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Testing the “tropical storm” hypothesis of Yucatan Peninsula climate variability during the Maya Terminal Classic Period

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ABSTRACT

We examine the “tropical storm” hypothesis that precipitation variability in the Yucatan Peninsula (YP) was linked to the frequency of tropical cyclones during the demise of the Classic Maya civilization, in the Terminal Classic Period (TCP, AD 750–950). Evidence that supports the hypothesis includes: (1) a positive relationship between tropical storm frequency and precipitation amount over the YP today (proof of feasibility), (2) a statistically significant correlation between a stalagmite (Chaac) quantitative precipitation record from the YP and the number of named tropical cyclones affecting this region today (1852–2004) (calibration *sensu lato*), and, (3) correlations between the stalagmite Chaac precipitation record and an Atlantic basin tropical cyclone count record and two proxy records of shifts in macro-scale climate and ocean states that influence Atlantic tropical cyclongenesis. At face value, regional paleotempestology proxy records suggest that tropical storm activity in the YP was either similar or significantly lower than today during the TCP. The “tropical storm” hypothesis has implications for our understanding of the role the hydrological cycle played in the collapse of Classic Maya polities and the role of tropical storms in possibly ameliorating future drought in the YP and other tropical regions.

Introduction

During the Terminal Classic Period (TCP, AD 750–950) the Classic Maya socio-political system disintegrated in a context of endemic warfare, dynastic conflicts and drastic demographic change (Demarest et al., 2004). Hypotheses to explain this collapse have invoked internal socio-political aspects and exogenous factors such as climate change, particularly drought (Hodell et al., 1995; Curtis et al., 1996; Gill, 2000; Demarest et al., 2004; Hodell et al., 2005; Medina-Elizalde et al., 2010; Medina-Elizalde and Rohling, 2012). Climate archives as diverse as marine sediments (Haug et al., 2003), lacustrine sediments (Hodell et al., 1995; Curtis et al., 1996, 1998; Rosenmeier et al., 2002; Hodell et al., 2005) and speleothems (Webster et al., 2007; Medina-Elizalde et al., 2010; Kennett et al., 2012) have all been found to support the hypothesis that reduced rainfall hindered cultural development during the TCP.

Lacustrine and speleothem records suggest that during the TCP the YP experienced a series of drought events (high evaporation and low precipitation) mostly driven by decreases in summer precipitation between 30% and 50% relative to the average amount falling over the preceding century (AD 700–800) (Medina-Elizalde and Rohling, 2012). Yet, the causal factors that brought about drought in the region during the disintegration of the Classic Maya civilization remain unresolved (Medina-Elizalde et al., 2010). Many details of the relationship between water availability and Maya cultural history also remain unclear. As illustrated by this study focused on the TCP, an understanding of the driver(s) of precipitation variability is essential to assess the vulnerability of ancient and modern civilizations to adverse climate change.

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Considerable progress has been made in characterizing the magnitude and spatial extent of hydrological variability in the YP during the disintegration of the Classic Maya civilization. Regional lacustrine and stalagmite $\delta^{18}O$ records show positive $\delta^{18}O$ excursions that likely reflect reductions in summer precipitation (Medina-Elizalde and Rohling, 2012), and eight particular events of precipitation reductions of significant magnitude and duration (6–18 years) between AD 800–1000 (Hodell et al., 1995, 2005; Curtis et al., 1996; Medina-Elizalde et al., 2010). Based on the location of the YP within the path of Atlantic tropical storms and the potential contribution of these storms to regional precipitation, Medina-Elizalde and Rohling (2012) suggested that $\delta^{18}O$ excursions in these paleoclimate records reflect a deficit of the lighter isotope (O^{16}) due to decreased rainfall fluxes from tropical storms and depressions. In the tropics, rainfall associated with tropical cyclones is characterized by distinctly negative $\delta^{18}O$ values (Lawrence and Gedzelman, 1996; Price et al., 2008). This signature appears to leave a brief imprint in highly resolved analyses of stalagmites from Central America (Frappier et al., 2007). The YP, on the other hand, experiences an annual and seasonal rainfall deficit (i.e., evaporation amount exceeds precipitation amount), thus a short-term net positive freshwater balance may result from rainfall fluxes associated with tropical storms and depressions (Jauregui, 1995; CONAGUA, 2011). Conceivably, therefore, precipitation variability during the TCP could reflect the frequency of tropical storms (Medina-Elizalde and Rohling, 2012). Such an effect might have been particularly important at this time because mean precipitation (824 mm) was ~25% lower than modern (~1100 mm, AD 1940–2004), thus increasing the contribution of tropical storm rainfall to the regional hydrological balance (Medina-Elizalde et al., 2010; Medina-Elizalde and Rohling, 2012).

Alternatively, studies have invoked mean latitudinal shifts in the position of the ITCZ to explain precipitation variability in the YP during the TCP (Haug et al., 2003; Kennett et al., 2012). This hypothesis is based on the premise that the belt of convective activity associated with the ITCZ controls precipitation regimes in northern South America, particularly the Cariaco Basin (CB), and simultaneously, in the YP. Uncoupled climate regimes between these regions are suggested, however, by YP and CB paleoclimate records and by the instrumental record of precipitation (Hodell et al., 1995, 2005; Curtis et al., 1996; Medina-Elizalde et al., 2010). This is likely because the ITCZ does not directly reach the latitudes of the YP to significantly influence regional climate regimes, as pointed out by Hodell et al. (2008) and indicated by observational data (Hastenrath, 1984; Waliser and Gautier, 1993).

The present study examines the influence of tropical cyclones in driving precipitation variability in the Yucatan Peninsula during the TCP, here referred to as the "tropical storm" hypothesis. We explore the "tropical storm" hypothesis by: (i) determining the modern contribution of tropical storms to regional precipitation, using the instrumental record (i.e., from 1851 to 2011); (ii) assessing the existence of a tropical storm signal in the stalagmite Chaac precipitation record (Medina-Elizalde et al., 2010) over the instrumental period; (iii) statistically evaluating the correlation between the stalagmite Chaac precipitation record and proxy records of macroscale factors controlling Atlantic tropical cyclongenesis and a tropical cyclone (TC) count record, and (iv) examining evidence from existing regional paleotempestology proxy records.

Methods

Modern tropical storm precipitation amounts over the YP

We performed a detailed compilation of instrumental precipitation data associated with named tropical storms (i.e., tropical storms and hurricanes) and performed an evaluation of their precipitation contributions to summer and annual precipitation amounts over the entire YP (Supplementary Table S1). Tropical storms affecting the YP were identified using the best track data at the NOAA-National Hurricane Center. Storm precipitation amounts were determined from a database of daily precipitation data from 46 meteorological stations widely distributed within the YP (Fig. 1). In order to determine the rainfall contribution from each tropical storm, we used daily precipitation data from meteorological stations that were located within a radius of 100 km from the eye of the storm as it passed over or near the YP (within 100 km of the coast). We compiled only precipitation data above 30 mm coincident with the passing of a tropical storm. We calculated average *summer* precipitation from June to October (i.e., the *rainy or hurricane season)* from meteorological stations that recorded the passing of a tropical storm (i.e., total precipitation above 30 mm) in order to calculate the percent contribution of tropical cyclones to total summer precipitation (Supplementary Fig. S1). Note that our selected criteria likely underestimates precipitation contributions from tropical storms because our compilation does not include storms that passed more than 100 km from the coast of the YP or that were named or numbered after they passed the YP. In 2013, for instance, tropical depression Andrea reached its category of tropical depression in the Gulf of Mexico, but in association, the northeastern YP received close to half the average annual amount of rainfall. Figure S1, derived from this compilation, illustrates the range of precipitation amounts associated with the total number of tropical cyclones per year observed in the Yucatan Peninsula between 1942 and 2012. For instance, considering the years when the region experienced only one tropical storm, their associated precipitation amount ranged between 30 mm and 260 mm (left Y axis), representing contributions between ~2 and 30% of total summer precipitation during those years, respectively (right Y axis).

Paleoclimate proxy record comparisons

The proxy environmental records that we examine include:

(i) the stalagmite Chaac $\delta^{18}O$-derived precipitation amount record from the Tzabnah cave (20°45′N, 89°28′W, 20 m asl), which reflects equilibrium isotopic conditions and the local "amount effect" operating on interannual and seasonal time scales (Vuille et al., 2003; Medina-Elizalde et al., 2010; Medina-Elizalde and Rohling, 2012). Stalagmite Chaac precipitation percent changes were estimated by Medina-Elizalde and Rohling (2012) by scaling the local annual precipitation cycle (5-yr monthly averages, 1999–2003) and thus precipitation $\delta^{18}O$, so that the annual amount-weighted $\delta^{18}O$ of precipitation captures the variance of the Chaac $\delta^{18}O$ anomalies. Chaac $\delta^{18}O$ anomalies were calculated relative to the record's mean $\delta^{18}O$ composition during the century preceding the Terminal Classic Period (Medina-Elizalde and Rohling, 2012). A precipitation change uncertainty of $6 \pm 4\%$ (1 standard deviation, SD) is determined based on the 80% confidence interval of the amount effect characterized instrumentally by a recent study from the eastern Yucatan Peninsula ($\delta^{18}O_{precipitation}/\Delta_{precipitation\ amount} = -0.0137 \pm 0.0031‰$ per mm) (Medina-Elizalde et al., 2016). Cross-validation analysis using hydrological modeling and lacustrine paleoclimate records supports this stalagmite $\delta^{18}O$-based precipitation record and suggests that it reflects primarily a summer precipitation signal (Medina-Elizalde and Rohling, 2012).

Correlation field analyses of the instrumental record of precipitation relative to meteorological station data from the