Impacts of Climate Change on the Collapse of Lowland Maya Civilization

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Abstract

Paleoclimatologists have discovered abundant evidence that droughts coincided with collapse of the Lowland Classic Maya civilization, and some argue that climate change contributed to societal disintegration. Many archaeologists, however, maintain that drought cannot explain the timing or complex nature of societal changes at the end of the Classic Period, between the eighth and eleventh centuries CE. This review presents a compilation of climate proxy data indicating that droughts in the ninth to eleventh century were the most severe and frequent in Maya prehistory. Comparison with recent archaeological evidence, however, indicates an earlier beginning for complex economic and political processes that led to the disintegration of states in the southern region of the Maya lowlands that precedes major droughts. Nonetheless, drought clearly contributed to the unusual severity of the Classic Maya collapse, and helped to inhibit the type of recovery seen in earlier periods of Maya prehistory. In the drier northern Maya Lowlands, a later political collapse at ca. 1000 CE appears to be related to ongoing extreme drought. Future interdisciplinary research should use more refined climatological and archaeological data to examine the relationship between climate and social processes throughout the entirety of Maya prehistory.

1. INTRODUCTION

Over the past 20 years, paleoclimatologists and archaeologists have devoted substantial effort to exploring how past climate influenced ancient societies (e.g., Sandweiss et al. 1999, McIntosh et al. 2000, deMenocal 2001, Weiss & Bradley 2001, Giosan et al. 2013). This research topic has gained increasing attention, in part because of the realization that the Holocene Epoch (i.e., the past 11,700 years of Earth history, during which human civilizations first arose), which was previously characterized as a period of climatic stability, was in fact marked by substantial climate variability (Alley et al. 1997, Bond et al. 1997, deMenocal et al. 2000, Mayewski et al. 2004).

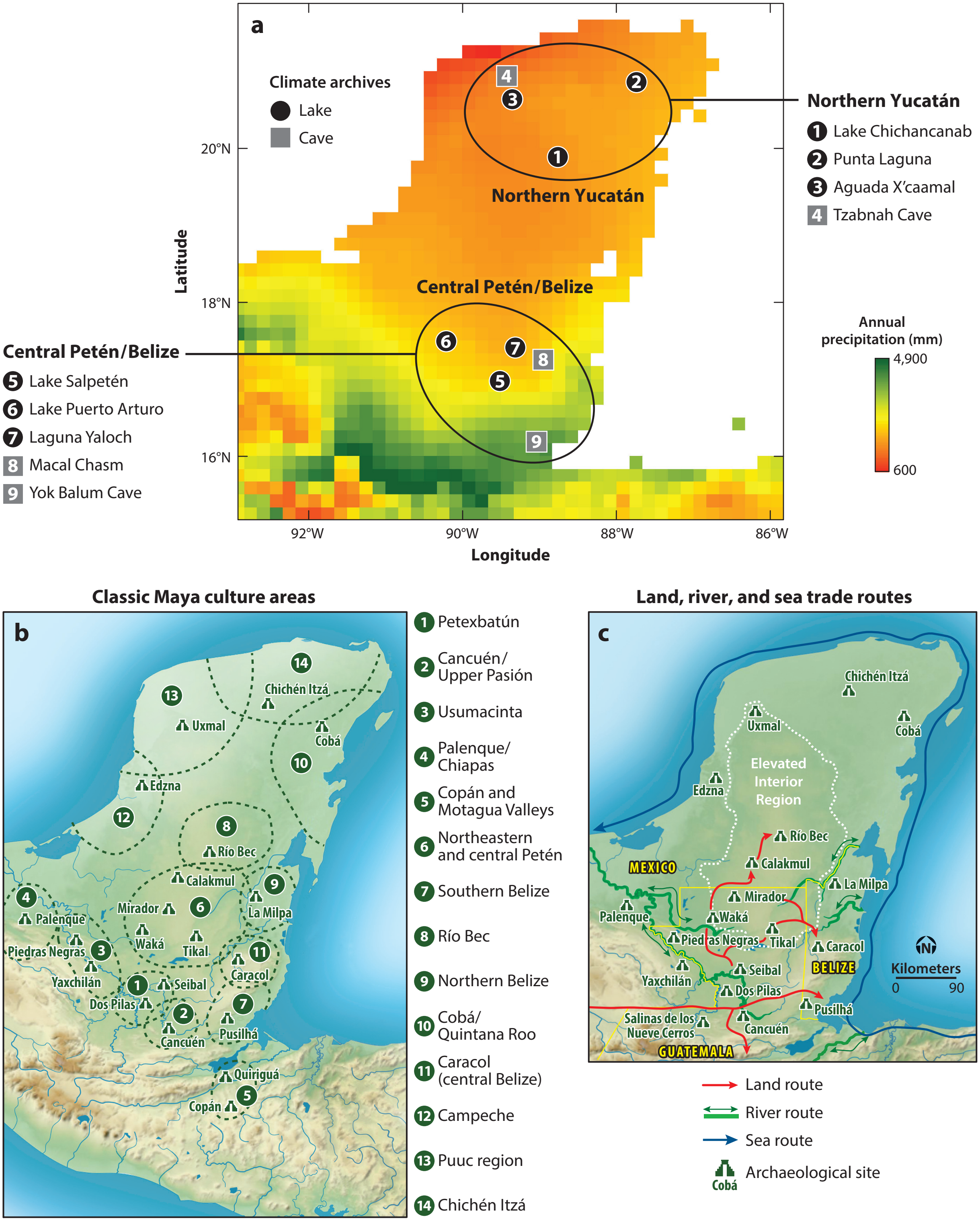
As our understanding of Holocene climate variability evolved, it became apparent that many periods of past climate change coincided with archaeological and/or historical evidence for cultural change, including societal collapse (e.g., Hodell et al. 1995, Binford et al. 1997, Cullen et al. 2000, Staubwasser et al. 2003, Zhang et al. 2008, Buckley et al. 2010, Lachniet et al. 2012, McCormick et al. 2012). Interactions between climate and past societies provide a new perspective on human history, showing how climate change influenced the rise and decline of complex societies. The study of how climate impacted ancient societies also offers potential analogs for understanding societal vulnerabilities to predicted future climate changes and might provide insights into how humans can successfully adapt to climate change in the future.

The Lowland Classic Maya civilization of southeastern Mexico and northern Central America is often cited as an example of an ancient society affected by climate change (Gill 2000, deMenocal 2001, Haug et al. 2003, Diamond 2005). Empirical evidence for a temporal correlation between protracted, severe droughts and societal collapse in the ninth and tenth centuries of the Common Era (CE) was first identified over 20 years ago (Hodell et al. 1995). In the past two decades, additional evidence for these droughts has been inferred from multiple paleoclimate archives, including lake sediments, marine deposits, and cave stalagmites (Curtis et al. 1996; Hodell et al. 2001, 2005a; Rosenmeier et al. 2002a; Haug et al. 2003; Webster et al. 2007; Medina-Elizalde et al. 2010; Kennett et al. 2012; Wahl et al. 2014; Douglas et al. 2015b) (**Figure 1*a***).

Over the same period of time, however, archaeological research in the Maya region has increasingly emphasized the complex nature of societal change during the eighth to eleventh centuries CE and has led to reinterpretation of what has traditionally been called the Classic Maya collapse as the final expression of a protracted period of sociopolitical disintegration (Demarest et al. 2004, 2016; Fash et al. 2004; Iannone 2014). Archaeological evidence suggests particularly acute crises in the southern lowlands in the mid-eighth to early ninth centuries CE in the southern lowlands, and in the late tenth to eleventh centuries CE in the northern and western regions of the Yucatán Peninsula, specifically the cities in the Puuc region, as well as Chichén Itzá (**Figures 1*b*** and **2**). Many social scientists argue that the archaeological record is at odds with the inference for a simple, causal link between drought and societal collapse (Coombes & Barber 2005, McAnany & Yoffee 2009). Therefore, although the Classic Maya civilization is often invoked as a prime example of the link between climate change and societal disruption, the climate-society relationship remains incompletely understood, as well as controversial.

Figure 1

(*a*) Map of the Maya Lowlands showing the locations of proxy climate archives and the modern distribution of annual rainfall (New et al. 2002). (*b*) Some major culture areas of the Classic Maya civilization in the eighth to eleventh centuries CE. These are broad designations based on generally similar aspects of architecture, monuments, ceramics, material culture, geography, and/or ecology. (*c*) Area of the hydraulically challenged Elevated Interior Region of the northern Petén and central Yucatán Peninsula and major trade routes of the Classic Maya world (river routes are shown with green lines and land routes with red). Both the land and river routes collapsed into chaos and then fell from significant use between 743 and 810 CE, leaving the more efficient sea route, shown with a blue line, as the dominant channel of commerce from the ninth century CE until the Spanish Conquest.


a
Climate archives
Lake
Cave
Northern Yucatán
Central Petén/Belize
Northern Yucatán
1 Lake Chichancanab
2 Punta Laguna
3 Aguada X'caamal
4 Tzabnah Cave
Central Petén/Belize
5 Lake Salpetén
6 Lake Puerto Arturo
7 Laguna Yaloch
8 Macal Chasm
9 Yok Balum Cave
Annual precipitation (mm)
4,900
600
20°N
18°N
16°N
Latitude
92°W
90°W
88°W
86°W
Longitude
Classic Maya culture areas
b
Chichén Itzá
Uxmal
Cobá
Edzna
Río Bec
Calakmul
Mirador
Palenque
Piedras Negras
Waká
Tikal
La Milpa
Caracol
Yaxchilán
Seibal
Dos Pilas
Cancuén
Pusilhá
Quiriguá
Copán
1 Petexbatún
2 Cancuén/ Upper Pasión
3 Usumacinta
4 Palenque/ Chiapas
5 Copán and Motagua Valleys
6 Northeastern and central Petén
7 Southern Belize
8 Río Bec
9 Northern Belize
10 Cobá/ Quintana Roo
11 Caracol (central Belize)
12 Campeche
13 Puuc region
14 Chichén Itzá
Land, river, and sea trade routes
c
Chichén Itzá
Uxmal
Cobá
Elevated Interior Region
Edzna
Río Bec
MEXICO
Calakmul
La Milpa
Mirador
Palenque
Waká
Piedras Negras
Tikal
Caracol
Yaxchilán
Seibal
BELIZE
Dos Pilas
Pusilhá
Salinas de los Nueve Cerros
Cancuén
GUATEMALA
N
Kilometers
0
90
Land route
River route
Sea route
Archaeological site
Cobá

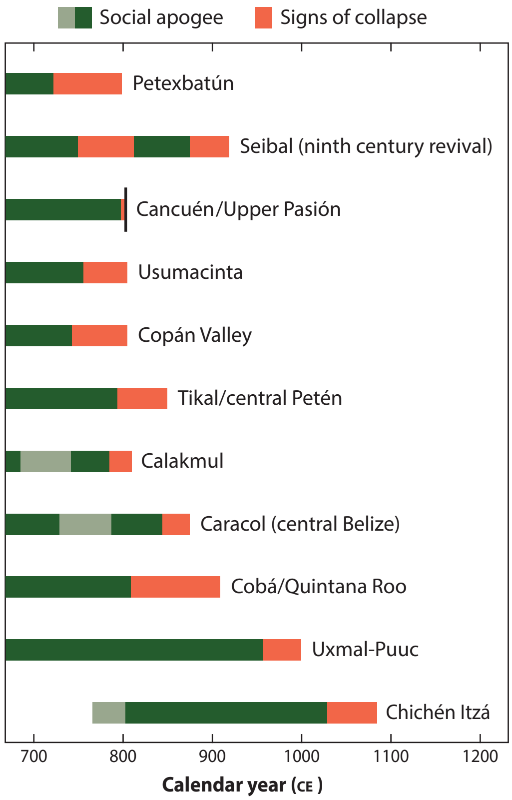


Figure 2

Broad, approximate timelines for the apogees (*dark green*) and periods indicating manifestations of collapse (intensive war, political disintegration, emigration, or a combination thereof) (*orange*) for some major Classic Maya sites or regions. Light green lines indicate periods of decline followed by subsequent recovery. The vertical black line indicates an abrupt conquest and depopulation.

Closer collaboration between paleoclimatologists, archaeologists, and historians could help clarify the relationship between climate variability and the history of the Maya civilization. The location of Lowland Maya civilization in the low-elevation Neotropics makes the human relationship with climate change particularly relevant to considerations of future climate change impacts. Many tropical regions, including southeastern Mexico and Central America, will be at a high risk for drought as a consequence of ongoing anthropogenic climate change (Christensen et al. 2007, Karmalkar et al. 2011, Lau & Kim 2015).

For this review, we begin with a brief introduction to the Lowland Maya civilization. We then summarize the late Holocene paleoclimate data from the Maya Lowlands, with the goal of producing a synthetic climate history for the region, and discuss the proposed causes for past droughts. Finally, we explore how this climate history can be integrated with Lowland Maya archaeology, with a focus on the end of the Classic Maya civilization.

2. THE COMPLEX NATURE AND HISTORY OF LOWLAND MAYA CIVILIZATION

Recent research in Maya archaeology has revealed great regional and temporal variability in all aspects of Lowland Maya civilization. Indeed, simply defining broad sociocultural subregions within the Maya Lowlands during the Classic Period (300–900 CE; see **Figure 1*b***) can prove contentious. The Lowland Maya shared a common culture, which is best known for its beautiful art and architecture displayed in spectacular stone temples, palaces, tombs, and monuments carved with hieroglyphic texts. The latter reveal great sophistication in mathematics, astronomical knowledge, and calendrics, related not to science, per se, but rather to astrology, prophecy, and the legitimation of royal power (Demarest 2004, Sharer & Traxler 2006, Houston & Inomata 2009).

Despite their cultural unity, the Lowland Classic Maya were not members of a monolithic political entity (Martin & Grube 2008, Foias 2013). Instead, Lowland Maya civilization consisted of numerous polities of different, and time-variable, scale and power. However, there are a number of important common features of Classic Maya polities, particularly in the southern lowlands (Sharer & Traxler 2006, Houston & Inomata 2009, Demarest 2015, Demarest et al. 2016). One shared structural feature of the Classic Maya political organization was the centrality of the *k'ujul ajaw*, or holy lords, who were both the political and religious leaders of their polities (Fields 1989, 2008; Iannone et al. 2016). These rulers were further supported by dynastic royal courts composed of family members, religious and administrative officers, and artisans (Inomata & Houston 2001a,b; Miller et al. 2004). Moreover, these royal courts and *k'ujul ajaw* often formed part of large regional entities—such as kingdoms—through a complicated network of alliances and wars (Martin & Grube 2008). In fact, the Lowland Maya developed a series of other royal titles to denote ranks of rulership both above and below that of the *k'ujul ajaw* (Houston & Stuart 1996, Jackson & Stuart 2001, Sharer & Traxler 2006). Yet these larger political formations and the titles that accompanied them were in a constant state of realignment.

As is typical of divine kingship systems based on political alliance, religious authority, and limited administrative institutions, the Maya states were very unstable (Demarest 1992, Marcus 1992, Martin & Grube 2008, Demarest et al. 2016, Iannone et al. 2016). Royal dynasties would expand and extend their influence over several other polities, subordinating them through a diverse set of strategies including marriage alliance, trade, and conquest (Canuto & Barrientos 2011, Canuto & Bell 2013). However, rivalry among members of these extended dynastic families resulted in competition in the form of rituals, architecture, and monuments that often led to the dissolution of larger regional systems and fomented warfare (Demarest 2006, Sharer & Traxler 2006, Martin & Grube 2008, Canuto & Barrientos 2011, Demarest et al. 2016). Because political alliances were based on interpersonal obligations they were typically short lived. As a result, throughout the Classic Period, the Lowland Maya engaged in a constant effort at political unification, and formed occasional political hegemonies that were regional in scope, but never achieved widespread political unification.

Ancient Maya economic structure included various forms of exchange and forms of a market economy (Feinman & Nicholas 2004, Scarborough & Clark 2007, McAnany 2010). Systems of exchange included a political economy controlled by elites who redistributed materials to their local communities (Pohl 1994, McKillop 2002) and a market economy in which goods were acquired based on individual needs and economic means (Braswell 2010, Masson & Freidel 2012). These systems of exchange likely provided some measure of risk management, but they were not comparable in scale, complexity, and resilience to the international large-scale market and commodity production and exchange systems that had developed centuries earlier in the highlands and Gulf Coast of Mexico (Sabloff & Andrews 1986; Masson & Freidel 2012; Demarest 2015, 2016).

Although the art, architecture, and monuments of the Lowland Maya states are their best known attributes, the truly impressive achievement of this civilization was to sustain cities and a population of several million people in a tropical forest environment (Culbert & Rice 1990). The ancient Lowland Maya developed a variety of agricultural techniques that were well adapted to the delicate fragile soils and ecological challenges of their environment, such as highly seasonal rainfall (Dunning & Beach 2011, Turner & Sabloff 2012). Many Maya states developed in the riverless karstic upland area of the central lowlands, referred to here as the Elevated Interior Region (EIR). In this region, the ancient Maya confronted the near absence of surface water by developing an infrastructure of small- and large-scale hydraulic storage and control systems that included reservoirs, catchment wells, canals, and dams, while erosion and leaching of soils were mitigated through terraces and check dams (Chase & Chase 1998, Dunning et al. 2002, Dunning & Beach 2011, Scarborough et al. 2012, Turner & Sabloff 2012).

Elevated Interior Region (EIR): an upland karst region of the Maya Lowlands, which contained many powerful Classic Maya states, and which is devoid of surface rivers and has an inaccessible water table

The success of the Maya subsistence system was not, as sometimes characterized (e.g., Demarest 2004), due to a discovery of a brilliant sustainable agricultural strategy that failed at the end of the Classic Period. Rather, the Maya created a mosaic of wetland and dry farming systems that were constantly challenged, maintained, renewed, or replaced by the ongoing efforts of individual households and farming communities as well as states, all of which sought to control the damaging impact of growing populations and resource extraction on soils and agronomy (Dunning et al. 2002, 2012; Lentz et al. 2014). Thus, it was most likely effective and continuous "environmental crisis management," rather than "sustainability," that characterized the development and maintenance of Maya polities (Demarest 2016).

The volatile history of the Lowland Maya states has been traditionally subdivided into three time intervals: (*a*) a Preclassic Period from about 1100 BCE to 250 CE, initially considered to be a developmental phase; (*b*) a Classic Period of perceived apogee from about 250–300 to about 800–900 CE; and (*c*) a Postclassic Period, once considered a decline, from circa 900–1000 CE to the time of the Spanish Conquest in the sixteenth century CE (Sharer & Traxler 2006). The past half-century of research has discredited the developmental characterizations of this simple chronological scheme, which was strongly influenced by the prevalence of monuments with dated inscriptions. We now know that major cities had already arisen by 300 BCE in the Preclassic Period (Hansen 2005). Furthermore, in the Postclassic Period, there was a change in political and economic systems that led to a great reduction in the investment in elite art and architecture, but which is no longer regarded as a general cultural decline (Demarest et al. 2004).

Note that our characterizations above emphasize relative terms (less, more, most, etc.), rather than the absolute presence/absence dichotomies that dominate much discourse on the Classic Maya. This collaboration between paleoclimatologists and Maya archaeologists has sought to move beyond polarized debates and terminologies by accepting and accounting for the complexity of ancient Maya culture and history. Of particular relevance here is our abandonment of the term and concept of the Terminal Classic Period for the period of the Classic Maya collapse. This term was originally defined using the end of a Classic Maya calendric period and the introduction of a new ceramic style after 830 CE (Willey et al. 1967, Culbert 1973). It has since been discovered that crises, declines, or collapses began at many southern lowland centers up to a century earlier and in some northern regions more than a century and a half later (Demarest et al. 2004) (**Figure 2**). In this review, an evolving fine-grained understanding of the archaeological chronology of the Late Classic Period is considered in the context of advances in dating paleoclimate proxy records and an incipient understanding of spatial variability in climate change.

The complex geography of the Maya Lowlands is also considered in our analysis, with regard to both paleoclimate and archaeological data. The paleoclimate data come from two areas—(*a*) the northern Yucatán Peninsula and (*b*) Belize and the northern Guatemalan Department of Petén (**Figure 1*a***)—and do not encompass all of the major subregions of the Lowland Maya world. When discussing the archaeology, we refer to the EIR/non-EIR geographic and hydraulic zones (**Figure 1*c***), as well as to southern versus northern lowland patterns. In addition, more fine-grained geographic divisions, reflecting key cultural, ecological, and geological features that distinguish subregions of the Maya Lowlands (**Figures 1*b***), are discussed in specific aspects of our analysis.

3. EVIDENCE FOR CLIMATE CHANGE

3.1. Paleoclimate Data

For this review, we focus on geochemical indicators of past climate change, as opposed to records of vegetation change inferred from pollen, sedimentological records of soil erosion, and paleofauna or paleo-osteological studies. This is because most paleoecologists recognize that late Holocene pollen records from the Maya Lowlands primarily reflect human-induced land-cover change (Leyden et al. 1998, Leyden 2002, Wahl et al. 2006, Mueller et al. 2010). Furthermore, although osteological and paleofauna studies provide insights into animal ecology, and animal and human diet (Wright 1997, 2006; Emery et al. 2000; Emery 2008), this information is only indirectly related to climate and its evolution. An overview of geochemical climate proxy methods relevant to the Maya Lowlands can be found elsewhere (Douglas et al. 2015a).

In addition, we do not include paleoclimate proxy data collected from outside of the Maya Lowlands. In some cases, specifically coastal trace element records from the marine Cariaco Basin north of Venezuela, such data have been used to infer the occurrence of drought affecting the Lowland Maya (Haug et al. 2003). However, the geographic extrapolation of changes in precipitation patterns underlying these inferences are not well constrained (Medina-Elizalde et al. 2010). Although we consider the Cariaco Basin records to be largely uninformative regarding past climate changes experienced by the Lowland Maya, they are valuable in understanding broader circum-Caribbean climate variability and the causes of drought in the Maya Lowlands (Section 3.5).

3.1.1. Records from the northern Yucatán Peninsula. Much of the early evidence for drought at the end of the Classic Period came from the northern Yucatán Peninsula (**Figure 1*a***). This created an initial spatial mismatch between archaeological and paleoclimate evidence from the end of the Classic Period, in that the largest and most politically important Maya polities were located further to the south (**Figure 1*b***), and the earliest manifestations of societal collapse began in the south (see Section 4.1).

Lake Chichancanab (**Figure 1*a***) was one of the first targets for paleoclimate study in the Maya Lowlands, beginning with a pioneering study of oxygen isotopes in sedimentary carbonate fossils (Covich & Stuiver 1974). Oxygen isotope ratios ($\delta^{18}O$) of biogenic carbonates in closed-basin lakes reflect changes in the ratio of precipitation to evaporation (P/E) and thus are sensitive to droughts (Covich & Stuiver 1974, Hodell et al. 1995, Brenner et al. 2003). Although the study by Covich & Stuiver (1974) did not yield a high-temporal-resolution record of Holocene climate change, it paved the way for future paleolimnological studies at Lake Chichancanab and elsewhere across the Maya Lowlands.

Lake Chichancanab is an exceptional paleoclimate archive because its waters are supersaturated with respect to calcium sulfate, which forms the mineral gypsum (Hodell et al. 1995, 2005a; Perry et al. 2002). During drought intervals with low rainfall and high evaporation, gypsum precipitates from the lake water and accumulates as a mineral deposit in lake sediments. High-resolution analyses of sulfur concentrations, paired with carbonate $\delta^{18}O$ measurements, in a well-dated lake sediment core provided the first direct evidence for intense drought between 800 and 1000 CE (**Figure 3*e***), coinciding with the end of the Maya Classic Period (Hodell et al. 1995). Subsequent studies further refined the chronological precision and resolution of records of gypsum precipitation and carbonate $\delta^{18}O$ (**Figure 3*d***), indicating that approximately six intense droughts occurred in the ninth, tenth, and eleventh centuries CE (Hodell et al. 2001, 2005a). More recently the hydrogen isotope ratio of plant-wax lipids (δD_{wax}), which is controlled by the isotopic composition of plant water and is correlated with rainfall amount (Douglas et al. 2012), was measured in Lake Chichancanab sediments (Douglas et al. 2014, 2015b). These measurements provided independent evidence of intense droughts between the ninth and eleventh centuries CE (**Figure 3*f***) and enabled insights into the spatial patterns of drought intensity (see Section 3.4).

Following the initial discovery of drought in the ninth and tenth centuries CE at Lake Chichancanab, paleoclimatologists analyzed records from other sites to corroborate evidence for late Holocene climate change. Analysis of a littoral lake sediment core with a high sediment accumulation rate, from Punta Laguna (**Figure 3*c***), provided a carbonate $\delta^{18}O$ record with higher temporal resolution than the record from Lake Chichancanab (Curtis et al. 1996). The Punta Laguna record confirmed that a series of droughts occurred between 800 and 1060 CE and presented intriguing evidence for a longer period of relatively dry climate between ~350 and 1050 CE, which encompassed much of the Lowland Maya Classic Period.

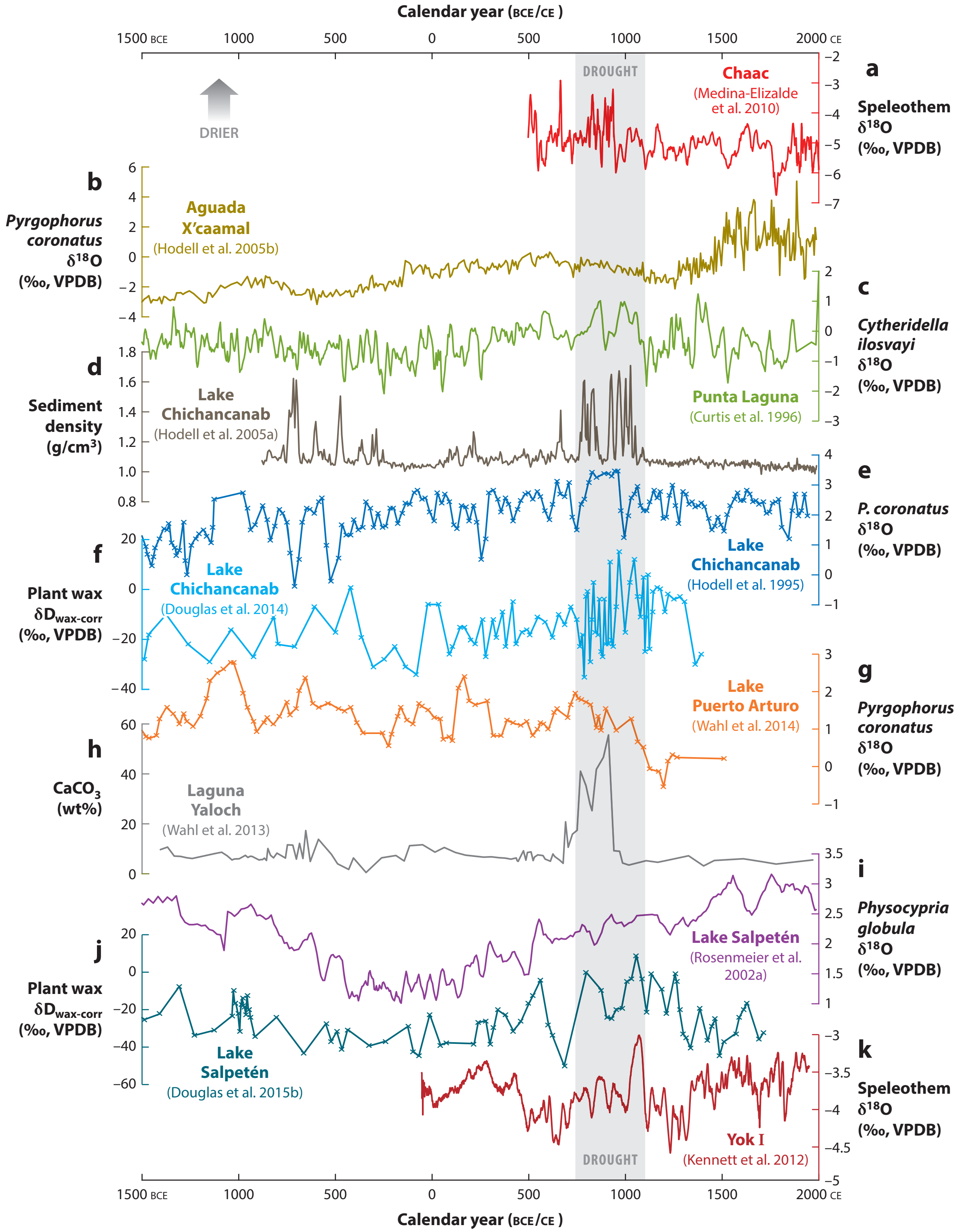
Not all paleolimnological records from the northern Yucatán Peninsula, however, presented a consistent picture of hydrological change. A lake sediment $\delta^{18}O$ record from Aguada X'caamal (Hodell et al. 2005b) (**Figure 3*b***), for example, did not record substantial drought between the ninth and eleventh centuries CE, but it did contain evidence for a transition to much drier conditions around 1500 CE that was not observed in sediment cores from other regional lakes. There is evidence that Aguada X'caamal transitioned from being a hydrologically open to a closed-basin lake over the past 3,500 years, thus compromising its fidelity as a long-term paleoclimate record (Hodell et al. 2005b, Medina-Elizalde et al. 2010).

Whereas initial paleoclimate research in the Maya Lowlands focused on lake sediment cores with relatively coarse, radiocarbon-based chronologies, the Chaac speleothem (stalagmite) $\delta^{18}O$ study from Tzabnah Cave (Medina-Elizalde et al. 2010) (**Figure 3*a***) represented a breakthrough in Maya Lowlands paleoclimatology by yielding a decadally resolved record of changing hydroclimate. The greater temporal precision of this study resulted from the application of the $^{234}U/^{230}Th$ radioactive isotope chronometer (Richards & Dorale 2003, Douglas et al. 2015a). The Chaac $\delta^{18}O$ data were interpreted to reflect rainfall amount, which is thought to control the $\delta^{18}O$ of precipitation in this and many other tropical regions (Rozanski et al. 1993, Lachniet & Patterson 2009). This record displays evidence for eight distinct drought intervals between 800 and 950 CE. By calibrating recent speleothem $\delta^{18}O$ variability to modern rainfall data, Medina-Elizalde et al. (2010) also provided the first quantitative estimate of late Holocene precipitation variability from the Maya Lowlands, which suggested rainfall decreased by 52% to 36% during the droughts between 800 and 950 CE (see Section 3.3).

3.1.2. Records from Belize and the central Petén. When paleoclimatological studies in the Maya Lowlands began, there was a dearth of data from areas south of the northern Yucatán Peninsula, despite the relative archaeological importance of the southern Maya Lowlands. An increasing number of geochemical records from the Petén region of Guatemala and from Belize have now been published (**Figure 1*a***). This broader spatial distribution of paleoclimate data

Figure 3

Compilation of paleoclimate records from the Maya Lowlands, arranged from north to south: (*a*) Chaac speleothem (Tzabnah Cave) $\delta^{18}O$; (*b*) Aguada X'caamal $\delta^{18}O$; (*c*) Punta Laguna $\delta^{18}O$; (*d*) Lake Chichancanab sediment density; (*e*) Lake Chichancanab $\delta^{18}O$; (*f*) Lake Chichancanab $\delta D_{wax\text{-}corr}$; (*g*) Lake Puerto Arturo $\delta^{18}O$; (*h*) Laguna Yaloch weight percent calcium carbonate ($CaCO_3$); (*i*) Lake Salpetén $\delta^{18}O$; (*j*) Lake Salpetén $\delta D_{wax\text{-}corr}$; (*k*) Yok I speleothem (Yok Balum Cave) $\delta^{18}O$. The gray bar indicates the period of intense drought between 760 and 1100 CE. Individual data points are shown if they are readily resolved. Abbreviation: VPDB, Vienna Pee Dee Belemnite; VSMOW, Vienna Standard Mean Ocean Water. $\delta D_{wax\text{-}corr}$ values indicate δD_{wax} values corrected for the influence of vegetation change, as detailed by Douglas et al. (2015b).



Calendar year (BCE/CE)
1500 BCE
1000
500
0
500
1000
1500
2000 CE
DROUGHT
DRIER
a
Chaac
(Medina-Elizalde et al. 2010)
Speleothem $\delta^{18}O$ (‰, VPDB)
b
Pyrgophorus coronatus $\delta^{18}O$ (‰, VPDB)
Aguada X'caamal
(Hodell et al. 2005b)
c
Cytheridella ilosvayi $\delta^{18}O$ (‰, VPDB)
Punta Laguna
(Curtis et al. 1996)
d
Sediment density (g/cm^3)
Lake Chichancanab
(Hodell et al. 2005a)
e
P. coronatus $\delta^{18}O$ (‰, VPDB)
Lake Chichancanab
(Hodell et al. 1995)
f
Plant wax $\delta D_{wax-corr}$ (‰, VPDB)
Lake Chichancanab
(Douglas et al. 2014)
g
Pyrgophorus coronatus $\delta^{18}O$ (‰, VPDB)
Lake Puerto Arturo
(Wahl et al. 2014)
h
$CaCO_3$ (wt%)
Laguna Yaloch
(Wahl et al. 2013)
i
Physocypria globula $\delta^{18}O$ (‰, VPDB)
Lake Salpetén
(Rosenmeier et al. 2002a)
j
Plant wax $\delta D_{wax-corr}$ (‰, VPDB)
Lake Salpetén
(Douglas et al. 2015b)
k
Speleothem $\delta^{18}O$ (‰, VPDB)
Yok I
(Kennett et al. 2012)

is providing new insights into how climate change affected the most important Classic Maya population centers, and into the spatial variability of climate change across the lowlands.

The first target for paleoclimate study in the central Petén region was Lake Petén-Itzá, a very large (~100 km^2) and deep (maximum water depth of 160 m) lake (Curtis et al. 1998). The late Holocene carbonate $\delta^{18}O$ record from this lake displayed almost no variability, however, probably because of the insensitivity of lake water $\delta^{18}O$ to climate change on relatively short timescales in this large-volume water body.

A carbonate $\delta^{18}O$ record from the nearby but much smaller Lake Salpetén indicated substantial late Holocene hydroclimate variability (Rosenmeier et al. 2002a) (**Figure 3*i***). This variability, however, does not match closely the $\delta^{18}O$ records from the northern Yucatán Peninsula in that it records longer-term climatic drying between 200 and 1550 CE, with relatively minor variability in $\delta^{18}O$ during the ninth and tenth centuries CE. It was suggested that the Lake Salpetén $\delta^{18}O$ record was strongly influenced by anthropogenic land use, which influenced runoff and thereby modified climatic signals inferred from $\delta^{18}O$ values. Subsequent comparisons with paleoclimate records from Belize and the central Petén and isotopic modeling of the Salpetén catchment hydrology, however, indicated that the Salpetén $\delta^{18}O$ record does reflect shifts in past rainfall amount (Rosenmeier et al. 2015). Recent analyses of δD_{wax} from the Lake Salpetén sediment core (**Figure 3*j***) provided an independent record of rainfall variability (Douglas et al. 2015b). These data support paleoclimate inferences from the Lake Salpetén $\delta^{18}O$ record, and comparison with the δD_{wax} data from Lake Chichancanab indicates spatial variability in drought intensity between the northern Yucatán Peninsula and central Petén (Section 3.4).

More recent paleolimnological studies targeted lakes north of Lake Salpetén. Laguna Yaloch, in the northeastern Petén, was the subject of a multiproxy paleoecological study that included analyses of weight percent calcium carbonate (**Figure 3*h***), which is thought to be controlled by changes in evaporation and rainfall, similar to the gypsum deposition climate proxy at Lake Chichancanab (Wahl et al. 2013). There was a substantial increase in weight percent calcium carbonate in Laguna Yaloch sediments between 750 and 900 CE, which was inferred to represent a period of drought. An 8,700-year carbonate $\delta^{18}O$ record from a sediment core collected in Lake Puerto Arturo, in the northwestern Petén, provided a longer-term perspective on climate change in the Petén than was previously available (Wahl et al. 2014) (**Figure 3*g***). This record displayed evidence for drought between 700 and 850 CE but also indicated there had been stronger droughts at ~1000 BCE and between 150 and 250 CE.

Speleothems from caves in Belize have also become important sources of paleoclimate data. Macal Chasm in west-central Belize was the site of the first speleothem-based climate reconstruction in the Maya Lowlands (Webster et al. 2007). The $\delta^{18}O$, $\delta^{13}C$, and luminescence records from the stalagmite were relatively coherent and indicated there had been a series of droughts between 750 and 1150 CE, although this inference relied on a relatively low-precision age model. Paleoclimate interpretation in this study came largely from the luminescence data, which constitute a speleothem climate proxy that is less well developed than $\delta^{18}O$ (Shopov et al. 1994, Douglas et al. 2015a).

The Yok I speleothem $\delta^{18}O$ record (**Figure 3*k***), from Yok Balum Cave in southern Belize, provides the highest-precision and highest-resolution paleoclimate chronology from the Maya Lowlands, which is based on the $^{234}U/^{230}Th$ chronometer (Kennett et al. 2012). The $\delta^{18}O$ data from this speleothem—which, as in the case of the Chaac speleothem, are interpreted as a record of past rainfall amount—are resolved at the subannual level. The Yok I $\delta^{18}O$ record provides evidence for a drying trend and periodic pronounced droughts between 750 and 1100 CE, with particularly dry conditions at ~1080 CE. The excellent temporal precision of the Yok I $\delta^{18}O$ record has the potential to resolve correlations between climatic and societal events at a much finer resolution than is possible using most paleoclimate records, though uncertainty in some archaeological chronologies and the source of archaeological inferences still complicate such comparisons (see Section 4.1). However, the climate fidelity of the Yok I $\delta^{18}O$ record may have been influenced by kinetic isotope effects (Kennett et al. 2012) or early diagenetic alteration of the speleothem aragonite (Lachniet 2015). These processes could have influenced the recorded isotopic fractionation between cave water and speleothem carbonate, thereby compromising the use of the $\delta^{18}O$ data for inferring past changes in rainfall.

3.1.3. Other regions of the Maya Lowlands.

There are critical regions of the ancient Maya world, including the Pasión and Usumacinta regions, the Copán and Motagua Valleys, and the southeastern Maya Lowlands, for which there are no paleoclimate data (**Figure 1*a*,*b***). Although there have been numerous paleoecological, paleofaunal, and bioarchaeological studies in these regions (Rue 1987; Dunning et al. 1997; Wright 1997, 2006; Emery et al. 2000; Rue et al. 2002; Emery & Thornton 2008; McNeil et al. 2010), the lack of geochemical paleoclimate data from much of the Maya Lowlands represents a substantial gap in our understanding of climate change impacts on ancient Maya populations.

3.2. Paleoclimate Data Synthesis

3.2.1. Compilation of synthetic paleoclimate records.

We sought to generate a comprehensive picture of late Holocene climate variability in the Maya Lowlands. From the records discussed above, we selected continuous climate proxy data, namely isotope measurements on carbonates or organic molecules. We excluded records of gypsum or calcium carbonate concentrations in sediments, because mineral precipitation occurs at a chemical threshold (on/off) related to the saturation state of gypsum or carbonate minerals (Hodell et al. 1995, 2005a; Medina-Elizalde & Rohling 2012; Wahl et al. 2013). Whereas these records indicate periods of mineral deposition as water-column saturation occurs under conditions of reduced runoff and increased evaporation, they are probably not linearly related to the magnitude of reductions in rainfall. In particular, these records do not record wet climate intervals, as periods of wetter than average climate do not cause changes in mineral precipitation. We also excluded the Aguada X'caamal $\delta^{18}O$ record, given the uncertainty of its climate fidelity (Hodell et al. 2005a, Medina-Elizalde et al. 2010), and the Macal Chasm stalagmite records, because the data were not accessible.

To normalize paleoclimate records and to place them into a common reference frame, we recalculated each data series as a suite of z-scores:

$$z = \frac{(x - \bar{x})}{\sigma},$$

where x is a given proxy value in a time series, $\bar{x}$ is the mean value of the proxy time series, and σ is the standard deviation of the time series. A z-score indicates the deviation of an individual proxy measurement from the mean value of a record—that is, how wet or dry conditions were relative to the mean of that record. Consequently, z-scores are uninformative regarding the relative magnitudes of drought among sites. To develop a synthetic estimate of drought intensity, we resampled each time series at decadal intervals and averaged the z-scores for each decadal interval across all available records. We performed this exercise for the two regional clusters of paleoclimate data (**Figure 1*a***)—(*a*) the northern Yucatán Peninsula (**Figure 4*a***) and (*b*) Belize and the central Petén (**Figure 4*b***)—as well as for all of the records combined (**Figure 4*c***).

There are two important caveats with respect to this synthesis. First, we used the published age models for these data sets and assumed they are equally accurate, which is unlikely. However,

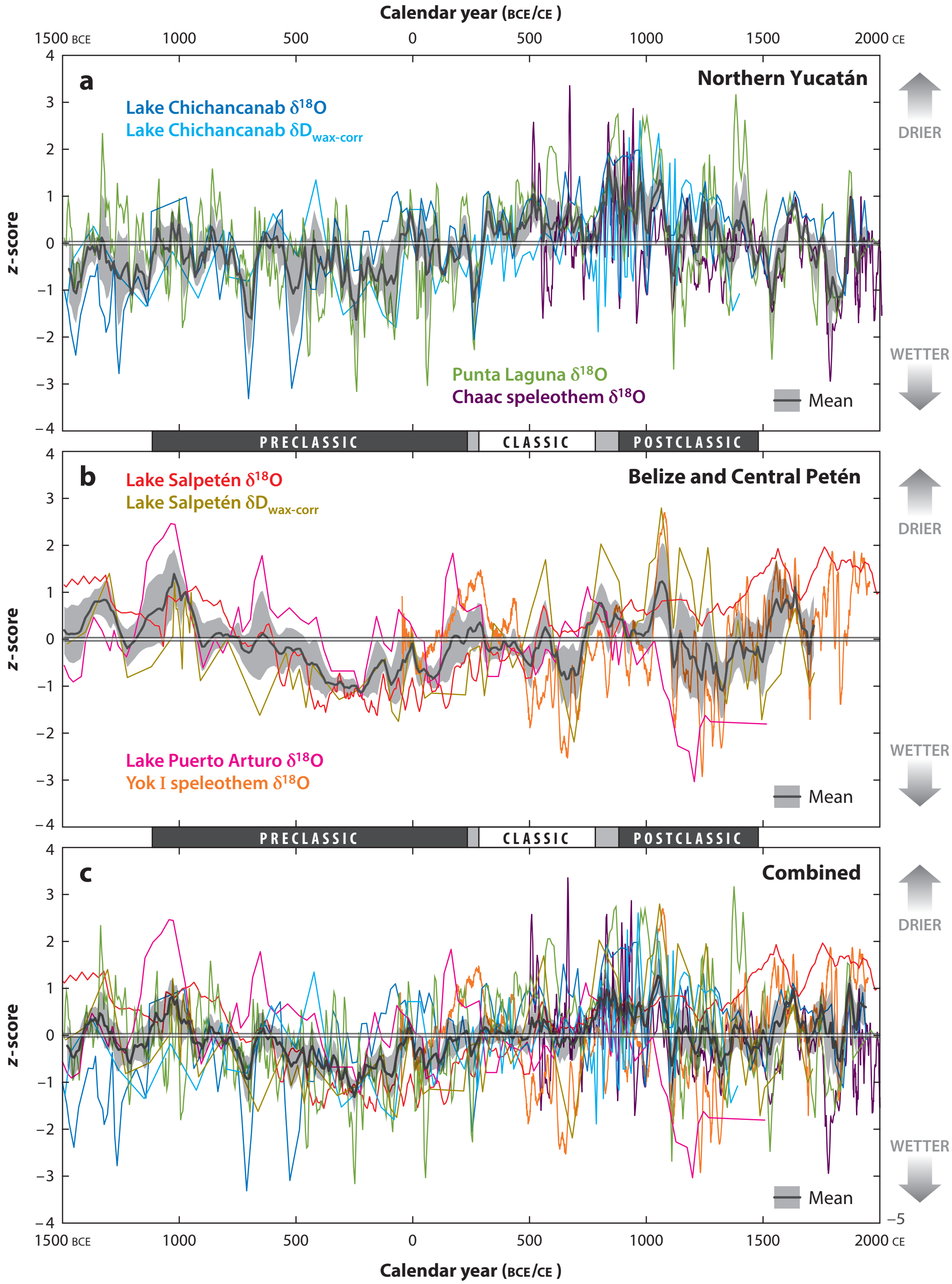


Figure 4

Our *z*-score data synthesis time series for (*a*) the northern Yucatán Peninsula, (*b*) Belize and the central Petén, and (*c*) all records from the Maya Lowlands. The thick dark gray line indicates the mean *z*-score, and the gray envelope indicates the standard error of the mean. An approximate chronology of major Maya periods is shown; gray areas indicate periods of chronological uncertainty or disagreement.

we argue that this conservative approach avoids indefensible assumptions related to tuning the paleorecords. Second, each data set spans a different range of calendar dates; thus, the mean values for each data set derive from different time intervals and may slightly bias interpretations of drought intensity inferred from the *z*-scores in each record. It also means that the number of data points included in the mean *z*-score differs through time. A data compilation that addresses these sources of error should be a goal for future studies of past climate change in the Maya Lowlands.

3.2.2. Ninth- to eleventh-century CE droughts. Paleoclimate research across the Maya Lowlands has focused on hydroclimate variability from the ninth to the eleventh century CE, a period that temporally overlaps with the collapse of the Classic Maya civilization (see Section 4.1). Our data synthesis suggests that the droughts during this time were unprecedented in terms of both frequency and intensity, for at least the preceding 1,800 years (**Figure 4**). Therefore, these droughts were likely anomalous relative to the changes in climate that the Lowland Maya had experienced previously, and they could have had substantial disruptive societal impacts.

In the compiled paleoclimate records, we observe two distinct dry intervals, at 770–950 and 1000–1100 CE, separated by an intervening period of relatively wet conditions (**Figure 4**). The intervening period of wetter conditions is expressed more strongly in the records from Belize and the central Petén. However, not all of the records contain evidence of strong drought spanning both time intervals. For instance, the second phase of drought is not expressed strongly in the Chaac speleothem $\delta^{18}O$ record from the northern Yucatán Peninsula (Medina-Elizalde et al. 2010) (**Figure 3*a***) or in the Puerto Arturo carbonate $\delta^{18}O$ record from the central Petén (Wahl et al. 2014) (**Figure 3*g***). In contrast, the first drought phase is much less intense than the second in the Yok I speleothem $\delta^{18}O$ record from Belize (Kennett et al. 2012) (**Figure 3*k***).

The discrepancy between the Chaac and Yok I speleothems is especially noteworthy because they are the two most precisely dated paleoclimate records from the Maya Lowlands, and the differences in inferred climate history are thus unlikely to be a consequence of simple dating errors (**Figure 5**). Because both phases of drought are recorded in paleorecords from the northern Yucatán Peninsula and from Belize and the central Petén (**Figure 3**), we argue that this difference probably did not result from spatial differences in the timing of drought either. Instead, we suggest that complications in the speleothem $\delta^{18}O$ climate proxy led to these two intervals of drought being expressed inconsistently in the two records. For a detailed discussion of possible complications in speleothem $\delta^{18}O$ values, see Douglas et al. (2015a) and Lachniet (2009).

3.2.3. Climate variability before the ninth century CE. Of the paleoclimate records that extend beyond the Common Era, many indicate severe droughts between 1500 and 500 BCE, with especially strong evidence for drought between ~1150 and 950 BCE in the central Petén (**Figure 4**). In contrast, most proxy climate records indicate a prolonged period of wet conditions, with few substantial droughts, from ~500 BCE to 200 CE (**Figure 4**). This period represents the wettest and least drought-affected interval of ancient Maya history, but it was briefly interrupted by drought at ~20 BCE, which appears to have been more pronounced in the northern Yucatán Peninsula.

There is an overall shift toward a drier mean climate by ~250 CE, first identified by Curtis et al. (1996) at Punta Laguna, which marks the end of the preceding, prolonged wet period. In the northern Yucatán Peninsula drought intervals occur at both ~250 and ~500 CE, with the latter drought being more pronounced. These droughts were less frequent and severe than those between 800 and 1100 CE (**Figure 4*a***). Paleoclimate records from Belize and the central Petén also indicate drought events at ~250 and ~500 CE, although their intensities differ among sites (**Figure 4*b***). Whereas the ~500 CE drought is strongly expressed in the Lake Salpetén δD_{wax} and $\delta^{18}O$ records (Rosenmeier et al. 2002a, Douglas et al. 2015b), the ~250 CE drought is more

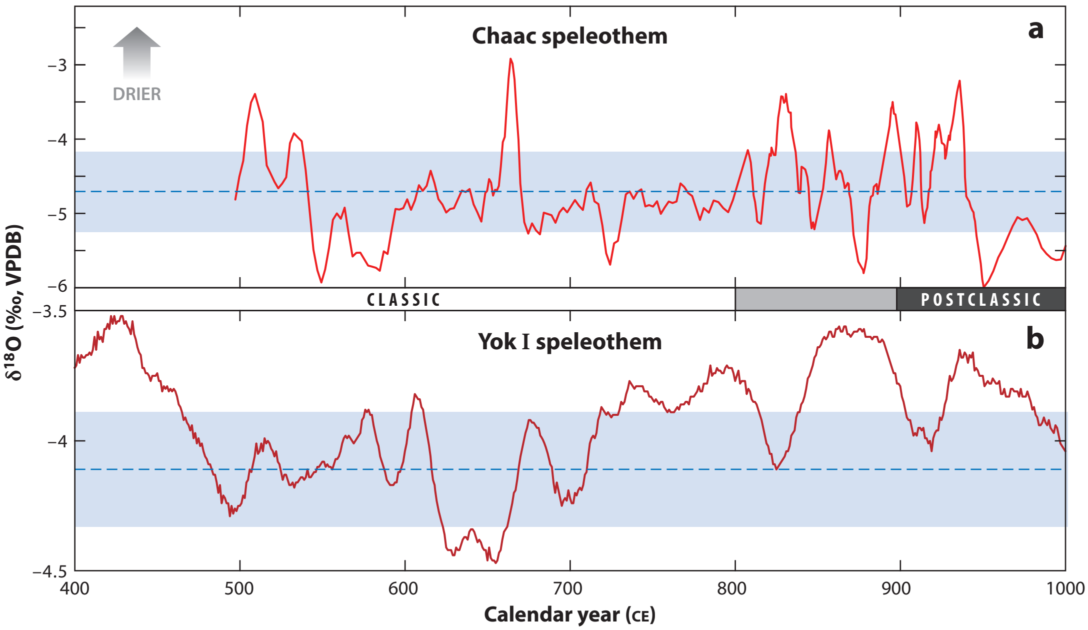


Figure 5

High-resolution speleothem $\delta^{18}O$ records for the period from 400 to 1000 CE from the (*a*) Chaac speleothem at Tzabnah Cave (Medina-Elizalde et al. 2010) and (*b*) Yok Balum (Kennett et al. 2012) Caves. The dashed blue line indicates the average value for the period of 150 years preceding the onset of drought (600–750 CE), and the blue band indicates 1 σ for this pre-drought period. An approximate chronology of major Maya periods is shown in the middle of the plot; gray areas indicate periods of chronological uncertainty or disagreement. Abbreviation: VPDB, Vienna Pee Dee Belemnite.

pronounced in the Yok I, Macal Chasm, and Puerto Arturo records (Webster et al. 2007, Kennett et al. 2012, Wahl et al. 2014).

In many records, there is evidence for relatively wet conditions from ~600 to ~730 CE (**Figure 4**). This wet period is particularly pronounced in the Yok I speleothem $\delta^{18}O$ and Lake Salpetén δD_{wax} records. Most paleoclimate records from the northern Yucatán Peninsula indicate that mean conditions were wetter and that intense droughts were absent throughout much of the eighth century CE (**Figure 4*a***).

3.3. Quantitative Estimates of Drought

To estimate the magnitude of past droughts accurately, it is necessary to relate geochemical proxy records to quantifiable climate variables. To date, the only quantitative estimate of past rainfall variability comes from the Chaac speleothem. Quantitative rainfall estimates were achieved by evaluating the linear regression of speleothem $\delta^{18}O$ values against annual precipitation amounts recorded in the nearby city of Mérida, Mexico, for the period 1966–1994 (Medina-Elizalde et al. 2010). Although the two variables are significantly correlated ($r = -0.62$), the relationship is not strong (**Figure 6*a***). More problematic is the fact that the magnitude of $\delta^{18}O$ variability in the Chaac record (−6.8‰ to −2.9‰) spans a much wider range than the magnitude of $\delta^{18}O$ variability from the recent, 29-year calibration period (−6.1‰ to −4.9‰). Medina-Elizalde et al. (2010) applied error terms generated from the calibration data set (± 81 mm/year) to past rainfall estimates, equivalent to 7% of modern annual precipitation (1,120 mm/year). Given the substantial scatter

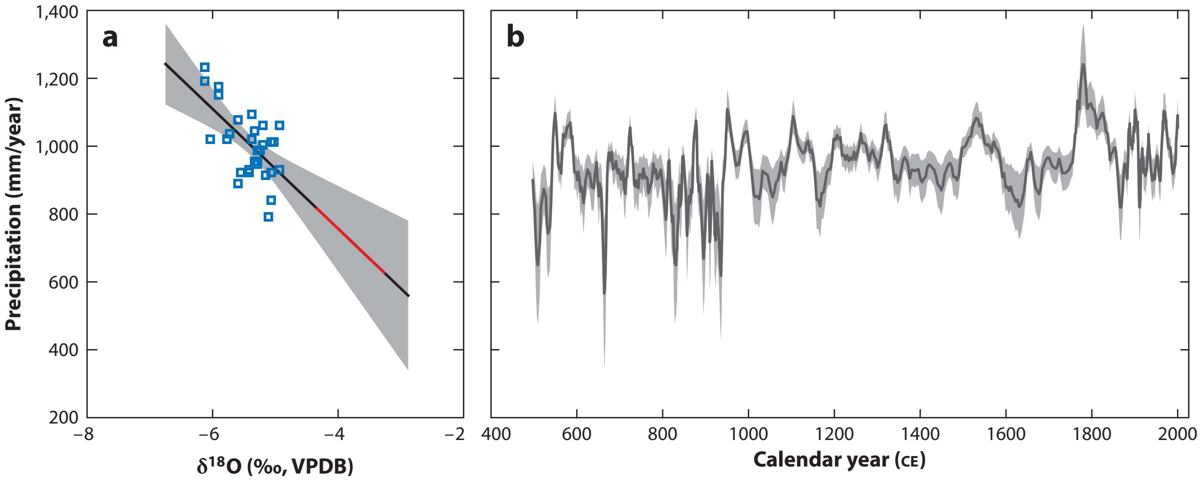


Figure 6

(*a*) Linear regression of Chaac speleothem (Tzabnah Cave) δ^{18}O values versus annual rainfall in Mérida, México for the period 1966–1994 (Medina-Elizalde et al. 2010). The gray envelope indicates the 95% confidence interval. The red line segment indicates the range of δ^{18}O values observed during droughts between 800 and 950 CE. (*b*) The Chaac speleothem estimated rainfall record, with an error envelope (*gray*) based on the confidence interval from **Figure 4*a***. Abbreviation: VPDB, Vienna Pee Dee Belemnite.

in the calibration data set, a larger uncertainty is apparent when extrapolating this calibration to the much higher δ^{18}O values observed before the twentieth century. We calculated a 95% confidence interval for this linear regression (**Figure 6*a***) and determined that the error in annual rainfall during the droughts of 800–950 CE is approximately ±160 mm/year (**Figure 6*b***), twice that estimated by Medina-Elizalde et al. (2010). This greater uncertainty is equivalent to 14% of modern annual precipitation at the site.

Accounting for this increased uncertainty, the Chaac speleothem suggests reductions in precipitation, relative to modern precipitation, of 20–65% during the eight droughts between 800 and 950 CE (**Figure 6*b***). A subsequent study that quantified the impacts of decreasing rainfall on lake level and lake water isotope values (Medina-Elizalde & Rohling 2012) indicated that reductions in precipitation of this magnitude are consistent with the isotope and gypsum deposition records from the Lake Chichancanab and Punta Laguna sediment cores (Hodell et al. 1995, 2005a; Curtis et al. 1996). Although this analysis referred to the estimated decrease in precipitation as "modest," a 20–65% decrease in precipitation would likely have represented very severe reductions in water available for agriculture and domestic use for the ancient Maya on the northern Yucatán Peninsula, especially given the high potential evapotranspiration (1,450–1,900 mm/year) in this warm tropical region (Trabucco et al. 2008), which leads to rapid evaporation of surface water. Agriculture would have been particularly sensitive to reduced summer (wet season) rainfall, which Medina-Elizalde & Rohling (2012) inferred was most consistent with the isotopic data.

3.4. Spatial Variability in Drought Impacts

Given the increasing focus on the variability of societal change at the end of the Classic Period, it is important to understand spatial variability of drought impacts during that time. Unfortunately, determining how droughts differed from region to region is challenging given the paucity and uneven distribution of data coverage. Furthermore, although lacustrine and speleothem carbonate δ^{18}O records can provide robust records of climate variability at a particular site, local hydrological variables influence absolute isotope values and complicate intersite comparisons (Rosenmeier et al. 2002a,b; Douglas et al. 2015a,b).

In a recent study, Douglas et al. (2015b) used δD_{wax} from lake sediments to evaluate changes in annual precipitation amount in both the Yucatán Peninsula (Lake Chichancanab) and central Petén (Lake Salpetén). The analysis was based on the observation that δD_{wax} values from lake sediments and soils were significantly correlated with spatial variability in annual precipitation amount in a data set that spanned the Maya Lowlands (Douglas et al. 2012, 2015b). The modern annual rainfall gradient between the two lakes is approximately 680 mm/year, with substantially higher rainfall at Lake Salpetén. Results of this study suggest that the magnitude of drying between 760 and 1100 CE was substantially greater in the central Petén than on the northern Yucatán Peninsula. The study also implies that the modern north-south rainfall gradient effectively disappeared during peak periods of drought.

A related question is whether drought during the Late Classic Period began simultaneously across the landscape, or whether the onset of drying occurred at different times in different regions. This is important to consider in light of the fact that societal collapse appears to have begun much earlier in some sociocultural subregions than others, with the earliest manifestations of collapse occurring in the Pasión Valley (see Section 4.1). If the timing of drought was also heterogeneous, it might help to explain the spatiotemporal variability in societal change. Comparison of the Chaac and Yok I speleothem $\delta^{18}O$ records (**Figure 4**), which are both constrained by decadally resolved chronologies, suggests that long-term drying began as early as 700 CE at Yok Balum Cave (Yok I speleothem) (**Figure 5*b***), whereas the first drought interval at Tzabnah Cave (Chaac speleothem) occurred 100 years later, at approximately 800 CE (**Figure 5*a***). The early eighth-century CE droughts detected in the Yok I record were relatively minor, however, and the first instance of drought outside the normal variability of the Late Classic Period occurred at ~750 CE (**Figure 5*b***). Furthermore, $\delta^{18}O$ values in the Yok I record do not exceed those recorded earlier in the Classic Period (~400 CE), until the middle of the ninth century CE (**Figure 5*b***). Our data synthesis also suggests that the onset of drying occurred slightly earlier in Belize and the central Petén than in the northern Yucatán Peninsula, with evidence for mid-eighth-century CE drying in three out of four records (**Figure 4*b***).

In summary, available data indicate that droughts during the end of the Classic Period were not identical across the Maya Lowlands, but instead varied across both space and time. Specifically, it appears that drought conditions were more intense and began earlier in Belize and the central Petén relative to the northern Yucatán Peninsula. As discussed in Section 4.2, these spatial differences provide new insights into how drought relates to the complex outcomes of Maya polities at the end of the Classic Period.

3.5. Causes of Drought in the Maya Lowlands

To understand how drought intervals in the Maya Lowlands relate to global Holocene climate variability, and to assess the implications of those past droughts for future climate impacts in the region, it is important to consider the forcing mechanisms that caused the droughts. A number of causal mechanisms for droughts in the Maya area have been proposed, but there is no consensus among researchers regarding a single causal mechanism. Instead, it is likely that multiple mechanisms were involved.

3.5.1. Solar variability. Spectral time series analyses indicated that droughts recorded by gypsum deposition in Lake Chichancanab, the $\delta^{18}O$ of Punta Laguna carbonates, and the $\delta^{18}O$ of the Chaac speleothem record, all on the northern Yucatán Peninsula, recurred at ~200-year intervals (Hodell et al. 2001, Medina-Elizalde et al. 2010). This 200-year periodicity approximately matches the timing of the De Vries Cycle observed in the abundance of cosmogenic nuclides, specifically ^{14}C in tree rings and ^{10}Be in ice cores (Wagner et al. 2001, Steinhilber et al. 2012). Cosmogenic nuclide production is inversely related to solar activity, as higher solar activity shields Earth from cosmic ray particles that collide with ^{14}N and ^{16}O atoms in the atmosphere to produce ^{14}C and ^{10}Be (Steinhilber et al. 2012). Solar forcing has been implicated in influencing Holocene hydroclimate change at a number of other locations based on comparison with cosmogenic nuclide records (e.g., Gupta et al. 2005, Wang et al. 2005, Asmerom et al. 2007). The directionality of solar influences on precipitation, however, is not consistent, and the mechanism by which small shifts in solar output translate into hydrological changes in the tropics remains uncertain (Shindell et al. 2006).

Comparison of a compiled record of solar irradiance (Steinhilber et al. 2012) (**Figure 7*b***) with Maya Lowlands droughts (**Figure 7*a***) suggests that some periods of reduced solar radiation correspond to major drought intervals, particularly at ∼1050 CE, but a consistent correlation is not evident. We note that, whereas the 200-year periodicity is apparent in many records from the northern Yucatán Peninsula, this periodicity has not been identified in records from Belize and the central Petén, and in general, high-frequency climate variability is less apparent in these latter records (**Figures 3** and **4*b***). This spatial difference in the frequency of climate change suggests a more prominent role for solar variability on the Yucatán Peninsula than in Belize and the central Petén, but further spectral analyses are required to validate this possibility.

Atlantic Meridional Overturning Circulation (AMOC): an ocean current characterized, in part, by the transport of warm surface waters to the North Atlantic, which may play an important role in global climate variability

Intertropical Convergence Zone (ITCZ): a belt of low pressure that circles Earth near the equator where the trade winds converge and promote convective precipitation

Sea surface temperature (SST): the temperature of ocean surface waters, which can have important effects on atmospheric circulation and precipitation in tropical regions

3.5.2. North Atlantic climate variability. Holocene episodes of cooling in the North Atlantic (Bond events), detected as increased concentrations of ice-rafted debris in ocean sediments, recurred at intervals of 1,470 ± 500 years and have been identified as a key feature of Holocene climate variability (Bond et al. 1997, 2001). A well-defined cause for the Bond events remains elusive. Bond et al. (2001) proposed that solar variability was the likely cause, but later reevaluations suggested that other forcing factors, including volcanism, periodic glacial melting, and internal climate dynamics, likely played important and variable roles throughout the Holocene (Wanner et al. 2011, 2015).

It has been suggested that North Atlantic cooling during Bond events reduced the strength of the Atlantic Meridional Overturning Circulation (AMOC), potentially through decreased sinking of surface-ocean waters caused by advection of fresh ice-melt to regions of deep sinking (Bond et al. 1997, Bianchi & McCave 1999, Keigwin & Boyle 2000). Reduced AMOC strength, in turn, has been hypothesized to influence tropical rainfall through its effects on ocean temperature gradients (Dahl et al. 2005, Evangelista et al. 2014), possibly by inducing southward shifts in the Intertropical Convergence Zone (ITCZ) (Zhang & Delworth 2005, Schmidt & Spero 2011).

Changes in Atlantic temperature gradients, and specifically sea surface temperatures (SSTs) in the Caribbean warm pool, likely have an important effect on rainfall in the Maya Lowlands (Enfield & Alfaro 1999, Giannini et al. 2000, Taylor et al. 2011), and a link between North Atlantic climate variability and past hydroclimate change in the Maya Lowlands has been discussed in a number of studies (Gunn & Adams 1981, Curtis et al. 1996, Gill 2000). Several drought episodes in the Maya Lowlands correlate temporally with Bond events (**Figure 7*c***), namely at ∼1000 BCE, ∼800 CE, and ∼1500 CE, but these broad-scale temporal correlations need to be tested more thoroughly.

3.5.3. Shifts in the position of the Intertropical Convergence Zone. Trace metal (Ti and Fe) concentrations in sediments from the marine Cariaco Basin (Haug et al. 2001, 2003) (**Figure 6*c***) have been applied to infer latitudinal shifts in the position of the ITCZ. This inference is based on two phenomena related to the ITCZ: (*a*) convective precipitation over northern South America in

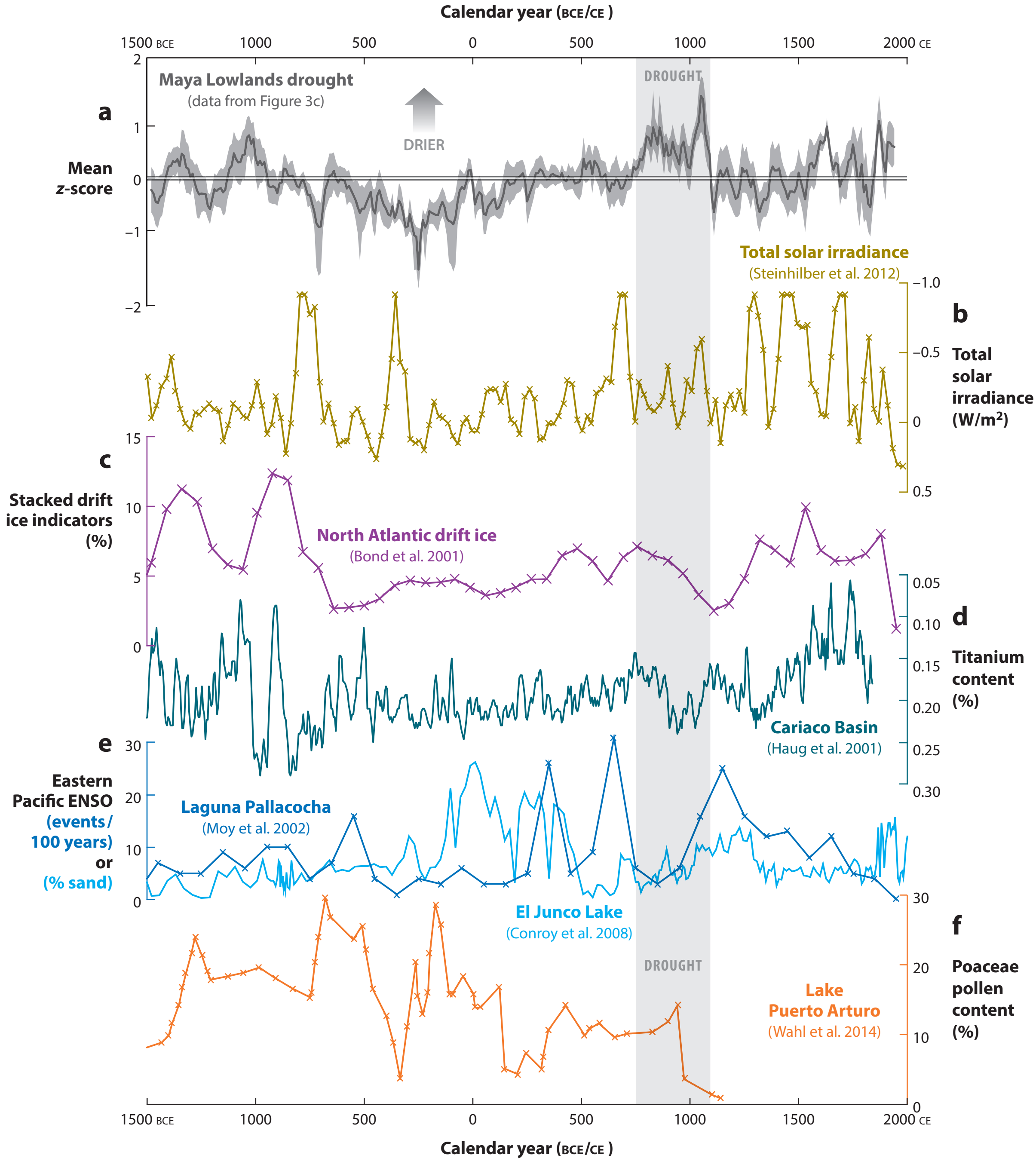


Figure 7

Comparison of the synthetic Maya Lowlands drought record with proxy records for possible forcing factors. (*a*) Mean *z*-score of Maya Lowlands paleoclimate records from **Figure 4*c***; (*b*) total solar irradiance; (*c*) North Atlantic drift ice proxy data indicating Bond events; (*d*) Cariaco Basin titanium content; (*e*) indices of Eastern Pacific El Niño–Southern Oscillation (ENSO) event frequency from Laguna Pallacocha, Ecuador, and El Junco Lake, Galapagos; and (*f*) percent grass pollen from Lake Puerto Arturo, an indicator of deforestation in the northern Petén. The gray band indicates the droughts of the ninth to eleventh centuries CE.

summer, which increases runoff of continental Ti and Fe to marine sediments, and (*b*) trade-wind-driven upwelling in winter, which increases marine biological productivity and calcareous and siliceous microfossil deposition (Haug et al. 2001). During periods of southerly ITCZ displacement, precipitation in northern South America would decrease, while upwelling would increase, leading to decreased concentrations of Ti and Fe in sediments. However, this analysis constrains hydrological change only over a relatively small area, and inferences regarding the hemispheric ITCZ require unconstrained assumptions regarding the geographic extrapolation of the observed trends. Changes in the position of the ITCZ during the late Holocene could have been related to reduction in the strength of the AMOC (Section 3.5.2), or, as argued by Haug et al. (2001), to El Niño–Southern Oscillation (ENSO) event frequency in the Eastern Equatorial Pacific. When ENSO events are frequent, water temperatures in the Eastern Equatorial Pacific are, on average, warmer, which could promote southward displacement of the ITCZ (Fedorov & Philander 2000).

El Niño–Southern Oscillation (ENSO): a recurring climate change related to changing sea surface temperatures in the Eastern Tropical Pacific Ocean, which has strong effects on precipitation in many tropical regions, including Central America

The Cariaco Basin record is interpreted as reflecting southward shifts of the ITCZ during both the ~250 CE and ~800–1100 CE droughts in the Maya Lowlands (**Figure 7*d***). Some Maya Lowlands paleoclimate records, particularly the Yok I speleothem $\delta^{18}O$ record, correlate strongly with the Cariaco Basin records (Kennett et al. 2012), whereas others, such as the Chaac speleothem $\delta^{18}O$ record, display a poor correlation (Medina-Elizalde et al. 2010). Furthermore, analysis of twentieth-century rainfall variability (Medina-Elizalde et al. 2010) indicates there is no significant correlation between the Cariaco Basin and the northern Yucatán Peninsula, implying the Cariaco record is not directly linked to climate conditions in the Maya Lowlands. The Cariaco Basin and Maya Lowlands are separated by ~2,500 km, and it is possible that movement of the ITCZ had different effects in the two areas.

3.5.4. Pacific Ocean influences. Some studies have suggested a direct link between past climate variability in the Maya Lowlands and other parts of Mesoamerica and changes in Pacific Ocean circulation, specifically the frequency of ENSO events (Lachniet et al. 2004, 2012; Wahl et al. 2014). Studies of sedimentary indicators of storm events in lake sediments from mainland Ecuador and the Galapagos Islands (**Figure 7*e***) led to inferences for long-term increases in ENSO frequency during the late Holocene (Moy et al. 2002, Conroy et al. 2008), although these two records display large discrepancies in ENSO frequency on shorter timescales. Modern climate data show that warm Eastern Tropical Pacific SSTs reduce Central American summer rainfall (Enfield & Alfaro 1999; Taylor et al. 2002, 2011), although linkages between rainfall and ENSO events are complex and are influenced by both Tropical Atlantic and Eastern Tropical Pacific SSTs (Giannini et al. 2000). Increased ENSO frequency, or longer-term warming of the Eastern Tropical Pacific, could therefore plausibly be linked to drying in the Maya Lowlands during the late Holocene, and inferred long-term, late Holocene drying at Lake Puerto Arturo could be related to the reported increase in ENSO frequency (Wahl et al. 2014). Records of past ENSO, however, do not indicate a high frequency of occurrence during the ninth and tenth centuries CE, implying that changes in ENSO probably were not the direct cause of drought at that time (**Figure 7*e***).

3.5.5. Changes in tropical cyclone frequency. Medina-Elizalde & Rohling (2012) speculated that observed ninth- and tenth-century droughts on the northern Yucatán Peninsula could have been related to decreased frequency and/or intensity of tropical cyclones that made landfall in the region. This hypothesis is predicated on the assertion that a decreased amount of isotopically light rainfall from tropical cyclones is consistent with the absence of low $\delta^{18}O$ values in the records from Lake Chichancanab and Punta Laguna, and the Chaac speleothem, but is not supported by independent evidence for changes in cyclone frequency. A recent study tested this hypothesis by analyzing the frequency of mud layers in a speleothem from the northern Yucatán Peninsula, which were interpreted as indicators of cave flooding events induced by tropical cyclones (Frappier et al. 2014). This analysis found no evidence for reduced tropical cyclone frequency during the ninth and tenth centuries CE, relative to the twentieth century, implying that the reduced tropical cyclone hypothesis is not tenable.

3.5.6. Deforestation. Two studies have used atmospheric circulation models with preindustrial climatic boundary conditions to examine the idea that the Lowland Maya caused or enhanced droughts through deforestation (Oglesby et al. 2010, Cook et al. 2012). These studies compared simulated climates in the Maya Lowlands under forested, partially deforested, and fully deforested conditions and inferred that land clearance can lead to a 5–30% reduction in rainfall. Pollen studies from lake sediment cores in locations spanning the Maya Lowlands, however, have indicated that widespread deforestation had occurred by the Late Preclassic Period, some 800 years before the severe droughts of the ninth to eleventh centuries CE (Leyden 2002, Wahl et al. 2006) (**Figure 7*f***). Therefore, deforestation was probably not a leading cause of droughts during the ninth to eleventh centuries CE, but it could have contributed to long-term drying and potentially exacerbated the intensity of natural droughts.

3.5.7. Interoceanic temperature gradients. Studies of modern climatological data from the Caribbean region stress the importance of interoceanic temperature gradients. Summer rainfall in the Caribbean and Central America is suppressed when the Tropical Atlantic is anomalously cool and the Eastern Tropical Pacific is anomalously warm (Enfield & Alfaro 1999; Giannini et al. 2000; Taylor et al. 2002, 2011). Wahl et al. (2014) highlighted the importance of both the Atlantic and Pacific Oceans in controlling past hydroclimate variability in the central Petén, suggesting that drought in the Maya area was most strongly expressed during periods when positive ENSO overlapped with positive North Atlantic Oscillation anomalies. This hypothesis could be tested through comparison of paleohydrology records from the Maya Lowlands with reconstructions of SSTs in both the Tropical Atlantic and Eastern Tropical Pacific, but to our knowledge, SST records with the requisite temporal resolution are not currently available.

3.5.8. Summary of causal mechanisms for drought. The factors that controlled late Holocene hydroclimate change in the Maya Lowlands, and the ninth- to eleventh-century CE droughts in particular, remain uncertain. Although there is evidence that each of the causal mechanisms discussed above played a role, the totality of the data does not strongly support any singular cause. Several of the forcing mechanisms described above may be linked. For example, it has been suggested that solar variability controls the North Atlantic circulation changes expressed as Bond events, and that resulting changes in the AMOC could result in southward displacement of the ITCZ. However, such linkages remain tentative.

The lack of a clear correlation between any one causal mechanism and drought in the Maya Lowlands suggests that multiple factors were likely important. Modern climatological data provide compelling support for the hypothesis that interocean temperature gradients strongly influenced droughts. It is conceivable that variability in both Atlantic and Pacific SSTs, perhaps modulated by solar variability, was important and could have been expressed in part as shifts in the position of the ITCZ. Existing evidence suggests that the roles of tropical cyclones and deforestation were probably less important, but they cannot be ruled out as contributing factors at this point. Douglas et al. (2015b) speculated that forcing mechanisms could have varied spatially across the Maya Lowlands, such that the northern Yucatán Peninsula was influenced primarily by the North Atlantic, whereas a Pacific influence was stronger in Belize and the central Petén. Spatial differences in forcing mechanisms could help to explain differences in the severity and timing of drought between these regions (Section 3.4), but more study will be required to validate this explanation.

4. INTEGRATION OF PALEOCLIMATOLOGY AND ARCHAEOLOGY

Paleoclimate data indicate that multiple episodes of severe drought occurred in the Maya Lowlands between 800 and 1100 CE (**Figure 4**) and support the conclusion that regional drying was anomalous relative to what Lowland Maya society had experienced previously. However, this evidence does not prove that drought caused the Classic Maya collapse. A general critique of assertions that climate caused societal collapse is that they rely primarily on the temporal correlations between climate change and social upheaval but do not address the complex processes that link these two distinct phenomena (Coombes & Barber 2005). Interdisciplinary analysis, which combines paleoclimatological and archaeological evidence, is of critical importance in understanding the processes that link climate change and societal impacts. Here we discuss five key questions related to integrating paleoclimate and archaeological data:

1. How did the timing of societal collapse relate to drought?
2. Are spatial patterns of drought important for understanding societal collapse?
3. How can drought be integrated with other proposed causes of collapse?
4. Are previous periods of climate change associated with social upheaval?
5. Can drought help to explain the absence of recovery following the end of the Classic Period?

4.1. The Relative Timing of Drought and Societal Collapse

Understanding the relative timing of droughts and societal collapse is critical to ascribe a causal role to drought. This assessment involves vexing terminological and epistemological problems that have plagued debates over the "cause" of the "collapse." Archaeologists have uncovered abundant evidence that the onset of societal crisis and collapse began earlier than the traditional start of what has been called the Terminal Classic Period (830 CE) (Demarest et al. 2004), although it is difficult to assign a beginning date for the process of collapse given the regional variation in both the onset dates and nature of societal changes (Demarest et al. 2004) (**Figure 2**).

The most detailed evidence for political crisis and collapse of Classic Maya states comes from a few intensively investigated regions (**Figures 1*b*** and **2**), including Tikal and its environs in the northeastern Petén, the Copán Valley in Honduras, the Petexbatún and Pasión River regions, some areas in northern Belize, and the Puuc region of the northwest Yucatán Peninsula (Scarborough et al. 2003, 2012; Fash et al. 2004; O'Mansky & Dunning 2004; Demarest 2006; Dunning et al. 2012; Iannone et al. 2016). In particular, the Pasión River region of the southwestern Petén (**Figure 1*b***) has been the subject of 30 years of multidisciplinary studies that have concentrated on the problems and events of the collapse period (e.g., Dunning et al. 1997, O'Mansky & Dunning 2004, Demarest 2006, Wright 2006, Emery 2008, Emery & Thornton 2008, Inomata 2008, Eberl 2014). In other regions, less effort has been focused on the collapse period, and archaeological chronologies are often less precise, with study beyond site epicenters being more limited. Although some archaeological chronologies are fairly precise, on the order of 10–20-year intervals, chronologies from other regions or sites are often less exact. Complicating the story further, in many cases collapse processes were generically correlated to the so-called Terminal Classic Period, which, depending on the site or region, means anytime between 700 and 1100 CE.

Based on extensive data, widespread disruption began by the end of the seventh century CE in the Pasión River Valley and some other regions. Evidence for societal collapse is seen not just in epicenters and with inscriptions detailing war events, but also in investigations of minor centers, villages, and the intersite rural landscape (Dunning et al. 1997, 1998; Demarest et al. 2004; O'Mansky & Dunning 2004; Demarest 2006; Eberl 2014; Iannone et al. 2016) (**Figure 2**). These data document that after 695 CE in the Pasión Valley and other western regions there was (*a*) political balkanization, with rulers sharing power with lesser nobles and merchant elites; (*b*) militarization of ideology and site placement, even at the village level; (*c*) increasing warfare; and (*d*) internal and external migration. This trend toward political dissolution in the Pasión Valley parallels a half-century-long disintegration of a large regional hegemony dominated by the site of Calakmul located in the EIR (**Figure 1*b*,*c***), which controlled this river system from 656 to 695 CE. It appears that when this alliance ended, the region slid into toxic intercity warfare.

Societal disruption peaked between 743 and 761 CE, with more destructive warfare, site abandonments, and large-scale emigration. Between 760 and 800 CE the major trade routes of the western Maya Lowlands broke down (**Figure 1*c***), and most centers on the Pasión and Usumacinta River routes had been besieged, destroyed or greatly depopulated. Therefore, collapse in the Pasión River Valley can be seen as a complex multi-stage process of political disintegration and emigration, culminating in the middle to late eighth century (Demarest 2006, Inomata 2008, Eberl 2014, Demarest 2015). Many archaeologists now recognize that, in many parts of the southern lowlands, collapse was primarily an eighth-century CE phenomenon (**Figure 2**) and view the 800–850 CE period that coincided with the most intensive and widespread droughts (**Figure 4**) as a postcollapse era. For this reason, many archaeologists have dismissed drought as the primary cause for the Maya collapse. We note that some paleoclimate records from Belize and central Petén document drought beginning as early as 760 CE (Kennett et al. 2012, Wahl et al. 2013, Wahl et al. 2014, Douglas et al. 2015b) (**Figures 4*b*** and **5*b***), suggesting greater overlap between the periods of drought and societal collapse. It appears, however, that the first manifestations of societal collapse in the eighth century CE still precede even this earlier evidence of drought.

The emphasis on chronological priority when considering the "collapse" of the Classic Maya could be overly simplistic. It is valid with regard to physical phenomena that "A" can cause "B" only if "A" precedes "B", but social systems are typically far more complex. Societal collapse is often a multi-stage process, and one could look to either inherent structural weakness in political or economic systems, i.e., "root" causes, or proximate factors like war and drought as "the cause" (Cowgill 1988) (see Section 4.3). Furthermore, social processes, including societal collapse, are reversible. Thus, although the "collapse" began in the Pasión and other regions, apparently before the onset of major droughts, to understand the collapse as a complete process it is necessary to examine closely the climatological and archaeological evidence from other regions. Of particular importance is the EIR (**Figure 1*c***), which contained many large cities and was one part of the Maya Lowlands that was more vulnerable to drought (Dunning et al. 2012).

4.2. Spatial Patterns of Drought and Collapse

Archaeological research on the eighth to eleventh centuries CE demonstrates great spatial variability of outcomes in the Maya Lowlands, which include complete abandonment to disruption, or even florescence in some northern and coastal regions (Demarest et al. 2004) (**Figure 2**). Although the spatial patterns of societal collapse were complex, population centers continued in many coastal regions and on the northern Yucatán Peninsula, whereas most states collapsed and landscapes were depopulated in the Pasión, Usumacinta, Palenque, and southeast regions, and, most notably, the EIR (**Figure 1*b***). The EIR was the seat of many powerful Lowland Maya states, and drought, alongside warfare, would have limited the capacity of EIR states to respond to the collapse processes occurring elsewhere in the southern lowlands.

As discussed above, recent evidence indicates a greater degree of drying in the central Petén relative to the northern Yucatán Peninsula (Douglas et al. 2015b), offering one possible explanation for geographic differences in societal change during the eighth to eleventh centuries CE. Another factor that could have influenced spatial variability in societal outcomes is the availability of surface water and groundwater (Dahlin 2002). The very deep water table in the EIR would have exacerbated the effects of drought (Dunning et al. 2012), as populations there would have been dependent on rainwater stored either in manmade reservoirs or perched aquifers (**Figure 1*c***). In contrast, in coastal Belize and the northern Yucatán Peninsula, the shallow water table is accessible in surface rivers and *cenotes*, respectively, which could have mitigated the effects of low precipitation. However, there are also large surface rivers, lakes, and wetlands in the Copán Valley, the western lowlands, and especially the Pasión and Usumacinta regions (**Figure 1*b***), where societal collapse occurred earliest and most severely (**Figure 2**). It is clear, therefore, that access to freshwater cannot be considered as determining patterns of collapse.

Importantly, the longevity of the Puuc and Chichén Itzá polities of the northern Yucatán Peninsula was likely facilitated by access to the coast (**Figure 1*b***). Via their linked ports these states could engage in major coastal trade routes (**Figure 1*c***), which were increasing in importance at the end of, and following, the Classic Period (Sabloff & Andrews 1986). On the other hand, the economic advantages of the northern Yucatán Peninsula make it difficult to explain the later demise of the Puuc (~950–1000 CE) and Chichén (~1050–1100 CE) polities without considering environmental changes, particularly the severe droughts that continued to affect this region (**Figure 4**).

4.3. Integration of Drought with Other Causes of Collapse

There is definitive evidence for a number of proximate causes of the Classic Maya collapse, including drought, warfare, anthropogenic environmental deterioration, and overpopulation (Lucero 2002, Demarest et al. 2004, Fash et al. 2004, Inomata 2008, Dunning et al. 2012, Iannone 2014, Iannone et al. 2016). Given the evidence for the complexity of Classic Maya civilization and the multiple probable proximate causes of societal collapse, it is likely that several causal factors were involved in the spatially variable, but dramatic, collapse process. These proximate causes must also be considered in the context of deep structural problems, or ultimate causes, faced by the Maya civilization during the Late Classic Period, related to the increasingly archaic, noncompetitive nature of its divine kingship system. In preceding centuries, other states in Mesoamerica had developed a more resilient system of political leadership, that is, one capable of adaptation to internal and external change, with power shared among more institutions and leaders (Sharer & Traxler 2006, Demarest 2015, Demarest et al. 2016). In contrast, Classic Maya states achieved only a limited institutionalization of its power structures, with political power legitimized through an ideology of divine rulership embodied in the *k'ujul ajaw* (Iannone et al. 2016). This political system generated status-rivalry competition between rulers who sought to gain and hold legitimacy through magnificent monuments, architecture, grand rituals, and warfare, which were very costly in terms of both resources and labor. Attempts at larger regional integration were short lived, which exacerbated instability. Furthermore, Classic Maya kingdoms were heavily dependent on local, broad-based subsistence agriculture and could not easily shift to overproduction of basic food crops for exchange at a large scale (Lentz et al. 2014).

In this sense, the Classic Maya political and economic system of the lowlands perhaps faced inevitable collapse and/or radical change. Nonetheless, the evidence presented here suggests that, particularly in the EIR, climate change was a major contributing factor in the ninth-century inability of Maya states to reverse crises and political disintegration that had begun in the southern lowlands during the eighth century CE. Additionally, droughts may have been a central factor in the later rapid decline and collapse of the northern Yucatán Puuc and Chichén Itzá polities (**Figure 2**).

4.4. Relating Earlier Droughts to Societal Change

The ninth century CE drought was not the first period of drought to affect the Lowland Maya, although it was probably the most severe. To understand the role of droughts at the end of the Classic Period, it is valuable to compare them with evidence for drying during the Late Preclassic and Early Classic Periods (**Figure 4**; Section 3.2.2). Climatic drying between ∼100 and 300 CE (**Figure 3**) represented a major change from the wet climate of the Late Preclassic Period. Societal collapse occurred between 100 and 250 CE, at the end of the Preclassic, in various regions, notably within the politically dominant Mirador Basin of northern Guatemala (Hansen 2011) (**Figure 1*b***). Evidence from the Mirador region, and other regions of the Maya Lowlands, indicates major Late Preclassic episodes of erosion and soil deposition in lakes and swamps, which were related to the spread of slash-and-burn agriculture, deforestation for lime stucco production, and population growth (Dunning et al. 1997, 2002; Beach et al. 2006; Anselmetti et al. 2007; Hansen 2011). Thus, archaeological, paleoecological, and paleoclimate studies point to both anthropogenic environmental degradation and climate change as probable agents of societal collapse at that time.

A key difference between the Preclassic and Classic Maya collapse periods is that recovery after the end of the Preclassic occurred relatively quickly. As El Mirador and other centers declined, other polities in the southern lowlands rose rapidly in the Early Classic to take their place (Sharer & Traxler 2006). Under the drier and more variable climate of the Early Classic Period, it appears that water control became an important component of political economy in the EIR (Lucero 2002, Scarborough et al. 2012, Lentz et al. 2014). There is also evidence that drying during the Preclassic–Classic transition coincided with a shift in land use in some regions, from extensive agriculture to more intensive agriculture focused in wetlands (Dunning et al. 2002, Luzzadder-Beach et al. 2012, Douglas et al. 2015b). These patterns suggest that in most areas, particularly in the EIR, the ancient Maya successfully responded to a drier climate and other ecological challenges in the Early Classic by carefully managing water resources and intensifying agricultural production. Management of water and agricultural resources may have also contributed to the greater political centralization seen in some Classic Maya states.

This raises the question of why the adaptive strategies of the Classic Period, partially designed to deal with dry conditions, failed to prevent societal collapse or allow recovery across much of the Maya Lowlands during the ninth- to eleventh-century droughts. Possible explanations include the following: (*a*) Later droughts were more intense and surpassed the adaptive capabilities of the Lowland Maya; (*b*) societal changes during the Classic Period, such as higher population density, maximized resource use, and increased political complexity made the Late Classic Maya increasingly vulnerable to drought; and (*c*) economic changes across Mesoamerica rendered the inland lowland regions (most of the Maya Lowlands) unable to support large states.

4.5. Drought and the Absence of Postclassic Recovery

Understanding why Classic Maya society collapsed in the eighth to eleventh century CE is fundamentally related to the observation that Maya society never subsequently recovered throughout most of the lowlands. As discussed above, Maya prehistory was marked by earlier events, particularly the crises at the end of the Late Preclassic (100–250 CE), during which some prominent polities declined or collapsed but later recovered. What makes the Classic collapse different and more dramatic is that in many regions, particularly the EIR and western lowlands (**Figure 1*b*,*c***), social organization and population declined both dramatically and permanently. Notably, populations that did recover were primarily located along the Caribbean and Gulf Coast trade routes and in the vicinity of lakes in the central Petén (Sabloff & Andrews 1986) (**Figure 1*b***). It is telling that these two environments—coasts and lakes—correspond to the major trade routes and to the most secure access to permanent water bodies, respectively. Trade and water access are related to economic change and drought, respectively, two major factors that were likely involved in limiting recovery during the Postclassic.

Most paleoclimate records indicate that droughts continued into the Early Postclassic Period, up to ~1100 CE (**Figure 4**). Therefore, it is likely that persistent dry conditions for ~200 years after societal collapse, i.e., from ~900 to 1100 CE, would have discouraged efforts to rebuild large cities, particularly in the EIR, where populations relied on labor-intensive hydraulic systems and surface reservoirs (Dunning et al. 2012). However, it is difficult to explain based on climate alone why most of these areas did not gradually increase in population. More importantly, it does not explain the lack of a significant Early Postclassic recovery in the riverine and lake areas of the Pasión/Usumacinta and southernmost Petén zones (**Figure 1*b***), which had ample surface water and did not depend on water-storage systems. In this sense, part of the explanation for the absence of Postclassic recovery was economic and political. The redistribution of populations in the Postclassic corresponds closely to changes in economy and a shift to coastal trade routes (**Figure 1*c***), which would have left the interior regions with minimal economic potential (Sabloff & Andrews 1986), as they had little to offer in the way of resources for long-distance commodities production and exchange.

The paleoclimate data indicate that wetter conditions, similar to those experienced in the Classic Period, had returned by ~1100 CE (**Figure 4**). Therefore, adverse climate conditions would not have prevented reconstruction of cities in the EIR or other areas after that time. However, by that time, the changes in trade routes and economic systems that had rendered the EIR and western lowlands economically isolated were firmly established, and there would have been little incentive to reestablish the major cities of these regions.

5. CONCLUSIONS

There is now a large body of proxy data on late Holocene hydroclimate in the Maya Lowlands. These records make it clear that climate was variable throughout Maya prehistory and that the droughts of the ninth to eleventh centuries CE were unprecedented, at least with respect to the previous 1800 years. The causes of these droughts remain uncertain. We suggest that drought was related, at least in part, to temperature gradients between the Tropical Atlantic and Eastern Tropical Pacific that would have influenced convective summer rainfall in Central America.

Whereas there is unequivocal evidence for anomalous droughts during the ninth to eleventh centuries, archaeological research increasingly contradicts the notion that drought was the primary cause of societal collapse at that time. Revised archaeological chronologies and new multidisciplinary research on warfare and political disintegration in the context of pan-Mesoamerican culture change point to the eighth century as the initial period of crisis in the Pasión/Usumacinta region and some other regions as well. These crises preceded strong droughts.

The notion that drought alone reduced a highly functional civilization to rubble within a century appears untenable, or at least simplistic. It is now clear that the Lowland Maya suffered from long-term structural weaknesses during the Late Classic Period, which made them vulnerable to political disturbance and collapse. At the same time, it is highly likely that major droughts played an important role in exacerbating social turmoil in Maya polities that were both sensitive to drought and increasingly unstable. It is probable that the droughts, which intensified over the course of the ninth century CE, had powerful impacts on a society that was already destabilized by the warfare, economic challenges, failed attempts at unification, and the political crises of the preceding century.

Paleoclimate research related to the ancient Maya should shift its attention from a narrow focus on drought as a cause for societal collapse, toward documenting climate variability throughout Maya prehistory and examining societal responses to climate change on multiple timescales. This may appear less exciting than determining that drought caused collapse, but it will ultimately prove more rewarding for both climate science and archaeology. Between the Preclassic and Early Postclassic Periods, the Lowland Maya experienced a broad range of climates over time and space. Exploring the response of the Lowland Maya to different climate conditions offers a valuable opportunity to examine climate vulnerability and adaptation of complex societies in tropical environments.

An initial analysis of the long-term relationship between the ancient Maya and climate highlights the nonlinear nature of this relationship. By nonlinear, we mean that societies do not respond proportionally and unidirectionally to climate change. There are two particular examples from the Maya Lowlands. First, it appears that drying at the end of the Preclassic encouraged intensification of agriculture and water conservation, responses that allowed for increasing population and political complexity despite reduced water resources. It appears, however, that the Classic Maya were unable to adapt effectively to the even drier conditions of the ninth and tenth centuries CE, possibly because population growth, resource exhaustion, warfare, and economic change had made further adaptation impossible.

The second example concerns the aftermath of the Lowland Maya collapse. We suggest that the ninth- to eleventh-century CE droughts contributed to depopulation for the central EIR polities. However, these polities did not recover when relatively wet conditions returned by ~1100 CE, most likely because the development of coastal trade networks and new forms of economy left them at a geopolitical disadvantage. Therefore, the return of favorable climate conditions was not sufficient to enable recovery of cities that had been previously destabilized by drought. This concept of nonlinearity could ultimately prove to be a key lesson learned from studying the Classic Maya response to climate change.

SUMMARY POINTS

1. The period of severe droughts from the ninth to eleventh century CE were unprecedented in Maya prehistory.
2. There is spatial variability in drought timing and intensity, with evidence for earlier and stronger droughts in Belize and the central Petén relative to the northern Yucatán Peninsula.
3. On the northern Yucatán Peninsula drought events between 800 and 950 CE entailed a 20% to 65% reduction in rainfall.
4. No single forcing mechanism readily explains drought events in the Maya Lowlands, but variability in both Atlantic and Pacific Ocean temperatures were likely important.
5. Collapse processes at the end of the Classic Period in the Maya Lowlands began in several regions during the early eighth century CE, before the onset of major droughts.
6. Drought likely played an important role in later regional collapse processes.
7. There is evidence for Maya adaptation to an earlier period of drying climate between approximately 250 and 500 CE.

8. Drought and changing trade routes together appear to have prevented a significant recovery of complex society after the collapse of Classic Maya civilization in many interior regions of the lowlands.

FUTURE ISSUES

1. Paleoclimatological and archaeological chronologies should continue to be refined and integrated.
2. Improved characterization of spatial variability in drought impacts is needed.
3. Integrative analysis of the relationship between drought and other proximate and ultimate causes of societal collapse should be performed.
4. Understanding how the Maya responded to climate change throughout their history requires a broadened temporal focus.

DISCLOSURE STATEMENT

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