A ~43-ka record of paleoenvironmental change in the Central American lowlands inferred from stable isotopes of lacustrine ostracods


Abstract

We present a continuous ostracod isotope (δ18O and δ13C) record from Lake Petén Itzá, Petén, Guatemala, in the northern, lowland Neotropics that spans the last ~43 cal ka BP. Variations in oxygen and carbon isotopes closely follow lithologic variations, which consist of alternating gypsum and clay deposits that were deposited under relatively dry and wet climate, respectively. During the last glacial period, the greatest δ18O and δ13C values coincide with gypsum deposited during lake lowstands under arid climate conditions that were correlated previously with North Atlantic Heinrich events. In contrast, interstadials and the entirety of the Last Glacial Maximum (~24–19 cal ka BP) are marked by clay deposition and lower δ18O and δ13C values, reflecting higher lake levels and relatively moister climate.

Isotope results and pollen data, along with independently inferred past water levels, show the early deglacial period (~19–15 cal ka BP) was the time of greatest aridity and lowest lake stage of the past 43 ka. This period occurred during Heinrich Stadial 1 (HS 1), when an extensive tropical megadrought has been postulated (Stager et al., 2011). Heinrich Stadial 1 is represented by two episodes of gypsum precipitation and high δ18O and δ13C values in Petén Itzá, interrupted by an intervening period of lower δ18O and δ13C and clay deposition centered on ~17 cal ka BP. The two periods of inferred maximum cold and/or arid conditions at ~17.5 and 16.1 cal ka BP coincide approximately with two pulses of ice-rafted debris (IRD) recorded off southern Portugal (Bard et al., 2000). At ~15 cal ka BP, coinciding with the start of the Bolling-Allerod period, δ18O and δ13C decrease and gypsum precipitation ceases, indicating a transition to warmer and/or wetter conditions. Gypsum precipitation resumed while δ18O and δ13C increased at the start of the Younger Dryas at 13.1 cal ka BP and continued until 10.4 cal ka BP, near the onset of the Holocene.

Precipitation changes during the last glacial period in the northern hemisphere Neotropics were closely linked with freshwater forcing to the high-latitude North Atlantic, and sensitive to changes in the location of meltwater input. Climate was coldest/driest when meltwater directly entered the high-latitude North Atlantic, permitting sea ice expansion and weakening of Atlantic Meridional Overturning Circulation (AMOC), which resulted in a more southerly position of the Intertropical Convergence Zone (ITCZ). Upon deglaciation, when meltwater was directed to the Gulf of Mexico, at ~17 ka and...
1. Introduction

There are few well-dated, high-resolution records of continental climate change in the Neotropics during the last glacial period. The best regional record for the late Pleistocene comes from the marine Cariaco Basin, north of Venezuela (Hughen et al., 1996; Peterson et al., 2000; Lea et al., 2003). A handful of lacustrine records in Central America have been reported, including La Chonta Bog, Costa Rica (Hooghiemstra et al., 1992; Islebe et al., 1995), Lake La Yeguada, Panama (Piperno et al., 1990; Bush et al., 1992), and Lake Quexil, Guatemala (Deevey et al., 1983; Leyden et al., 1993).

In 2006, a complete 85-ka record was drilled in Lake Petén Itzá, Guatemala, as part of a project sponsored by the International Continental Drilling Program (ICDP). Hodell et al. (2008) and Mueller et al. (2010) reported on the lithology and sedimentology of long sediment cores from this lake. They interpreted the paleoclimate history on the basis of alternating bands of clay and gypsum during the last glacial and deglacial periods, which were thought to reflect wet and dry climate conditions, respectively. Beginning ~48 ka BP, climate varied between wetter conditions during interstadials and drier conditions during stadials. Arid periods were correlated to Greenland stadials and particularly Heinrich events, when the Atlantic Intertropical Convergence Zone (ITCZ) was located far to the south (Colinvaux et al., 1996; Baker et al., 2001; Bush et al., 2004). Moister conditions prevailed during interstadials and the Last Glacial Maximum (LMG).

Here we present a continuous, high-resolution (~decadal), stable isotope record ($\delta^{18}O$ and $\delta^{13}C$) from Lake Petén Itzá that spans the last ~43 ka. Interpretation of the oxygen isotope record in the context of lithologic change permits a detailed reconstruction of climate history for the last glacial period in the lowlands of northern Central America. Furthermore, the isotope record elucidates climate teleconnections between the northern Neotropical lowlands and the wider Caribbean, Gulf of Mexico, and North Atlantic basins.

2. Study site

Lake Petén Itzá (~16°55′ N, 89°50′ W) is located in the Petén Lake District, in lowland northern Guatemala (Fig. 1). It has a surface area of ~100 km² and a maximum water depth >160 m (Anselmetti et al., 2006). Lake Petén Itzá receives hydrologic inputs from direct rainfall, runoff, and subsurface groundwater. It lacks surface outlets and although some seepage loss may occur, it is effectively a closed-basin lake (Hodell et al., 2008). Lake Petén Itzá’s water is dilute (11.22 meq/l) and is dominated by calcium and magnesium cations and bicarbonate and sulfate anions (Hillesheim et al., 2005). Lakewater pH is high (~8.0) and at present the lake is saturated with calcium carbonate, which precipitates and accumulates in shallow zones of the lake (Hodell et al., 2008; Mueller et al., 2009). Today, lakewater $\delta^{18}O$ averages 2.6‰ (Hillesheim et al., 2005), greater than the mean value for regional surface and groundwater (~3.0‰) (Lachniet and Patterson, 2009), reflecting the importance of evaporation in the lake’s water budget.

Lake Petén Itzá is situated in a climatically sensitive region. Although the ITCZ does not reach latitudes higher than ~15°N, the...
amount of rainfall in the area is associated with the seasonal migration of the ITCZ and less spatially oriented tropical convective activity (Hastenrath, 1984; Poveda et al., 2006; Hodell et al., 2008). The rainy season, associated with the northward migration of the ITCZ, occurs between June and December, when easterly trade winds transport moisture from the Atlantic into the Caribbean Sea and the Yucatán Peninsula. The pronounced dry season occurs during northern hemisphere winter, January through May, when the ITCZ moves southward. During the dry season, light winter precipitation is sometimes brought to the Yucatán Peninsula by northerly winds from polar air masses (Portig, 1965; Hastenrath, 1984, 2002; Poveda et al., 2006).

3. Field and laboratory methods

Between 3 February and 11 March 2006, we collected sediment cores from seven sites in Lake Petén Itzá under the auspices of the ICDP (Hodell et al., 2006, 2008). Sediment cores from a water depth of 71 m at Site Pl-6 (Fig. 1) provide a continuous stratigraphic sequence to ~75.9 m composite depth (mcd), which represents ~85 cal ka of sediment accumulation (Hodell et al., 2008).

Samples from 1-cm core sections from Site Pl-6 were disaggregated with 3% H2O2 solution to obtain ostracod valves (Limnocythere opesta, Bröhm, 1939) for stable isotope analysis. Samples were washed through a 63-μm sieve and material was collected on filter paper and dried at 50 °C. When dry, the material was transferred to glass scintillation vials. Adult specimens of L. opesta were picked from the sieved, >212-μm fraction in each 1-cm sample using a binocular microscope. Prior to isotopic analysis, ostracod specimens were cleaned using 15% H2O2 to remove organic material, and rinsed in methanol before drying. Ostracod valves were checked for impurities and cleaned again if necessary. Approximately 12–20 individual ostracod valves, weighing a total of ~20–60 μg, were used for all samples. Multiple ostracod specimens were measured from each stratigraphic level to reduce the variance associated with analyzing single, short-lived individuals (Heaton et al., 1995; Escober et al., 2010). Ostracod valves were loaded into glass vials and CO2 was evolved from shells with a single aliquot acid digestion in a Kiel III carbonate preparation device attached to a Finnigan-MAT 252 isotope ratio mass spectrometer at the University of Florida. Summary statistics on the device attached to a Finnigan-MAT 252 isotope ratio mass spectrometer at the University of Florida.

The record for the last glacial period spans 43 to 10 cal ka BP and was produced by measuring stable isotopes of calcite composed of monospecific specimens of the ostracod L. opesta. This species is present and generally abundant throughout the glacial and Late-glacial periods (Pérez et al., 2011). Living specimens of L. opesta are today found to a maximum water depth of 40 m, though valves are encountered a greater depths, and L. opesta shells dominate surface sediment ostracod assemblages in water depths from the littoral zone to 40–50 m, i.e. to the base of the thermocline (Pérez et al., 2010). The Pleistocene/Holocene transition and Holocene oxygen isotope record was compiled using published data on three ostracod species from different coring sites in Lake Petén Itzá. The record for the Pleistocene/Holocene transition and early Holocene consists of isotope values measured on Pseudocandona sp., Kaufmann, 1900, Cytheridella ilosvayi, Daday, 1905 (Curtis et al., 1998), and Limnothyere sp., Brady, 1886 (Hillesheim et al., 2005).

Oxygen isotopes of calcite carapaces from modern individuals of these species from different water depths in Lake Petén Itzá indicate the ostracods do not precipitate calcite in oxygen isotopic equilibrium with ambient water. This is attributed to species-specific "vital effects" (Fig. 2). Oxygen isotopes of other species were normalized to those of L. opesta, which itself precipitates oxygen isotopes at an offset from equilibrium of about 0.5‰. On average, isotope measures on Pseudocandona sp. exceed those of L. opesta by 1.04‰, and mean values for C. ilosvayi are greater than those of L. opesta by 0.54‰. No attempt was made to normalize carbon isotopes because of the different depth habitats of ostracod species in both the water and sediment column.

4. Interpretation of proxies

4.1. Oxygen isotopes

In closed-basin Lake Petén Itzá, the relative amount of evaporation to precipitation (E/P) is the principal control on lakewater chemistry, including oxygen isotopes. Periods of high E/P are expected to yield lower lake levels, greater concentrations of
dissolved solids, and higher water-column $\delta^{18}O$. Conversely, during episodes of low E/P, lake stage is higher, lake water is more dilute, and $\delta^{18}O$ of water is lower.

In addition to changing E/P, the $\delta^{18}O$ of lake water is also affected by the $\delta^{18}O$ of rainfall that, in part, depends on the isotope composition of the moisture source, i.e., seawater. It is also influenced by the extent of moisture depletion (i.e., rainout) in the air mass as it is transported from the source area to the rainfall region. There is progressive depletion of $H_2^{18}O$ with increasing latitude, altitude, distance from the coast, and rainfall amount. Lastly, the $\delta^{18}O$ of rainfall is controlled by the relative humidity and temperature of the atmosphere from the time water evaporates from the ocean to the moment a raindrop hits the ground (Dansgaard, 1964; Darling et al., 2006; Leng et al., 2006).

Lakewater $\delta^{18}O$ and water temperature largely determine the $\delta^{18}O$ in the carbonate sediment of shell-forming aquatic organisms such as ostracods and gastropods. Colder temperatures yield greater $\delta^{18}O$ values in precipitated carbonate, whereas warmer temperatures produce lower $\delta^{18}O$ values. A switch from higher to lower $\delta^{18}O$ values in ostracod shells in a sediment sequence may reflect: (1) a change in precipitation source and/or isotopic composition, and/or (2) a change from colder and/or drier, to warmer and/or wetter conditions. Conversely, a change from lower to higher $\delta^{18}O$ could reflect: (1) a change in precipitation source and/or isotopic composition, and/or (2) a change to colder and/or drier conditions.

4.2. Carbon isotopes

The $\delta^{13}C$ of lakewater dissolved inorganic carbon (DIC) is influenced by a host of factors including: (1) the carbon isotope composition of input waters; (2) CO2 exchange between the lake and the atmosphere; (3) photosynthesis-respiration; and (4) processes that occur in the mud (organic carbon oxidation, sulfate reduction, and methanogenesis) (Oana and Deèvey, 1960). In thermally or chemically stratified lakes, a strong $\delta^{13}C$ gradient often develops between the epilimnion and hypolimnion as a result of photosynthetic biological pumping of $^{12}C$ from surface to deep water. Benthic ostracods record the $\delta^{13}C$ of overlying lakewater DIC and are also affected by pore water $\delta^{13}C$, which can be depleted or enriched relative to lake water owing to the oxidation of sediment organic matter or methanogenesis, respectively. Methanogenesis is suppressed in Lake Petén Itzá because of abundant dissolved sulfate in the water column and pore waters, the latter owing to gypsum in the sediments.

4.3. Lithology

Petén Itzá’s sediments consist of a mixture of inorganic and organic matter of autochthonous and allochthonous origin. Sediment organic matter produced within the lake comes from phytoplankton, higher plants, zooplankton, benthic organisms, and their fecal matter. Autochthonous inorganic matter comes in the form of calcite, dolomite, and gypsum, precipitated from the water column. External sources of organic matter include leaves, twigs, and pollen grains, as well as organic matter in eroded surface soils. Clay, principally montmorillonite, constitutes the major detrital input, but carbonates from the watershed may also reach the lake in detrital form. Gypsum crystals are precipitated when lake or pore water exceeds saturation, which occurs when evaporation rates are high and rainfall is relatively low. The presence of gypsum in sediments therefore indicates dry periods in the past, when the volume of Lake Petén Itzá was reduced (Hillesheim et al., 2005; Hodell et al., 2008; Mueller et al., 2010). In contrast, deposition of clay indicates wet periods and higher lake levels, when runoff and the influx of detrital material were enhanced. Variations in sediment magnetic susceptibility reflect changes in sediment lithology, with high values associated with clay-rich horizons and low values associated with gypsum deposits, thereby representing wet and dry climate episodes, respectively (Hodell et al., 2008).

5. Core chronology

All radiocarbon analyses were made on terrestrial macrofossils, thereby avoiding potential dating errors associated with autochthonous organic matter from this hard-water lake (Deevey and Stuiver, 1964). Samples were chemically pretreated (acid-base-acid). Radiocarbon ages include a background subtraction using an appropriate $^{14}C$-free matrix and $\delta^{13}C$ correction and are reported according to the convention set forth in Stuiver and Polach (1977).

The initial age/depth model for core PI-6 was developed using 18 AMS $^{14}C$ dates on terrestrial remains from cores taken at sites PI-6 and PI-3 (Hodell et al., 2008; Mueller et al., 2010). Dates from core PI-3 were projected onto core PI-6 by correlating the magnetic susceptibility records from the two sequences. New dates on terrestrial remains from cores taken at drill sites PI-2 and PI-6 enabled refinement of the age/depth model presented in Hodell et al. (2008) (Supplementary material). Dates from the PI-2 and PI-3 cores were again projected onto core PI-6 by detailed correlation of the magnetic susceptibility records (Fig. 3) as magnetic susceptibility variations reflect gypsum/clay variations that are thought to be synchronous across the basin. We assume no error in the projection of the individual stratigraphies onto the common depth scale. A total of 64 dates were obtained and span the last 43 ka of the record. In general, replicate analyses overlapped at 1-sigma analytical uncertainty. Such replicate samples were averaged and then calibrated. Clusters of samples producing reversals at 18O of rainfall that, in part, depends on the isotope fractionation of the carbon isotope, which can be depleted or enriched relative to lake water owing to the oxidation of sediment organic matter or methanogenesis, respectively. Methanogenesis is suppressed in Lake Petén Itzá because of abundant dissolved sulfate in the water column and pore waters, the latter owing to gypsum in the sediments.

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In contrast to the chronology presented in Mueller et al. (2010), which utilized the Fairbanks et al. (2005) calibration, we calibrated the $^{14}C$ ages using the IntCal-09 $^{14}C$-calendar calibration data (Reimer et al., 2009). Although both calibration approaches are based on surface marine samples (planktonic foraminifera and hermatypic reef-building corals) and assume constant surface ocean reservoir ages, a nearly continuous record derived from the updated Caribaco on Hulu Cave timescale (Reimer et al., 2009) and a rigorous comparison with alternative near calibration-data-sets, show that the IntCal-09 deglacial and older sequence is superior to that of Fairbanks et al. (2005). The tree-ring calibration sequence to ~12.5 ka is ‘common’ to the Fairbanks et al. (2005) calibration. Radiocarbon dates were calibrated using the program OxCal-INTCAL09 (Bronk Ramsey, 2001; 2008; Reimer et al., 2009). The age model is based on a piecewise linear interpolation that includes the underlying non-Gaussian uncertainty in the calibrated age probability distribution. Confidence intervals (95%) were estimated via
decrease of about $\sim 2^\circ$ occurred during the early to middle Holocene (Curtis et al., 1998).

Carbon isotopes show large variations, from values as low as $-11^\circ$ to as high as $+1^\circ$ (Fig. 5). High $\delta^{13}C$ values occurred during each of the Heinrich events, with the greatest values ($\sim -0.0^\circ$) occurring in the deglaciation, between $\sim 19.0$ and $\sim 15.3$ cal ka, during HS 1. From $\sim 15.3$ to $\sim 13.1$ cal ka, spanning much of the Bolling/Allerod period, $\delta^{13}C$ values decrease to $\sim -7.5^\circ$ (Fig. 5). Carbon isotopes increase to near 0$^\circ$ again from $\sim 13.1$ to $\sim 10.5$ cal ka during the Younger Dryas and Preboreal Periods (Fig. 5). This is followed by a sharp decrease in $\delta^{13}C$ during the Holocene (Fig. 5).

7. Discussion

Variations in ostracod $\delta^{18}O$ and $\delta^{13}C$ are tightly coupled with changes in sediment lithology, such that high isotopic values correspond to gypsum-rich layers and low values to clay-rich deposits. The simplest interpretation of these variables is they are responding to fluctuating climate conditions (evaporation/precipitation) and attendant changes in lake stage and volume. During periods of arid climate (high E/P), the lake volume is reduced, $\delta^{18}O$ increases, and gypsum saturation is exceeded. We speculate that variations in ostracod $\delta^{13}C$ are controlled by the position of Site PI-6 relative to the thermocline and secondarily by organic carbon flux to the sediment. Higher $\delta^{13}C$ is associated with lower lake level when the site is within the oxygenated epilimnion. Lower organic carbon ($C_{org}$) content in the gypsum sands deposited during arid intervals also results in less steep $\delta^{13}C$ pore water gradients between the sediment surface and depth. The ostracods thus record higher $\delta^{13}C$ values. During wetter climate conditions, $\delta^{18}O$ decreases and sediment composition is dominated by clay. During lake high stands, $\delta^{13}C$ records low-oxygen hypolimnetic DIC that is depleted in $^{13}C$ due to organic matter oxidation both in the water column and sediment pore waters. We interpret the climate history for the past 43 cal ka BP on the basis of varying $\delta^{18}O$ and $\delta^{13}C$ of ostracod calcite and sediment composition.

7.1. MIS 3 ($\sim 43$–$24$ cal ka BP)

Oxygen isotope values of L. opesta were fairly constant during late Marine Isotope Stage 3 (MIS3), averaging $\sim 5.0^\circ$, with maximum values of $\sim 7.0^\circ$. Oxygen and carbon isotopes show distinct peaks at 38, 31, and 24 cal ka BP, which coincide closely with the estimated timing of H4, H3 and H2 (Hemming, 2004). At these times, core lithology changed from clay to gypsum (Fig. 5), suggesting lake volume declined and concentrations of dissolved calcium sulfate exceeded saturation. The oxygen and carbon isotope records provide support for previous climate inferences based on lithologic variations (Hodell et al., 2008).

Modern L. opesta $\delta^{18}O$ values in samples to 100 m depth in Lake Petén Itzá range from $\sim 0.0^\circ$ to $\sim 15^\circ$. Thus, mean MIS3 values are $\sim 3.5^\circ$ greater than $\delta^{18}O$ of modern L. opesta, and values during Heinrich events are $\sim 5.5^\circ$ greater than modern. If the high $\delta^{18}O$ values in late MIS3 were attributable solely to temperature, it would have required a mean temperature decrease of 14.0 °C, and a decrease of 22.0 °C during Heinrich events, relative to present. These highly improbable temperature changes indicate that a substantial part of the $\delta^{18}O$ signal must be due to changing $\delta^{18}O$ of lake water. Measurement of gypsum hydration water during the Lateglacial period at Site PI-6 indicates that $\delta^{18}O$ of lake water ranged from 5.5 to 7$^\circ$, which is 2.5–4$^\circ$ greater than today (Hodell et al., 2012).
7.2. Last Glacial Maximum (~24–19 cal ka BP)

Ostracods are sparse during the LGM chronozone (~24–19 cal ka BP), but measured δ18O values are ~5‰, about equal to the mean late MIS3 δ18O value (Fig. 5). Contrary to interpretations from earlier studies (Leyden et al., 1993, 1994), the LGM was not especially dry in Petén. Clay-rich sediments accumulated rapidly between 24 and 19 cal ka BP (Mueller et al., 2010), indicating relatively high lake levels and relatively wet climate conditions (Hodell et al., 2008). Low δ13C is consistent with high lake levels, indicating the sediment–water interface at Site PI-6 was below the thermocline. Pollen analysis indicates an LGM assemblage consisting of a scrub oak or montane pine-oak forest, consistent with moist conditions and air temperatures at least 4.0–6.0 °C cooler than today (Bush et al., 2009), similar to temperatures in the low-latitude western Atlantic (Guilderson et al., 2001).

A wetter LGM in lowland Central America might be explained by greater summer precipitation, caused by a more northerly position of the Atlantic ITCZ. McManus et al. (2004) inferred that AMOC strength in the LGM was similar to the strength during the Bolling-Allerod period, a time for which there is evidence of a northerly

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**Table 1**

Age-depth points used to derive chronology shown in Fig. 3.

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Fig. 4. Calibrated radiocarbon dates versus mcd. Black lines represent a 95% confidence interval range.
ITCZ position (Peterson et al., 2000). Alternatively, greater winter precipitation from increased intensity and frequency from the north may also account for wetter LGM conditions in Petén (Hodell et al., 2008). During the LGM, the Laurentide Ice Sheet modified atmospheric circulation over North America. Wetter climate in the American southwest and western Mexico during the LGM has been explained by the split of the jet stream into a dry north and wet south branch, due to the presence of the Laurentide Ice sheet (Kutzbach and Guetter, 1986; Bradbury, 1997). Early climate models showed that a split westerly jet stream could bring precipitation to at least 20° N (Kutzbach and Guetter, 1986). More recent climate models suggest that the northern and southern branches were located farther south and that splitting of the westerly jet occurred only during winter months (Bromwich et al., 2004; Kim et al., 2008). The model of Kim et al. (2008) shows that although precipitation apparently increased in winter, it decreased during summer. In their model, average annual climate conditions during the LGM were drier than present. Wet conditions during the LGM in the Yucatan Peninsula might have also been a consequence of the mobile polar high (Leroux, 1993). Polar outbreaks of air from the north Pacific could have reached lower latitudes and migrated westward, and low-pressure cells could have moved moister eastern tropical Pacific air to the northeast, providing winter precipitation for the Yucatan Peninsula (Leroux, 1993).

### Heinrich Stadial 1 (~ 19–15 cal ka BP)

The Petén Itzá isotope results, together with pollen data and independent reconstructions of past water levels, show that the early deglacial period was the time of lowest lake stage, maximum...
The driest climate of the last 45 ka, inferred from the Petén Itzá record, occurred during or about HS 1. Dry conditions in the northern hemisphere tropics during HS 1 have been attributed to a mean southerly position of the ITCZ because of meltwater input to the North Atlantic that reduced AMOC (Ganopolski and Rahmstorf, 2001; Knutti et al., 2004; Cheng et al., 2007; Liu et al., 2009). Stager et al. (2011) found HS1 was also a time of profound and widespread megadrought throughout the Afro-Asian tropics. They suggested the pattern of megadrought during HS1 could not be attributed solely to inter-hemispheric movement of the ITCZ because it included Afro-Asian regions, i.e. north and south of the equator. Instead, the drought was likely related to cold tropical Atlantic sea surface temperatures (SSTs) and decreased moisture content in the ITCZ, regardless of its latitudinal position. Tropical North Atlantic SST also has an important influence on Caribbean and Central American summer rainfall variability (Hastenrath, 1978; Enfield, 1996; Enfield and Alfaro, 1999; Giannini et al., 2000; Taylor et al., 2002; Spencer et al., 2004; Wang et al., 2006), which may partly explain the generally arid condition during HS 1.

The entirety of HS1, however, was not arid. The Lake Petén Itzá δ18O record shows two cold, dry periods punctuated by a relatively warmer, wetter period (Fig. 6). This climate pattern might be explained by two events of freshwater flux to the North Atlantic during HS1. Two pulses of ice-rafted debris (IRD) were recorded off southern Portugal, at ~17.5 (H1b) and ~16.1 (H1a) cal ka BP, with an intervening period of warmer surface water (Bard et al., 2000). The two IRD pulses may correspond to the cold, arid events in the Petén Itzá record, and the intervening period of warm sea surface water may correspond to a short-lived event beginning at ~17 ka in the Petén Itzá record, when clay was deposited and ostracod δ18O decreased, indicating somewhat moist conditions. Other records from the Caribbean, Gulf of Mexico, and North Atlantic suggest that HS1 was interrupted by a similar event. In the Cariaco Basin, a distinct gray unit was deposited in the midst of HS1 and interpreted to represent increased rainfall and fluvial discharge (Yurco, 2010). On the Bermuda Rise, Carlson et al. (2008) showed an increase in temperature and a decrease in δ18O of Globorotalia inflata, d’Orbigny, 1839 at 16.5 ka, punctuating an otherwise cold period during HS1 (Fig. 6).

At about the same time (17 ka), the δ18O of the Orca Basin decreased below 0 ppm (SMOW), indicating early meltwater input to the Gulf of Mexico (GOM), which preceded the main meltwater pulse during the Bolling-Allerod (14.7–12.7 ka) (Williams et al., 2010). Although meltwater input to the GOM can affect AMOC,
7.4. Bolling-Allerod (~15–13 cal ka BP)

A large decrease in δ18O (~3.0‰) occurs from ~15 to ~13.1 cal ka BP, when sediment deposition switched from gypsum to clay, marking the transition to warmer and/or wetter conditions of the Bolling-Allerod period (Fig. 5). This interval coincides with the main meltwater pulses to the GOM between ~15.2 and 13.0 ka (Flower et al., 2004). At that time, deep-water circulation in the North Atlantic resumed as AMOC intensified (McManus et al., 2004; Liu et al., 2009), the ITCZ migrated north, and precipitation increased in the northern hemisphere Neotropics (Peterson et al., 2000) (Fig. 6). The Petén Itzá record appears to support the model of meltwater routing proposed by Clark et al. (2001), in that input to the GOM led to reduced sea ice, a northward shift of the ITCZ, and increased precipitation in the northern hemisphere Neotropics, whereas diversion to the east into the North Atlantic resulted in reduced AMOC, sea ice expansion, a southward shift in the ITCZ, and drier climate conditions in the northern hemisphere Neotropics.

7.5. Younger Dryas-Preboreal (~13–10.5 cal ka BP)

Higher δ18O values from ~13.1 to ~11.5 cal ka BP, at least ~4.5‰ greater than modern L. opesta δ18O values, mark the beginning of the Younger Dryas (YD) period (Fig. 5). The onset of the Younger Dryas coincided with a diversion of meltwater from the southern route into the GOM, to an easterly route into the North Atlantic (Broecker et al., 1989), where increased freshwater forcing weakened AMOC and sea ice expanded in the North Atlantic (McManus et al., 2004). During the YD, the Cariaco Basin, off northern Venezuela, experienced colder (~4.5 °C) and drier conditions that have been attributed to a southward shift of the ITCZ (Peterson et al., 2000; Haug et al., 2001; Lea et al., 2003).

Termination of the YD occurred at ~11.5 cal ka BP in Greenland, the Cariaco Basin, and many other geographically distant regions (Haug et al., 2001; NGRIP, 2004). In Petén Itzá, the end of the Younger Dryas is also identified by a modest decrease in δ18O, but not in the magnetic susceptibility record (Fig. 5). A decline in δ18O starting ~11.5 cal ka BP indicates a change to warmer and/or wetter conditions at the end of the predominantly dry deglacial. Although pollen data also suggest increased rainfall at that time (Bush et al., 2009), gypsum precipitation, which indicates reduced lake volume, continued until the end of the Preboreal period, ~10.0 cal ka BP. The discrepancy between the isotope and lithology data can be reconciled if we accept the idea that lake water levels began to rise around 11.5 cal ka BP, inferred from decreased δ18O, but only attained a sufficient volume to reduce the concentration of calcium and sulfate below gypsum saturation ca 10.0 cal ka BP. Oxygen isotope results from the Petén Itzá sediment core are supported by hydrologic proxies from the Cariaco Basin, i.e. increased Ti and Fe concentrations, which show wetter conditions from 11.5 to 10.5 cal ka BP (Haug et al., 2001), presumably as a consequence of a more northerly position of the ITCZ.

7.6. Holocene (~10.5 cal ka BP-present)

During the Pleistocene–Holocene transition, most of the Petén Itzá δ18O decrease occurred over an extended period between ~10.5 and 7.0 cal ka BP (Clark et al., 1998), whereas change in Greenland, the North Atlantic and Cariaco was more rapid and occurred before 10.0 cal ka BP (Fig. 7). Slow hydrologic filling of the large, deep Petén Itzá basin may partly explain the protracted period of isotopic change. The pollen record shows that tropical forest, much like the vegetation that characterizes the area today, was established early in the Holocene, indicating sufficient moisture availability to support such a plant community. Dense vegetation during that time period could have promoted high rates of evapotranspiration and soil moisture storage (Rosenmeier et al., 2002), reducing rainwater runoff to the lake. This may account for the slow filling of the basin and protracted period of oxygen isotope equilibration.

Several lines of evidence, however, suggest that regional lakes filled with water rapidly in the early Holocene. First, shallow-water cores from small, deep lakes in the Petén region yielded early
Holocene basal dates (Deevey, 1978), indicating these shallow-water sites were inundated shortly after the onset of wetter conditions. Second, deep-water cores from small, deep Petén lakes display laminated early Holocene deposits (Deevey et al., 1983), indicating water depths were great enough to enable stable thermal stratification, hypolimnetic anoxia and exclusion of benthic fauna. Third, radiocarbon dates on deep-water (51.6 and 58.2 m) and shallow-water (9.7, 20.9, and 30.0 m) cores from Lake Petén Itzá all show similar dates for the onset of Holocene limnetic sedimentation (11.0–10.2 \(^{14}\)C ka BP), with earliest deep-water Holocene sediments overlying gypsum, and shallow-water deposits overlying paleosols (Hillesheim et al., 2005). If indeed Lake Petén Itzá filled rapidly with the onset of wetter conditions in the early Holocene, it suggests that the decline in \(^{18}\)O values in the ostracod record between \(\sim 7\) and \(5\) cal ka BP, is attributable to a decrease in the isotopic signature of rainfall.

During the glacial and last deglacial periods, \(^{18}\)O and \(^{13}\)C fluctuations are positively correlated, whereas in the Holocene, they are negatively correlated. Increased lacustrine productivity during the early Holocene is inferred from higher organic matter content (Curtis et al., 1998) and greater concentrations of Botryococcus (Islebe et al., 1996) in a core from the shallow southern basin of Lake Petén Itzá. Algae discriminate against the heavier carbon isotope (\(^{13}\)C) in the dissolved inorganic carbon (DIC) of lakewater. The resulting fractionation yields algal biomass that is relatively depleted in \(^{13}\)C and a \(^{13}\)C-enriched DIC pool, the latter leading to relatively high \(^{13}\)C values in biogenic carbonates.

### 7.7. Comparison with Southern Hemisphere records

Because of the asynchronous or anti-phase relationship of millennial-scale climate variability between Greenland and
Antarctica during the last Glaciation (EPICA Community Members, 2006), Heinrich stadials and their associated dry periods in Petén are associated with warming in Antarctica during the last glaciation (Hodell et al., 2008). This is supported by the excellent and independent correlation between ostracod δ13C variations from Petén Itzá and temperature in the Dronning Maud Land area (EDML) ice core record from east Antarctica. Each warming in Antarctica is associated with an increase in δ13C and inferred drop in Petén Itzá’s lake level (Fig. 8). Furthermore, the peaks in δ13C during Heinrich stadials and Antarctic isotope maxima are anti-phase with wet periods in Brazil inferred from speleothems (Wang et al., 2004) and marine sediment cores off northeastern Brazil (Arz et al., 1998; Jenerijahn et al., 2004; Jaeschke et al., 2007). These observations strongly support an important role for ITCZ migration in affecting precipitation in the Neotropics of both hemispheres during cold stadial periods. Although the movement of the ITCZ has been largely viewed as a response to changes in AMOC and sea ice, we should not exclude the possibility that, instead, tropical climate change may have influenced thermohaline circulation (Guilderson et al., 2001; Seager and Battisti, 2007; Clement and Peterson, 2008).

8. Conclusions

A long sediment core from Lake Petén Itzá, Guatemala, provides a well-dated continental record of climate and environmental variability in the lowland Neotropics that extends into MIS 5A (~85 ka). Stable isotope measurements (δ18O and δ13C) on ostracod valves in the core yielded a high-resolution record of climate and lake level change spanning the last ~43 ka. Variations in δ18O and δ13C are correlated with changes in sediment lithology, suggesting that all three variables responded concurrently to changing climate and limnetic conditions. Gypsum-rich sediments are marked by high δ18O and δ13C, and were deposited under conditions of high evaporation/precipitation and low lake level. Clay-rich deposits are associated with low δ18O and δ13C, and represent relatively moister climate conditions and high lake level.

During the glacial period, the average δ18O value was >3.5‰ greater than mean values in modern ostracod shells, reflecting both cooler and drier glacial climate conditions. From 48 to 24 ka, during MIS 3, the thickest gypsum beds and greatest δ18O and δ13C values coincide with Heinrich Events 4, 3 and 2. The isotope records support previous interpretations that Heinrich stadials were associated with cold, arid periods in Petén when the ITCZ was displaced southward as a consequence of freshwater input to the North Atlantic, which caused sea ice to expand and AMOC to weaken (Hodell et al., 2008). In contrast, interstadials and the entirety of the Last Glacial Maximum (~24–19 cal ka BP) were marked by clay deposition with lower δ18O and δ13C values, reflecting higher lake levels and relatively moister climate.

The pollen, lithological and oxygen isotope data from the Petén Itzá core show that the transition from the LGM to the deglaciation involved a shift from cold-wet to cold-dry conditions during HS1. These findings are consistent with paleoclimate reconstructions from western North America and central Mexico (Bradbury, 1997). The isotope results, together with pollen data and independently inferred past water levels, indicate the deglacial period was the time of greatest aridity and lowest lake stage over the last 43 ka. Climate during HS 1 (~19–15 ka) was particularly extreme and the Petén Itzá isotope record contains two δ18O and δ13C peaks, with an intervening low. These represent two episodes of cold-arid climate and lake lowstands, separated by a relatively warmer, wetter period and high lake levels at ~17 ka. The isotope maxima coincide with pulses of ice-rafted debris (IRD) recorded off southern Portugal at 17.5 and 16.1 ka (Bard et al., 2000). The Bolling Allerod period marked a transition to clay deposition and low δ18O and δ13C values, followed by a return to gypsum precipitation and increased isotopic values at the start of the Younger Dryas. Cold-dry conditions persisted through the Younger Dryas and Preboreal periods, and did not ameliorate until the start of the Holocene, ~10.4 ka (Hillesheim et al., 2005).

The lithologic and stable isotope variations in the Lake Petén Itzá sediment core are linked to known changes in freshwater input to the North Atlantic and Gulf of Mexico. Cold-dry conditions in Petén occurred during times of increased freshwater delivery to the North Atlantic, especially during Heinrich events. When meltwater was diverted south to the Gulf of Mexico during the last deglaciation (e.g., 17 ka and Bolling-Allerod), Petén climate abruptly became more humid. We speculate that alternating routing of fresh water between the North Atlantic and Gulf of Mexico may explain some of the climate transitions observed in Petén Itzá and other North Atlantic records during Termination I. Numerical model experiments suggest that increased flux of fresh water to the North Atlantic decreases the strength of the AMOC, increases sea ice, and causes the ITCZ to shift to a more southerly position. In contrast, meltwater diversion to the Gulf of Mexico has less of an influence on AMOC and almost no effect on North Atlantic sea ice distribution, which has been identified as an important mechanism for ITCZ migration. Our findings appear to support the meltwater routing hypothesis of Clark et al. (2001).

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2012.01.020.