Tracing the effects of the Little Ice Age in the tropical lowlands of eastern Mesoamerica

Ma. del Socorro Lozano-García*†, Margarita Caballero‡, Beatriz Ortega‡, Alejandro Rodríguez§, and Susana Sosa*

*Instituto de Geología, ‡Instituto de Geofísica, and §Posgrado en Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México, México D.F., 04510, México

Communicated by Linda Manzanilla, National Autonomous University of Mexico, Mexico, D.F., Mexico, August 21, 2007 (received for review May 10, 2007)

The causes of late-Holocene centennial to millennial scale climatic variability and the impact that such variability had on tropical ecosystems are still poorly understood. Here, we present a high-resolution, multiproxy record from lowland eastern Mesoamerica, studied to reconstruct climate and vegetation history during the last 2,000 years, in particular to evaluate the response of tropical vegetation to the cooling event of the Little Ice Age (LIA). Our data provide evidence that the densest tropical forest cover and the deepest lake of the last two millennia were coeval with the LIA, with two deep lake phases that follow the Spörer and Maunder minima in solar activity. The high tropical pollen accumulation rates limit LIA's winter cooling to a maximum of 2°C. Tropical vegetation expansion during the LIA is best explained by a reduction in the extent of the dry season as a consequence of increased meridional flow leading to higher winter precipitation. These results highlight the importance of seasonal responses to climatic variability, a factor that could be of relevance when evaluating the impact of recent climate change.

climate variability | Late Holocene | Mexico | seasonality | tropical ecosystems

The Little Ice Age (LIA) (1350–1850 A.D.) has been identified as one of the most important climatic oscillations of the late Holocene and the last of several centennial to millennial scale Holocene cooling events centered over the North Atlantic (1–4). Low-latitude cooling during the LIA is evident from tropical glacier advances (5, 6), and reduced sea-surface temperatures in the Caribbean (7–9). Dry LIA conditions in the Caribbean are relatively well documented and explained by a change in the position of the Intertropical Convergence Zone (ITCZ) (10, 11), but little is known about the impact that this climatic event had on the lowland tropical ecosystems of the Americas. Lago Verde, near the coast of the Gulf of Mexico (Fig. 1), is a highly sensitive record of recent climate change (12, 13) where the response of the tropical vegetation and the lake system to the LIA cooling can be clearly traced, without any significant human impact. Multiproxy data from this lake show that in this tropical region the LIA is recorded by the deepest lake level and the densest forest cover of the last two millennia. In this article, we present arguments evaluating the role of solar forcing as an important element explaining climatic variability in the tropics and the North Atlantic region. We also discuss the role of regional moisture balance as a condition for the expression of regional precipitation trends, and, finally, we present an argument about the importance that changes in the seasonality of precipitation can have over the Gulf of Mexico coastal region, mitigating the dry LIA trend recorded in some areas of the Caribbean.

Study Site

This study is based mainly on pollen, charcoal particles, and diatom analyses on the sediment record from Lago Verde, a small, closed-basin lake at 200 m above sea level, on the outskirts of the Sierra de Los Tuxtlas (Fig. 1). Los Tuxtlas is a volcanic field on the Gulf of Mexico's coast where orographic uplifting results in the presence of some of the wettest climates in Mesoamerica. Topography also affects the vegetation distribution in the region, with tropical evergreen rainforest in the lowlands, <700 m above sea level, and mesophytic upland forests at the higher altitudes (14, 15). The climatic controls are similar to those in the Caribbean, with a summer rainfall season associated with the northerly shift of the ITCZ and an increased moisture supply from the trade winds, and with late summer and early autumn precipitation related with tropical storms and hurricanes. Orographic uplifting of polar air outbreaks produces winter precipitation (≈10% of a total annual mean of ≈2,500 mm) along with a temperature reduction of ≈10°C (16).

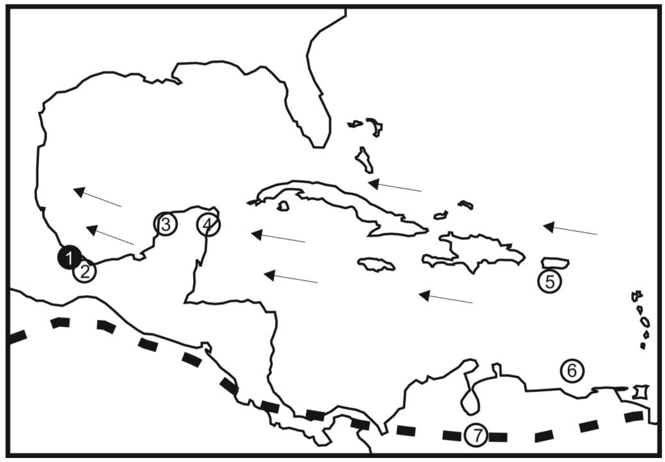

Fig. 1. Location map showing the study area in the context of eastern Mesoamerica and the Caribbean. ➊ Lago Verde (18° 36′ 46″N; 95° 20′ 52″W) and ② Pompal (18), both located in the Sierra de Los Tuxtlas. ③ Aguada X′caamal (10) and ④ Punta Laguna (21) located on opposite extremes of the Yucatan peninsula, along an east-west moisture gradient. ⑤ The sites off the coast of Puerto Rico where LIA colder conditions have been recorded in the Caribbean (7–9). ⑥ The location of Cariaco Basin (11). ⑦ Dashed line shows the summer location of the ITCZ, and arrows show the summer distribution of trade wind flow.

Results

The region of Los Tuxtlas was an important cultural center within Mesoamerica, with a demographic maximum during the early and middle Classic (200–750 A.D.) and abandonment of urban areas during the late Classic (750–900 A.D.) (17). This

Author contributions: M.d.S.L.-G., M.C., and B.O. designed research; M.d.S.L.-G., M.C., B.O., A.R., and S.S. performed research; M.d.S.L.-G., M.C., B.O., A.R., and S.S. analyzed data; and M.d.S.L.-G. and M.C. wrote the paper.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

Abbreviations: LIA, Little Ice Age; ITCZ, intertropical convergence zone; PAR, pollen accumulation rate; TF, tropical forest; STF, secondary tropical forest; UF, upland forest.

†To whom correspondence should be addressed. E-mail: mslozano@servidor.unam.mx.

www.pnas.org/cgi/doi/10.1073/pnas.0707896104

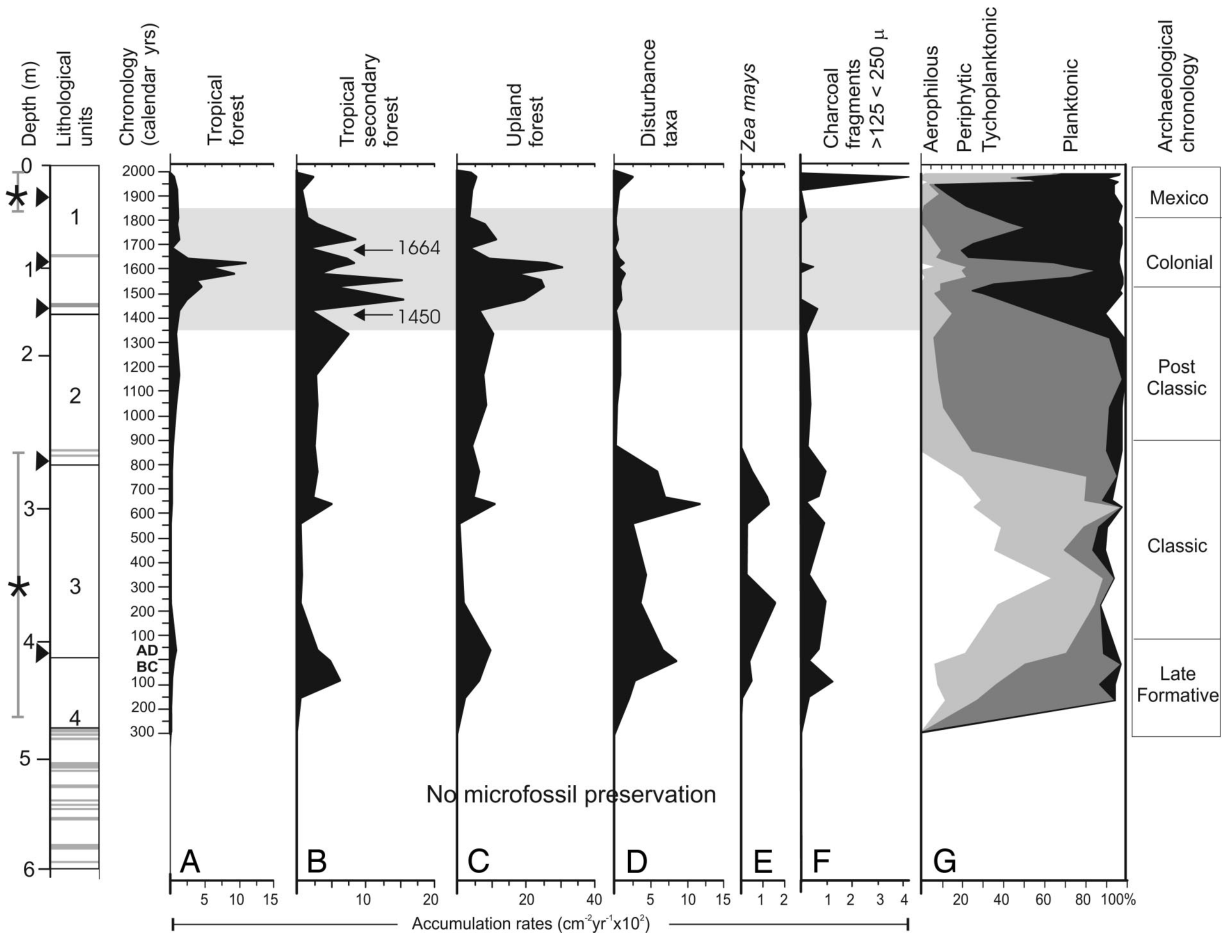

Fig. 2. Pollen groups, charcoal particles, and diatom groups from Lago Verde versus calendar years (B.C. and A.D.). (*A*) PARs (grains cm^{-2}·yr^{-1} $\times$ 100) of TF taxa. (*B*) PARs of STF taxa. (*C*) PARs of UF taxa. (*D*) PARs of disturbance taxa. (*E*) PAR of *Z. mays.* (*F*) Accumulation rates of macroscopic charcoal particles. (*G*) Percentage diagram summarizing diatom habitat groups. On the left are the lithological units with tephra layers in gray. Black arrows show episodes of volcanic impact within the LIA. Dated levels are marked by black triangles. Asterisks show episodes of human impact. On the right are the subdivisions of Mexico's cultural evolution.

pattern of occupation is evident in the Lago Verde record. Low arboreal pollen accumulation rates (PARs) and high PARs of disturbance taxa, *Zea mays* and charcoal particles, during the Classic period (Fig. 2) exhibit the agricultural occupation of the basin. Agricultural abandonment by ≈800 A.D. is recorded as a steep reduction in charcoal fragments and disturbance taxa and the absence of maize pollen. Between ≈800 and 1920 A.D., human presence around this lake was minimal (Fig. 2). A similar pattern is observed at Lake Pompal, located further south in the Sierra de Los Tuxtlas (Fig. 1) (18), which also indicates the lack of significant human presence in the region during the LIA that could obscure the effects of climatic variability. Two tephra layers within the LIA age interval indicate volcanic impacts; the older one dates to the late 15th century (≈1450), and the younger one represents the 1664 eruption of the nearby San Martín volcano (12), which is coincident with low PARs of all taxa (Fig. 2).

An increase in arboreal taxa is recorded around the time of agricultural abandonment indicating, as in Pompal (18), forest regeneration between 650 and 800 A.D.. However, at Lago Verde, the largest increase in accumulation rates of arboreal taxa, including the evergreen tropical forest (TF), secondary TF (STF), and mesophytic upland forest (UF), in association with a change in sedimentary facies (13), occurs 600 years after agricultural abandonment, between 1400 and 1850 (Fig. 2), during the LIA. The diatom assemblage shows a marked increase in the percentages of planktonic taxa with respect to the previous intervals (Fig. 2). This increase indicates deeper LIA lake level, with two main deep water episodes ≈1500–1550 and 1650–1700. A deeper LIA lake is also supported by the magnetic mineralogy data from this core, which records anoxic conditions leading to magnetite dissolution (13).

Discussion

Historical and geological records suggest that the LIA was not a continuously cold interval, but that it showed high temporal variability; for example, in some of the Greenland ice cores (19) and in the low-latitude North Atlantic (eastern North Atlantic and Bermuda Rise) (4, 20) the LIA shows a pattern with two main cooling events. This pattern is also present at Lago Verde, evident from the two deep water episodes (≈1500–1550 and 1650–1700), which correlate with an expansion of the UF taxa, particularly *Pinus* (Fig. 3), and together reflect two maximum cooling phases that follow the Spörer and Maunder minima in solar activity (Fig. 3). In the Caribbean the record from Punta Laguna (21), northeast Yucatan, also shows a signal that follows solar activity, with higher moisture during solar minima (6) (Fig. 3). The intermediate interval between both solar minima (Spörer and Maunder), during the late 16th century, is characterized at Lago Verde and Punta Laguna by a slight reduction in available moisture (Fig. 3). At Lago Verde the best representation of the TF occurs during the relatively higher solar

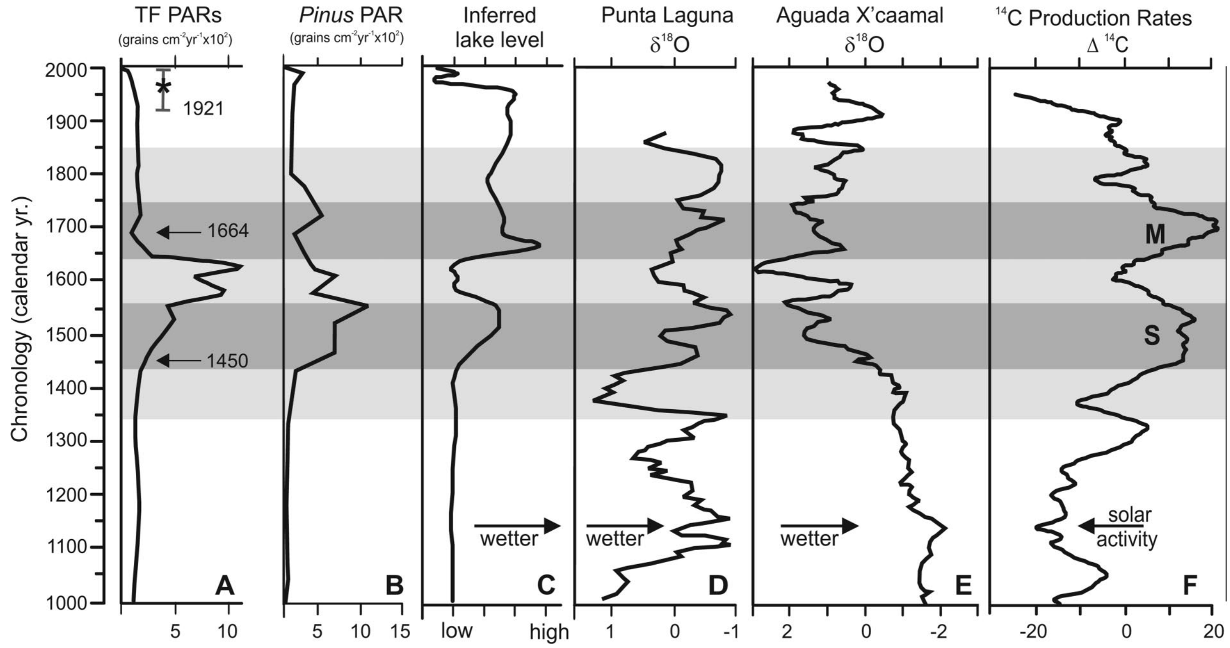

Fig. 3. Comparison of records from eastern Mesoamerica during the LIA with solar activity during the last 1,000 years. (*A*) PARs of the TF taxa in Lago Verde; arrows indicate disturbance in the vegetation caused by volcanic activity and the asterisk shows the recent anthropogenic impact beginning at ≈1921. (*B*) PAR of *Pinus* in Lago Verde. (*C*) Lago Verde diatom inferred lake level. (*D*) $\delta^{18}O$ record of *Cytheridella ilosvayi* from Punta Laguna (21), northeast Yucatan. (*E*) $\delta^{18}O$ of *P. coronatus* from Aguada X′ caamal (10), northwest Yucatan. (*F*) ^{14}C production rates (33), which are an inverse proxy for solar activity. Light gray-shaded area indicates the span of the LIA, and darker gray-shaded areas indicate the Spörer and Maunder minima in solar activity that correlate with high inferred lake level at Lago Verde and low $\delta^{18}O$ values from Punta Laguna, which are indicative of moister conditions.

output and likely warmer conditions between both solar minima (Fig. 3). This relatively warm episode in the late 16th century is recorded as one of the most important droughts during the last 500 years in northwest Mexico (ref. 22 and references therein), a region where currently arid climates are dominant, and as a time of historical deadly epidemics in central Mexico (23, 24). The data from Lago Verde strongly suggest that during the LIA lake levels and vegetation at Los Tuxtlas were responding to solar forcing and provide further evidence that solar activity is an important element controlling decadal to centennial scale climatic variability in the tropics (6) and in general over the North Atlantic region (2, 19).

The high arboreal taxa (TF, STF, and UF) PARs between 1350 and 1800 at Lago Verde suggest that during the LIA the region had higher moisture availability and a shorter or nonexistent dry season, given that moisture availability is an important limiting factor for evergreen tropical vegetation (25). Considering that present winter temperatures range close to 20°C, we infer a maximum winter cooling of 2°C, as winter temperatures <18°C constrain the development of TFs (25). This temperature estimate is in agreement with data from the low-latitude North Atlantic where sea surface temperature decrease estimates range between −1°C and −3°C in records from the Caribbean (7–9), the Bermuda Raise (20), and the eastern North Atlantic off the coasts of Africa (4). Some of these studies show a smaller temperature decrease for winter than for summer (8), which is relevant in this case, as winter temperatures are more important than summer temperatures as a limiting factor for tropical vegetation.

However, why did Los Tuxtlas have a relatively wet climate during the LIA if some sites in the Caribbean were drier? A dry LIA signal is recorded at Aguada X'caamal, northwest Yucatan, from high $\delta^{18}O$ values from ostracodes and gasteropods and the presence of the foraminifer *Amonia becarii*, which show an increase in salinity linked to increased aridity between 1450 and 1900 (10) (Fig. 3). In the Cariaco Basin (off the coast of Venezuela) (Fig. 1) an important decrease in the Ti content of laminated marine sediments is interpreted as lower rainfall and reduced runoff to this basin between 1500 and 1800 (11). Dry tropical conditions at northwest Yucatan and the Cariaco Basin have been related to a southward displacement of the ITCZ (10, 11) and hence reduced trade wind moisture supply to the Caribbean during the summer. The region of Los Tuxtlas should be sensitive to any reduction in the moisture supply by the trade winds, as they are the main moisture source for the summer rainfall season characteristic of this region. Nevertheless, wetter LIA conditions are recorded in Lago Verde and to a lesser extent also in Punta Laguna, located at the opposite end of the Yucatan peninsula from Aguada X'caamal (Fig. 3). At Punta Laguna (note limited dating control) the $\delta^{18}O$ from ostracodes and gasteropods (21) shows an initial drought event followed by two wet phases during the Spörer and Maunder minima in solar activity, as discussed previously. We suggest that the potential reduction in summer precipitation inferred from the Aguada X'caamal and Cariaco records was not great enough to generate a moisture deficiency at Los Tuxtlas, which is a particularly wet area, with a current net water surplus on the order of 900 mm/yr. In contrast Aguada X'caamal (northwest Yucatan) is located in a drought-sensitive area, with a net water deficit of ≈500 mm/yr. At Punta Laguna (northeast Yucatan), total precipitation is at least 50% higher than at Aguada X'caamal, and net water deficit is much lower, ≈100 mm/yr. Extended LIA drought conditions in the Yucatan are therefore evident only in areas where evaporation greatly outbalances precipitation, such as northwestYucatan. But in regions with higher moisture availability, the reduced summer moisture supply to the area during the LIA was not enough to generate intense drought conditions, and rather cooler LIA temperatures reduced the evaporation component of the moisture balance.

For the Gulf of Mexico coastal region, increased winter precipitation may be a critical factor explaining LIA climates, in particular, supporting our interpretation of a reduction in the extent of the dry season. Reduced LIA sea surface temperatures in the Caribbean (7–9) have been explained by a more intense winter meridional flow associated with more frequent outbursts of polar air. In the Sierra de Los Tuxtlas, an increase in polar air outbursts would be related with an increase in winter precipitation, reducing the intensity and duration of the dry season. This is a likely mechanism explaining the higher moisture availability recorded at Los Tuxtlas during the LIA as deep lake levels and as a general expansion of forest cover. This mechanism can be of importance in the climate of other regions where topographic uplifting favors moisture release, such as the coastal region of the Gulf of Mexico. The flat topography of Yucatan, in contrast, is not as favorable for this mechanism of increased winter rainfall.

Our data provide evidence of the variable geographical response to climate change in the Mesoamerican tropics and the relevance of seasonality in tropical environments. These are factors that can be valuable for explaining the patterns of decadal to centennial scale climatic variability that are emerging for tropical Africa where a precipitation gradient has been documented during the LIA (26), with dry conditions over western east Africa (i.e., Lake Malawi; ref. 27) contrasting with an increase in lake levels in the more eastern lakes (i.e., Lake Naivasha; ref. 28). Together, the African and Mesoamerican records show that the tropics cannot be considered as a climatic region responding unidirectionally to global change; instead they give evidence of more complex patterns of climatic variability that can offer new scenarios to asses the impacts of recent climate change at a regional level.

Methods

The sedimentary sequences from Lago Verde were recovered from the central part of the lake, using a nonrotatory piston corer. The chronology of the 6-m sediment sequence is based on five accelerator mass spectrometer radiocarbon dates determined on pollen extract to avoid the "old carbon" effect (13) and by correlation with a parallel core dated by 210 Pb and 137 Cs (12, 29). Charcoal, pollen, and diatom samples were collected on average every 8 cm, which gives a temporal resolution of 30–80 years. Pollen identification was made at the Instituto de Geología by using the pollen collection of the Tropical Biological Station at Los Tuxtlas (30, 31). Minimum pollen counts of 550 grains were used to calculate PARs (32). Taxa in Fig. 2 were assigned to ecological groups based on extensive botanical and ecological studies in the area (15). For the TF group, 31 taxa are included, and the most abundant are Moraceae-Urticaceae, *Ficus*, *Lonchocarpus*, *Miconia*, *Buchonsia*, *Alchornea*, *Aegiphylla costaricensis*, *Capparis*, *Cordia*, *Psychotria*, *Robinsonella mirandae*, *Tabebuia*, *Spondias*, *Eugenia*, and *Astrocaryum mexicanum.* The STF group includes 10 taxa, and the most abundant are *Cecropia*, *Trema*, *Heliocarpus*, and *Piper.* In the UF group, *Pinus*, *Quercus*, *Ilex*, *Ulmus*, *Liquidambar*, and *Carpinus* are the dominant taxa of the 10 pollen types included. The disturbance taxa group (22 taxa) includes *Ambrosia* with the highest accumulation rate and Compositae, Poaceae, *Acacia*, *Mimosa*, *Paspalum*, *Hyptis*, Chenopodiaceae-Amaranthaceae, *Heliotropium*, *Senna*, and *Desmodium.*

For macroscopic charcoal analysis, 1-cm^3 sediment samples were soaked in 50 ml of 5% sodium hexametaphosfate deflocculating solution for several days, then washed gently through 120- and 250-μm sieves. Charcoal particles were counted in each fraction through.

For diatom analysis, a minimum of 400 valves were counted and assigned to the habitat groups in Fig. 2. Main taxa in each group are: Aerophilous, *Luticula mutica*, *Hantzchia amphioxys*, *Pinnularia* spp., *Navicula arvensis*, *Navicula atomus*, *Navicula contenta*; Periphytic, *Achanthidium minutissimum*, *Nitzschia amphibia*, *Nitzschia palea*, *Gomphonema* spp., *Encyonema* spp.; Tychoplanktonic, *Pseudostaurosira brevistriata*, *Staurosirella pinnata*, *Staurosira construens*, *Cyclotella stelligera*; Planktonic, *Aulacoseira ambigua*, *Aulacoseira granulata*, *Aulacoseira muzzanensis.*

We thank L. Vázquez, J. Urrutia, and B. Martiny for their comments and the Limnological Research Center, University of Minnesota (Minneapolis, MN) for support. This work was supported by Consejo Nacional de Ciencia y Technología Grant G28528-T and Universidad Nacional Autónoma de México Grant IN107902.

1. Bond G, Showers W, Chesby M, Lotti R, Almasi P, deMenocal P, Cullen H, Hajdas I, Bonani G (1997) *Science* 278:1257–1266.
2. Bond G, Kromer B, Beer J, Muscheler R, Evans MN, Showers W, Hoffmann S, Lotti-Bond R, Hajdas I, Bonani G (2001) *Science* 294:2130–2136.
3. Poore RZ, Dowsett HJ, Verardo S (2003) *Paleooceanography* 18:1048.
4. DeMenocal P, Ortiz J, Guilderson T, Sarthein M (2000) *Science* 288:2198–2202.
5. Vazquez-Selem L (2000) PhD dissertation (Arizona State University, Tempe, AZ)
6. Polissar PJ, Abbott MB, Wolfe AP, Bezada M, Rull V, Bradley RS (2006) *Proc Natl Acad Sci USA* 103:8937–8942.
7. Winter A, Goenaga C, Maul GA (2000) *Geophys Res Lett* 27:3365–3368.
8. Watanabe T, Winter A, Oba T (2001) *Marine Geol* 173:2 1–35.
9. Nyberg J, Malmgren BA, Kuijpers A, Winter A (2002) *Paleogeogr Paleoclimatol Paleoecol* 183:25–41.
10. Hodell DA, Brenner M, Curtis JH, Medina-González R, Ildefonso-Chan Can E, Albornaz-Pat A, Guilderson TP (2005) *Q Res* 63:109–121.
11. Haug G, Günther D, Peterson LC, Sigman KA, Hughen B, Aeschliman B (2003) *Science* 299:1731–1735.
12. Caballero M, Váquez G, Lozano-García S, Rodríguez A, Sosa-Nájera S, Ruíz-Fernández C, Ortega B (2006) *J Paleolim* 5:83–97.
13. Ortega B, Caballero M, Lozano S, Vilaclara G, Rodríguez A (2006) *Earth Planet Sci Lett* 250:444–458.
14. Alvarez del Castillo C (1977) *Biotica* 2:3–54.
15. González-Soriano E, Dirzo R, Voigt R, eds (1997) *Historia Natural de Los Tuxtlas* (Universidad Nacional Autónoma de México, Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad, México DF, México).
16. Soto M, Gama L (1997) in *Historia Natural de Los Tuxtlas*, eds Dirzo R, González-Soriano E, Vogt R (Universidad Nacional Autónoma de México, Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad, México DF, México), pp 7–23.
17. Santley RS, Arnold PJ, III (1996) *J Field Arch* 23:225–249.
18. Goman M, Byrne R (1998) *Holocene* 8:83–89.
19. Dahl-Jensen D, Mosegaard K, Gundestrup N, Clow GD, Johnsen SJ, Hansen AW, Balling N (1998) *Science* 282:268–271.
20. Keigwin LD (1996) *Science* 274:1504–1508.
21. Curtis JH, Hodell DA, Brenner M (1996) *Q Res* 46:37–47.
22. Cleaveland MK, Stahle DW, Therrell MD, Villanueva-Díaz J, Burns BT (2003) *Climate Change* 59:369–388.
23. Acuña-Soto RD, Stahle DW, Cleaveland MK, Therrell MD (2002) *Emerging Infections Dis* 8:360–362.
24. Mendoza B, Jáuregui E, Díaz-Sandoval R, García-Acosta V, Velasco V, Cordero G (2005) *J Appl Meterol* 44:709–716.
25. Pennington TD, Sarukhán J (2005) *Arboles Tropicales de México* (Universidad Nacional Autónoma de México, Fondo de Cultura Económica, México DF, México).
26. Russell JM, Verschuren D, Eggermont H (2007) *Holocene* 17:183–193.
27. Brown ET, Johnson C (2005) *Geochem Geophys Geosyst*, 10.1029/2005GC00095.
28. Verschuren D, Laird KR, Cumming BF (2000) *Nature* 403:410–414.
29. Ruiz-Fernández C, Hillaire-Marcel C, Páez-Osuna F, Ghaleb B, Caballero M (2007) *Q Res* 67:181–192.
30. Lozano-García S, Martínez-Hernández E (1990) *Publication Especiales 3 Instituto de Biología* (Universidad Nacional Autónoma de México, México DF, Mexico).
31. Lozano-García S, Ibarra-Manríquez G, Sosa-Nájera S (1995) *Bol Soc Bot Mex* 57:79–102.
32. Grimm E (1992) Tilia Software (Illinois State Museum, Springfield, IL).
33. Reimer PJ, Baillie MGL, Bayliss A, Beck JW, Bertrand C, Blackwell PG, Buck CE, Burr G, Cutler KB, Damon PE, *et al.* (2004) *Radiocarbon* 46:1029–1058.

ENVIRONMENTAL SCIENCES