Major Mesoamerican droughts of the past millennium

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[1] Ancient Montezuma baldcypress (*Taxodium mucronatum*) trees found in Barranca de Amealco, Queretaro, have been used to develop a 1,238-year tree-ring chronology that is correlated with precipitation, temperature, drought indices, and crop yields in central Mexico. This chronology has been used to reconstruct the spring-early summer soil moisture balance over the heartland of the Mesoamerican cultural province, and is the first exactly dated, annually resolved paleoclimatic record for Mesoamerica spanning the Late Classic, Post Classic, Colonial, and modern eras. The reconstruction indicates that the Terminal Classic drought extended into central Mexico, supporting other sedimentary and speleothem evidence for this early 10th century drought in Mesoamerica. The reconstruction also documents severe and sustained drought during the decline of the Toltec state (1149–1167) and during the Spanish conquest of the Aztec state (1514–1539), providing a new precisely dated climate framework for Mesoamerican cultural change.
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1. Introduction

[2] Mesoamerica is one of the richest archaeological districts of the ancient world notable for large urban centers, monumental architecture, calendar and hieroglyphic writing systems that in some cases describe and accurately date conquests, dynastic succession, celestial phenomena, weather extremes, and drought [*Coe and Koontz*, 2008; *Therrell et al.*, 2004]. The post-Conquest colonial and modern record is also rich in detail on socioeconomic extremes, including famines, epidemics of infectious diseases, and warfare. Mesoamerica has not had a millennium-long, annually-resolved paleoclimatic record with which to test hypotheses concerning climate change, internal and external forcing of regional climate variability, or the possible role of multi-decadal climate anomalies in the rise and fall of pre-Hispanic city states, most famously including the hypothesized decline of the Classic Maya during the "megadroughts" of the 9th and 10th centuries [*Hodell et al.*, 1995; *Haug et al.*, 2003]. Millennium-old Montezuma baldcypress trees have been discovered at two locations in Mexico [Barranca de Amealco, Queretaro (Figure 1), and Los Peroles, San Luis Potosi], and the successful development of the 1,238-year chronology in Queretaro fulfills a longstanding goal of American dendrochronology to extend the long, exactly dated tree-ring record into Mesoamerica (Mexico and Central America) where it might be used to date archaeological sites and to reconstruct climate history during the rise and fall of pre-Hispanic civilizations (Figure 2a).

2. Methods

[3] Millennium-old trees have survived in the steep gorge at Barranca de Amealco, only 60 km from Tula, the principal city of the ancient Toltec state, and just 90 km from the Aztec capital of Tenochitlan in the Valley of Mexico. Core samples were extracted from the ancient trees and the microscopic and highly polished tree rings were exactly crossdated to their exact calendar year of formation with dendrochronology [*Stokes and Smiley*, 1995]. The dated tree rings were measured under the microscope on a stage micrometer to a precision of 0.001mm using custom software (P.J. Krusic; *http://www.ldeo.columbia.edu/res/fac/trl/public/publicSoftware.html*). Severe growth suppression rendered portions of some cores un-datable and the final numerical chronology was based on 74 cores from 30 trees. Dating and measurement accuracy was confirmed with segmented correlation analyses of all dated series using the computer program COFECHA [*Holmes*, 1983]. The mean inter-series correlation computed with COFECHA between each dated cores series and the mean index chronology based on all other cores is 0.48. The expressed population signal statistic (EPS) [*Wigley et al.*, 1984] calculated for 100-year segments with the ARSTAN program [*Cook*, 1983] (overlapping by 50 years and using detrended and prewhitened tree-ring series) remains at or above the 0.85 threshold for all segments from 880–1930, except for the segments centered at 880 (EPS = 0.817) and 1580 (EPS = 0.843, Figure 2b), indicating that the component time series in the derived chronology generally preserve the signal of a hypothetically perfect chronology based on an unlimited number of trees. The lower internal consistency among the available dated cores series at 880 is due to declining sample size before 930 (Figure 2c). The weakness at 1580 may reflect the influx of young age classes in the sample of dated cores, due to recruitment after the 16th century megadrought. Increasing the sample size of dated trees and cores during these intervals will help improve these EPS statistics, but the

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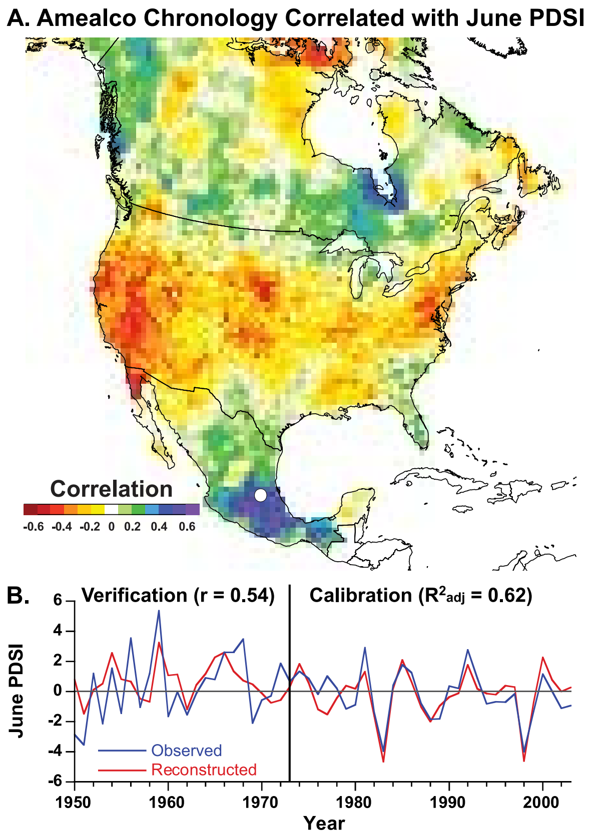

Figure 1. (a) The tree-ring chronology from Barranca de Amealco in central Mexico (white dot) is correlated with the gridded (0.5°) instrumental June PDSI over North America (1950–2003). Note the strong correlations over the cultural heartland of Mesoamerica, where instrumental June PDSI was extracted for 84 grid points and averaged into a regional time series for reconstruction (observed, in Figure 1b). (b) The instrumental and tree-ring reconstructed June PDSI time series for Mesoamerica are compared during the calibration and verification periods.

dendrochronological crossdating and segment correlation analyses in COFECHA indicate that the Amealco chronology is correctly dated from AD 771–2008.

[4] The severe growth suppression observed on many ancient cypress cores during the megadroughts of the 14th and 16th centuries was a major impediment to the development of the Amealco tree-ring chronology. Only a subset of trees grew well enough during these drought episodes to form clear annual rings more than 0.001mm in width, to minimize missing rings, and to allow precise crossdating among the ring width series. Consequently, the severity of the 14th and 16th century droughts may be underestimated because many trees must have died and other severely impacted survivors could not be dated during these intervals. The extremely low to zero radial growth registered on these dead and dying trees was therefore not included in the mean index chronology. This survivorship effect may also impact the estimation of early 10th century drought severity at Amealco, in addition to the low sample size at that time.

[5] To develop the final chronology, the measured ring series were detrended and standardized using a smoothing spline (50% frequency response of 100 years for all series [*Cook and Peters*, 1981]). The mean-index chronology was computed using robust estimation to discount statistical outliers and the variance was stabilized with a 100-year spline using the ARSTAN program. Detrending and variance stabilization have preserved inter-annual to multidecadal variability, including evidence for major droughts during the pre-Hispanic and early colonial eras, but have removed multi-centennial variance that cannot be discriminated from growth trend associated with increasing tree size and age, and changing sample size.

[6] The derived tree-ring chronology is strongly correlated with the Palmer Drought Severity Index (PDSI) over most of central and southern Mexico, peaking in the early growing season (Figure 1a). The PDSI is a soil moisture balance index based on station precipitation and temperature data, and provides a reasonable approximation for the climate forcing of tree growth [*Cook et al.*, 1999]. Gridded PDSI values were computed for North America from a 0.5° gridded temperature and precipitation dataset, which was created from a high-quality suite of 5,639 temperature and 7,852 precipitation data records from across the United States, Canada, and Mexico. The station temperature data were treated for documented and undocumented change points, and outlier checks were applied to all station records. Climatologically-aided interpolation was used to grid the station data [*Willmott and Robeson*, 1995]. PDSI values were extracted from the Palmer drought dataset for the 84 grid points well correlated with the tree-ring chronology in central Mexico ($r > 0.40$). The 84 grid points were then averaged into a single regional time series to represent the early growing season soil moisture balance for Mesoamerica.

[7] The standard ring-width chronology was then calibrated with this regional PDSI series using regression for a 31-year common period (1973–2003), after the predictor chronology and the predictand PDSI time series were each autoregressively (AR) modeled and prewhitened on the basis of the AR structure identified during the calibration period. The AR model of the instrumental PDSI was added to the prewhitened tree-ring estimates and the resulting reconstruction explains 62% of the variance in the observed PDSI ($R^2_{adj} = 0.62$; 1973–2003, Figure 1b). The reconstruction was statistically verified on independent June PDSI from 1950–1972 (Pearson $r = 0.54$ ($P < 0.01$), reduction of error = 0.32, coefficient of efficiency = 0.28 [*Cook et al.*, 1999]). The gridded Palmer drought indices for Mexico prior to 1950 were not used because fewer high quality stations are available and the gridded indices are not well correlated with the tree-ring data. Finally, the reconstruction was rescaled by the ratio of observed and reconstructed standard deviations (1973–2003) to recover the variance lost in regression. The instrumental and reconstructed June PDSI for central Mexico, all calibration and verification statistics, and the coordinates of the 84 grid points used to compile the regional June PDSI for Mesoamerica are presented online (*http://www.uark.edu/dendro/mesoamerica.xls*).

3. Results

[8] The new reconstruction of June PDSI is the first exactly dated millennium long tree-ring estimate of past climate yet developed for Mesoamerica. The deepest and most profound droughts reconstructed for central Mexico (Figure 1a) seem to be recorded in other paleoclimate

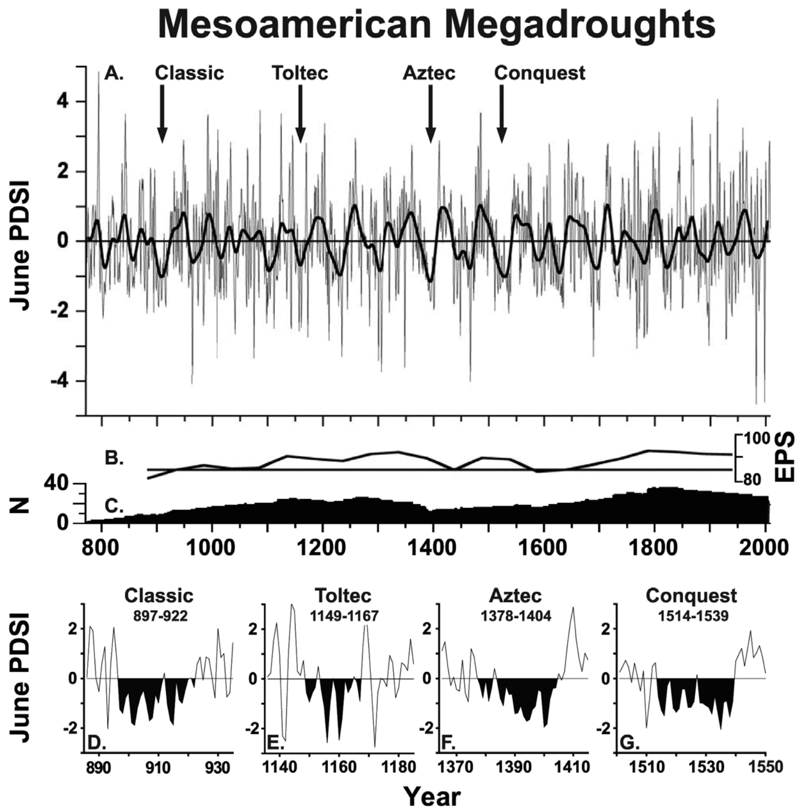

Figure 2. (a) Tree-ring reconstructed June PDSI for Mesoamerica (annual and smoothed estimates highlighting 30-year departures), (b) EPS statistics for 100-year segments, (c) sample size, and 50-year subperiods illustrating the (d) Terminal Classic, (e) Toltec, (f) Aztec, and (g) Conquest-era droughts.

estimates from Mesoamerica based on sedimentary and speleothem records, even though these other proxies are dated with less accuracy and precision than is possible with dendrochronology. The titanium record from laminated sediments at Laguna de Juanacatlan, Jalisco, is believed to represent a proxy for warm season rainfall over west-central Mexico and covers the last 2000 years based on an age-depth model constrained by 26 AMS radiocarbon dates [*Metcalfe et al.*, 2010]. Within the dating uncertainties of the titanium record (not shown), there are indications of drier conditions in Jalisco during some of the megadroughts reconstructed from Queretaro, especially during the early 10th, early 12th, and late 14th centuries (Figure 2a) [*Metcalfe et al.*, 2010]. The early 16th century drought (1514–1539) is only partially synchronous with drier conditions in Jalisco, and historical information indicates rising lake levels in the Valley of Mexico from 1517–1524 and declining levels thereafter [*O'Hara and Metcalfe*, 1997]. The degree to which these comparisons might be biased by dating uncertainties, differences in the seasonal climate response among the proxies, or real spatial differences in pre-Hispanic or Colonial climate over central Mexico will have to be resolved with further research. But tree-ring dating should play an increasingly important role in the reconstruction of late Holocene climate over Mesoamerica because 900- to 1500-year old Montezuma baldcypress have been sampled at other sites in central and southern Mexico and efforts to build exact chronologies are underway.

[9] The June PDSI reconstruction also provides valuable, exactly dated information on early growing season climate conditions during the rise and fall of pre-Hispanic civilizations in Mesoamerica. For example, the reconstruction indicates that the Terminal Classic drought extended into the central Mexican altiplano from AD 897–922, where it was one of the worst megadroughts of the past 1200-years (Figures 2a and 2d). This may represent at least part of the same episode of extended drought reported from lake sediments and speleothems in the Yucatan and Jalisco, within the constraints of the various age estimates [*Hodell et al.*, 1995; *Medina-Elizalde et al.*, 2010; *Metcalfe et al.*, 2010]. The reconstruction also identifies Late Classic droughts centered at AD 810 and 860, which were previously reconstructed for the Caribbean sector from laminated sediments in the Cariaco Basin [*Haug et al.*, 2003]. Whether adverse climate conditions were a key factor in the decline of Mayan city states during the Terminal Classic period is contentious and alone cannot explain the complex chronology of regional cultural changes identified in the archaeological record during the late Classic/early Post-Classic periods [*Demarest et al.*, 2004]. But the new reconstruction from Queretaro confirms the Terminal Classic drought, documents its penetration into the highlands of central Mexico, and narrows the timing of this central Mexican megadrought to AD 897–922.

[10] The Toltec state was the dominant imperial civilization of central Mexico during the early Post-Classic era and archaeological, chronometric, and historical data indicate that the collapse of Tula occurred ca. 1150 [*Diehl*, 1983], a

period of reconstructed drought (Figure 2e). The tree-ring reconstruction is an estimate of the soil moisture balance prior to the *canicula* (mid-summer drought), and early growing season drought can negatively impact the germination, maturation, and yield of maize, especially in highland Mesoamerica where freezing weather in autumn can truncate the growing season and reduce yields (the reconstruction is correlated with modern maize yield over central Mexico at: $r = 0.58$, $P < 0.001$, 1980–2001; data from *Therrell et al*. [2004]). *Diehl* [1983, p. 158] noted that "subsistence agriculture has always been a precarious enterprise in the arid Tula area….dry years meant total crop losses on un-irrigated fields and river levels which were so low that water could not be drawn off into the canal systems. A single bad year caused hunger; several in a row could easily create famine. The Toltecs faced this problem all along, but it became more critical as the population grew." The new reconstruction identifies a 19-year drought from AD 1149 to 1167, the first evidence that the massive mid-12th century megadrought, the most extreme drought of the past 1000-years over western North America [*Cook et al.*, 2007], extended into central Mexico. The mid-12th century drought in Mesoamerica was not as extreme as the subsequent early 13th century drought (Figure 2a), but based on the gridded PDSI reconstructions [*Cook et al.*, 2007] the 12th century event worsened to the north and may have been a push factor in the migration of militaristic Chichimeca who have been associated archaeologically with instability within the Toltec state and potentially with the abandonment of Tula [*Coe and Koontz*, 2008; *Diehl*, 1983].

[11] The most extreme Mesoamerican drought since AD 771 is reconstructed during the late 14th century (1378–1404, Figures 2a and 2f). The social impacts of this drought during the expansion of the Aztec state are not presently known, but drought is reconstructed during the 1454 "Famine of One Rabbit," the worst in Aztec history, evidence that Aztec crop yields were vulnerable to drought and frost [*Therrell et al.*, 2004]. The collapse of the Aztec state came with Spanish conquest in 1521. The reconstruction indicates that early warm season drought over Mesoamerica preceded the arrival of Cortez and persisted for 26 years (1514–1539, Figure 2g). The conquest of Mexico was a clear military victory for the Spanish, but prolonged drought over Mesoamerica during the early Colonial era may have interacted with epidemic disease to contribute to the catastrophic depopulation of Aztec Mexico in the aftermath of conquest [*Acuna Soto et al.*, 2002]. The tree-ring evidence for severe sustained drought during the major social transitions of the Terminal Classic, Post-Classic, and early Colonial eras provides an interesting new environmental framework for the study of Mesoamerican cultural change.

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