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A model of the 4000-year paleohydrology ($\delta^{18}O$) record from Lake Salpetén, Guatemala

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ABSTRACT

A simple mass-balance model provides insights into the influence of catchment vegetation changes and climate variability on the hydrologic and stable oxygen isotope ($\delta^{18}O$) evolution of Lake Salpetén, in the Maya Lowlands of northern Guatemala. Model simulations for the last 4000 years incorporate pollen-inferred changes in vegetation cover and account for 75% of the variance observed in the biogenic carbonate $\delta^{18}O$ record from a long lake sediment core. Vegetation-driven hydrologic changes, however, failed to capture the full range of late Holocene sediment core $\delta^{18}O$ variability. The model requires incorporation of additional shifts in catchment vegetation cover, inclusion of regional precipitation changes, or likely both, to explain the fluctuations observed in the lake core oxygen isotope record. Climatic interpretation of the model results suggests that there was relatively greater moisture availability between about 2400 and 1800 years ago, but increased $\delta^{18}O$ values centered at ~3300, 2900, 500, and 200 calendar years before present (cal yr BP) indicate abrupt precipitation decreases. There is evidence for protracted aridity between 1500 and 800 cal yr BP.

1. Introduction

Over the last several decades, interest in late Holocene paleoclimate of the Maya Lowlands has grown. Earth scientists have exploited a number of natural archives of past climate information, including speleothems (cave stalagmites) (Medina-Elizalde et al., 2010; Medina-Elizalde and Rohling, 2012; Kennett et al., 2012 and Webster et al., 2007), marine sediments (Haug et al., 2003) and lake deposits (Hodell et al., 1995, 2005a,b, 2007, 2012; Curtis et al., 1996; Douglas et al., 2014; Rosenmeier et al., 2002a,b) to infer long-term variability in regional rainfall amount, and thereby provide a climate context for ancient Maya cultural development and decline. Pollen in lake sediment cores from the region is largely uninformative about late Holocene climate change because ancient inhabitants cleared much of the forest for agriculture and construction (Deevey et al., 1979; Vaughan et al., 1985; Leyden, 2002; Wahl et al., 2006). Thus, paleolimnological studies of late Holocene climate in the Maya Lowlands have relied largely on stable oxygen isotope ($\delta^{18}O$) values in carbonate shells of snails (molluscs) and ostracods (crustaceans), which were thought to be immune from the influence of human activities. The rationale for this approach has been spelled out in detail elsewhere (Talbot, 1990; Chivas et al., 1993; Curtis and Hodell, 1993; Holmes, 1996; Brenner et al., 2003; Douglas et al., 2015), but is summarized briefly here.

1.1. Rationale for isotope-based paleoclimate studies in the Maya Lowlands

Oxygen isotope values in carbonate shells from lakes are largely controlled by the $\delta^{18}O$ of the lake water, the temperature at which the shell carbonate (calcite or aragonite) precipitation occurred, and taxon-specific fractionation. Most isotope-based paleolimnological studies of past climate utilize shell material from adult specimens of a single taxon to eliminate potentially confounding differences in fractionation between species, or between developmental stages of a single species. In cases for which a single taxon is not encountered throughout the sediment record, multiple taxa can be used, but it is helpful to assess inter-species differences in isotopic equilibrium, which can sometimes be achieved by comparing $\delta^{18}O$ values in shells of the two taxa at depths where they co-occur in the sediment profile.

Temperature is assumed to have had minimal influence on shell carbonate $\delta^{18}O$ in Holocene lake sediment cores from the Maya Lowlands, in part because infaunal (burrowing) and epifaunal (bottom-dwelling) gastropods and ostracods experience near-constant temperatures at the sediment–water interface year-round, particularly in deeper lakes (Pérez et al., 2013). Intra-annual surface-water temperature variations in the region are also relatively small (typically <5 °C), suggesting that

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shallow-water taxa, likewise, experience a limited range of temperatures throughout their lives.

Perhaps more importantly, emerging evidence indicates that inter-annual (year-to-year) temperature variability in the Maya Lowlands was also limited during the late Holocene. Specifically, new dual-isotope measurements on paired shell aragonite and gypsum samples from Lake Chichancanab, Mexico, suggest that mean temperature (26 °C) and temperature ranges (23 to 29.5 °C) in the northern Yucatán Peninsula *ca*. 1200 years ago were similar to values in the region today (Hodell et al., 2012). Thus, changing lake water $\delta^{18}O$ was probably the principal control on shell carbonate $\delta^{18}O$ in regional lakes during the late Holocene.

One determinant of lake water $\delta^{18}O$ is the isotopic signature of hydrologic input water, *i.e.*, rainfall plus surface and sub-surface runoff. The $\delta^{18}O$ of rainfall can vary as a function of temperature, relative humidity, and changing source water. Assuming that input water $\delta^{18}O$ values were relatively constant throughout the late Holocene, shifts in the hydrologic budget of the lake, *i.e.*, relative changes in inputs to outputs (evaporation plus surface and sub-surface outflow), were the primary determinant of the oxygen isotope ratio of lake water. Most lakes in the tropical karst terrain of the Maya Lowlands lack surface outflows. In such "closed-basin" tropical water bodies, it is generally assumed that the major control on the lake hydrologic budget is the relation between evaporation (E) and precipitation (P) (Lister et al., 1991). Whereas this assumption is appropriate for lakes in many tropical areas, it may not be fully justified in the Maya Lowlands, where ancient, human-mediated deforestation probably altered watershed hydrology, thereby invalidating the assumption that stratigraphic shifts in the $\delta^{18}O$ of shells in lake sediment cores reflect solely E/P fluctuations.

Variations in the oxygen isotopic composition ($\delta^{18}O$) of biogenic carbonate in sediment cores from Lake Salpetén, Guatemala, for example, were used to infer past environmental changes in the southern Maya Lowlands of the Yucatán Peninsula (Rosenmeier et al., 2002a,b). Results indicated that there had been pronounced changes in watershed hydrologic balance over the last ~4000 years. Strictly climatic interpretation of the $\delta^{18}O$ record suggested higher precipitation during the early period of Maya settlement expansion, between 2400 and 1800 cal yr BP, corresponding roughly to the Late Preclassic (Rosenmeier et al., 2002a,b). Alternatively, this ~600-year period of low $\delta^{18}O$ values may have been a consequence of increased surface runoff and ground water inflow to the lake, related to watershed deforestation by the ancient Maya. Population in the southern Maya Lowlands began to decline at the end of the Late Classic period, *ca*. AD 900, as $\delta^{18}O$ values in sedimented biogenic carbonates increased as a consequence of reduced hydrologic input to the lake, associated with decreased precipitation or forest recovery (Mueller et al., 2010).

1.2. Study objectives

Isotope mass balance approaches have been used to evaluate past hydrologic changes in large and small lakes (Hostetler and Benson, 1994; Ricketts and Johnson, 1996; Cross et al., 2001; Rowe and Dunbar, 2004; Jones et al., 2007; Steinman et al., 2010, 2013; Steinman and Abbott, 2013). We applied this method to Lake Salpetén to assess quantitatively the impact of catchment vegetation changes and climate on lake level and lake water $\delta^{18}O$. Model simulations of lake hydrologic inputs and outputs (and associated $\delta^{18}O$ values) were constrained by modern meteorological and catchment data, and palynologically inferred changes in forest cover. These simulations tested the plausibility that systematic changes in late Holocene precipitation controlled the hydrologic and isotopic evolution of the lake. Model results were compared with $\delta^{18}O$ variations in ostracod and gastropod shells from sediment cores taken in Lake Salpetén and other water bodies on the Yucatán Peninsula.

1.3. Study site

The karst limestone landscape of Petén, northern Guatemala (Fig. 1a), is generally characterized by well-drained forest soils and tropical semi-deciduous and evergreen vegetation (Lundell, 1937). Regional terrain varies in elevation between approximately 100 and 300 m above sea level and the water table lies deep below the land surface. Surface waters, however, are perched, resulting in numerous lakes and seasonally inundated topographic depressions in the landscape (Deevey et al., 1980). The Petén Lake District contains a number of terminal basins distributed along a series of east–west aligned faults at ~17°N latitude (Fig. 1a). Principal water bodies of the lake chain extend approximately 100 km from westernmost Lake Perdida, eastward to the twin basins of Lakes Yaxhá and Sacnab (Brenner et al., 2002). Lake Salpetén, located near the center of the lake chain, is a small water body (2.55 km^2) with a catchment area of 6.36 km^2 (Fig. 1b) and no surface inflows or outflows. The lake lies ~104 m above sea level and has a maximum depth of ~32 m (Anselmetti et al., 2007).

Rainfall in Petén varies from ~1500 to 2100 mm yr^{-1} (Table 1). The rainy season occurs between late May and October and is associated with northward migration of the inter-tropical convergence zone (ITCZ) and the North Atlantic high-pressure system (Hastenrath, 1984). During this period, tropical low-pressure systems are carried westward by the trade winds across the Atlantic into the Caribbean, at times bringing heavy rainfall, lightning, and strong winds to the Yucatán Peninsula (Wilson, 1980). Drier conditions develop in November and December and persist through early May, as the ITCZ and North Atlantic subtropical high (Azores–Bermuda high) move southward and atmospheric subsidence becomes predominant. Mean monthly air temperatures in Petén vary between ~20 and 29 °C (Table 1), but diurnal temperatures display a greater range of variability.

2. Materials and methods

2.1. Model description

The hydrologic balance of a lake (∂V_L) is controlled by the transfer of water to and from the catchment, according to the equation:

$$\partial V_L = \Sigma I + P - \Sigma O - E \quad (1)$$

where ΣI and ΣO are the total surface and sub-surface inflows (I) to and outflows (O) from the lake, P is direct precipitation on the lake, and E is the evaporative loss from the lake (Dinçer, 1968; Gat, 1981). A similar expression can be written for the oxygen isotopic composition of lake water (δ_L):

$$\partial V_L \delta_L = \Sigma I \delta_I + P \delta_P - \Sigma O \delta_O - E \delta_E \quad (2)$$

where δ is the isotopic composition of the various inputs and outputs. In lakes with negligible surface outflow, the hydrologic balance and lake water isotopic composition are determined by the difference between evaporation and precipitation over the lake, the water balance of the surrounding catchment (ΣI), and losses through sub-surface seepage (ΣO). The mass balance relations in the above equations represent the governing components in the models we constructed with ISEE Systems™ *STELLA*® software.

2.2. Hydrologic model equations

The model calculates lake water balance through the volumetric addition of direct precipitation and runoff from the catchment, and subtraction of lake evaporation and outflow. The model assumes no temporal lag between surface and sub-surface flows to the lake and therefore, no distinction is made between surface and sub-surface components of catchment runoff (Vassiljev et al., 1998). In the absence of