Lacustrine stable isotope record of precipitation changes in Nicaragua during the Little Ice Age and Medieval Climate Anomaly

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ABSTRACT

Discerning the influences of the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) on drought variability in the tropics during the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) will help to improve our understanding of climate system responses to internal and external forcing. Sediments from Lago El Gancho, Nicaragua, provide an ~1400 yr record of water balance (precipitation and evaporation) changes from a region that is sensitive to teleconnected Pacific and Atlantic ocean-atmosphere dynamics. Oxygen isotope values of ostracod carapaces ($\delta^{18}O_{ostracod}$) are consistently low in El Gancho sediments between ca. A.D. 950 and 1250, indicating that wetter conditions prevailed during the MCA, a period of La Niña–like mean state conditions in the tropical Pacific, and a positive mean state of the NAO. The ~150 yr period between the MCA and LIA was marked by an abrupt shift to persistently drier conditions at a time of highly variable Pacific sea-surface temperatures, and a transition toward a more negative NAO phase. In sediment from ca. A.D. 1450 to the present, $\delta^{18}O_{ostracod}$ values increase, suggesting that drier conditions persisted through most of the LIA, a time of a relatively negative NAO phase and El Niño–like mean state conditions in the tropical Pacific. The long-term precipitation trends inferred from the El Gancho data are not entirely consistent with modern associations between precipitation in the circum-Caribbean region and the NAO, suggesting that present-day hydroclimatic shifts resulting from variability in synoptic climate patterns are dissimilar to changes resulting from teleconnected ocean-atmosphere dynamics that operated during the MCA and LIA.

INTRODUCTION

The climate of Central America is controlled largely by variability in synoptic modes of atmospheric circulation and sea-surface temperatures (SSTs) in both the Pacific and Atlantic ocean basins. Changes in precipitation and temperature along the Central American Pacific margin are driven principally by the El Niño Southern Oscillation (ENSO) (Dai and Wigley, 2000; Diaz et al., 2001), the position of the Intertropical Convergence Zone (ITCZ) (Sachs et al., 2009), and the North Atlantic Oscillation (NAO) (Giannini et al., 2000, 2001). How the tropical hydrologic cycle might change in response to shifting mean state conditions of the tropical Pacific and Atlantic has been debated (DiNezio et al., 2010), and explored through both proxy analyses (Seager et al., 2007; Sachs et al., 2009) and modeling studies (Graham et al., 2007). Investigations of paleoclimate variations in the Caribbean and in Central America are therefore important for understanding the physical processes that produce teleconnections between ocean basins on longer, preinstrumental time scales.

Here we present an ~1400 yr ostracod-based oxygen isotope ($\delta^{18}O$) record from Lago El Gancho, Nicaragua, that documents past changes in the regional balance between precipitation and evaporation (P/E). We interpret the record using lake mass-balance model simulations demonstrating that El Gancho water and ostracod $\delta^{18}O$ values are primarily influenced by changes in lake-catchment hydrologic balance (Benson and Paillet, 2002; Steinman et al., 2010a, 2010b). The El Gancho record provides quantitative insight from Central America on how the hydrologic cycle in the tropics and subtropics varied during the Medieval Climate Anomaly (MCA; A.D. 950–1250) and the Little Ice Age (LIA; A.D. 1400–1850), providing further insight into the timing and causes of hydroclimate changes in Central America that resulted from synoptic ocean-atmosphere variations during the late Holocene.

SITE DESCRIPTION

Lago El Gancho (11.906°N, 85.918°W, 44 m above sea level, asl) is a small, seasonally closed-basin lake located on a peninsula within Lago Nicaragua (Fig. 1). El Gancho is ~10 m higher than Lago Nicaragua (34 m asl), and the lakes are not directly connected by surficial flow. Field observations and topographic maps indicate that most of the inflow to El Gancho is from precipitation and catchment runoff during the wet season.

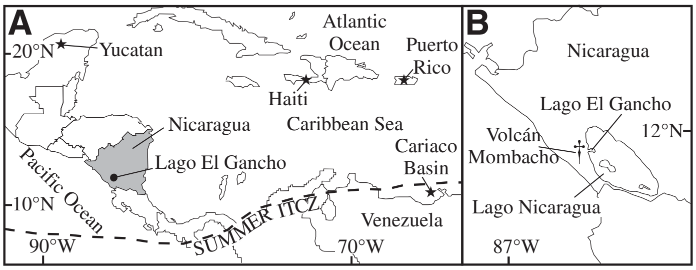

Figure 1. Location map of El Gancho (Nicaragua) and sites mentioned in text. Dashed line in A approximates the summer position of Intertropical Convergence Zone (ITCZ) (adapted from Hastenrath, 1967).

Precipitation patterns in Central America are driven largely by interactions between the North Atlantic subtropical high-pressure system and the eastern Pacific ITCZ (Giannini et al., 2000). Generally, in regions north of Panama, moisture is derived mostly from the Caribbean, and there is no clear secondary source from the Pacific Ocean. More precipitation falls on the Caribbean side of Nicaragua (where the average is ~500 cm yr^{-1}) than on the Pacific coastline (where the average is ~120 cm yr^{-1}) (Hastenrath, 1967; Instituto Nicaragüense de Estudios Territoriales, 2001). Typically, greater regional precipitation amounts are associated with warmer Caribbean SSTs, and a more northern position or intensification of the Pacific ITCZ, whereas a weaker ITCZ leads to decreased convection, reduced cloud cover, and smaller precipitation amounts.

Interannual rainfall patterns over Central America are also affected by ENSO and Atlantic SSTs (related to the NAO) and the influence that these ocean-atmosphere patterns have on the ITCZ (Haug et al., 2001). The warm phase of ENSO typically produces smaller wet season rainfall amounts along the Pacific coast of Nicaragua, and the opposite occurs during cold phases (Dai and Wigley, 2000; Diaz et al., 2001). North Atlantic and Caribbean SST changes are closely related, such that positive sea-level pressure anomalies associated with the NAO in the North Atlantic usually result in stronger trade winds, leading to lower SSTs and drier

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conditions; negative anomalies usually result in weaker trade winds, leading to higher SSTs and wetter conditions (Giannini et al., 2001).

METHODS

Sediment cores were collected from El Gancho in 2004 (see the GSA Data Repository[1]). An age-depth model (Fig. 2) was produced using calibrated radiocarbon ages measured on charcoal (Table DR1), and by applying Bayesian statistical methods compiled by the OxCal age model analysis program (with the P-sequence deposition method; Bronk Ramsey, 2008). Aggregates of ~30 adult ostracod carapaces of the genus *Physocypria*, with no evidence of corrosion, were isolated from sediment for oxygen isotope analysis at 1–2 cm intervals. Surface-water samples for hydrogen (δD) and oxygen isotopic ratio analysis were collected in 2003 and 2004 (Fig. 3).

The hydrologic and isotope mass-balance model applied here is based on the lake-catchment model in Steinman et al. (2010a) and was designed to simulate the isotope dynamics of a shallow, seasonally overflowing lake with a large surface area/volume ratio, located in a tropical climatic setting with a highly seasonal distribution of precipitation (see the Data Repository). The model is defined by a system of four ordinary differential equations. The model equations integrate a system of two water reservoirs (one defining lake water mass balance, and one defining catchment-groundwater balance), and volumetric fluxes to the reservoirs including direct precipitation over the lake area, inflow from the catchment-groundwater reservoir, and subtraction of lake water evaporation and overflow. Steady-state simulations were conducted using average monthly climate data (Table DR3) to investigate long-term (i.e., multidecadal) lake responses to climate forcing.

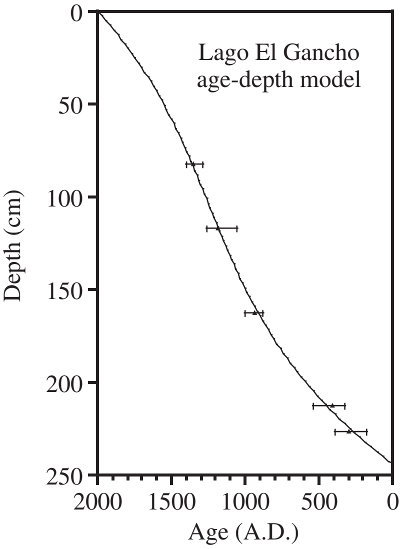

Figure 2. Age-depth model developed using third-order polynomial fit between radiocarbon samples from El Gancho, Nicaragua (Table DR1; see footnote 1). Error bars represent 2σ range.

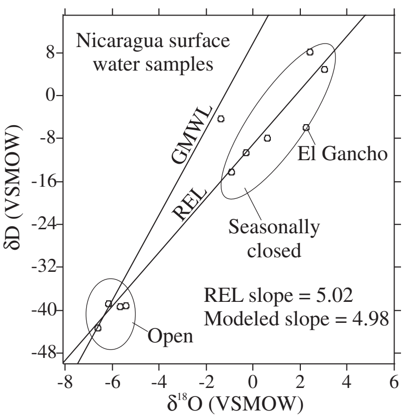

Figure 3. Oxygen and hydrogen isotopic values of surface-water samples collected in Nicaragua plotted versus global meteoric water line (GMWL) (Bowen and Revenaugh, 2003). Also shown are slopes of the modeled (see the Data Repository [see footnote 1]) and measured regional evaporation lines (REL). VSMOW—Vienna standard mean ocean water.

SEDIMENT ISOTOPIC RESPONSES TO CLIMATE FORCING

Radiocarbon measurements (Table DR1) indicate that El Gancho contains a continuous sediment record spanning the past ~1400 yr, and that each isotope value represents an average of ~5 yr. The $\delta^{18}O_{ostracod}$ values in the El Gancho record steadily decrease, and remain consistently low from ca. A.D. 600 to 1250, followed by an abrupt shift to higher isotopic values in sediment from ca. A.D. 1250 to 1400 (Fig. 4). Isotopic values decrease from ca. A.D. 1400 to 1450, followed by steadily increasing values from ca. A.D. 1450 to 1900.

Closed-basin lake water and sediment $\delta^{18}O$ values are influenced by many climatic variables including temperature, humidity, precipitation, and seasonality (Gat, 1995; Steinman et al., 2010a). In lakes that lose an appreciable amount of water through groundwater seepage or seasonal overflow, precipitation is potentially the primary influence on water $\delta^{18}O$ values; secondary control includes changes in temperature and relative humidity (assuming that interannual and intraannual variance in precipitation is large) (Steinman et al., 2010b). Conversely, in lakes that lose water almost entirely through evaporation, temperature and relative humidity

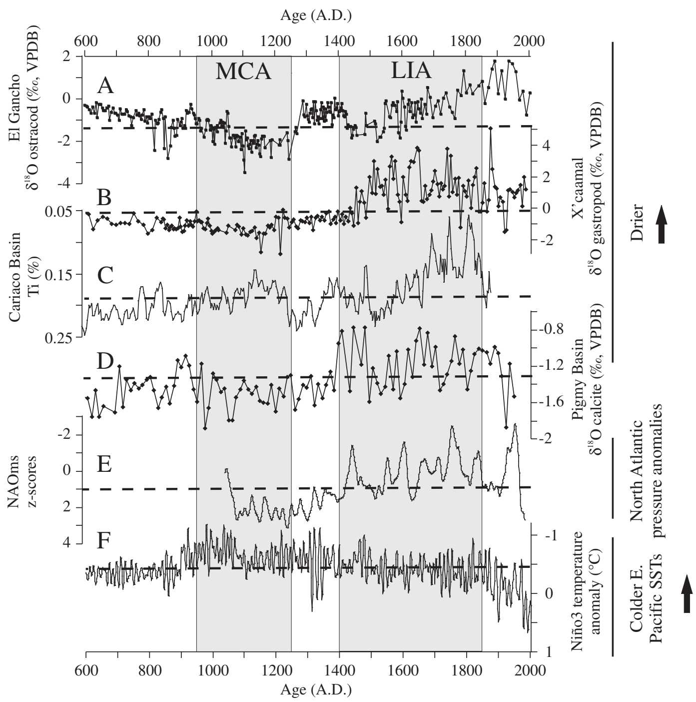

Figure 4. A: Lago El Gancho (Nicaragua) isotope data. MCA—Medieval Climate Anomaly; LIA—Little Ice Age; VPDB—Vienna Peedee belemnite. B–D: Isotope data plotted versus other regional records (dashed lines represent average values) (Haug et al., 2001; Hodell et al., 2005; Richey et al., 2007). E: Consistently wetter conditions during the MCA in the northern tropical Americas correspond with more positive North Atlantic Oscillation (NAO) values (Trouet et al., 2009). F: Consistently wetter conditions during the MCA in the northern tropical Americas correspond with La Niña–like sea-surface temperatures (SSTs) (Mann et al., 2009). The shift to a consistently drier LIA in Central America corresponds to more El Niño–like mean state in tropical Pacific, and to a more negative NAO phase.

[1]GSA Data Repository item 2013037, supplemental information, model description and data tables, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

(which control evaporation rates and equilibrium and kinetic fractionation) are the strongest decadal- to century-scale isotopic controls (Gibson et al., 2002).

Oxygen isotope values of El Gancho surface water samples are enriched by ~8‰ relative to local meteoric water (Fig. 3), indicating substantial water loss through both evaporation and nonfractionating outflow pathways (i.e., overflow and outseepage through the lake bed), and a resulting lake water isotopic sensitivity to changes in hydrologic balance. Isotopic and hydrologic modeling supports these assertions, indicating that precipitation is the principle control on El Gancho lake water $\delta^{18}O$ values. For example, in response to modeled precipitation changes of ±50%, El Gancho exhibited water and ostracod $\delta^{18}O$ increases of >1.5‰ and decreases of >1.0‰, respectively; largely as a result of hydrologic control of the proportions of water lost through evaporation and overflow (Table DR5). On the contrary, in model simulations of changes in relative humidity (of ±5%) and temperature (of ±2 °C), El Gancho water and ostracod variations were considerably smaller (i.e., <0.7‰).

Ostracods form low-magnesium calcite carapaces that archive isotopic and geochemical information about the surrounding lake water at the time of carapace formation (Leng and Marshall, 2004). The isotopic fractionation between ostracod calcite and water is temperature dependent (Kim and O'Neil, 1997), with a positive and approximately constant offset from theoretical equilibrium values due to a genus-specific vital effect (Leng and Marshall, 2004). Estimated centennial time-scale temperature changes (of ~2 °C) in Central America during the LIA and MCA (Hodell et al., 2005; Richey et al., 2009) are not large enough to explain the full range of El Gancho $\delta^{18}O$ variability. For example, a theoretical water temperature increase of 2 °C would produce a $\delta^{18}O$ decrease of ~0.5‰ (Kim and O'Neil, 1997), substantially less than the difference between average MCA and LIA $\delta^{18}O$ values. Furthermore, atmospheric temperature changes of ±2 °C in El Gancho model simulations resulted in average annual water and $\delta^{18}O_{ostracod}$ offsets of <0.4‰ (Table DR5), suggesting that lake isotope dynamics are relatively insensitive to temperature changes. We therefore assert that atmospheric temperature effects on ostracod isotope content were minimal during the past ~1500 yr, and that the ostracod-based stable isotope record from El Gancho represents changes in lake water isotopic composition primarily resulting from variations in hydrologic balance. Ostracod carapaces with lower oxygen isotope values likely formed in wetter climatic conditions; i.e., when precipitation amounts were higher or evaporation rates were considerably lower (high P/E), and vice versa.

A speleothem calcite record of oxygen isotope content in precipitation from Puerto Rico (Winter et al., 2011) does not show source $\delta^{18}O$ variations of a magnitude large enough to explain the large shifts (of >4‰) in the El Gancho record. A shift to predominantly Pacific (rather than Atlantic) derived moisture is also an unlikely source of substantial isotopic variability because measurements of $\delta^{18}O$ values of precipitation and carbonates suggest that sources of rainfall across the region did not vary considerably during the Holocene (Lachniet et al., 2007). This supports the assertion that water balance variations, and not source changes, were the principle control on El Gancho $\delta^{18}O_{ostracod}$ values.

SYNOPTIC CLIMATE VARIATIONS DURING THE MCA AND LIA

The general pattern evinced by the El Gancho data suggests a persistently wetter MCA and a drier LIA. This is consistent with other proxy records from the northern tropical Americas, including the Yucatan (Hodell et al., 2005), the Gulf of Mexico (Richey et al., 2007), lowland Venezuela (Curtis et al., 1999), the Cariaco Basin (Haug et al., 2001), and Haiti (Hodell et al., 1991). The El Gancho record also suggests that a period of consistently drier conditions occurred during the ~150 yr interval between the MCA and LIA. Notably, the El Gancho $\delta^{18}O$ data are inconsistent with speleothem records from Panama that indicate that conditions were drier during the MCA (Lachniet et al., 2004). This finding is difficult to explain in light of the aforementioned abundance of proxy-based evidence and the fact that climate modeling studies generally reproduce late Holocene trends (of a wetter MCA and a drier LIA) inferred from the paleoclimate data (Seager et al., 2007; Burgman et al., 2010).

The El Gancho $\delta^{18}O$ record demonstrates that strong associations exist between precipitation in Nicaragua and mean state changes in the eastern Pacific and Atlantic Oceans. Proxy reconstructions of Niño 3 region (Niño3) SSTs (Mann et al., 2009) positively correlate ($R = 0.39$) with El Gancho $\delta^{18}O$ values, implying that warmer Niño3 temperatures commonly occurred when climate was drier in western Nicaragua and vice versa. In contrast, proxy-based reconstructions of the NAO (Trouet et al., 2009) negatively correlate ($R = 0.49$) with El Gancho $\delta^{18}O$ values, indicating that positive NAO phases generally corresponded with wetter conditions in western Nicaragua over the past ~1000 yr, and vice versa. This result contradicts the observed NAO-precipitation relationship (i.e., that positive NAO phases result in lower precipitation amounts in the circum-Caribbean region) (Giannini et al., 2000, 2001), and points to the possibility that observational data may not fully characterize synoptic-scale ocean-atmospheric forcing of climate, especially on longer time scales.

The El Gancho record suggests that nonstationarity of Pacific and Atlantic ocean-atmosphere forcing should be considered when investigating the long-term perspective of precipitation changes in Central America. Climate model simulations indicate that positive NAO conditions during the MCA were likely enhanced by a strengthening of the Atlantic Meridional Overturning Circulation (Delworth and Greatbatch, 2000), which produced a stronger equatorial SST and salinity gradient in the Atlantic, weaker northeasterly trade winds, warmer Caribbean SSTs, and a northward displacement of the ITCZ in the tropical Atlantic and eastern tropical Pacific (Graham et al., 2007; Burgman et al., 2010). These modeling results help to reconcile the disparity between modern NAO and precipitation pattern relationships and associations inferred from proxy-based evidence spanning the past millennium.

While additional records are needed to resolve discrepancies in NAO proxy data (Trouet et al., 2012), there is strong evidence from El Gancho and other records that the LIA was a period of cooler Caribbean SSTs, drier conditions in much of Central America (Hodell et al., 2005), a more negative NAO phase in the Atlantic (Trouet et al., 2009), El Niño–like mean state conditions in the Pacific (Mann et al., 2009), and a more southern ITCZ (Haug et al., 2001; Sachs et al., 2009). The El Gancho data also demonstrate that a period of rapid change in northern low-latitude hydrologic balance occurred from A.D. 1250 to 1400, when Pacific (Niño3) SSTs were highly variable (Fig. 4) and as the NAO shifted to more negative values. Collectively, proxy records from the Caribbean indicate that during the MCA, interactions between the tropical Pacific and Atlantic ocean-atmosphere systems may have produced climatic responses that are not exhibited in the current configuration of the climate system. In general, these results show that present-day hydroclimatic shifts resulting from variability in synoptic climate patterns may not be a complete analogue for centennial time-scale changes (i.e., during the MCA and LIA) that occurred when external forcing conditions (i.e., solar and volcanic) were dissimilar to those of present.

CONCLUSIONS

The El Gancho $\delta^{18}O$ record provides newly detailed information on hydroclimate variations in Central America during the late Holocene and exhibits trends that are similar to regional drought patterns identified in other proxy records from the northern tropical and subtropical Americas. More specifically, the ostracod-based oxygen isotope record from El Gancho, Nicaragua, indicates that wetter conditions prevailed from as early as ca. A.D. 600 until the end of the MCA, ca. A.D. 1250. An abrupt shift toward arid conditions occurred during the ~150 yr interval between the MCA and the LIA, and was followed by a generally drier climate that has persisted until present. The wetter climate of Nicaragua during the MCA was closely associated with inferred La Niña–like mean state conditions in the Pacific Ocean, along with a consistently positive phase of the NAO in the Atlantic Ocean. Conversely, the drier climate of Nicaragua during the LIA occurred in response to a progression toward a more negative NAO phase in the Atlantic, El Niño–like mean state conditions in the Pacific, and a more southern position of the ITCZ. Proxy evidence from Lago El Gancho further indicates that mean state changes in the tropical Pacific and Atlantic Oceans during the MCA and LIA produced hydroclimatic conditions in Central America that are not entirely consistent with observed climatic anomalies related to teleconnected ocean-basin dynamics.

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