A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change

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ABSTRACT

Droughts are a recurring feature of Mexican climate, but few high-resolution data are available to test for climate-change forcing of Mesoamerican civilizations. We present a quantitative 2400 yr rainfall reconstruction for the Basin of Mexico, from a precisely dated and highly resolved speleothem, that documents highly variable rainfall over the past 2400 yr. Dry conditions peaked during a 150-yr-long late Classic (ca. 600–900 CE) (Common Era) megadrought that culminated at 770 CE which followed centuries of climatic drying that spanned the fall of the city of Teotihuacán ca. 550 CE. The wettest conditions in the 1450s CE were associated with flooding in the Basin of Mexico. Our data suggest that rainfall variability was likely forced by the El Niño–Southern Oscillation, and impacts on spring-fed irrigation agriculture may have been a stressor on Mesoamerican civilizations.

INTRODUCTION

The relationship between climate and cultural change in Mexico is poorly understood, despite repeated droughts evidenced in the instrumental (Stahle et al., 2009) and paleoclimate records (Hodell et al., 2001, 1995). Few high-resolution and well-dated records are available to test hypotheses of climate and cultural change in the highland Basin of Mexico (Fig. DR1 in the GSA Data Repository[1]), where the first large urban Mesoamerican civilizations arose in the monumental cities of Teotihuacán (ca. 100 before Common Era, BCE, to 600 CE) and Aztec Tenochtitlán (ca. 1325–1521 CE). Speleothems in suitable tropical caves are ideally suited to test hypotheses of past climate changes, because their oxygen isotope composition is a robust proxy for past rainfall amount (Lachniet, 2009). We test a drought hypothesis for the fall of Teotihuacán and other cultural changes in Mesoamerica from a climate-calibrated rainfall reconstruction from a precisely dated stalagmite.

The urban center of Teotihuacán was the largest early Mesoamerican city (Millon, 1967), and its rapid rise in the first century BCE (Cowgill, 1997) has been linked to spring-fed irrigation agriculture (Millon, 1954; Sanders, 1977). Extensive use of rainwater capture (Linné, 2003) and canals and reservoirs (Lorenzo, 1968; Sanders et al., 1979) at Teotihuacán suggests exploitation of primary spring water sources (Sanders, 1977) that could have resulted in human susceptibility to drought, and the city may have been located upon now-dry springs (Mooser, 1968). The Teotihuacán Valley population reached 125,000 ca. 500 CE, and the city exerted broad influence in Mesoamerica (Millon, 1967). Archeological data support burning and looting of Teotihuacán during the "Big Fire" of ca. 550 CE (Beramendi-Orosco et al., 2009; Soler-Archelade et al., 2006), prior to its fall as a major regional power (Cowgill, 1997; Millon, 1967). Other hypotheses for the fall of Teotihuacán include climatic drying (García, 1974; Millon, 1967), social and environmental problems, nomad incursions, bad administration of economy and politics (Manzanilla, 2003), deforestation and soil erosion (Sanders et al., 1979; Sears, 1955), and volcanic eruptions (Siebe et al., 1996).

SPELEOTHEM CALIBRATION AND RAINFALL RECONSTRUCTION

Stalagmite JX-6, from Juxtlahuaca Cave, Sierra Madre del Sur, is anchored by 1230 stable isotope values and 20 ultraprecise uranium-series ages (±1%; see the Data Repository). The JX-6 $\delta^{18}O$ record (Fig. 1) shows multidecadal variability superimposed upon several multicentennial-scale trends. The most recent stalagmite $\delta^{18}O$ values are anticorrelated with Basin of Mexico precipitation (Fig. 2), showing our record to be a robust proxy for rainfall amount (see the Data Repository for details). Correlation of 1 yr interpolated $\delta^{18}O$ data and Tacubaya wet season (May through November, MJJASON, comprising 95% of the annual total) rainfall (1880–2010 CE) is strongest when

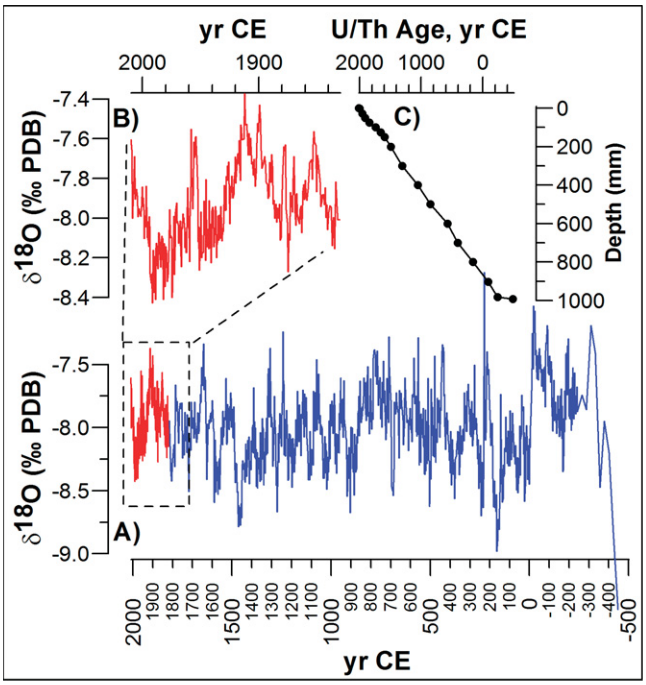

Figure 1. A: Stalagmite JX-6 $\delta^{18}O$ time series over past 2400 yr (CE—Common Era). Red is 0.25 mm resolution and blue is 1.0 mm resolution sampling. PDB—Peedee belemnite. B: Detail of high-resolution $\delta^{18}O$ used for modern climate calibration in Figure 2. C: Uranium-series age versus depth plot. Age uncertainties are smaller than symbols.

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[1]GSA Data Repository item 2012065, background and methods, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

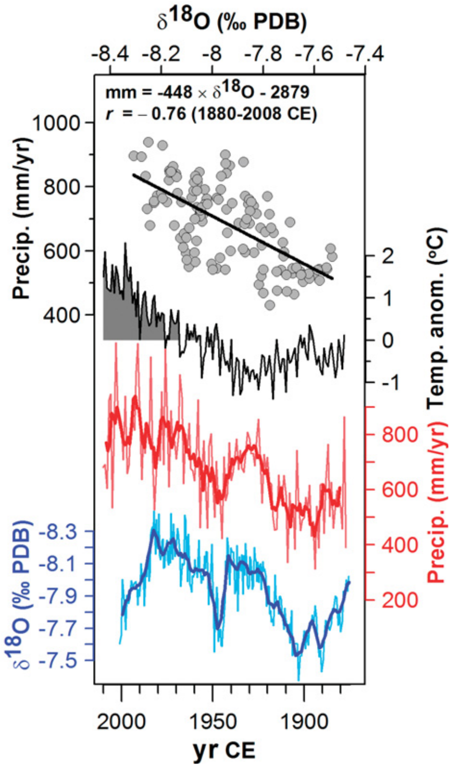

Figure 2. Top: Cross-plot of JX-6 δ^{18}O (9 yr lag) and Mexico City rainfall (both with 5 yr smoothing). PDB—Peedee belemnite. Bottom: Tacubaya annual temperature anomalies (Temp. anom.; black), relative to 1951–1970 CE mean; JX-6 δ^{18}O (blue), and precipitation (Precip.; red) time series show remarkable correlation between 1878 and 1988 CE, and demonstrate that δ^{18}O values are proxy for rainfall in Basin of Mexico.

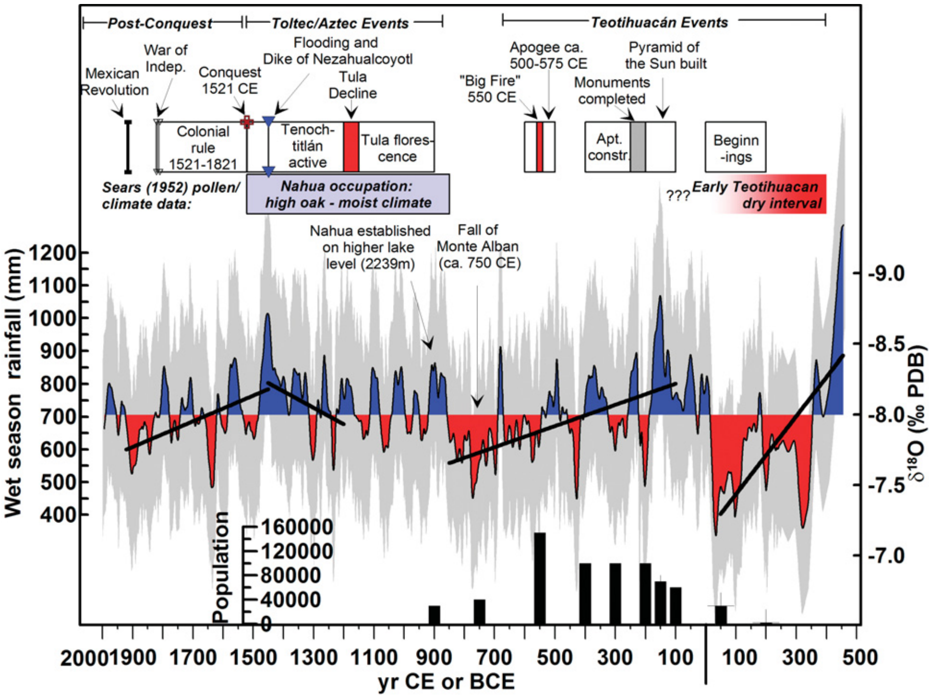

Figure 3. A 2500 yr rainfall reconstruction for central Mexico and comparison to cultural change; δ^{18}O time series and rainfall reconstruction (gray) with 11 yr running averages are for wet (blue) and dry (red) conditions about reconstruction mean of 705 mm/yr. PDB—Peedee belemnite. Trend lines for key intervals of cultural history are: 400 BCE (before Common Era) to 50 CE (early Teotihuacán period), 100–800 CE (Teotihuacán period), 1250–1521 CE (Nahua period), and 1450–1920 CE (peak Nahua to 20th century drying interval). Bottom is estimated population of Teotihuacán Valley. Top shows key cultural events and pollen zones in Basin of Mexico."Beginnings" is initial construction and growth in Teotihuacán. Apt. constr.—apartment construction.

δ^{18}O lags rainfall by 5 yr (r = –0.55, n = 124) and 11 yr (r = –0.54). Because the epikarst is likely to smooth high-frequency variability, we also correlated 5 yr smoothed rainfall and δ^{18}O data (1878–2008 CE), returning the strongest correlation when δ^{18}O lags rainfall by 8 yr (r = –0.76). If the most recent anthropogenically altered climate data after 1988 are excluded (Jauregui, 1990) (see the Data Repository), the correlation improves to r = –0.89 with a 9 yr JX-6 lag. The lag correlograms (Fig. DR2) suggest an ~9 yr transit time for epikarst water to reach the stalagmite tip, which is supported by the ~160 m bedrock thickness and the absence of evidence for fast conduit flow paths over the sample site. Our stalagmite chronology was thus adjusted to 9 yr older (Fig. 3). The δ^{18}O/rainfall regression of the 5 yr running average δ^{18}O and wet season rainfall is (in millimeters) = –448 × δ^{18}O – 2879 (see the Data Repository), with an uncertainty envelop estimated by varying the δ^{18}O/rainfall slope by its standard error (SE = 34.9 mm).

The statistical observation of the Tacubaya rainfall and δ^{18}O anticorrelation, as well as observational studies of tropical rainfall (Lachniet and Patterson, 2009; Rozanski et al., 1993), leads us to interpret the δ^{18}O variations as reflecting the amount effect. The amount effect is clearly evident in rainfall amounts from the Basin of Mexico and Veracruz (Fig. DR3), and is best interpreted to record air mass rainout history along its transport trajectory, so at-site δ^{18}O variations record prior rainout amount on a regional scale. Furthermore, because summer monsoon rainfall is the dominant precipitation source at the study area, we interpret the δ^{18}O data as a proxy for summer monsoon intensity. Cave pool water δ^{18}O values of –7.6‰ (Vienna standard mean ocean water) are within the range of regional surface waters (–8.3‰ ± 1.1‰) and groundwaters of –8‰ to –9‰ (Wassenaar et al., 2009), suggesting that they reflect mean annual recharge.

Our rainfall reconstruction (Fig. 3) indicates that Basin of Mexico wet season rainfall varied between ~400 and 1000 mm/yr (mean = 705 ± 139 mm/yr) on multidecadal time scales. Our data are strikingly consistent with pollen-based climate reconstructions for Basin of Mexico cultural horizons. Sears (1955) indicated peak wetness during the Archaic (ca. 1500 to 400 BCE) and maximum lake levels ca. 500 BCE. Although our data are sparse for this period, peak rainfall (~1000 mm/yr) occurred ca. 450 BCE. Teotihuacán Valley settlement during the first two centuries BCE coincided with below-normal rainfall (Fig. 3) and low lake levels, as evidenced by high pine pollen concentrations in archaeological sediments (Sears, 1952). The population increase was possibly due to immigration from the wetter southern basin due to disruptive volcanic events (Plunket and Uruñuela, 2006; Siebe et al., 1996). Our data suggest that above-average rainfall was associated with the initial construction of the monumental architecture at Teotihuacán between the first and third centuries CE.

The decline of Teotihuacán ca. 550 CE, when the population fell from its high of ~125,000 (Adams, 2005; Cowgill, 1997), came near the end of a 500 yr drying trend that culminated with a 150 yr megadrought centered on 770 CE. The drying trend is defined by successively reduced rainfall maxima separated by increasingly dry rainfall minima (Fig. 3). Our data show that the 50 yr preceding the "Big Fire" at 550 CE (Soler-Arechalde et al., 2006) were defined by a 30% decrease in rainfall from a relative high ca. 500 CE (Fig. 3). Thus our data strongly suggest that climatic drying, and by inference decreases in aquifer recharge and spring discharge, was associated with population decline at Teotihuacán.

Recharge to the Basin of Mexico aquifer is derived from bordering mountains with a transit time in local flow systems of 5–200 yr, such that subdecadal to longer rainfall variability likely resulted in spring discharge variations (Ortega-Guerrero and Farvolden, 1989). Our data support climatic drying as a primary control for the drying of springs and other environmental changes that may have included forest loss and soil erosion (Mooser, 1968; Sanders, 1977; Sanders et al., 1979).

The rainfall reconstruction shows continued drying for 260 yr after 600 CE, at which time the population and regional influence of Teotihuacán was significantly diminished. Additional evidence for dry conditions in the late Classic is derived from oxidized lake sediments from the Iguala Valley dated to ca. 650–665 CE, or possibly slightly younger if hard-water effects are assumed (Piperno et al., 2007). The mega-drought of 690–860 CE (Fig. 3) was a time of minimal cultural activity in the Basin of Mexico, bridging the period between the fall of Teotihuacán ca. 600 CE and the rise of the Nahua people ca. 900 CE. We hypothesize that hydrological resources during this period were not able to sustain a large population in the Basin of Mexico.

A return to wetter climate (700–900 mm/yr) occurred between the 9th and 16th centuries (Fig. 3), when Nahua groups occupied land surfaces upon which rich organic soil was formed and a high-oak moist climate was prevalent (Sears, 1952). The beginning of this wet period is associated with the rise of Tula (the Toltec capital) between 900 and 1150 CE (Evans, 2004). Our data do not support multiannual drought as a factor in the fall of the Toltec state ca. 1150 CE (Stahle et al., 2011) that occurred against a backdrop of high rainfall amounts and diminished variability. The Aztec city of Tenochtitlán arose on an island ca. 1325 CE in the western shallows of Lake Texcoco, and comparison to our record shows that its history was one of increasing rainfall, culminating in the wettest conditions of the past millennia ca. 1450 CE.

The Nahua depended on spring discharge for *chinampa* (lake margin) agriculture and for drinking water. The wettest conditions in our record coincided with the construction of a large flood-protection dike east of Tenochtitlán in 1449 CE, to protect the freshwater chinampas from devastating floods of the saline waters of Lake Texcoco (Evans, 2004; Hassig, 1981). A wet Aztec climate is also supported by documentary data of an expansion of irrigated lands in the Teotihuacán Valley 15 km downvalley to the Lake Texcoco margin, and a 60% water supply increase (Sanders, 1977; Sanders et al., 1979). Coincidental to this wet climate, cold weather and early frosts in the 1450s destroyed maize crops, and resulted in famine and outmigration (peaking in the "One Rabbit" famine of 1454 CE) in the Basin of Mexico (Evans, 2004; Hassig, 1981). Tree ring and historical evidence suggests that a series of droughts around the 1450s contributed to the famine and disease epidemics (Hassig, 1981; Therrell et al., 2004). However, our data suggest that these events were either not linked to multidecadal-scale water availability, or were too short to be recorded by our stalagmite.

Average rainfall amounts in the early 16th century (including the Spanish conquest of 1521 CE; Fig. 3) followed nearly 200 yr of high rainfall. The Colonial period was characterized by a rainfall decline and multidecadal variability. Following a relative high in 1865 CE, rainfall decreased to low levels ca. 1905, and did not return to normal until ca. 1920. This period of low rainfall spanned the Mexican Revolution of 1910–1920 CE, an event that has previously been linked to drought (Florescano and Swan, 1995), and is evident in the Mexico City rainfall data (Fig. 2).

DISCUSSION

Our results show that rainfall variability over the past 2.5 k.y. was linked to Basin of Mexico cultural changes. However, our data reveal differences in the timing of regional dry periods. The Terminal Classic drought in the Maya lowlands (Laguna Chichancanab) occurred as two pulses, between 770 and 870 CE and 920–1100 CE (Hodell et al., 2005), broadly consistent with high speleothem $\delta^{18}O$ values (dry conditions) from the Yucatan (Medina-Elizalde et al., 2010). Our data show a single late Classic drought beginning ca. 690 CE, peaking at 770 CE, and terminating by 860 CE. Lake sediment data from Guerrero also support a 7th century CE drought (Piperno et al., 2007), suggesting that the timing of drought in the Mexico highlands may have preceded that in the lowlands. Climatic drying and water-table lowering may have resulted in double peril for Teotihuacán by decreasing spring discharge for irrigation and rainfall capture for domestic consumption. It is intriguing that archaeological evidence of smashed "Storm God" artifacts (associated with thunderstorms and crop devastation; equivalent to the later Aztec god Tláloc) were found in "Big Fire" horizons (Manzanilla, 2003), suggesting that Teotihuacános may have implicated abandonment of the rain god during this drought period.

Tree-ring data from central Mexico documented early summer wetness over the past 1238 yr (Stahle et al., 2011), but these data are poorly correlated to our rainfall reconstruction. Two observations may explain this discrepancy. First, the stalagmite record is unable to resolve annual-scale events because of smoothing and delay of the climate signal in the epikarst. Second, and more likely, the two wetness reconstructions record different climate signals. The tree-ring record was calibrated to early wet season (June) drought severity, which may reflect antecedent moisture conditions and be a poor predictor of total wet season rainfall. Analysis of rainfall data from Higgins et al. (1999) indicates that a late monsoon onset (e.g., late May to June) is most commonly associated with higher (not lower) average seasonal rainfall.

We suggest that the core phenomenon governing climate in the study area is the strength of the North America monsoon (Higgins et al., 1999; Stensrud et al., 1995). Modern climate is strongly linked to the El Niño–Southern Oscillation (ENSO), with warm El Niño events associated with a weak monsoon, and vice versa (Higgins et al., 1999; Magaña et al., 2003). Wet La Niña events are forced by negative sea-surface temperature (SST) anomalies, which enhance the land-sea thermal contrast, strengthening the monsoon, and vice versa for El Niño (Higgins et al., 1999). Thus, we attribute summer monsoon rainfall variability over the past 2.5 k.y. to SST forcing in the eastern tropical Pacific Ocean.

However, few SST records are available at a sufficiently high resolution to test this hypothesis directly, so we do so indirectly by comparison of $\delta^{18}O$ time series spectra (Fig. DR4) against known ocean-atmosphere phenomena, i.e., the Pacific Decadal Oscillation (PDO, 15–25 and 50–75 yr) (Mantua and Hare, 2002), the Atlantic Multidecadal Oscillation (AMO) (Knight et al., 2005), a variation in North Atlantic SSTs with an ~65–80 yr periodicity that may influence Mexican rainfall (Bernal et al., 2011), and solar variability (11, 22, 88, and 208 yr), which has been linked to rainfall variability in Mesoamerica (Hodell et al., 2001). Our $\delta^{18}O$ record contains spectral power at 4–10 yr above the 95% confidence interval, which we attribute to ENSO. The lack of lower frequency spectra does not provide evidence for a PDO or AMO forcing. Furthermore, our results demonstrate an absence of spectral peaks at or near the 11, 22, 88, and 208 yr solar frequencies at any confidence interval. Based on the spectra and dissimilarity to the ^{10}Be and $\Delta^{14}C$ records (not shown), we conclude that solar irradiance variations are not a direct forcing of the Mexican portion of the North American monsoon. A more rigorous test of our ENSO hypothesis of Mesoamerican rainfall requires subdecadally resolved SST records from the core ENSO regions of the tropical Pacific Ocean.

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