Peninsula records from lacustrine deposits suggest that 50 to 130-year long droughts struck this region during the TCP. The droughts suggested by Chaac represent rainfall reductions between 52 and 36% (compared to today's annual mean), had durations from 3 to 18 years, and occurred during major depopulation events of Maya kingdoms and city-states of the TCP. The intensity and short duration of these droughts help explain why the Terminal Classic Period disintegration of the Maya civilization occurred over a 150-year period and not abruptly. The potential implications of these successive droughts; decreased environmental carrying capacity, increased interstate rivalry for resources, famine, disease, and popular dissent from 'divine' rulership that failed to prevent recurrent drought (Schele and Miller, 1986; Gill, 2000; Webster, 2002; Demarest et al., 2004), may have slowly weakened the Classic Maya socio-political system, while the more benign intervals between these droughts allowed the civilization to partially recover and linger, as exemplified by the short-lived florescence of the Puuc region.

The Chaac climate record suggests that solar forcing played an important role in driving precipitation changes in the Yucatán Peninsula on decadal and centennial time scales. In addition, Chaac suggests that climate records from northern South America, such as from the Cariaco Basin, Venezuela, are not expected to be a suitable climate analog for the Yucatán Peninsula.

The Terminal Classic Period reduction in annual precipitation implied by Chaac is within projected rainfall reductions in the Yucatán Peninsula and Central America by the end of the 21st century under the IPCC AR4 A1B scenario, highlighting the potential vulnerability of modern societies in this region to future climate trends.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Grant No. OCE 0602362 (DWL). Medina-Elizalde M. was supported by the NOAA/UCAR Postdoctoral Fellowship and von Gunten L. was supported by the Swiss NSF (PBBEP2-126056).We thank William R. Slocombe (Amherst College) for his support with stalagmite cutting, M.S. Alejo Medina-Elizalde (U. Cordoba) for helping with monitoring physicochemical conditions in the cave of Tecoh and Dr. Gerardo Gold-Bouchot (CINVESTAV-IPN) for his help with field work logistics. We thank Secretaría de Ecología (OFICIO # VI/00340/2004) for granting us the permit to collect specimens from caves of Yucatán.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2010.08.016.

References

Asmerom, Y., et al., 2006. Routine high-precision U–Th isotope analysis for paleoclimate chronology. Geochim. Cosmochim. Acta 70 (18), A24.
Braswell, G.E., et al., 2004. Defining the Terminal Classic at Calakmul, Campeche. In: Demarest, A.A., Rice, P.M., Rice, D.S. (Eds.), The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation. University Press of Colorado.
Carmean, K., Dunning, N., Kowalski, J.K., 2004. High times in the hill country: a perspective from the Terminal Classic Puuc region. In: Demarest, A.A., Rice, P.M., Rice, D.S. (Eds.), The Terminal Classic in the Maya Lowlands: Collapse, Transition, and Transformation. University Press of Colorado, pp. 424–449.
Cheng, H., et al., 2000. The half-lives of uranium-234 and thorium-230. Chem. Geol. 169, 17–33.
Christensen, J.H., et al., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Culbert, T.P., Rice, D.S., 1990. Precolumbian Population History in the Maya Lowlands. In: Culbert, T.P., Rice, D.S. (Eds.), University of New Mexico Press, Albuquerque.
Culbert, T.P., et al., 1990. The Population of Tikal, Guatemala. In: Culbert, T.P., Rice, D.S. (Eds.), University of New Mexico Press, Albuquerque, pp. 103–121.
Curtis, H.J., Hodell, D.A., Brenner, M., 1996. Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. Quatern. Res. 46, 37–47.
Demarest, A.A., Rice, P.M., Rice, D.S., 2004. The Terminal Classic in the Maya Lowlands: Collapse, Termination, and Transformation. In: Demarest, A.A., Rice, P.M., Rice, D.S. (Eds.), University Press of Colorado, Boulder, CO, p. 676.
Dunning, N.P., Beach, T., 2004. Ecology and Agriculture of the Petexbatun Region: An Ancient Perspective on Rainforest Adaptation. Vanderbilt University Press, Nashville, TN.
Emery, K., 1997. The Maya Collapse: A Zooarchaeological Investigation. Ph.D. dissertation, in Anthropology, 1997, Cornell: Ithaca NY.
Emery, K., 2004. Ancient Fauna, Bone Industries, and Subsistence History of the Petexbatún Region. Vanderbilt University Press, Nashville, TN.
Folan, W.J., 1988. Calakmul, Campeche: el nacimiento de la tradición clásica en la gran Mesoamérica. Inf. UACM 13, 122–190.
Gill, R.B., 2000. The Great Maya Droughts: Water, Life, and Death. University of New Mexico Press, Albuquerque.
Gunn, J.D., Folan, W.J., Robichaux, H.R., 1995. A landscape analysis of the Candelaria watershed in Mexico: insights into paleoclimates affecting upland horticulture in the Southern Yucatan peninsula semi-karst. Geoarchaeology 10, 3–42.
Hastenrath, S., 1984. Interannual variability and the annual cycle: mechanisms of circulation and climate in the tropical Atlantic sector. Mon. Weather Rev. 112, 1097–1107.
Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Röhl, U., 2001. Southward migration of the Intertropical Convergence Zone through the Holocene. Science 293, 1304–1308.
Haug, G.H., Gunther, D., Peterson, L.C., Sigman, D.M., Hughen, K.A., Aeschlimann, B., 2003. Climate and the collapse of Maya civilization. Science 299, 1731–1735.
Hodell, D.A., Curtis, H.J., Brenner, M., 1995. Possible role of climate in the collapse of Classic Maya civilization. Nature 375, 391–394.
Hodell, D.A., Brenner, M., Curtis, J.H., Guilderson, T., 2001. Solar forcing of drought frequency in the Maya lowlands. Science 292, 1367.
Hodell, D.A., Brenner, M., Curtis, H.J., 2005a. Terminal Classic drought in the northern Maya lowlands inferred from multiple sediment cores in Lake Chichancanab (México). Quat. Sci. Rev. 24, 1413–1427.
Hodell, D.A., et al., 2005b. Climate change on the Yucatan Peninsula during the Little Ice Age. Quat. Res. 63, 109–121.
Holmes, J.A., et al., 1999. Late Holocene paleolimnology of Bal Lake, Northern Nigeria, a multidisciplinary study. Palaeogeogr. Palaeoclimatol. Palaeoecol. 148, 169–185.
Lozano-García, M., Caballero, M., Ortega, B., Rodriguez, A., Sosa, S., 2007. Tracing the effects of the Little Ice Age in the tropical lowlands of eastern Mesoamerica. PNAS 104 (41).
Magaña, V., Amador, J.A., Medina, S., 1999. The midsummer drought over Mexico and Central America. J. Climate 12, 1577–1588.
Mann, M.E., Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophys. Res. Lett. 30 (15).

Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693–712.

O'Mansky, M., 2003. The Petexbatun Regional Survey: Settlement and Land Use in a Late Classic Maya Kingdom. Ph.D. dissertation, in Anthropology, 2003, Vanderbilt University, Nashville, TN.

O'Mansky, M., Dunning, N.P., 2004. Settlement and late classic political disintegration in the Petexbatún region, Guatemala. In: Demarest, A.A., Rice, P.M., Rice, D.S. (Eds.), The Terminal Classic in the Maya Lowlands: Collapse, Transition, And Transformation. University Press of Colorado, pp. 83–101.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., 2002. A 4000-year lacustrine record of environmental change in the southern Maya lowlands, Petén, Guatemala. Quatern. Res. 57, 183–190.

Schele, L., Miller, M.E., 1986. The Blood of Kings: Dynasty and Ritual in Maya Art. In: Braziller, I. George (Ed.), New York and Kimbell Art Museum, Fort Worth.

Sharp, Z., 2007. Principles of Stable Isotope Geochemistry. Pearson Prentice Hall, Upper Saddle River, NJ.

Shindell, D.T., Faluvegi, G., Miller, R.L., Schmidt, G.A., Hansen, E., Sun, S., 2006. Solar and anthropogenic forcing of tropical hydrology. Geophys. Res. Lett. 33.

Street-Perrott, F.A., Holmes, J.A., Waller, M.P., Allen, M.J., Barber, N.G.H., Fothergill, P.A., Harkness, D.D., Ivanovich, M., Kroon, D., Perrott, R.A., 2000. Drought and dust deposition in the West African Sahel: a 5500-year record from Kajemarum Oasis, Northeastern Nigeria. Holocene 10, 293–302.

Turner, B.L., 1990. Population Reconstruction for the Central Maya Lowlands: 1000 B.C. to A.D. 1500. In: Culbert, T.P., Rice, D.S. (Eds.), University of New Mexico Press, Albuquerque, pp. 301–324.

Valdes, J.A., Fahsen, F., 2004. Disaster in sight: the terminal classic at Tikal and Uaxactún. In: Demarest, A.A., Rice, P.M., Rice, D.S. (Eds.), The Terminal Classic in the Maya Lowlands: Collapse, Transition and Transformation. University Press of Colorado, pp. 140–161.

Vuille, M., Bradley, R.S., Werner, M., Healy, R., Keimig, F., 2003. Modeling $\delta^{18}O$ in precipitation over the tropical Americas: 1. Interannual variability and climatic controls. J. Geophys. Res. 108 (D6), 4174. doi:10.1029/2001JD002038.

Waliser, D.E., Shi, Z., Lanzante, J.R., Oort, A.H., 1999. The Hadley circulation: assessing NCEP/NCAR reanalysis and sparse in situ estimates. Clim. Dyn. 15 (10), 719–735.

Webster, D., 2002. The Fall of the Ancient Maya: Solving the Mystery of the Maya Collapse. Thames and Hudson, London. 368 pp.

Webster, J.W., Brook, G.A., Railsback, L.B., Cheng, H., Edwards, R.L., Alexander, C., Reeder, P.P., 2007. Stalagmite evidence from Belize indicating significant droughts at the time of Preclassic Abandonment, the Maya Hiatus, and the Classic Maya collapse. Palaeogeogr. Palaeoclimatol. Palaeoecol. 250, 1–17.

Wright, L.E., 2004. Nutrition, Diet, and Health at the Time of the Maya Collapse: Osteological Evidence from the Petexbatún. Vanderbilt University Press, Nashville, TN.

Zhang, P., et al., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. Science 322, 940–942.