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Key Points:
- Mud layers in a stalagmite record years with cave flooding from hurricane rain
- Mud layers are less likely to be recorded after drought lowers water table
- Hurricanes mask drought severity leading to Chaac proxy rainfall overestimates

Supporting Information:
- Readme
- Text S1
- Table S5
- Table S6

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Two millennia of tropical cyclone-induced mud layers in a northern Yucatán stalagmite: Multiple overlapping climatic hazards during the Maya Terminal Classic "megadroughts"

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Abstract An annually laminated stalagmite from the northern Yucatán Peninsula contains mud layers from 256 cave flooding events over 2240 years. This new conservative proxy for paleotempestology recorded cave flooding events with a recurrence interval of 8.3 years during the twentieth century, with the greatest frequency during the twentieth century and the least frequent during the seventeenth century. Tropical cyclone (TC) events are unlikely to flood the cave during drought when the water table is depressed. Applying TC masking to the Chaac paleorainfall reconstruction suggests that the severity of the Maya "megadroughts" was underestimated. Without a high-resolution radiometric geochronology of individual local TC events, speleothem isotope records cannot resolve whether the Terminal Classic Period in the northern Maya Lowlands was punctuated by several brief drought breaks with normal TCs, or whether the region was very dry and peppered by unusually severe and frequent hurricane seasons.

1. Introduction

Tropical cyclones (TCs), including tropical depressions, tropical storms, and hurricanes (also known as typhoons and cyclones) [*Neumann et al.*, 1993], are devastating and climate-sensitive natural hazards that affect communities directly through storm surges, wind damage, mass movement, rainfall, and inland flooding [e.g., *Pielke et al.*, 2008; *Mendelsohn et al.*, 2012; *Prat and Nelson*, 2013; *Wallace et al.*, 2014]. Major TCs also cause extended ecological disturbance through agricultural and forest damage, enhancing the risk of subsequent wildfires and pest outbreaks [*Whigham et al.*, 1991; *Liu et al.*, 2008; *Lugo*, 2008; *Boucher*, 1990; *Torres*, 1992]. TCs can also replenish water supplies and break droughts [*Sugg*, 1968; *Lam et al.*, 2012; *Kam et al.*, 2013; *Maxwell et al.*, 2013]. Predicting the consequences of the present climate warming trend for future TC activity is an area of active research for which paleotempestology can provide essential data about the association between TC activity in different locations and past episodes of climate change [*Frappier et al.*, 2007a]. The ancient lowland Maya endured many TC events; indeed, *Hurakan*, one of their creator gods, gave the hurricane its name. Yet any written works in which Maya scholars may have recorded the timing of storm strikes were destroyed, and so paleotempestology in the Yucatán is key to illuminating the full range of TC-climate interactions in this region. Today, hurricanes strike the Yucatán Peninsula frequently [*Knapp et al.*, 2010], and its climate has been extensively studied in part to understand the environmental context of the rise and decline of the Classic Maya civilization [*Hodell et al.*, 1995; *Haug et al.*, 2001; *Aimers and Hodell*, 2011; *Luzzadder-Beach et al.*, 2012; *Kennett et al.*, 2012]. Many paleoclimate records from the northern Yucatán show the most prolonged, intensive drought of the late Holocene occurred during the Terminal Classic Period (TCP) from ~800 to 950 Common Era (C.E.) [*Hodell et al.*, 2005; *Medina-Elizalde et al.*, 2010]. Drought in the Yucatán has been attributed to causes including shifts in the intertropical convergence zone [*Haug et al.*, 2003], Bermuda High and Atlantic easterly waves [*Hastenrath*, 1984], some El Niño events [*Giddings and Soto*, 2003], and solar activity [*Hodell et al.*, 2001].

1.1. Paleotempestology Potential of Mud Deposits in Speleothems From Cave Flooding Events

The cave-ridden Yucatán platform has diverse potential sites for paleotempestology. In the tropics and subtropics, some of the most extreme rainfall events are TCs, able to deliver a large amount of isotopically distinct water over a large area in a few days, which may be recorded by growing speleothems [*Frappier et al.*, 2007b]. TCs often raise the groundwater level, which can take months to relax to ambient levels [*Escolero et al.*, 2007]. Stalagmites have the potential to yield paleoclimate proxy records with precise chronologies, but work in the northern Yucatán has been complicated by frequent flooding events in many of the mostly low-lying cenotes, or caves intersecting the groundwater table. Speleothem studies generally avoid cave sites and rooms that flood periodically [*Hill and Forti*, 1997], because the formations may be abraded/corroded, and Th-bearing mud deposits incorporated into the calcite structure impede the potential for precise U/Th dating [*Schwarcz and Latham*, 1989]. If dating hurdles can be overcome, muddy stalagmites from various locations and elevations within the cave may have differing sensitivity as flood recorders, complicating replication efforts [*Dorale and Liu*, 2009]. The few studies that have worked with these settings illustrated the potential for muddy stalagmites to record paleohydrological extremes, particularly in caves with useful hydrological flooding characteristics [*Dorale et al.*, 2005; *Knight et al.*, 2006; *Jaillet et al.*, 2006; *Dasgupta et al.*, 2010]. TC-induced cave flooding events have been documented. For example, Hurricane Camille in 1969 caused over 3 m of flooding in a Virginia cave after the area received 63–71 cm of rainfall in 8 h [*Doehring and Vierbuchen*, 1971], and mud layers in stalagmites deposited by TCs have been reported for separate cave systems [*Denniston et al.*, 2011; *Pyburn*, 2009].

Local residents in the Ring of Cenotes report that TCs cause cenote flooding, often lasting many days (Brown et al., personal communication, 18 and 27 July 2007). We observed the effects of cave flooding events following TCs: mud drapes on surfaces including speleothems, water level marks on walls, and clean, bright white stalagmite tips highlighting the locations of active drips. After floodwaters recede below the level of the stalagmite growth surfaces, active drip impacts and dripwater flow evidently work to clean most flood deposits off the tops of the stalagmites below. Any residual flood debris on a stalagmite is ultimately covered by subsequent mineral deposits, preserving a stratigraphic marker of the flood event within the structure of the growing stalagmite.

Sensitivity to recording mud layers deposited by cave flooding events varies both between and within caves. Caves have site-specific hydrological characteristics that control their propensity to flood in a given storm event, principally storm water storage capacity and drainage rate. Thus, for the same storm, some sensitive caves may flood while other insensitive caves nearby will not. It has been long recognized that caves that are excessively sensitive to flooding can inhibit speleothem formation, generate frequent erosional unconformities, and/or deposit mud layers too closely spaced to develop an accurate geochronology [*Schwarcz and Latham*, 1989] rendering these formations of poor utility for paleoclimatology. In some low-lying regions, many caves flood when the regional groundwater table rises rapidly; elsewhere isolated caves or localized sections may flood only above a drainage restriction. Within a cave, the elevation of stalagmites above the ambient water table is a key factor in the sensitivity of individual speleothems. Low-elevation stalagmites often contain a more complete record of flooding events and a correspondingly greater challenge for U/Th dating, whereas elevated stalagmites have a higher flooding threshold that makes them better suited for both U/Th dating and recording only the most extreme local recharge events. Within a given stalagmite, cave flooding episodes can also differ over time, depending on the amount and rate of rainfall, duration of flooding above the stalagmite surface, amount of debris and geochemistry of the floodwaters, preexisting stalagmite surface geometry, and preexisting groundwater level. Given this diversity of sensitivity, the use of muddy stalagmites to record past cave flooding events can provide a conservative, minimal record of extreme precipitation and, in selected cases, TC activity. Furthermore, the different patterns of change observed for high-probability weak TCs compared to more rare catastrophic events [e.g., *Elsner et al.*, 2008; *Holland and Bruyére*, 2014] must be expected to generate different records of storm activity in stalagmites with different flooding thresholds. Although these complexities remain to be fully quantified, we present the first record of TC-induced cave flooding events from a muddy stalagmite, CH-1. This stalagmite contains modern mud layers that were calibrated to the historical record of local TC events. The resulting long-term chronology of cave flooding events from ~232 before the Common Era (B.C.E.) to 2007 C.E. provides a conservative, minimum record of annual TC activity in the region.

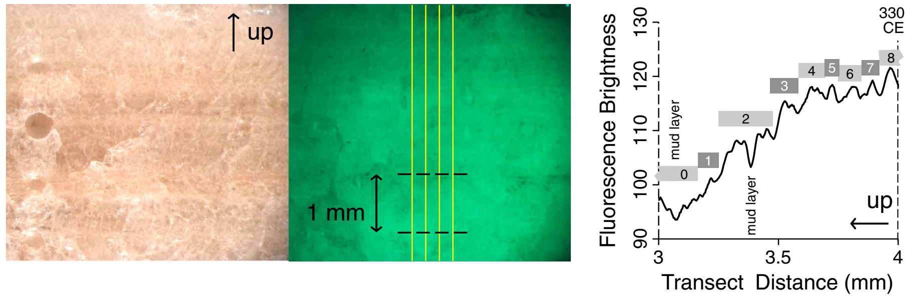

Figure 1. An example of bright-dark laminae and mud layers in CH1, from paired photomicrographs in plain and fluorescent light. Fluorescence intensity varies on scales from centimeter to submicron, and bright-dark band pairs occur annually. Locations of fluorescence brightness transects are shown as yellow lines. A fluorescence brightness plot for a 1 mm section (between dashed lines) shows both fluorescent intensity cycles interpreted as annual (labeled as layer counts). Some layers contain smaller-amplitude subseasonal fluorescent oscillations (e.g., layers 2–4). The locations of two mud layers are shown, each embedded within a layer. Many mud layers are discontinuous across the center of the stalagmite, as shown here. Although the mud layers are not readily apparent in the plain light photomicrograph, they are evident in plain light near the flanks of the speleothem at the stratigraphic level shown and in some cases also as layers of lower fluorescence in the center of the stalagmite, as in layer 2.

2. Methods

2.1. Study Site and Stalagmite Sampling

In July 2007, stalagmite CH-1 was collected from Cenote Chaltun Ha (20.46 latitude, −89.17 longitude, 35 m elevation), Huhí, Yucatán, Mexico, using a modified selection approach from *Frappier* [2007] (supporting information). The region's strong wet-dry seasonality facilitates annually layered speleothem deposits. The 16.9 cm tall stalagmite CH-1 was growing on a curtain wall, 4.4 m above the cenote water table at the time of collection, about 10 m below the surface (supporting information). The fragile calcite stalagmite was embedded in epoxy, sectioned vertically into slabs, and the central axis was polished for stratigraphic description and photomicrography in plain and fluorescent light.

2.2. Stratigraphy and Age Model

In plain light, couplets of dark compact calcite (DCC) and bright white palisade calcite (WPC) [*Kendall and Broughton*, 1978] coincide with oscillations in fluorescence intensity [*Baker et al.*, 1993]. The DCC laminae correspond to brighter fluorescence (wet season May–October), and the WPC laminae are characterized by weaker fluorescence (dry season November–April). The CH-1 age model was developed using fluorescence layer counting combined with standard U/Th mass spectrometric and ^{210}Pb α-counting dating techniques [*Edwards et al.*, 1987; *Baskaran and Iliffe*, 1993] (supporting information). The radiometrically determined growth rates for two sections were the same, within error, as the growth rates for those sections as determined by layer counting.

A series of overlapping photomicrographs of the polished surface of CH-1 were collected at 6X magnification using a CM-2 (Carpenter Microsystems) epifluorescence microscopy module using a broadband fluorescence excitation lamp with a Chroma 49000 series cyan fluorescent protein (CFP) filter. The pixel scale was calibrated using a micrometer. Calcite fluorescence intensity in CH-1 varies on centimeter to submillimeter scales, but mud layers are not fluorescent. Using Image J64 software, four gray scale 1-pixel transects were drawn on each epi-fluorescence photomicrograph perpendicular to the laminae in the center of the growth axis of CH-1, and parallel to the growth axis (Figure 1). The transects were stacked, and a three-point (3-pixel) running mean was then applied to remove high-frequency noise. The resulting brightness value series was plotted as a function of depth below the growth surface, revealing cycles of grayscale brightness that reflect fluorescence intensity (Figure 1). Each bright/dark laminae couplet (cycle of variation in fluorescence brightness) was assumed to represent one hydrological year, and the brightness cycles were manually counted and measured. For sections with a large trend in gray scale values, brightness transects were detrended before counting layers. Asymmetrical double peaks in fluorescence brightness were noted for many layers (discussed in the supporting information). In such cases, because layers visible in plain light were found to correspond to the more extreme local fluorescence intensity variations, the

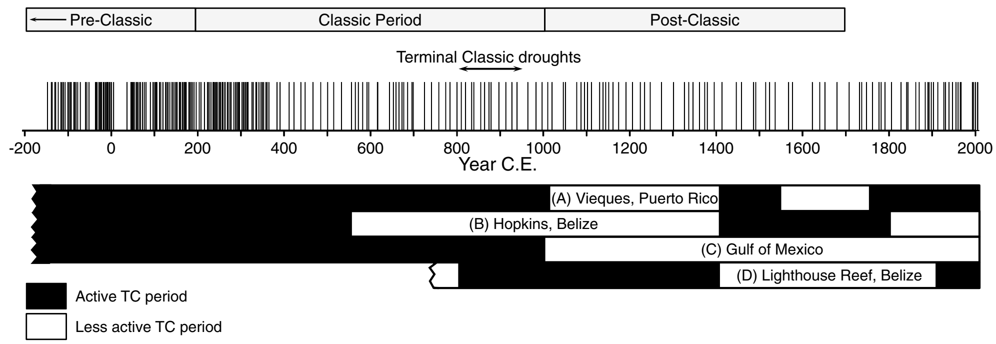

Figure 2. CH-1 record of 256 cave flooding events (232 B.C.E. to 2007 C.E.). Mud layer frequency decreased by half at ~365 C.E., which coincides with a sharp decrease in the vertical growth rate, suggesting a sudden reduction in cave flooding sensitivity. Mud layer frequency prior to 365 C.E. thus is not directly comparable to the subsequent period. TC records from CH-1 and other regional paleotempestology proxies show similar temporal patterns of stormy TC activity (black bars) and less active halcyon periods (white bars), from A [*Donnelly and Woodruff*, 2007], B [*McCloskey and Liu*, 2013], C [*Liu*, 2004], and D [*Denommee et al.*, 2014].

larger fluorescence oscillations were used to identify annual layers. We assume that the top layer is part of the 2007 hydrological year (i.e., the year collected) and that there are no significant hiatuses, large subannual couplets, or missing layers. A calendar year was assigned to each annual layer thus identified, counting backward from the sample collection date in 2007. The accuracy of dating stalagmite annual layers using band-counted ages has been estimated at ±10% [*Shen et al.*, 2013]. For the top section of CH-1, independent counts of 100 layers by two of us were different by ±2%. High-resolution absolute dating cannot be achieved in CH-1 due to the frequency of mud layers containing high Th concentrations. Layer counting back from the date of collection resulted in a high-resolution chronology for CH-1. Each opaque mud layer was assigned to the counted calendar year of the band pair in which it was embedded (Figure 1 and supporting information).

2.3. Historical Proxy Sensitivity Analysis

For the period of record when nearby TCs have been recorded (1851–2007), we compared the years with and without mud layers to historical storms that tracked within a 370 km radius using International Best Track Archive for Climate Stewardship (IBTrACS) Data accessed from NOAA's Coastal Services Center Database (http://csc.noaa.gov/hurricanes/). The Atlantic TC record is thought to be complete since the satellite observation era (post-1970), but data quality in terms of storm counts and intensity estimates are lower earlier in the record, and some storms are likely missing from the record particularly for the 1800s [e.g., *Landsea and Franklin*, 2013; *Vecchi and Knutson*, 2011]. We counted the number of storms per year within the database's maximum storm track radius, as well as maximum local intensities and minimum track-to-cave distances for each storm. We assessed the accuracy of the proposed mud layer proxy for recording storm and nonstorm years, as well as the relative abundance of false positives (mud layers in nonstorm years) and false negatives (no mud layers in storm years). The resulting 2240 year mud layer record is interpreted to represent local TC activity.

3. Results

CH-1 is finely laminated throughout, with 2240 visible couplets corresponding to the local seasonal hydrological cycle, and 256 opaque mud layers embedded in the calcite. In cross section, some mud layers are continuous across the stalagmite growth surface; others are clearly visible along the flanks but pinch out near the central growth axis (supporting information). The CH-1 chronology of mud layer frequency (Figure 2) shows the resulting chronology of cave flooding events with variations on interannual to millennial scales. Historical era calibration provides essential context for the interpretation of the CH-1 record.

3.1. Historical Sensitivity Analysis of the Mud Layer Proxy for TC Activity

During the 55 year period 1951–2006, the northern Yucatán and Quintana Roo states were struck by 18 landfalling hurricanes, a recurrence interval of 3.3 years. CH-1 recorded eight mud layers during this period. Over the entire 155 year IBTrACS historical TC record since 1852 [*Knapp et al.*, 2010], there were

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45 years without TCs, and 195 TCs (e.g. Tropical Depression to Category 5 hurricane) tracked within 370 km of the cave site. With one exception, the 20 mud layers in CH-1 that postdate 1852 correspond to a year in which one or more known TCs tracked within the 370 km capture radius of the cave site. One mud layer was deposited in 1884 when no local TCs are evident in the IBTrACS data set, but because late nineteenth century TC records are not complete, we cannot be confident that this mud layer represents a false positive proxy signal. Many historical mud layers occurred in years with multiple local storm strikes (e.g., 2005, with three storms), but in no case were multiple mud layers observed within a single annual layer in CH-1. Since 1852, the longest spans were 5 years between TCs, 11 years between hurricanes (Category 1–5), and 20 years between major hurricanes (Category 3–5). During the same interval, the longest span between mud layers in CH-1 was 25 years, and the most frequent span was 8 years. Because the maximum number of mud layers per annual layer is one, we infer that the final cave flooding event of the hurricane season of sufficient magnitude to submerge CH-1 was the primary source of the embedded mud layer and that the mud layer proxy for cave flooding events is limited to the annual scale. The historical calibration period revealed no definitive false positives, further suggesting that mud layers are only emplaced by TC-induced cave flooding events.

CH-1 thus provides a minimal, conservative record of years with substantial TC rain in the northern Yucatán, which caused Cenote Chaltun Ha to flood above the stalagmite level of at least 4.5 m above the ambient water table at the time of collection. Despite this success, the historical calibration detected many false negatives, showing that CH-1 does not provide a complete record of annual TC activity for this site. Many historical TCs that affected the cave site are not represented by mud layers in CH-1. The stalagmite records only 19% of the locally active TC years during the twentieth century. Yet because CH-1 grew at an elevated location, it is not surprising that in many years, TC rainfall was insufficient to raise the water table above the mud layer recording threshold. Most locally active storm years that lack a mud layer are cases in which the storms were weak (e.g., tropical depression to tropical storm intensity), had a small or asymmetrical rain shield, were fast moving, tracked far from the cave site, and/or produced low precipitation amounts near the cave site (e.g., Hurricane Allen in 1980).

One important exception to this explanation for the sensitivity of the mud layer proxy for TCs is the case of Hurricane Gilbert, a category 5 hurricane that devastated the northern Yucatán in 1988 when it passed within 75 km of the cave site (D. M. Roth, Tropical Cyclone Rainfall Data: Hurricane Gilbert—14–21 September 1988, Hydrometeorological Prediction Center, http://www.hpc.ncep.noaa.gov/tropical/rain/gilbert1988.html, accessed 10 August 2012). The lack of a cave flooding event recorded in CH-1 in that year can be explained by the effect of regional climate anomalies prior to the storm event. The northern Yucatán experienced one of the most severe droughts of the twentieth century during 1986–1988 [*Giddings and Soto*, 2003; *Mendoza et al.*, 2007]. Evidently, this exceptionally severe and prolonged dry climate anomaly lowered the regional water table to such an extent that the 130–330 mm deluge of rain from Hurricane Gilbert was unable to raise the groundwater level in this cenote above the level of CH-1. In Merida, the water level in a groundwater well rose about 2 m immediately following Hurricane Gilbert, and overland flow was reported in some locations [*Marín et al.*, 1990]. These observations lead us to conclude that the mud layer proxy record in CH-1 is more sensitive to recording storm years that occur during and following wet periods when the ambient water table is elevated, and correspondingly less sensitive to recording active storm years that occur during and following dry periods when the ambient water table is depressed. Given that instrumental era droughts in Yucatán are less frequent but more extreme than wet anomalies [*Giddings and Soto*, 2003], we expect that the mud layer proxy for TC rainfall in this region will be more liable to under-record cave flooding events during dry periods than to over-record during wet periods. Further work will be required to quantify the extent to which local rainfall trends and TC activity each contribute to mud layer emplacement.

CH-1 shows a stepwise decrease in mud layer frequency after about 365 C.E., coincident with a sudden decrease in the stalagmite's annual layer thickness from 0.16 $mm \cdot yr^{-1}$ to 0.044 $mm \cdot yr^{-1}$. The cave flooded twice as frequently when the stalagmite was growing more rapidly, with 21.6 mud layers per century before 365 C.E. Together, these changes may indicate prevailing wetter conditions and a higher water table from about 200 B.C.E. until the Maya Early Classic expansion. The annual growth rate in CH-1 also stabilized at the same time, indicating that the CH-1 record prior to ~365 C.E. is not directly comparable to the more recent growth interval.

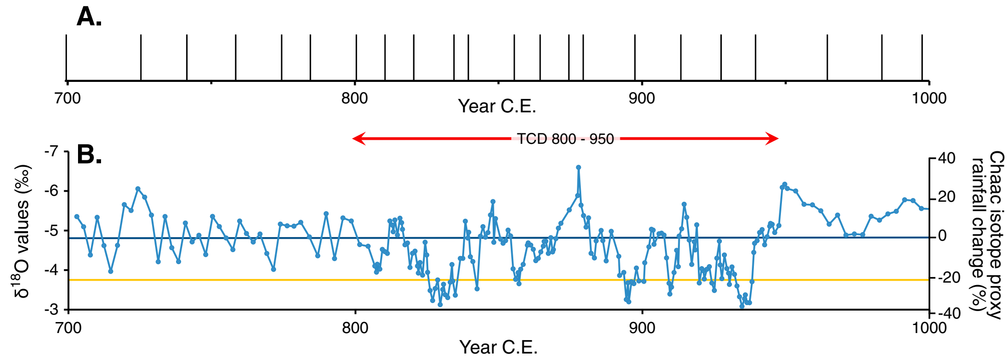

Figure 3. (top) Cave flooding events from CH-1 in comparison to the (bottom) Chaac stable isotope-based rainfall reconstruction [*Medina-Elizalde and Rohling*, 2012] during the Maya Terminal Classic Period (TCP). Cave flooding events were common during this anomalously dry period. The TC masking hypothesis [*Frappier*, 2013] suggests that the TC droughts (identified as times when Chaac $\delta^{18}O$ values are below the yellow line) were more intense and perhaps more persistent than shown by the Chaac rainfall proxy reconstruction (left abscissa). Together, these records show that TCP Maya communities in the northern Yucatán experienced an unusual combination of hydroclimatic extremes including persistent drought and frequent instances of extraordinary recharge from TC events, with large-amplitude variations in rainfall and groundwater level.

Since 365 C.E., an average of 7.5 mud layers per century were deposited, and the mean climatological frequency (# storms/30 years) was 2.3. The highest centennial frequency of mud layers ($n = 12$) occurred during the twentieth century (supporting information). Cave flooding was also frequent ($n = 10$) during the late seventh, ninth, and nineteenth centuries. CH-1 was inundated rarely ($n = 4$ to 5) during the thirteenth, and fifteenth–seventeenth centuries; this latter period coincides with frequent U.S. East Coast TC strikes [*Donnelly et al.*, 2011].

4. Discussion

Historical mud layers in CH-1 were deposited by cave flooding events associated with years of substantial local TC rainfall. The occurrence of mud layers throughout CH-1 shows that cave flooding events have been commonplace for the last two millennia. Although the CH-1 mud layer record of past hurricane seasons is incomplete, it provides a conservative and consistent record of TC activity from ~365 to 2007 C.E. During the twentieth century, cave flooding events occurred frequently (recurrence interval (RI) = 8.3 years). Because paleoclimate reconstructions from lakes and stalagmites in the Northern Maya Lowlands show a series of prolonged and intensive drought episodes lasting 3–18 years during 150 year Maya Terminal Classic Period (TCP) [*Medina-Elizalde et al.*, 2010; *Medina-Elizalde and Rohling*, 2012; *Hodell et al.*, 2005; *Hodell et al.*, 1995; *Curtis et al.*, 1996], we expected that the sensitivity of CH-1 to mud layer deposition from TC events would have been lower due to the prevailing drought conditions. If so, the deeper water table would result in fewer mud layers during periods of extended drought. Furthermore, low rainfall during the TCP has been blamed on a lack of TCs [*Medina-Elizalde and Rohling*, 2012]. Contrary to expectation, CH-1 recorded 13 cave flooding events during the TCP (Figure 3). This corresponds to an RI of 11.6 years, similar to the eighteenth century when regional droughts were less frequent [*Mendoza et al.*, 2007]. The record suggests that TC activity in the Northern Maya Lowlands during the TCP was unlikely to have been significantly lower than during the twentieth century, contrary to the interpretation by *Medina-Elizalde and Rohling* [2012]. Documented cave flooding events suggest a highly variable water table elevation during the TCP "megadroughts." Local records of both TCs and moderate to severe drought during the TCP can be explained by one of the following possibilities:

1. The Cenote Chaltun Ha system maintained a consistent propensity to flood in response to TCs despite the drought-induced reduction in the regional water table during the TCP. This would require the existence of a phreatic hydrological drainage blockage that restricts storm water flow only when the water table is low. In this case, the mud layers do not indicate changes in either TC activity or the level of the regional water table during the TCP.

2. The mud layers were deposited during those few active hurricane seasons that occurred after some period of wet anomalies returned the water table to near-ambient levels. Under this scenario, the mud layers indicate that breaks in the prevailing TCP drought were accompanied by substantial TC rainfall.
3. Severe hurricane seasons with extreme rainfall and/or multiple storm strikes are capable of raising the water table from the lower drought level over the ambient threshold level of +4.5 m. This explanation suggests that TCP mud layers indicate years with severe local TC activity.

We discount the first explanation; not only is this mud layer record of storm activity consistent with independent paleotempest data from the region [*Donnelly and Woodruff*, 2007; *McCloskey and Liu*, 2013; *Denommee et al.*, 2014] (supporting information), but there is also no evidence for such a hypothetical drainage obstruction or any diagnostic variations in sensitivity at the onset or cessation of the “megadroughts” period. As for the second explanation, several breaks in the prevailing TCP drought were inferred from nearby precipitation proxy reconstructions from caves and lakes [*Medina-Elizalde et al.*, 2010; *Hodell et al.*, 2005]. A recent interpretation of the nearby Chaac stalagmite stable isotope record suggested that TCP rainfall was reduced during a series of eight droughts lasting 3–18 years because of a lack of TC activity [*Medina-Elizalde and Rohling*, 2012]. In contrast, the TCP mud layers in CH-1 provide evidence that TCs were active in the northern Yucatán during this period, with major cave-flooding events spaced about 4–18 years apart. The CH-1 mud layer record likely under-records years with TC rain during the TCP, as it does during the modern period. Therefore, we infer that TC events were common in the northern Yucatán during the TCP.

Given that TCs likely affected the northern Yucatán frequently during the TCP, TC masking [*Frappier*, 2013] likely affects the Chaac stable isotope-based rainfall reconstruction, because TC rainwater has characteristically low oxygen isotope ratios that can lower the oxygen isotope ratio of speleothem calcite. Isotopically light rain can extend for tens to hundreds of kilometers from the eye of the storm [*Lawrence and Gedzelman*, 1996]. In the northern Yucatán, about 10% of rainfall is TC derived on average, with the annual contribution from TCs ranging from zero to over 50% [*Escolero et al.*, 2007]. No Global Network of Isotopes in Precipitation stations are located near the cave site, and the modeled amount effect relationships [e.g., *Bowen*, 2014] do not account for TC rainfall’s anomalous stable isotope composition. This unaccounted-for isotope effect can lead to precipitation reconstruction errors in this region on the order of 15–20% on average, and well over 50% for very active TC years [*Frappier*, 2013]. The regional amount effect for speleothems must be modulated by TC rainfall amount. Frequent TCs can thus lead to underestimates of the severity and duration of drought conditions and/or overestimates of breaks in prevailing drought conditions. Indeed, breaks in the drought inferred from the Chaac oxygen isotope record may have been milder and/or more brief than the interpretation would suggest. Further work to test the TC masking hypothesis is underway.

Due to the persistent drought conditions during the TCP, some severe TC years were likely not recorded by CH-1, analogous to the 1988 Hurricane Gilbert example. In this context, the 13 mud layers recorded during the TCP may instead represent a series of extremely active TC years with high rainfall and/or multiple storm strikes, analogous to the 2005 season in which four TCs including two major hurricanes affected the cave site (Category 4 Hurricane Emily and Category 5 Hurricane Wilma; rainfall as high as 170 cm in 42 h at Isla Mujeres, more than the average annual rainfall) [*Pasch et al.*, 2006]. In this scenario, TCs would be capable of flooding CH-1 despite the drought-induced reduction in the water table. The CH-1 record suggests that in some years during the TCP, TC activity in the northern Yucatán Peninsula was likely considerably greater than anything experienced in modern times. Although TCs can function as drought-breakers [*Maxwell et al.*, 2013], history shows that agriculturally important drought in the northern Yucatán can persist following major TCs, such as following Hurricane Gilbert [*Clifton*, 1991]. The CH-1 record illuminates TCs as another potentially important factor in the complex story of the decline of the Maya high culture [*Dunning et al.*, 2012]. Indeed, our results are consistent with the interpretation that the TCP “megadroughts” were punctuated by years with unusually severe hurricane activity, including perhaps multiple storm strikes or extremely heavy rainfall within individual hurricane seasons, and linked to associated subsequent hazards including wildfires [*Ciesla*, 2011; *Lopez-Portillo et al.*, 1990; *Sánchez-Sánchez and Islebe*, 1999] and insect pest outbreaks [*Clifton*, 1991].

5. Conclusions

This study presents a new annually resolved proxy for paleotempestology, based on mud layers in stalagmites from caves that flood in response to the extreme rainfall and extraordinary recharge of TCs.

The sensitivity of the mud layer paleotempestology proxy varies between cave sites, between stalagmites, and over time as the groundwater level responds to persistent climatic anomalies. Nevertheless, each historical mud layer in CH-1 provides a conservative record of years when documented TC events affected the area surrounding the cave site. Additional mud layer records and independent paleotempest proxies from the Caribbean and Central America are needed to develop a more complete chronology of past regional TC activity [*Frappier et al.*, 2007a]. Stalagmite sampling for mud layer paleotempestology should focus on selecting speleothems moderately sensitive to submergence during extreme rainfall events, to optimize radiometric dating potential during occasional flood-free periods. Local studies of karst water level fluctuations in response to water balance anomalies would provide additional context for quantifying the sensitivity of this mud layer proxy to background climate. Ultimately, replication need not be carried out within a single cave system, and other caves in the region should provide stalagmites with a range of flooding thresholds.

Evidence of locally active TCs during the ninth and tenth centuries C.E. (cf. this study; *Denommee et al.* [2014]) suggests that the TCP droughts were not only more severe than recent paleorainfall estimates from the Chaac stable isotope record but also not likely to have been caused by a lack of hurricanes [*Medina-Elizalde and Rohling*, 2012]. To avoid errors in quantifying paleoprecipitation in TC-prone regions using stable isotopes in precipitation, TC masking must be taken into account [*Frappier*, 2013]. Fruitful approaches might include rainfall proxy calibrations explicitly accounting for local tropical cyclone rain effects on stalagmite oxygen isotope values [e.g., *Haig et al*., 2014], or a nearby independent proxy record of seasonal or individual tropical cyclone events [e.g., *Frappier et al*., 2007b; *Miller et al*., 2006; *Nott et al*., 2007].

The decline of the Classic Maya civilization was a complex process involving both cultural and climatic factors [e.g., *Kennett et al.*, 2012]. The northern lowland Maya likely experienced a multiplicity of climatic hazards throughout their occupation of the region and were demonstrably accustomed to hazards including seasonal drought [*Scarborough et al.*, 2012], TCs [*Dunning and Houston*, 2011], and wildfires [*Nigh and Diemont*, 2013]. Combinations of interacting disturbances that are unusually severe, widespread, persistent, or clustered in time are capable of triggering sudden shifts in ecosystems to alternative states [*Paine et al.*, 1998]. Particularly during the TCP, new evidence shows that the combination of recurrent decades of prolonged and severe drought episodes with frequently active and severe hurricane seasons, and by inference accompanied by related fires and pest outbreaks amplifying agricultural and wildland resource losses is unparalleled in the history of human occupation of this region. The combined severity, duration, and recurrence of multiple climatic hazards during the TCP revealed by multiple high-resolution proxy records from the region suggests that the combination of extreme events may have had a comparatively devastating impact on socioeconomic development across the region, with individual polities affected most during different years of the TCP. Paleo-hazard studies provide invaluable documentation of worst-case scenarios that have already played out [*Frappier et al.*, 2007a]. As the ongoing rapid climate change trend increases the probability of some climatic extremes, we can expect that multiple converging hazards will amplify vulnerabilities and losses in some localities [*Intergovernmental Panel on Climate Change*, 2012]. A full assessment of the vulnerability of communities to climatic extremes will benefit from studies aimed at quantifying the risk of overlapping and co-occurring natural hazards by interrogating geological archives. The implications of the CH-1 record for Maya archaeology and the human impacts of multiple climatic extremes place a new emphasis on testing this hypothesis by further developing high-resolution chronologies of multiple hazards in this and other vulnerable regions throughout the late Holocene, including drought, flooding, TC activity, and wildfires. Locally, more calendar year-dated proxy records are necessary for effective comparison to archaeohistorical timelines, which may more clearly illuminate the changing environmental context during the rise and decline of the Maya high culture.

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