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Supporting Online Material for

Collapse of Classic Maya Civilization Related to Modest Reduction in Precipitation

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This PDF file includes:

Materials and Methods
SOM Text
Table S1
References (*31–34*)

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Materials and Methods

Model Description

To ensure that we run representative modern climatic variables, we use five-year average monthly values of precipitation (*P*), evaporation (*E*), temperature (*T*), as well as the δ^{18}O value of precipitation (δ_p). *P*, *E*, and *T* are obtained from a very nearby meteorological station to Lake Chichancanab (Dziuché Town) (*21*). The δ_p values are taken from a more remote station (Veracruz city) (*31*). We use these δ_p to characterize the seasonal cycle, but shift the mean to –4.2‰ corresponding to the annual mean δ^{18}O value of regional precipitation (*31,32*). The amount effect is then determined from the relationship between δ_p –adjusted for Yucatán – and a 5-year monthly average of *P* (years 1999-2003) at the location of Lake Chichancanab ($\delta_P/\Delta P$ = –0.0234 ‰ per mm; R^2 = 0.80).

We use a combination of mass and isotope conservation to set a realistic value for the lake catchment area ratio (γ). As a first approximation, we use the observed 5-year mean annual *P* and *E* values (1999-2003) to estimate γ so that it ensures annual mass balance, which is required since the lake has been an existing feature for the entire Late Holocene (*9*). Mass balance from modern *P* and *E* values requires precipitation to be integrated over an area about 10% larger than the area affected by evaporation (γ = 1.1). This estimation of γ allows for seasonal and interannual lake level (H_L) variability at $H_L \leq 8$ m, the mean depth of Lake Chichancanab today. When $H_L > 8$ m, we assume that the lake –located in a very flat area – floods its catchment, and therefore set γ=1 to account for the equal areas of evaporation and precipitation. While maintaining annual mean mass balance, our model uses observed (5-year average) monthly mean *P* and *E* values to calculate monthly changes in the lake-water level. The lake level seasonal cycle thus found has a range of about 400 mm. Isotopic developments in the basin are calculated as follows:

$$(\delta_L)_n = \frac{\gamma(P)_n(\delta_P)_n + (E)_n\{(\delta_L)_{n-1} + (\delta_{eq})_n\} + (H_L)_{n-1}(\delta_L)_{n-1}}{\gamma(P)_n + (E)_n + (H_L)_{n-1}}$$

Here

$(\delta_{eq})_n = -1000\ln(\alpha_{eq})_n$

where $(\alpha_{eq})_n$ is determined for each month's temperature value (T_n) using the equation of ref. (*32*). In the above, subscript *eq* stands for values affected by equilibrium fractionation, subscript *n* stands for the month being considered, and *n*–1 therefore for the previous month. The calculations start with estimate values H_L = 8000 mm, and δ_L = 0‰. Monthly *P* and *E* values to be used are in mm. Although we start with an arbitrary δ_L = 0‰, this choice does not affect the final equilibrated lake-water isotope value, which turns out to be +3.9‰. This value agrees with observed values for Lake Chichancanab (*9, 15, 19*), suggesting that any kinetic fractionation upon evaporation is small, presumably because of very high relative humidity in the region's boundary layer.

The total amplitude in Lake Chichancanab $\delta^{18}O_{Pyrgophorus\ sp.}$ and Lake Punta Laguna $\delta^{18}O_{Pyrgophorus\ sp.}$ is ~50% smaller than our simulated fluctuations (Fig. 2 main text). This difference may be related to temperature effects on both lake and cave calcite $\delta^{18}O$, non-equilibrium isotopic fractionation of calcite $\delta^{18}O$ and shifts in δ_P associated with isotope source changes. It is unlikely that this difference reflects a larger catchment area or amount effect than prescribed here, since the shift in any of these parameters that would be necessary to reconcile the modeled and paleoclimate signals, would result in negligible lake mass variations and thus be incompatible with evidence of significant lake gypsum precipitation (*15*). Despite these caveats related to the historical complexity of these isotopic/hydrological systems, our study provides the first integrative quantitative interpretation of environmental records during the crucial Terminal Classic Period.

<u>Scenarios of perturbation to the seasonal precipitation cycle</u>

In the first scenario we run an experiment in which we "locked" summer precipitation in a winter precipitation mode, as it is fully explained in the main text.

In the second scenario, we calculate the summer factional change in precipitation (f) associated with the Chaac $\delta^{18}O$ anomalies, by solving f from the following equation:

$$\overline{\delta_{P_{ann}}} = \frac{5f\overline{P_{sum}}\left[\overline{\delta_{P_{sum}}} + (f-1)\overline{P_{sum}}\frac{\Delta\delta_P}{\Delta P}\right] + 7\overline{P_{win}}\,\overline{\delta_{P_{win}}}}{5f\overline{P_{sum}} + 7\overline{P_{win}}}$$

where $\delta_{P_{ann}}$ is Chaac's annual precipitation $\delta^{18}O$ anomaly, f is the fractional change in monthly summer precipitation, P_{sum} and P_{win} are summer and winter precipitation in mm, respectively, and $\Delta\delta_p/\Delta P$ is the amount effect (–0.0234 ‰ per mm). The horizontal overbars indicate monthly mean values. The base period for referencing Chaac's $\delta^{18}O$ anomalies was A.D. 700-800; the century prior to the TCP.

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<u>Records and location description</u>

Lake Chichancanab

Lake Chichancanab (19° 52'N, 88° 46'W) is a tectono-karstic basin with a base rock composed of Tertiary limestone and gypsum. It represents the largest lake in the state Yucatán region with a maximum depth of about 14 m. Total annual rainfall in the Chichancanab basin is about 1300 mm. Rainfall affects lake levels directly (precipitation) and indirectly (groundwater) (*33*, 34). Measured lake water $\delta^{18}O$ ranges from 3.4-5.4 ‰ (*9, 15, 19*). Lake Chichancanab is in saturation equilibrium with gypsum; thus, the SO_4^{2-} concentration in this lake is governed by gypsum solubility. Gypsum is regularly precipitated around the lake bank (*20*) The Lake Chichancanab *Pyrgophorus coronatus* $\delta^{18}O$ record evaluated in this study corresponds to the upper 1 m of a 4.9 m sediment core that extends back to ~ 9,000 years.

Lake Punta Laguna

Lake Punta Laguna comprises two interconnected basins located in the north east of the Yucatán Peninsula, near the Maya archaeological site of Coba. The lake has an area of 90ha and a maximum depth of ~10m. Lake Punta Laguna sediments are mainly composed of calcium carbonate (90-95%) preserving continuous records of ostracod and gastropod shells. The Lake Punta Laguna ostracod *Cytheridella ilosvayi* $\delta^{18}O$ record evaluated in this study represents the upper 2 m sequence of a continuous

6.3 m sediment core retrieved from the western basin of the lake in the year 1993 (*10*).

Chaac $\delta^{18}O$ record

The stalagmite Chaac (named after the Maya god of Rain) is a 45 cm specimen collected from the Cave Tzabnah in the locality of Tecoh (20° 45'N, 89° 28'W, 20 m above sea level), only 50 km south of Mérida; the largest city in the Yucatan Peninsula. The surface of Tzabnah lies 20 m above sea level. The residence time of the groundwater is very short; dripwater rates are strongly correlated to the seasonal precipitation variability with higher drip rates occurring during the rainy season (Jun-Oct) and lower during the dry season (Jan-Apr). The chronology of Chaac is based on 12 U-Th dates with uncertainties between (38-112 years). Lamina counting and U-Th dates suggest, however, a maximum absolute age uncertainty of ±10 years during the Terminal Classic Period (A.D. 800-950) (*14*). The average time resolution of the Chaac $\delta^{18}O$ record is 2.3 year but with annual resolution over the TCP. Hendy tests and isotopic equilibrium calculations indicate that Chaac's calcite was precipitated under or near equilibrium conditions and faithfully records rainfall $\delta^{18}O$ variability (Supplementary Fig. S3 in ref (*14)*).

<u>Records Tuning</u>

We graphically tuned Lake Chichancanab and Punta Laguna records to the Chaac $\delta^{18}O$ record over the TCP interval. Tuning implied assigning four age control points to Lake Punta Laguna and two age control points to the Lake Chichancanab $\delta^{18}O$ and sediment density records (Table S1). Only two of these tuning dates (in L. Punta Laguna) somewhat exceed the combined 2σ error of the radiocarbon dates and the Chaac $\delta^{18}O$ chronology (*9,10,14,15*).

Table S1. Tuning correlation tiepoints based on the time scale of the reference Chaac $\delta^{18}O$ record (*11*).

Age Chaac	Age L. Chichancanab $\delta^{18}O$ record	Age L. Chichancanab sediment density Record	Age L. Punta Laguna $\delta^{18}O$ record
819	788	771	830
843			881
893			963
940	986	1034	1068

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