

# Chapter 5

## Re-evaluation of Climate Change in Lowland Central America During the Last Glacial Maximum Using New Sediment Cores from Lake Petén Itzá, Guatemala

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**Abstract** Glaciological data derived from moraines, and multiproxy data from lake sediment cores (e.g. fossil pollen, diatoms, and isotope data) indicate cooling in the Central American tropics during the last ice age. Contrary to prior inferences, however, new lake core data from Lake Petén Itzá, lowland Guatemala, indicate that climate was not particularly dry on the Yucatan Peninsula during the last glacial maximum (LGM) chronozone, around 23,000–19,000 cal. yr BP. We present pollen and lithologic data from Lake Petén Itzá and an improved chronology for climate changes in lowland Central America over the last 25,000 years. The driest period of the last glaciation was not the LGM, but rather the deglacial period (~18,000–11,000 cal. yr BP). Causes of climate shifts during the last glaciation are ascribed to precessional changes in insolation, the position of the Inter-Tropical Convergence Zone, and southward penetration of polar air masses.

**Keywords** Pleistocene · Guatemala · Fossil pollen · Petén Itzá · Glaciation · Aridity

### 5.1 Introduction

High-resolution paleoecological records spanning the last 25,000 years are sparse in Central America. The principal sources of evidence for environmental change have been glaciological data (i.e., moraines) and lake sediment cores that have yielded isotope, fossil pollen, charcoal, and diatom data. It is well known that glaciers descended to lower elevations in high-altitude regions of Central America during the last glacial, broadly coincident with the Last Glacial Maximum (LGM) (Lachniet and Vazquez-Selem 2005). The LGM has been variously defined as the coldest glacial time, the time of lowest sea level, the time of regional maximum ice expansion, and simply as the period about 22,000 years ago (hereafter thousands

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of years ago is expressed as ka). However, as these events were not synchronous (Peltier and Fairbanks 2006), we chose to follow the working definition of the LGM chronozone ( $21 \pm 2$  ka) adopted by Mix et al. (2001).

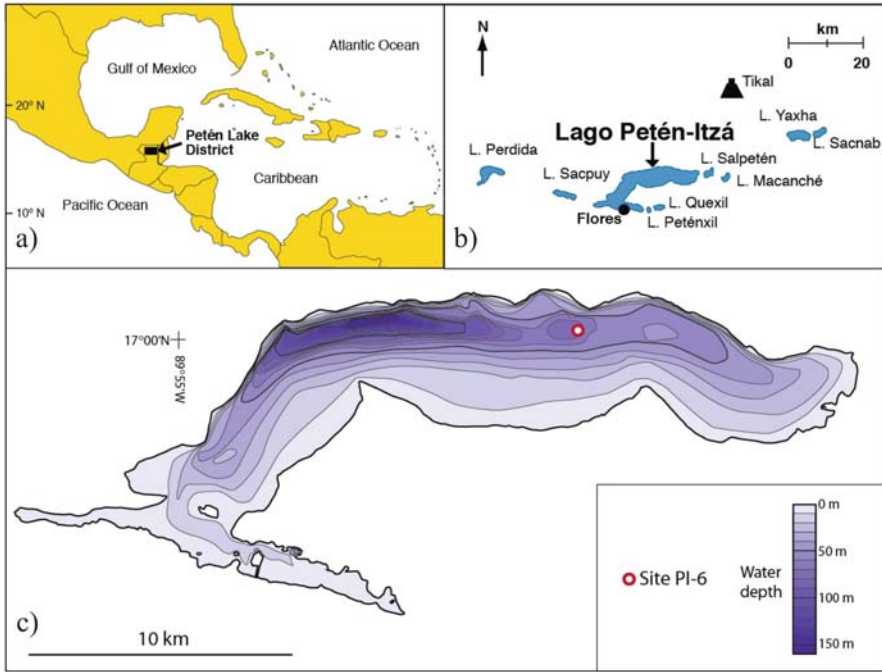
Substantial questions remain regarding Central American climate during the last ice age (1) Did montane and lowland regions experience similar cooling during the LGM? (2) Was the LGM characterized by regional aridity? (3) What climatic processes were responsible for temperature and precipitation changes during the LGM (23–19 ka) and the deglacial ( $\sim 18$ –11 ka)? We address these questions using previous paleoclimate work from Central America and new data from the Lake Petén Itzá Scientific Drilling Project (PISDP).

Lake Petén Itzá lies within the Yucatan Peninsula, an area demonstrated to have extreme sensitivity to climate change. In the 1970s, Edward S. Deevey and colleagues spearheaded an exploration for Pleistocene lake records in the lowlands of Guatemala, culminating in the raising of a long core from Lake Quexil (Deevey et al. 1983). This 19.7-m core (Quexil 80-1) was drilled in 29 m of water and had an extrapolated basal age of c. 36 ka. The pre-Holocene chronology of the core from this karst lake was based on a single radiocarbon date ( $27,450 \pm 500$   $^{14}\text{C}$  yr BP) from a shell taken at 15.96 m. Importantly, that date was not corrected for hard-water lake error. In the basal section of the core, the pollen indicated vegetation that was more temperate than today and marked by a montane pine-oak forest, suggesting cool-moist conditions with temperatures  $4.7$ – $6.5^\circ\text{C}$  lower than present (Leyden et al. 1993, 1994). This section of core was overlain by deposits containing pollen indicative of an *Acacia*-rich scrubland that was initially interpreted, based on peaks of *Juniperus* pollen, to indicate temperatures c.  $6.5$ – $8^\circ\text{C}$  lower than today (Leyden et al. 1993, 1994). Replacement of the open-water alga *Botryococcus* during this dry period by the littoral and marsh taxa *Potamogeton*, *Alternanthera*, and *Typha*, suggested that the lake was considerably reduced and may have been ephemeral.

Chemical data, and especially gypsum deposition, reinforced evidence for drying derived from the pollen record during the period attributed to the LGM in core Quexil 80-1. The  $\delta^{13}\text{C}$  values of long-chain n-alkanes ( $\text{C}_{27}$ ,  $\text{C}_{29}$ ,  $\text{C}_{31}$ ) in core Quexil 80-1 were 4‰ greater during the “marshland phase” than those of the early Holocene, indicating a higher proportion of C4 plants in the watershed prior to the Holocene (Huang et al. 2001). Such a shift can indicate the transition from a drought tolerant C4 species to a tree dominated (C3-rich) Holocene landscape. Below, we re-interpret the chronology of climate changes inferred from the Quexil 80-1 core based on correlation to well-dated cores from nearby Lake Petén Itzá.

### ***5.1.1 The Lake Petén Itzá Scientific Drilling Project (PISDP)***

Lake Petén Itzá (area =  $\sim 100$  km<sup>2</sup>, maximum depth = 160 m), the deepest lake in lowland Central America, is located at  $\sim 16^\circ 55'\text{N}$ ,  $89^\circ 50'\text{W}$  in the Department of Petén, northern Guatemala (Fig. 5.1). Prior to the most recent drilling efforts, a detailed seismic survey of the basin was made using 3.5-kHz and airgun profiling



**Fig. 5.1** (A) Map of the Intra America Seas showing the location of the Department of Petén, northern Guatemala and Cariaco Basin off northern Venezuela. (B) Map of the Petén Lake District. (C) Bathymetric map of Lake Petén Itzá showing the location of primary and alternate coring sites. Coring location PI-6 is labelled as 6

(Anselmetti et al. 2006). The survey revealed the underlying karst topography and several deep pockets of sediment that became the focus of the coring campaign. Seismic images from the deepest part of the basin indicated possible slumping of deposits from the steep north shore. Consequently, when the GLAD 800 drilling rig was deployed on Lake Petén Itzá, between January and March 2006, a transect of drill sites from the deep to the shallow-water was targeted for coring in order to recover the optimal sediment sequences for paleoenvironmental reconstructions.

Holes were drilled at seven sites in the lake, with multiple holes drilled at six locations (Hodell et al. 2006, 2008). Sediments were generally composed of green or gray lake muds, but in particular sections of the core, white bands of gypsum (calcium sulfate) formed distinct layers. These high-density bands, as well as ash layers and changes in magnetic susceptibility, were used to correlate stratigraphically the multiple cores raised from each drill site. Among the cores, Site PI-6 consisted of three holes that were correlated stratigraphically to provide a continuous 75.9-m-long sediment column.

Chronology of this record was based on 23 AMS  $^{14}\text{C}$  dates on terrigenous organic matter and the occurrence of three identifiable ash layers with ages between  $53 \pm 3$  ka and  $84 \pm 0.5$  ka (Hodell et al. 2008). The deep ash layer was “fingerprinted”

geochemically by electron microprobe glass analysis. The ash was derived from the Los Chocoyos eruption of the Atilán Caldera in the Guatemalan highlands that occurred at 84 ka, during Marine Isotope Stage (MIS) 5a (c. 85–78.5 Ka) (Ledbetter 1984). The lithology and chronology of PI-6 are described in detail by Hodell et al. (2008). This core appeared to offer a continuous sedimentary record from 0 to 85 ka.

Glacial-age deposits consisted of interbedded clays and gypsum that were clearly expressed by variations in magnetic susceptibility of the sediment (Fig. 5.2). Authigenic gypsum displayed relatively low magnetic susceptibility values compared with detrital clays, which had high susceptibility values.

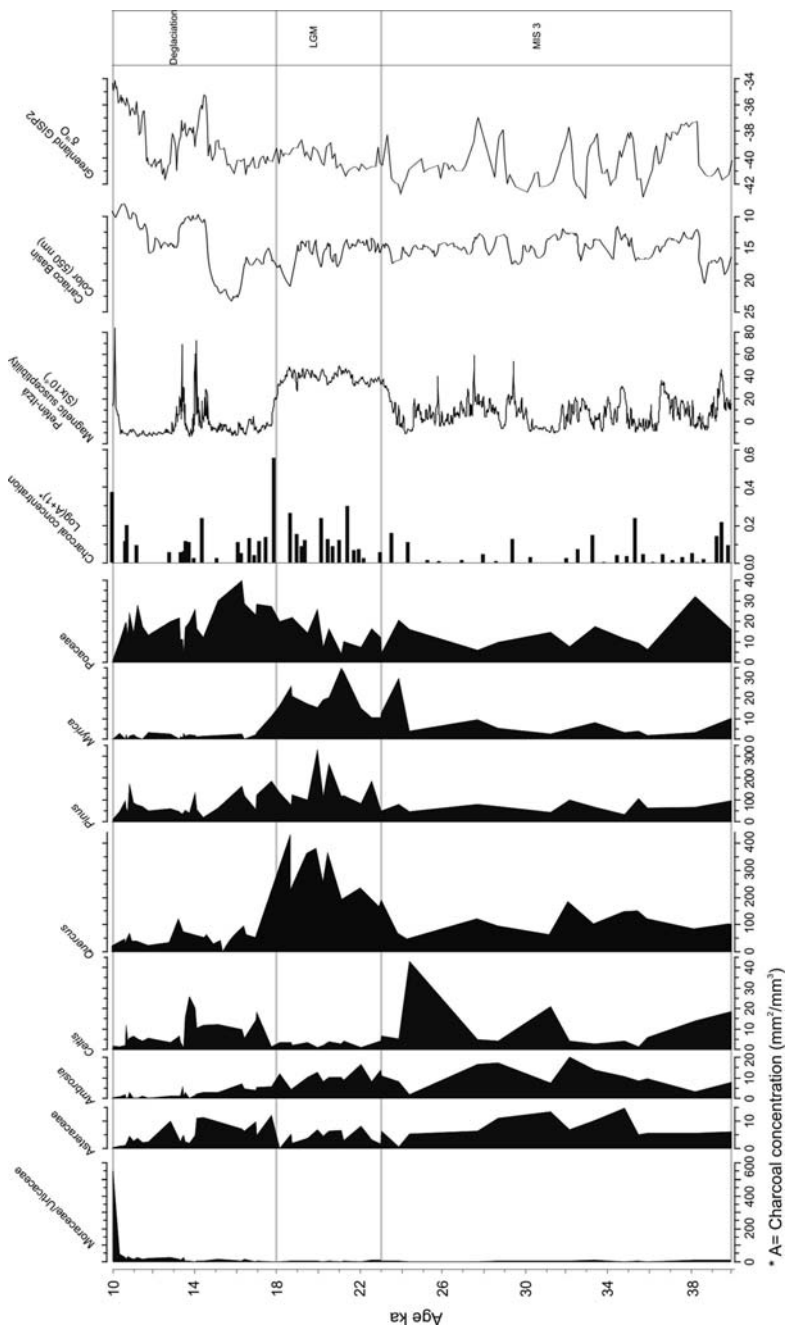
Preliminary analyses of cores from Site PI-6 in Lake Petén Itzá revealed that lithology of LGM sediments was dominated by clays thought to have been deposited in deep water under relatively wet climate conditions. In contrast to these clays, gypsum was deposited during lake lowstands. Interbedded gypsum and clay layers were deposited from 45 to 23 ka during MIS 3, and the last deglaciation (~18–11 ka), but gypsum is conspicuously absent from sediments deposited during the LGM (23–19 ka). Thus the last deglaciation was much drier than the LGM. Evidence of a substantially lowered lake level in the late glacial was also revealed in the seismic profiles of Petén Itzá. Transects reveal a wave-cut bench and paleoshoreline buildups ~56 m below modern lake level, suggesting a lowering of lake level by that amount, which is equivalent to an 87% reduction in lake volume (Anselmetti et al. 2006, Hodell et al. 2008).

The fossil pollen record from Petén Itzá reveals that during the LGM regional vegetation was rich in *Myrica*, *Quercus*, and *Pinus* (Fig. 5.2). Charcoal increases in abundance in the LGM compared with MIS 3, an observation consistent with the relatively frequent but low intensity fires documented in pine-oak forests of Mexico (Fule and Covington 1997). Throughout the LGM Poaceae and *Ambrosia* were only c. 10% of the pollen sum, leading us to investigate Mexican montane oak-pine forests as a possible analog.

The Mexican pine-oak vegetation complex spans a large environmental range and further work is needed to refine which modern community most closely approximates the LGM conditions recorded in PI-6. Our initial estimate is consistent with observations made by Leyden et al. (1994) that this LGM pine-oak forest probably formed under conditions that were c. 3–5°C cooler than present.

In the deglacial phase at Petén Itzá, Poaceae increased in abundance, while *Pinus* and *Quercus* declined. The period of northern hemispheric deglaciation was also marked by increased abundances of Amaranthaceae pollen, an indication of fluctuating lake level, similar to that seen in the “marshland phase” of Lake Quexil.

The superior chronology of the new cores from Petén Itzá permits re-interpretation of the poorly-dated record from Quexil 80-1. The montane *Pinus-Quercus* pollen assemblage interpreted by Leyden et al. (1993, 1994) to have been deposited during MIS 3 instead represents the LGM (23–19 ka). Similarly, the postulated LGM flora of xeric thorn scrub, in fact represents the period of maximum aridity during deglaciation (~18–11 ka). During this latter interval, the open water of Lake Quexil was probably replaced by a *Typha* swamp. If this driest period of Lake Quexil is aligned with the driest event in Petén Itzá, then the preceding period,



**Fig. 5.2** The paleoecological record of core PI-6 from Lake Petén Itzá, Guatemala, 40–10 ka. Percentage data for fossil pollen (*Quercus* and *Pinus* excluded from the pollen sum) of selected taxa, charcoal concentrations, and magnetic susceptibility are shown. Low magnetic susceptibility indicates gypsum deposition and low lake level. Also shown are the  $\delta^{18}\text{O}$  of the Greenland Ice Core (Grootes et al. 1993) and color reflectance values from the Cariaco Basin (Peterson et al. 2000)

dated to the LGM in Petén Itzá, displays a very similar flora at both sites. The *Pinus-Quercus* assemblage of the LGM could be consistent with a cooling of 3–5°C for the lowlands, whereas the suggestion of a 6.5–8°C cooling (Leyden et al. 1993) for what is now dated to the deglacial phase, will be investigated further as data emerge from the Petén Itzá record.

Near the Pleistocene/Holocene boundary (~12 ka), Petén lakes filled rapidly in response to increased precipitation. Pollen studies demonstrated that the Petén tropical forest arose abruptly after 12.5 ka and was dominant by ~11 ka (Leyden 1984, Leyden et al. 1993, 1994). The Petén Itzá record offered a slightly more refined insight into these events. Transition toward a more “tropical” system began around 18 ka, but though warming, this was also a period of strong drought. Between 15 and 13 ka (the precise boundaries have yet to be established) a climatic oscillation intensified the dry conditions. Between 13 and 11 ka there was gradual change toward more mesic conditions. A mixed community formed in which mesic lowland elements, e.g. *Urticaceae/Moraceae*, and *Ficus*, coincided with mesic upland taxa, e.g. *Quercus*, *Pinus*, *Hedyosmum* and *Alnus*, and xeric lowland indicators, e.g. *Acacia*, *Bursera* and *Hymenaea*, co-existed. At that time, communities changed rapidly and probably formed a landscape mosaic of vegetation types without modern analog. A major wet event elevated *Urticaceae/Moraceae* from c. 40 to 60% of the pollen sum between 11 and 10.3 ka (Fig. 5.2), and gypsum deposition terminated about 10.3 ka.

## 5.2 Did Montane and Lowland Regions Experience the Same Degree of Last Glacial Maximum Cooling?

### 5.2.1 Glaciological Evidence

At the height of the LGM ice caps developed in montane regions of Central America, South America, and Mexico (Lachniet and Vazquez-Selem 2005, Lachniet 2007). Terminal moraines formed at about 3000 m in the Talamancas of Costa Rica, where glaciers descended below their equilibrium line altitude (Lachniet and Vazquez-Selem 2005). In Guatemala, an ice cap of ~60 km<sup>2</sup> existed on the high plateau, with moraines at elevations of 3470–3600 m (Lachniet 2004). The record of past glacial activity can be used to recreate the glacial equilibrium line altitude (ELA). This measure denotes where the mass balance of the glacier was zero, i.e. where accumulation = ablation. Temperature, local topography, shading, and precipitation can all influence local ELAs. However, if taken regionally, the ELA in combination with the moist air adiabatic lapse rate (lapse rate) can provide an index of past temperature change.

The use of a specific lapse rate to calculate temperature depression during the LGM needs to account for the potential influence of humidity. As air becomes drier, lapse rates increase. Van der Hammen and Hooghiemstra (2000) invoked a Pleistocene lapse rate different from today to suggest that the high Andes may have cooled much more than the Amazon lowlands. However, large changes in lapse rate

are unlikely in a region that receives maritime airflow. Furthermore, given the presence of abundant evapo transpiring vegetation during the LGM (the case for this follows), it is likely that the lapse rate was similar to that of today (Rind and Peteet 1985), i.e. between  $\sim 5.5$  and  $6^\circ\text{C}/\text{km}$ .

Applying a  $5.6^\circ\text{C}/\text{km}$  lapse rate yields a range of estimates for LGM cooling of  $4.6$ – $8.5^\circ\text{C}$  (Lachniet and Vazquez-Selem 2005). The low value of  $4.6^\circ\text{C}$  for Vaquerías, Mexico, is the minimal cooling estimate, and is similar to other north- or northwest-facing Mexican sites of similar latitude. Only 8 of 25 Mexican sites were reported to have ELAs lowered by  $<1000$  m. Mexican sites facing south and east tended to have ELAs lowered by about  $1000$ – $1500$  m at the LGM. From these data, it is apparent that peaks above  $3200$  m often had ice caps, consistent with high-elevation cooling of c.  $8^\circ\text{C}$ .

Poor chronological control on the timing of glacial advances made comparisons with other paleoclimate records difficult. In Mexico, a major glacial expansion at c.  $151$ – $126$  ka, dated using  $^{36}\text{Cl}$  exposure was, within the limits of this dating technique, consistent with the glacial maximum of MIS 6 (c.  $160$ – $132$  ka) (Martinson et al. 1987). Other moraines were dated to c.  $19$ – $18$  ka and  $15$ – $14$  ka (Vazquez and Givnish 1998), with a last brief expansion at about  $10$  ka (ibid).

Many moraines, including all those of Guatemala and Costa Rica, remain undated and age estimates rely on correlation with the Mexican moraines that have radiometric ages. Moraine morphology and weathering characteristics are used to infer temporal equivalence of advances. While direct dating of moraine advances has not been possible in Costa Rica, a minimum estimate for deglaciation of c.  $12,360$ – $11,240$  cal. yr BP is available from basal sediments in a corrie (cirque) lake at  $3480$  m elevation (Horn 1990).

### 5.2.2 Palynological Evidence

Evidence of subalpine temperature depression comes primarily from fossil pollen records. Lachner Bog ( $2400$  m elevation) in Costa Rica provided the first long record of vegetation change for Central America (Martin 1964). At that site, pollen of *Quercus* was abundant in sediments beyond the range of bulk radiocarbon dating. During the last glacial, *paramo* grasslands replaced these forests. About  $10$  ka, grasslands were replaced by *Quercus* forest that has persisted until modern times. The inferred descent of *paramo* grasslands at the LGM (Martin 1964) indicates a minimum displacement of dominant species in these assemblages of at least  $600$  m. Given a local lapse rate of  $5.6^\circ\text{C}/\text{km}$ , this descent of grasslands suggests a minimum of  $3^\circ\text{C}$  cooling, somewhat less than the  $8^\circ\text{C}$  cooling inferred from glaciological studies. However, the grassland signature, at least at the level of detail revealed in Martin (1964), could also be consistent with a cooling of as much as  $9^\circ\text{C}$ .

In Panama, the  $57$ -m-long sediment sequence from El Valle provided the first transglacial record for lowland Central America (Bush and Colinvaux 1990). El Valle is a *caldera* whose walls extend to about  $1100$  m above sea level (masl), whereas the ancient lakebed that forms the floor of the *caldera* lies at  $500$  masl.

A continuous 130,000-year fossil pollen record from El Valle suggests a descent of *Quercus* forest to the elevation of the *caldera* rim, and in the late glacial, to the *caldera* floor. Between c. 35 and 20 ka, the lake contracted and became a *Typha* swamp. That this record shows no evidence of the wet events of the early Holocene recorded at other Panamanian and Central American locations (Bush et al. 1992), suggests that at least some of the apparent drying may have been a product of hydrarch succession rather than simply climate change. However, the relative importance of hydrarch succession versus climate drying has yet to be tested.

These data are consistent with cooling that would have been sufficient to bring *Quercus* close to the floor of the El Valle crater. As *Quercus* does not currently grow in this portion of Panama and is restricted to elevations above c. 1700 m (Bush 2000), the c. 600–1200 m descent of *Quercus* within the El Valle *caldera* is consistent with c. 3–5°C cooling.

Another insight into Panamanian deglacial climates comes from Lake La Yeguada (650 masl). This lake did not begin to accumulate sediment until c. 16,000 cal. yr BP, at which time *Quercus* had descended and grew near the lake (Bush et al. 1992). Thus the La Yeguada data are consistent with a cooling of c. 5°C within the deglacial period. Together, the La Yeguada and El Valle data indicate that lowland Panama experienced cooling of about 5°C at the LGM (Bush 2002).

The new data from Petén Itzá are consistent with these estimates of lowland cooling. So far, the peak of *Juniperus* pollen described by Leyden et al. (1993, 1994) has not been identified in the analysis of the PI-6 sediment. Leyden et al. (1993, 1994) used *Juniperus* to infer a c. 6.5–8°C cooling in sediments thought to have been deposited during the LGM (now re-assigned to the early deglacial period). Despite the absence of a *Juniperus* peak in PI-6, the presence of what appears to be either a scrub oak or a montane oak-forest community at the LGM is consistent with c. 4–6°C cooling. The cooling in lowland Central America inferred from pollen studies is more extreme than estimates from many tropical, deepwater oceanic records (e.g. Ballantyne et al. 2005, Zhang 2006). In general, a 1–3°C cooling has been suggested for the tropical Atlantic and Pacific. Schmidt et al. (2004) suggested c. 2.5°C cooling for the western Caribbean at the LGM, slightly warmer than Guilderson et al.'s (1994) estimate of a 3–5°C cooling in the shallow waters off Barbados.

Overall, it seems that montane regions cooled about 5–8°C, while the lowlands cooled approximately 5°C, and the oceans cooled somewhat less.

### 5.3 Was the LGM Characterized by Aridity?

Last Glacial Maximum paleoclimate records from Central and South America remain rare, whereas Holocene records are relatively abundant. As glacial-age aridity was identified in paleoecological studies of the African tropics (Livingstone 1967, 1975), a simplistic model of wet interglacials and dry glacials was applied to



characterize all Neotropical climates. Observations in the early 1990s of millennial-scale climate variability in Greenland ice cores, however, made it apparent that tropical climate variability during the last glacial cycle consisted of periods of both wetter and drier climate (Peterson et al. 2000).

The simple wet-dry dichotomy was also challenged spatially by a regional synopsis from which a pattern of high lake level was inferred at the LGM for the Southwestern USA and western Mexico, whereas low lake stage was observed for Panama and the Yucatan Peninsula (Bradbury 1997). In support of this hypothesis was the observation that many shallow lakes in the lowlands of northern Central America and southeastern Mexico first filled with water in the early Holocene, about 10.5–8 ka (e.g. Leyden 1984, Vaughan et al. 1985, Whitmore et al. 1996). The first appearance of these lakes in the early Holocene is easily explained by a wet phase that followed a late glacial dry phase.

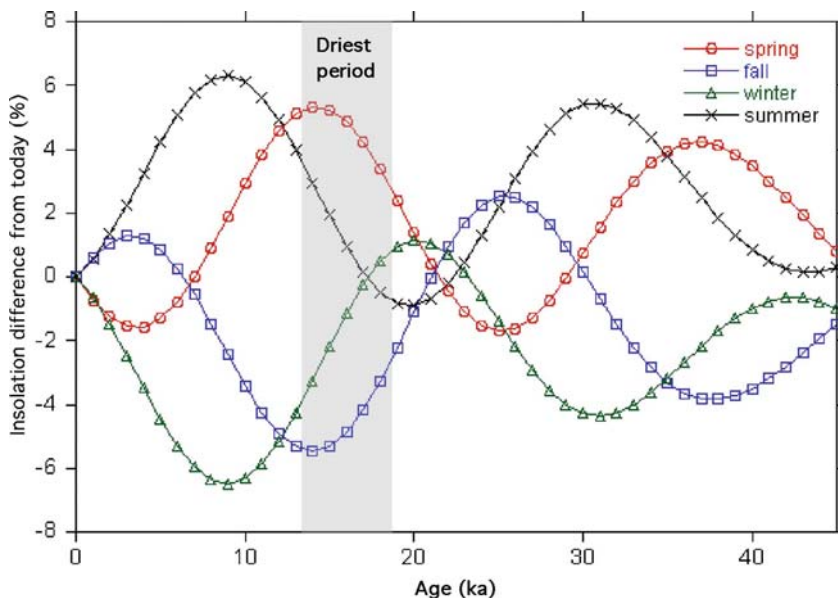
The Petén Itzá data contribute to the growing body of evidence that the LGM itself was not necessarily a dry time in the Neotropics. The clays deposited during the LGM and the presence of a montane *Quercus-Pinus-Myrica* community are consistent with cool conditions relative to today, but with no indication of a marked increase in soil-moisture deficits. Preliminary diatom data for the LGM suggest that lake level was higher than the latter part of MIS 3 or the deglacial period, but lower than the Holocene. As in other locations, it is the early deglacial period that appears to have been the driest time.

Notably, the lake at El Valle deepened at c. 16 ka, broadly coincident with the formation of Lake La Yeguada (Bush and Colinvaux 1990, Bush et al. 1992). At Petén Itzá, where a more detailed record is available, the rising lake levels coincident with the Bølling-Allerød period (14.9–12.8 ka) were punctuated by a dry event during Meltwater Pulse 1A (14.1–13.5 ka; Fairbanks et al. 2005).

## 5.4 Precession as a Long-Term Driver of Precipitation Change in Central America

Our understanding of the causes of climate change at the LGM is still limited. In particular, Central America is poorly represented in the relatively coarse resolution of most Global Climate Model simulations due to its complex topography and small width. Consequently, our first approximation of climate forcing is based on rather simple assumptions relating insolation to climate. Insolation forcing operates on multi-millennial, orbital time scales with the precession cycle and its harmonics (~11 and 5.5 ka) (Berger et al. 2006). It cannot directly explain abrupt change at shorter time scales (addressed in Section 5.5).

A readily quantifiable insolation parameter is the precession-driven variability of insolation in the upper atmosphere. Numerous papers point to the importance of precessional rhythms in the Neotropics, especially on patterns of precipitation (e.g. Berger 1978, Hooghiemstra et al. 1993, Bush et al. 2002, Rowe et al. 2002, Clement et al. 2004, Wang et al. 2004, Cruz et al. 2005, Hodell et al. 1991, 2000). It has been



**Fig. 5.3** Changes in insolation at  $15^{\circ}\text{N}$  over the last 40,000 years. Amount of insolation received ( $\text{watts per m}^2$ ) for spring (March 21), summer (June 21), autumn (Sept 21), and winter (Dec 21). Data from Analyseries 1.2 (Berger 1992, Paillard et al. 1996)

suggested that increased wet season insolation translates into elevated wet season rainfall, and that high (low) seasonality broadly relates to maximum (minimum) differences in seasonal insolation. Clement et al. (2004) identified the importance of precession to Pleistocene tropical climates, but cautioned that complex land-ocean interactions played an important modifying role.

Here we provide a very simple set of observations regarding precessional changes that may have influenced the climate of Petén over the last 30,000 years. These observations should really be taken as a set of hypotheses to be tested rather than a definitive history. For latitudes between  $10^{\circ}\text{N}$  and  $23^{\circ}\text{N}$ , the seasonal insolation pattern during the LGM was similar to that of today, and characterized by reduced seasonality relative to the deglacial and early Holocene (Fig. 5.3). The onset of wet conditions at the LGM c. 23 ka, coincided with a time of minimum seasonality during which summer insolation was relatively low and winter insolation was relatively high (i.e. similar to today).

We hypothesize that trajectories of insolation change leading up to and out of the LGM were highly significant influences on vegetation and lake levels on the Yucatan Peninsula. The previous peak of seasonal insolation difference (i.e. maximum difference between summer and winter insolation) occurred at c. 31 ka and transitioned to the LGM through an orbital configuration when perihelion occurred during northern hemisphere autumn.

On a regional scale, if summer heating of the ocean induces the northward migration of the Hadley cell, then thermal inertia of the ocean probably caused sea surface temperature (SST) increases to lag insolation. Consequently, wet season precipitation maxima would have lagged insolation maxima. This lag may have reduced summer convective activity during the LGM, but the increased autumn insolation may have prolonged the wet season. We suggest that the net effect of those changes was to produce a less intense, but longer wet season that maintained mesic conditions overall.

In the deglacial precessional transition, perihelion occurred in the northern hemisphere spring. During this period, spring insolation was higher than summer insolation. We hypothesize that weak summer insolation reduced convective activity and caused reduced wet season precipitation. The springtime peak of insolation would have occurred during the dry season, too early in the year for the ocean to have warmed and generated rainfall.

Ecologically, rainfall deficits in the dry season have far more influence on vegetation than equivalent reductions in wet season precipitation, when there is excess moisture in the system. In the Caribbean, the migration of the Inter-tropical convergence zone (ITCZ) results in wet season convective activity and delivers the majority of moisture to the region. The combination of a strengthened dry season and relatively weak ITCZ between c. 16 and 14 ka led to the greatest aridity within the last 50,000 years.

## 5.5 Short-Term Drivers of Precipitation and Temperature

Superimposed upon the longer-term effects of insolation were the influences of frontal activity, migration of air masses, and ocean currents. All of these factors were influenced by high-latitude (North Atlantic) climate. For example, the cooling that influenced the tropics came about as a consequence of high-latitude ice sheet expansion that influenced atmospheric (e.g. jet streams) and ocean circulation. Indeed the weight of each of these factors may have been different at various times in the past. Clement et al. (2004) isolates glacial boundary conditions from precessional forcing as potential influences on tropical climate. Bush (2002) suggested that the growth of the Laurentide ice mass was responsible for a change in forcing that affected the El Valle record, Panama at c. 45 ka. While we know the limits of that ice sheet and can model its volume, its teleconnective linkages with the tropics remain speculative. Empirical data support the idea that the polar jet was displaced southward or split to flow around the ice mass during the northern hemispheric winter (e.g. COHMAP 1988).

Global Climate Models, supported by empirical paleoclimatic data, indicate that when the meridional overturning circulation (MOC) was weakened (the extreme situation being Heinrich events), heat was retained in equatorial waters of the southern hemisphere. Furthermore, the presence of the northern-hemispheric ice mass, and stronger polar than equatorial cooling, steepened the pole-equator temperature gradient. Under these circumstances, the northern migration of the ITCZ was

weakened, while that of the southern migration was strengthened (Koutavas and Lynch-Stieglitz 2004, Chiang and Bitz 2005).

Modern precipitation over the Yucatan Peninsula is strongly seasonal, with the vast majority arriving in late northern hemispheric summer when the ITCZ lies to the north. We hypothesize that if the ITCZ fails to migrate far northward or its influence is weakened by the southward displacement of the westerlies (Ganopolski et al. 1998) and a steepened temperature gradient, then wet season (May–October) precipitation over Yucatan will be reduced.

The most striking feature of the paleoclimate record from Petén Itzá is that the LGM of the Yucatan Peninsula appears to have been moist, and it was the deglacial period that was driest. We hypothesize that the strengthened incursion of cold polar air masses (today referred to locally as *nortes*) at the LGM, resulted in relatively cool, wet winters.

As the Laurentide ice mass expanded southward, steepening the pole-equator temperature and pressure gradients, outbursts of polar air would likely have penetrated into Central America. Assuming that the weather associated with modern *nortes* was similar in the past, the *nortes* would have brought a rain front, followed by days of cold, dry weather. If the *nortes* penetrated into the Neotropics more frequently than today, and if they started from a more southerly polar jet, they would be expected to have enhanced seasonality in terms of temperature, but reduce soil moisture deficits in the dry season. The same basic mechanism, which promotes a cool, moist, and rather weakly seasonal precipitation system, though in that case fed by westerlies rather than *nortes*, was proposed to explain records from central Mexico (Metcalfe et al. 2007).

Toward the southern end of their range, the principal cooling of *nortes* comes not from air temperature, but from the blockage of insolation by clouds (Marengo and Rogers 2001). Cloudiness (or lack of it) could have moderated or accentuated insolation effects. To date, no models incorporate cloudiness, and although we can calculate insolation at the top of the atmosphere, insolation on the ground could have been very different.

Relatively dry events surrounding the wetter conditions of the LGM may have resulted from a combination of factors. Heinrich events H1 and H2, which bracket the LGM, may have caused reduced precipitation in Petén due to the postulated southward migration of the ITCZ (e.g. Vellinga and Wood 2002). Additionally, reduced incursions of *nortes* after ~18,000 years ago may have contributed to lowered lake levels and a change in vegetation. Drier conditions coincided with increased seasonality in insolation and a change in the vegetation. We hypothesize that a shift to fewer *nortes* resulted in milder, but drier dry seasons. Climate oscillations, including cooler periods of the Oldest Dryas, Older Dryas, and Younger Dryas, as well as intervening warm periods all appear to be present in the Petén Itzá record. The clear representation of events such as the deglacial Meltwater Pulse of c. 14 ka and Heinrich events suggest that the Petén Itzá record is sensitive to fluctuations in the strength of the MOC.

## 5.6 Conclusions

New data from Lake Petén Itzá sediment cores contribute to our understanding of late Pleistocene Central American paleoclimate, though much still remains to be discovered. The first question we addressed was whether there was cooling in the lowlands equal to that in montane settings at the LGM. Our data suggest that vegetated areas of montane and lowland regions probably both experienced cooling of  $\sim 5^{\circ}\text{C}$  in the LGM. However, ELA estimates for mountaintops suggest that this cooling may have been as great as  $8.5^{\circ}\text{C}$  above c. 3,300 m elevation. Assuming these proxies are reliable, it appears that there was steepening of the thermal gradient on mountainsides, especially above the vegetated zone.

The second question we addressed was whether the LGM was characterized by regional aridity? The Petén Itzá data provide very strong evidence that the LGM was cool, but wet enough to maintain a forest cover, whereas the deglacial  $\sim 17\text{--}14$  ka was markedly drier than today. The deglacial, rather than the Last Glacial Maximum, was the time of maximum aridity in lowland Guatemala, a finding consistent with paleoclimate data from other Central American localities.

In light of these data, we re-interpreted the paleoecological record from Lake Quexil (Leyden et al. 1993, 1994). The pre-Holocene chronology of this core was based on a single  $^{14}\text{C}$  date on an aquatic mollusc shell, uncorrected for hardwater lake error. Consequently, the  $^{14}\text{C}$  age was too old, and deglacial-age sediments (c. 17,000–15,000 cal. BP) were attributed erroneously to the LGM. The new core from Petén Itzá has 23  $^{14}\text{C}$  dates on terrigenous organic matter and yielded a far superior chronology for investigating climate change in the Central American lowlands.

New pollen data from Lake Petén Itzá indicate that from 23 to 19 ka (i.e. LGM chronozone), the catchment was occupied by a forest rich in oaks and pines that co-existed alongside tropical elements. Whether this forest constituted a no-analog assemblage or a close analog to Mexican pine-oak forests has yet to be determined.

The third question we addressed dealt with the cause(s) of precipitation change in Central America over the last 23,000 years. Although several mechanisms that influenced LGM climate in Central America have been identified, i.e. the southward shift of the westerlies, migration of the ITCZ, precessional insolation variability, cold fronts, SSTs, and cloudiness, the relative importance of each at any given time in the past remains unknown.

We hypothesize that the relatively mesic conditions of the LGM may have been a consequence of more evenly distributed precipitation than that of today, with reduced wet season inputs, but increased dry season moisture availability. A mechanism to account for this pattern and its timing is suggested based upon a combination of orbital forcing and stronger and more frequent cold fronts that brought rain to the region during winter (dry season). There exists a need to generate new, highly-resolved (both temporally and spatially) climate models that portray the Central American region at different times in the past realistically. Until that is achieved, we can provide empirical data on local climate conditions, but must speculate as to their cause.

**Table 5.1** Data for Late Quaternary glacial descent in Mexico and Central America. Of 25 Mexican glaciers given in Lachniet and Vazquez-Selem (2005), the extreme cases, i.e. with the greatest and least changes in equilibrium line altitude (ELA) relative to modern, are listed here. Temperature depression during the Last Glacial Maximum, relative to modern, was calculated assuming a lapse rate of  $5.6^{\circ}\text{C}/\text{km}$ : Data from Lachniet and Vazquez-Selem (2005)

Location	Latitude $^{\circ}\text{N}$	Modern ELA (m)	Last Glacial Maximum ELA (m)	Temperature depression ( $^{\circ}\text{C}$ )
Vaquerías valley, Mexico	19.20	4970	4146	4.6
Tancítaro, Mexico	19.43	4900	$3390 \pm 50$	8.5
Cuchumatanes ice cap, Guatemala	15.5	4900	3544	7.6
Talari Glacier, Costa Rica	9.47	5000	3489	8.5
Morrenas Glacier, Costa Rica	9.5	5000	3464	8.6

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