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Late Quaternary moisture export across Central America and to Greenland: evidence for tropical rainfall variability from Costa Rican stalagmites

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ABSTRACT

We present a high-resolution terrestrial archive of Central American rainfall over the period 100–24 and 8.1–6.5 ka, based on $\delta^{18}O$ time series from U-series dated stalagmites collected from a cave on the Pacific Coast of Costa Rica. Our results indicate substantial $\delta^{18}O$ variability on millennial to orbital time scales that is interpreted to reflect rainfall variations over the cave site. Correlations with other paleoclimate proxy records suggest that the rainfall variations are forced by sea surface temperatures (SST) in the Atlantic and Pacific Oceans in a fashion analogous to the modern climate cycle. Higher rainfall is associated with periods of a warm tropical North Atlantic Ocean and large SST gradients between the Atlantic and Pacific Oceans. Rainfall variability is likely linked to the intensity and/or latitudinal position of the intertropical convergence zone (ITCZ). Periods of higher rainfall in Costa Rica are also associated with an enhanced sea surface salinity gradient on either side of the isthmus, suggesting greater freshwater export from the Atlantic Basin when the ITCZ is stronger and/or in a more northerly position. Further, wet periods in Central America coincide with high deuterium excess values in Greenland ice, suggesting a direct link between low latitude SSTs, tropical rainfall, and moisture delivery to Greenland. Our results indicate that a stronger tropical hydrological cycle during warm periods and large inter-ocean SST gradients enhanced the delivery of low latitude moisture to Greenland.

1. Introduction

The tropical hydrological cycle plays a key role in regulating global climate through the export of heat and moisture to higher latitudes, and through its interaction with thermohaline circulation (THC) via the freshwater export from the Atlantic to the Pacific Ocean (Broecker and Denton, 1989; Stocker and Wright, 1991; Zaucker and Broecker, 1992; Zaucker et al., 1994; Broecker, 1997; Romanova et al., 2004). However, it is unclear *a priori* how moisture export across the isthmus varies with the mean position of the ITCZ. Evidence from the Cariaco Basin suggests that moisture transport is greatest when the ITCZ is in a northerly position during wet interstadials (Peterson and Haug, 2006) and moisture easily passes through prominent gaps in the Panama canal zone, the Nicaragua Trough, and the Gulf of Tehuantepec (Xu et al., 2005). In contrast, some modeling studies suggest that freshwater export is greatest when the ITCZ is in a more southerly position (Lohmann, 2003), although the model resolution is not sufficient to capture the potential blocking effect of the high Andes on the atmospheric transport (Zaucker and Broecker, 1992). Thus, proxy records of past hydrologic variability from Central America and the surrounding seas may help elucidate the role of the tropical hydrological cycle in past climate changes (Leduc et al., 2009). Herein, we hypothesize that periods of wet conditions in Costa Rica are associated with enhanced freshwater atmospheric export over the Isthmus of Panama, and will test the hypothesis by comparison of our rainfall proxy record with other records of sea surface temperature and salinity in the Caribbean Sea and Pacific Ocean.

Because our site lies in the heart of the intertropical convergence zone (ITCZ) at ~10°N, it is an important location to test the teleconnection between moisture export, tropical rainfall, tropical sea surface temperatures and salinities, and high latitude climate change. Studies from other northern tropical locations commonly show a tight correlation between rainfall and the pronounced millennial-scale stadial and interstadial (e.g. Dansgaard/Oeschger)

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events recorded in Greenland Ice (Wang et al., 2001; Burns et al., 2003). In the southern tropics and further from North Atlantic Ocean forcing, rainfall appears to be closely correlated with insolation on precessional time scales (Baker et al., 2001; Cruz et al., 2005; Wang et al., 2007). During Heinrich events in the North Atlantic Ocean, freshwater input and SST decreases resulted in a southward displacement of the ITCZ, which produced wet periods in the southern tropics (Wang et al., 2004; Jaeschke et al., 2007). The existing data suggest that cold periods in the northern hemisphere are associated with a southward displacement of the ITCZ and reduced thermohaline circulation (Vellinga and Wood, 2002; Peterson and Haug, 2006). The combined influence of SST anomalies (SSTAs) in both tropical Atlantic and Pacific Oceans is a dominant control on modern climate in Central America (Poveda et al., 2006; Lachniet, 2009b), and may also have controlled the strength and latitudinal position of the neotropical ITCZ in the past, yet little is known of the tropical hydrologic cycle in sites sensitive to forcing from both oceans.

Further, although modeling studies suggest a coupling between the tropical hydrological cycle and high latitude climate (Vellinga and Wood, 2002; Broccoli et al., 2006), few data constrain past delivery of moisture to Greenland. Moisture source variations in Greenland over the late Quaternary have been linked to changes in source latitude and temperature (Masson-Delmotte et al., 2005), and were interpreted to have an obliquity fingerprint. Periods of low obliquity would result in more mean annual tropical insolation, a larger tropics-to-pole temperature gradient, and enhanced meridional storm activity. Modeling studies have implicated the subtropical and tropical North Atlantic Ocean as an important moisture source for Greenland (Werner et al., 2001), contributing up to 42% of the precipitation that falls over central Greenland. The source areas of moisture to Greenland may be tracked with the deuterium excess ($d = \delta D - 8 \times \delta^{18}O$), because d is dependent upon the climatic conditions associated with evaporation at the source areas (Armengaud et al., 1998; Werner et al., 2001). However, few data are available to test whether the tropical hydrologic cycle had an influence on moisture delivery to Greenland. We also test the hypothesis that the strength of the ITCZ may have modulated the delivery of low latitude moisture to Greenland on orbital to multi-millennial time scales.

1.1. Study area and cave climate

Our study area is located on the Nicoya Peninsula, Pacific Coast of Costa Rica (Fig. 1). Terciopelo Cave (Mora-Castro, 1981; Hempel et al., 1989) in Barra Honda National Park is located at 10° 10′ N, 85° 20′ W, at an altitude of 370 m a.s.l. The cave is located on Cerro Barra Honda, composed of likely Eocene–Oligocene aged reef limestones overlying siltstone of the Rivas Formation (Mora-Castro, 1981; Hempel et al., 1989; Mora-Castro, 1992). The limestones are not overlain by any other unit, suggesting continued uplift and exposure since cessation of deposition. The karst is most intensively developed in association with near vertical jointing. Hydrologically, the cave is located in a local groundwater flow system beneath bedrock <80 m thick. Year round observations by cave guides indicate a distinct seasonality in drips within Terciopelo Cave, with rapid rates during the boreal summer wet season, and slow or non-existent drips during boreal winter dry season. The drip seasonality suggests a fast transit time of locally-derived dripwaters from the soil zone to the stalagmite, thus ensuring a near contemporaneous recording of climate changes in the samples. The cave room where the samples were collected is poorly ventilated and we measured relative humidity between 94 and 97%, which is the upper accurate limit of our hand-held meters. Observation of condensation on cave walls indicates air is close to or at 100% relative humidity, so that significant drip water evaporation is unlikely. Results from 14 months (January 2004–March 2005) of temperature and relative humidity measurements in Terciopelo Cave with a HOBO H8 Pro Series data logger indicate constant (<0.7 °C fluctuation) temperature, and moisture saturated conditions. Hand-held temperature probe measurements while in the cave recorded temperatures consistently around 27 °C, which is equivalent to the mean annual temperature for the area. The data logger temperatures were lower by ~3 °C relative to portable probes, perhaps because of a logger malfunction in the warm and humid environment. The relative humidity sensors at deployment began logging values of ~99% relative humidity, which increased to 104% after 5 days. Such impossibly high readings likely reflect a condensing environment (HOBO, 2004). Upon removal of the cave to non-saturated air outside the cave, the logger resumed accurate relative humidity measurements, as confirmed by our hand-held hygrometers.

1.2. Modern climate

The modern climate of the study area is humid tropical with a boreal winter dry season. Vegetation is seasonal dry forest (Hempel et al., 1989). The region currently receives 2220 mm of annual rainfall and has a 4 month dry season (December–March) and an 8 month wet season (April–November) following the annual migration of the ITCZ (Fig. 2). Mean annual temperature is 26.9 °C (in the town of Nicoya). Northeasterly trade winds traverse the isthmus during the December–April dry season, and the wet season is associated with enhanced onshore flow from the Pacific associated with southwesterly winds (Hastenrath, 2002; Poveda et al., 2006).

Rainfall variability is forced by large-scale ocean-atmosphere phenomena, such as the El Niño/Southern Oscillation (ENSO), and sea surface temperature anomalies (SSTAs) in bordering oceans (Hastenrath, 1967; Estoque et al., 1985; Waylen et al., 1994; Waylen et al., 1996a; Enfield and Mayer, 1997; Waylen and Laporte, 1999; Giannini et al., 2000; Giannini et al., 2001a; Hastenrath, 2002). Regionally, rainfall anomalies are most pronounced when SSTAs are of opposite sign across the isthmus (Enfield and Alfaro, 1999; Poveda et al., 2006). Wettest conditions on the Pacific Coast happen when the tropical North Atlantic is warm and the eastern Pacific is cold, due to enhanced convection and a northward displacement of the ITCZ over Central America. Such a situation happens when La Niña events are paired with a warm tropical North Atlantic (Estoque et al., 1985; Poveda et al., 2006). El Niño (La Niña) events are associated with dry conditions and a lengthened (shortened) dry season (Estoque et al., 1985), and reduced (increased) stream discharge on the Pacific Coast of Costa Rica (Waylen and Laporte, 1999). The rainfall response to SSTAs on the immediate Caribbean Coast appear opposite to those on the Pacific Coast, and the rainfall response on many areas on the isthmus are influenced by local topography (Enfield and Alfaro, 1999). Such an opposite response may relate to the transfer of SSTAs across the isthmus via anomalous atmospheric circulation. During warm El Niño events, trade wind strength over the Caribbean decreases, resulting in less loss of heat from surface waters and a corresponding SST increase (Enfield and Mayer, 1997). The SST response in the Caribbean lags the peak El Niño warming by one to two seasons, and may relate to a northward displacement of the ITCZ (Giannini et al., 2001b), in contrast to the southward displacement in the eastern tropical north Pacific Ocean. Because the opposing coasts of Central America respond conversely to the similar forcing, disentangling *a priori* the effect of ENSO and tropical North Atlantic SSTAs on Central American rainfall and $\delta^{18}O$ is difficult.

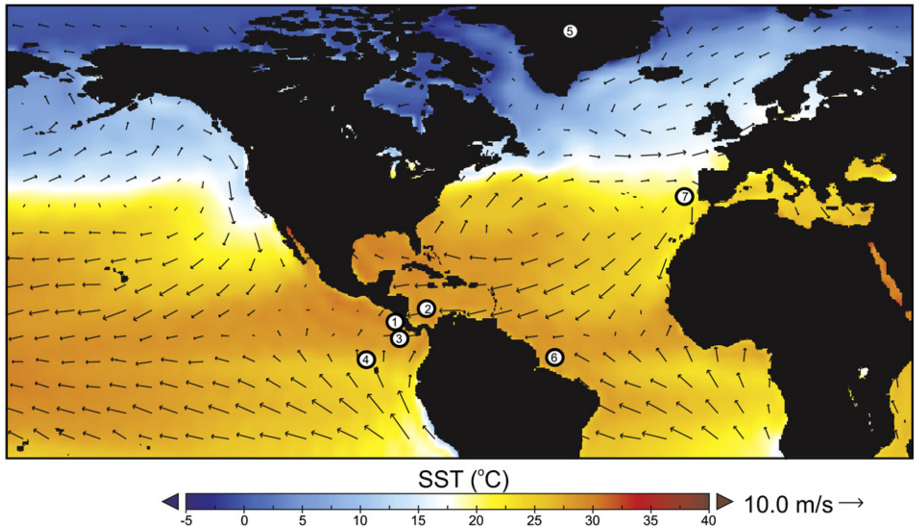

Fig. 1. Map of study area and other paleoclimate proxy records mentioned in the text. (1) Is Barra Honda National Park on the Nicoya Peninsula of Costa Rica; (2) is core ODP-999A, Caribbean Sea; (3) is core MD02-2529 offshore Costa Rica; (4) is core TR163-22 in the Pacific cold-tongue near Galápagos; (5) is Greenland Ice Sheet; (6) is GeoB 3910-2 offshore Brazil; and (7) is core MD95-2042 off the Iberian margin. Color is sea surface temperature from the NCEP reanalysis data (Kalnay et al., 1996); vector arrows are wind direction and speed.

In Central America, the $\delta^{18}O$ value of rain is inversely correlated to rainfall amount at a site (the 'amount effect' (Dansgaard, 1964; Rozanski et al., 1993)), and decreasing rainfall, surface water, and stalagmite $\delta^{18}O$ values across the isthmus indicate the dominant moisture source is the Caribbean Sea (Lachniet and Patterson, 2002; Lachniet and Patterson, 2006; Lachniet et al., 2007; Lachniet and Patterson, 2009). The $\delta^{18}O$ values of rain falling over our Pacific Coast study area primarily reflects distillation of air masses as they traverse the isthmus, with a secondary moisture source of the eastern tropical Pacific during the late wet season. During wetter periods, enhanced moisture distillation results in rain with low $\delta^{18}O$ values. Analysis of zero-lagged $\delta^{18}O$ anomalies on the Pacific Coast of Panama indicate that $\delta^{18}O$ values are higher (lower) by ~2.3‰ during El Niño (La Niña) months, and lower (higher) by ~1.8‰ when the tropical North Atlantic is warm (cold) (Lachniet, 2009b). These data suggest that precipitation $\delta^{18}O$ values reflect rainfall amount and ocean-atmosphere processes related to SST anomalies such as ENSO (Trenberth, 1997) and tropical Atlantic variability (Enfield et al., 1999; Giannini et al., 2001a).

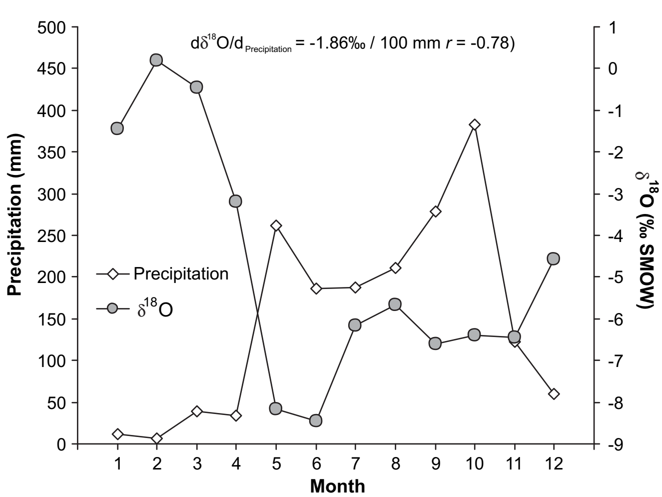

Fig. 2. Averaged monthly precipitation amount and $\delta^{18}O$ values for stations in and near the Nicoya Peninsula of Costa Rica from the GNIP database (IAEA/WMO, 1998). The data show a clear seasonal amount effect.

Stalagmite $\delta^{18}O$ values may be robust proxies for past drip and rain water $\delta^{18}O$ (Fairchild et al., 2006; Lachniet, 2009a) if the calcite has been precipitated in equilibrium. Because stalagmite calcite $\delta^{18}O$ tracks variations in drip water oxygen isotopes, greater rainout amount at and/or upwind of the cave site are recorded as more negative calcite $\delta^{18}O$ values in many humid tropical regions, and *vice versa* (Lachniet et al., 2004b; Cruz et al., 2005; Fairchild et al., 2006; Wang et al., 2007; Lachniet, 2009a) due to the 'amount effect'. Thus, we interpret the stalagmite $\delta^{18}O$ time series to reflect rainfall amount over the cave site, such that low (high) $\delta^{18}O$ values are representative of wet (dry) periods.

2. Methods

2.1. Stalagmites and sampling protocol

The samples were collected at the end of a small dead-end side passage approximately 70 m from the entrance at a depth of −60 m (Fig. 1). Four stalagmites were analyzed: CT-1 (365 mm), CT-5 (306 mm), CT-6 (343 mm beneath a hiatus), and CT-7 (372 mm). CT-7 was recovered in growth position and the others were collected already broken from the cave floor for cave conservation purposes. The stalagmite stratigraphy revealed in split sections is defined by white calcite with color- and porosity-driven banding on millimeter to centimeter scales. Calcite is dense along the sampled growth axes. Thin sections prepared from stalagmites CT-6 and -7 reveal columnar calcite fabric and long (up to several cm) and overlapping calcite crystals that extend in the growth direction. No clastic material was observed within the stalagmites. These petrographic observations suggest that the stalagmites have not undergone post-depositional recrystallization since growth cessation. Stalagmites CT-1, -5, and -7 do not contain evidence for hiatuses. Stalagmite CT-6 contains a hiatus at 344 mm (all distances are heights from base), defined by a distinct change in calcite growth fabric, so we report stable isotope and U-series data from beneath it. We analyzed 1684 $\delta^{18}O$ subsamples at the Universities of Massachusetts and Saskatchewan, and at the Las Vegas Isotope Science Laboratory at the University of Nevada, Las Vegas. Stalagmites CT-5, -6, and -7 were subsampled for stable isotopes at a 1.0 mm interval, whereas CT-1 was subsampled every 0.5 mm. Samples were analyzed on ThermoElectron Delta + or Delta V mass spectrometers in Kiel III and IV automated carbonate preparation devices, where samples were reacted with phosphoric acid at 70 °C to liberate CO_2 gas. Values are reported as ‰ relative to the VPDB standard via regular calibration to an internal laboratory standard. Precision is better than 0.06‰ for $\delta^{18}O$. A composite time series was created from stalagmites CT-1, -5, and -6 by splicing together the three records. The time series was then interpolated at a 100 year interval, and corrected for changes in the isotopic composition of the ocean according to the reconstruction of (Waelbroeck et al., 2002).

2.2. Chronology

Subsamples weighing between 80 and 450 mg for U-series were drilled at regular intervals along the densest portions of the growth axes. The stalagmite surface was cleaned and the uppermost 0.3–0.6 mm of calcite from each drill pit were discarded to avoid surface contamination. The powders were dissolved in HNO_3 and mixed with a ^{229}Th–^{233}U–^{236}U spike, which eliminates propagation of weighting error into the age uncertainties. No insoluble material was noted after acid dissolution, showing that macroscopic detrital contamination with clays and silts is negligible. U and Th were coprecipitated with $FeOH_3$ and separated in anion exchange columns. Isotopic ratios were measured on a Micromass Sector 54 thermal ionization mass spectrometer with a high-abundance sensitivity filter using an ion-counting Daly multiplier, and later measurements on a ThermoElectron Neptune Multi-Collector ICP-MS at the University of New Mexico. The global initial $^{230}Th/^{232}Th$ atomic ratio value of $4.4 \times 10^{-6} \pm 50\%$ (with the exception of CT-5 and -6, which were ± 100%) was used to correct for detrital Th (Richards and Dorale, 2003). All errors are absolute 2σ.

3. Results

3.1. Climate and $\delta^{18}O$

We statistically analyzed $\delta^{18}O$ data from precipitation collection stations in the vicinity of the cave site that were operated for 8–18 months between 1990 and 1991 (IAEA/WMO, 1998). The stations were located at altitudes of less than 200 m, with the exception of one station (Santa María) at 825 m (Table 1). The monthly $\delta^{18}O$ values and precipitation amounts were averaged to produce monthly means, and are shown in Fig. 2. The wet season is May–October, with the wettest months being May, September, and October (Fig. 2). Lowest $\delta^{18}O$ values (−8.0 to −8.5‰) are associated with May and June rainfall, which is primarily sourced from the Caribbean Sea during the early wet season. These air masses experience isotopic depletion in heavy isotopes as the air masses traverse the central Cordillera. During the late wet season, $\delta^{18}O$ values are slightly higher (approximately −6.5‰) even though rainfall amount is greater. This is due to the mixing of Caribbean moisture with the advection of moisture from the Pacific Ocean that has not experienced as much prior rainout as the Caribbean-sourced moisture because of a lack of significant orographic effects. The magnitude of the amount effect from these data is −1.86‰/100 mm of monthly rainfall ($r = -0.78$).

Table 1
Costa Rican isotope stations from the GNIP database, and precipitation-weighted stable isotope values.

Station	Lat. (Dec. Deg.)	Long. (Dec. Deg.)	Alt. (m)	Wtd δ D (‰ SMOW)	Wtd $\delta^{18}O$ (‰ SMOW)
Puntarenas	9.58	84.5	3	−55	−8.4
Herradura	9.39	84.39	3	−48	−7.3
Cobano	9.41	85.06	160	−46	−7.1
Nosara	9.58	85.4	15	−43	−6.3
Santa Rosa	10.19	85.47	25	−58	−8.6
Cartagena	10.23	85.41	63	−47	−6.3
Puerto Humo	10.18	85.21	10	−41	−6.5
Monte Galan	10.38	85.34	60	−37	−6.0
Santa Maria	10.2	85.15	825	−39	−5.9
Hacienda Tempisque	10.3	85.32	22	−42	−6.2

The precipitation-weighted mean $\delta^{18}O$ value of rainfall on the Nicoya Peninsula of Costa Rica is −6.6 ± 2.4‰, as constrained by 79 monthly isotope analyses. The data yield a local meteoric water line of $\delta D = 7.8 \times \delta^{18}O + 7.2$ (Fig. 3). Twenty two surface water $\delta^{18}O$ values (Lachniet and Patterson, 2002) from rivers and lakes on the Nicoya Peninsula average −8.1 ± 1.0‰, and overlap but are lower on average than the precipitation $\delta^{18}O$ data. The lower surface water $\delta^{18}O$ values relative to precipitation may be a result of rainfall occurring at higher catchment altitudes over the cordilleras. Drip waters in the cave were collected, but found to have altered values due to evaporation of small water volumes in the sample bottles in the 2 years elapsed between sample collection and analysis. Drip evaporation in the cave is not likely given the high relative humidity.

3.2. Stalagmite chronology

Results from the U-series analysis indicate that the stalagmites grew over various intervals between ca 24 and 100 ka (CT-1, -5, and -6), and ca 6.5 to 8 ka (CT-7) (Fig. 4 and Table SM1). No stalagmites dated to the Last Glacial Maximum at 21 ka. A large number of U-series analyses for these stalagmites was necessary due to the low uranium concentration (typically <100 ng/g), low $\delta^{234}U$ values (ranging from −7.6 to 14.3‰), and apparently variable initial $^{230}Th/^{232}Th$ values, as shown by the scatter in the age/depth relationship. The daughter thorium concentrations were quite low, resulting in a larger age uncertainty due to correction for detrital ^{230}Th.

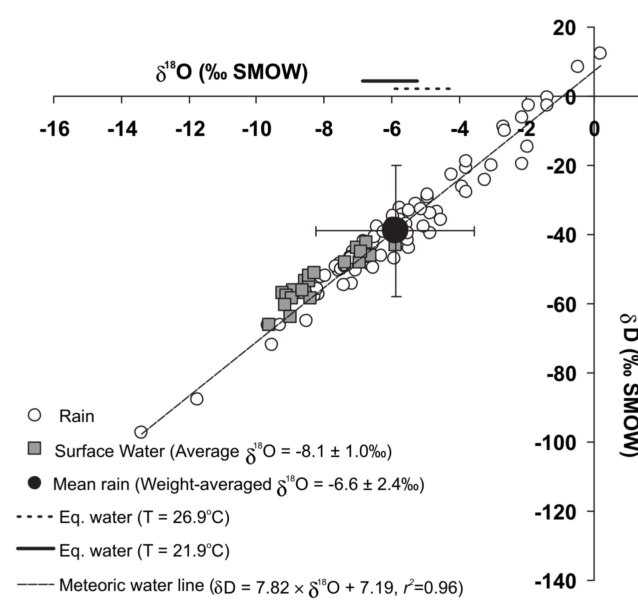

Fig. 3. Meteoric water line and surface water $\delta^{18}O$ values from the Nicoya Peninsula. The large black circle is the mean precipitation $\delta^{18}O$ value ± one standard deviation. The local meteoric water line (LMWL) is $\delta D = 7.82 \times \delta^{18}O + 7.19$. The thin dashed black line above the $\delta^{18}O$ axis is the range of drip water values that are in equilibrium with the measured stalagmite $\delta^{18}O$ values at the modern temperature of 26.9 °C; the thick black line is the same except for modern temperatures decreased by 5 °C.

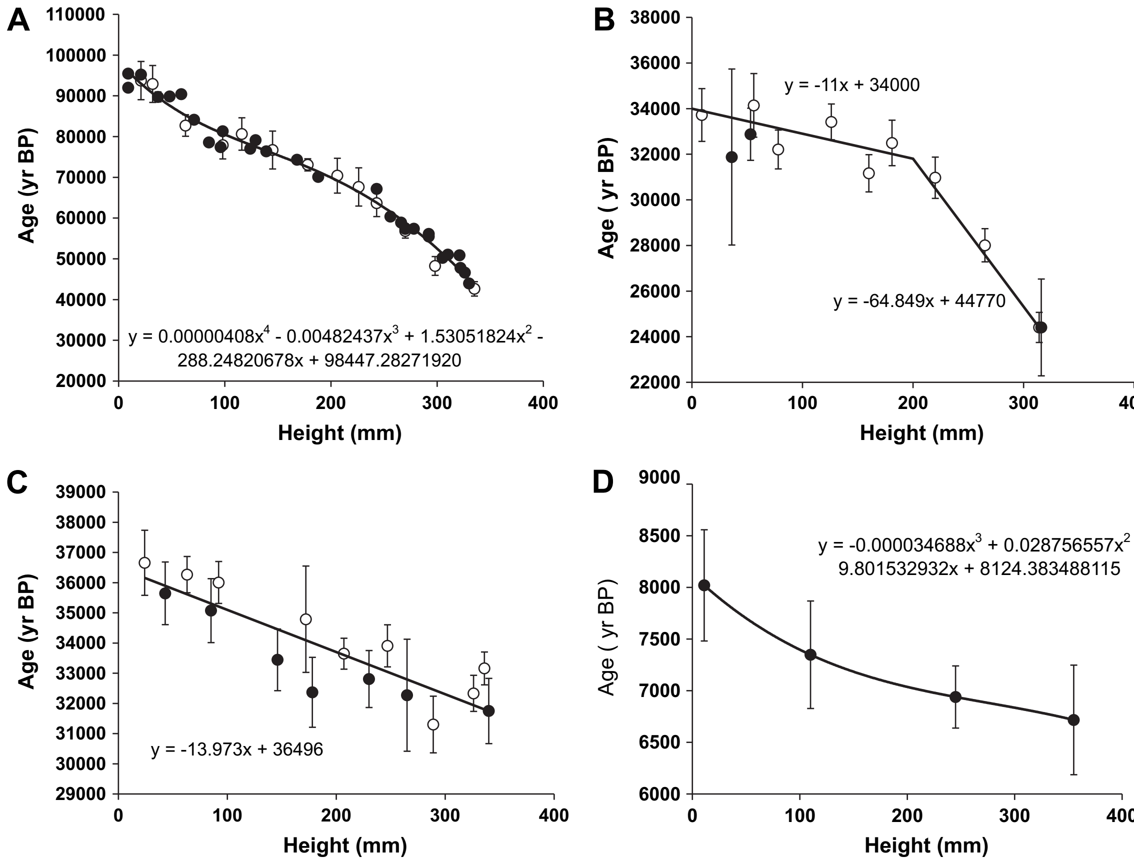

Fig. 4. Age-depth models for stalagmites from Terciopelo Cave, Barra Honda National Park. (A) CT-1; (B) CT-5; (C) CT-6; and (D) CT-7. Ages for stalagmites CT-5 and -6 are shown with 2 σ uncertainty bars to take into account uncertainty in the initial thorium correction. The age scatter about the axis is likely related to variable initial thorium ratios. ICP-MS analyses are shown in open circles, TIMS analyses in black circles.

The chronology of stalagmite CT-1 is based on 35 U-series ages (Fig. 4 and Table SM1), the details of which will be reported elsewhere (Johnson et al., in prep.). The age model is a fourth order polynomial that shows a very good fit to the U-series data. Samples above 335 mm were not used in the age model, as they appeared anomalously young and variable. The U-series constrain the stalagmite growth period as between 98.3 and ~35 ka (extrapolated age at tip). Variability of ages about the age model are likely the result of variable initial thorium, which is also evident in the U-series of the other stalagmites from this cave. The time interval covered by stalagmite CT-1 represents ~4/5th of the last glacial record in our composite time series.

The chronology for stalagmite CT-5 is based on 12 U-series age determined principally on the MC-ICPMS. A synthetic age model was created by creating two linear fits that produced a logical age-depth relationship. The base of the stalagmite beneath 200 mm was fit with a linear relationship of age $= -11 \times$ height (mm) $+$ 34,000. Above 200 mm, a linear fit expressed as age $= -64.92 \times$ height (mm) $+$ 44,784 was used. The scatter in the age-depth model is likely related to variable initial thorium ratios and the low uranium concentrations. The U-series data constrain the stalagmite growth interval to between 34.0 and 24.0 ka. The chronology for stalagmite CT-6 was based on 16 U-series ages from both the TIMS and MC-ICPMS. The age model was created with the linear age-depth relationship of age $= -16.02 \times$ height (mm) $+$ 37,000. The scatter evident in the age-depth model is consistent with the other stalagmites' chronology and is likely due to the complicated U-series systematics on this sample. The Th split (denoted "−2") for subsamples at 43, 178, and 340 mm were analyzed twice on the TIMS, and the final age used was a weight average. The U-series data define a growth interval of this stalagmite between approximately 36.6 and 31.5 ka. Because the variable ages for stalagmites CT-5 and -6 is likely related to a variable initial thorium value, we used an initial correction of $4.4 \times 10^{-6} \pm 100\%$ for the ages. Stalagmites CT-5 and -6 represent ~1/5th of the time interval covered by our composite time series. The growth interval of stalagmite CT-7 is defined by four U-series ages, which were determined based on weight averaging of three to five subsample powders drilled from individual stratigraphic layers. The age data show that stalagmite CT-7 grew between 8.1 and 6.7 ka.

Humid tropical stalagmites are notoriously difficult to date (Beck et al., 2001; Lachniet et al., 2004a; Hillaire-Marcel et al., 2005; Lachniet et al., 2005; Partin et al., 2007). Because of the complex U-series systematics in these stalagmites, the true ages may vary by several percent, more so over the interval covered by stalagmites CT-5 and -6. Initial attempts using the TIMS resulted in relatively large age uncertainties, and subsequent analyses on the MC-ICPMS improved precision but not the age-depth relationships. Therefore, we speculate that there are variable initial thorium ratios both within individual growth bands and along the stalagmites' growth axes. Attempts at constructing isochrons to constrain the initial thorium ratios were unsuccessful, due to low ^{230}Th concentrations, a small spread in $^{230}Th/^{232}Th$ ratios within growth layers relative to analytical uncertainty, and highly local initial thorium ratio variability within stratigraphic layers. Age uncertainty due to variable and unconstrained initial thorium ratios in some cases may be larger than our analytical precision, as evidenced by the age scatter in the growth models. Similar U-series problems were encountered in humid tropical stalagmites from Borneo (Partin et al., 2007) and the Bahamas (Beck et al., 2001; Richards and Dorale, 2003). In the Borneo stalagmites, initial thorium ratios determined from isochrons were high, variable, and poorly constrained; they ranged from $\sim$45 to 140×10^{-6}. The magnitude of the age scatter in the Costa Rican stalagmites is comparable to the uncorrected ages from the Bahamian stalagmite (Beck et al., 2001), which also have high $^{230}Th/^{232}Th$ ratios. Age corrections due to high $^{230}Th/^{232}Th$ ratio were up to 3 ka in some cases for the Bahamian stalagmite (Richards and Dorale, 2003). Those authors suspected that the thorium may have been transported as colloids and coprecipitated with uranium in the stalagmite carbonate, and similar issues may be involved with our stalagmites.

Because of the additional uncertainty in the ages due to complex U-series behavior, the focus of this paper is on the interpretation of the multi-millennial to orbital time scale (ca. 11 ka and greater) climate variations in Central America. The growth interval of stalagmite CT-1 is much better constrained than the others and covers most of the time interval ($\sim$4/5th) studied in this paper. The chronology defined by stalagmite CT-1 is robust over the time interval of 40–98 ka, whereas the time interval between 24 and 40 ka ($\sim$1/5th of the time interval) is less well constrained. The mid Holocene stalagmite CT-7 is also well constrained by the U-series ages. Interpretation of sub-millennial-scale climate variability is thus complicated by the scatter in U-series ages for the last glacial stalagmites CT-5 and -6, and may result in shifts of individual peaks in our $\delta^{18}O$ time series of up to ca 1000 years over the interval of $\sim$24–40 ka. However, these age uncertainties will largely not affect our conclusions that are based on the multi-millennial to orbital-scale climate changes. Overall, our chronology is superior to most other paleoclimate records dated with radiocarbon or orbital tuning for time periods beyond ca 35 ka, and does not rely upon non-radiometric age determinates such as orbital tuning or ice sheet flow models. Therefore, our U-series chronology for this study, although imperfect over 24–40 ka, is sufficient to constrain the multi-millennial-scale climate variability in Central America over much of the past 100 ka.

3.3. Stalagmite $\delta^{18}O$

The stable isotope values show substantial variability on all time scales ranging from multidecadal to multi-millennial (Fig. 5). $\delta^{18}O$ values vary between -5.0 and $-10.0‰$. There are five prominent anomalies of low $\delta^{18}O$, which are numbered as I (7 ka), II (27–40 ka), III (67–72 ka), IV (78–84 ka), and V (87–96 ka), with the oldest anomaly also being the lowest of the entire record. Highest $\delta^{18}O$ values occur around 58–63 ka, with other relative high values between 72–78 and 84–86 ka. The magnitude of $\delta^{18}O$ variability within each stalagmite is $\sim$3–4‰. The $\delta^{18}O$ time series of stalagmites CT-5 and -6 replicate relatively well over the common interval of 31.5–34.0 ka, suggesting that errors in the age models over this time interval are small, and that calcite $\delta^{18}O$ values are at or close to equilibrium. The most pronounced and abrupt isotopic shift occurred at ca 64 ka, when $\delta^{18}O$ values increased from -9 to $-6‰$, then gradually decreased back to $-9‰$ at around 38 ka.

Another notable characteristic of the Costa Rica stalagmite time series is the absence of significantly different $\delta^{18}O$ values in the Holocene relative to the wettest intervals during the last glacial. Average Holocene $\delta^{18}O$ values (from CT-7) are nearly identical to those in early Marine Isotope Stage (MIS) 2 and late MIS 3, and comparable to the wettest periods during MIS 4 and 5 (Fig. 5). Because the $\delta^{18}O$ value of the ocean has changed by ca 1‰ on glacial–interglacial time scales, the similar stalagmite $\delta^{18}O$ values between MISs may not be directly comparable, as the $\delta^{18}O$ of the oceanic source area has changed over time. Thus, we corrected the stalagmite

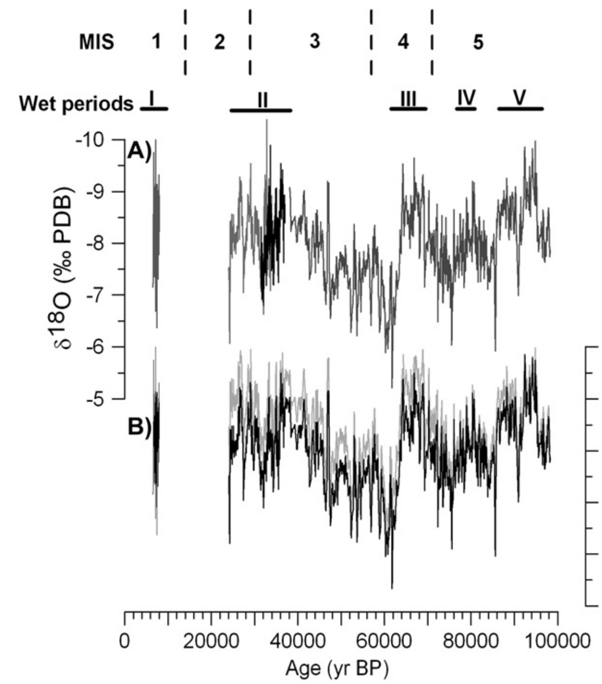

Fig. 5. $\delta^{18}O$ values of the Costa Rica stalagmites. (A) Top are the stalagmite $\delta^{18}O$ time series lines, from left to right: CT-1 (light grey solid), CT-5 (black dashed), CT-6 (dark grey solid), and CT-1 (black solid). The $\delta^{18}O$ values vary between -5 and $-10‰$ on multidecadal to multi-millennial time scales. Also shown are boundaries of Marine Isotope Stages. Prominent wet periods are denoted I, II, III, IV, and V, and their durations shown by the horizontal bars. (B) Black line is the composite $\delta^{18}O$ time series created by splicing the records and interpolating at a 50-year resolution, and gray line is the composite record corrected for changes in the isotopic composition of the oceans due to variations in global ice volume. In subsequent plots, the non-ice volume corrected composite time series is used.

record for the change in the $\delta^{18}O$ of the ocean (Waelbroeck et al., 2002) by subtracting the oceanic $\delta^{18}O$ time series from the Costa Rican stalagmite record, with both records interpolated at a 100-year resolution. Such a correction assumes that the $\delta^{18}O$ values of rain over Central America were also affected by the $\delta^{18}O$ change in the oceanic source waters, which is relatively small ($\sim$1‰) compared to the large seasonal variations in precipitation $\delta^{18}O$ ($\sim$8‰). The relative relationships between wet periods remains even if the time series is corrected for changes in the $\delta^{18}O$ value of the ocean (Fig. 5). This is primarily due to the relatively small amplitude of the glacial change in ocean $\delta^{18}O$ relative to the large amplitude of change in the stalagmite records. The magnitude of the $\delta^{18}O$ variability of 2–3‰ are comparable although slightly larger than the $\delta^{18}O$ interannual variability in modern precipitation in Panama (Lachniet, 2009b). There, rainfall $\delta^{18}O$ values during warm and dry El Niño events were $\sim$2.3% higher than during wet La Niña events, and rainfall associated with a warm Caribbean Sea was $\sim$1.8‰ higher than a cold state. Thus, about 2/3rd of the stalagmite $\delta^{18}O$ variability is within the modern variation observed in modern precipitation.

Because the stalagmites were not active when collected, it is more difficult to assess whether calcite was precipitated in equilibrium with drip waters. Ideally, modern drip waters over one or more seasonal cycles should be collected and measured for $\delta^{18}O$, and the equilibrium calcite value at the modern cave temperature calculated and compared to the $\delta^{18}O$ value of modern calcite. However, the stalagmites were inactive when collected, and the modern equilibrium stalagmite $\delta^{18}O$ value is unknown. Additionally, modern drip waters were collected but their $\delta^{18}O$ values are unreliable due to post-collection evaporation of the small water volumes into the bottle air headspace in the 2 years between analysis and collection. As a rough test for equilibrium deposition, we estimated the $\delta^{18}O$ value of drip waters that are in equilibrium with the measured calcite $\delta^{18}O$ values for both the modern temperature (26.9 °C), and for temperatures decreased by 5 °C, using the equilibrium calcite fractionation equation (Kim and ONeil, 1997). The $\delta^{18}O$ calcite values of CT-1, -5, -6, and -7 are -7.9 ± 0.7, -8.2 ± 0.6, -8.2 ± 0.6, and -8.3 ± 0.5‰, respectively, giving a one standard deviation range of −8.8 to −7.2‰ PDB. This range yields equilibrium drip water $\delta^{18}O$ values of −5.9 to −4.2 ‰ SMOW at the modern temperature of 26.9 °C, and −6.8 to −5.3‰ SMOW at modern temperature lowered by 5 °C, a typical amount associated with full glacial cooling (shown on Fig. 3). The calculated water values that are in equilibrium with the stalagmite calcite for modern conditions are slightly higher than, but overlap, the range in the mean rainfall $\delta^{18}O$. For the −5 °C scenario, the calculated water values that are in equilibrium with the stalagmite $\delta^{18}O$ values overlap the mean precipitation $\delta^{18}O$ value (Fig. 3). These data suggest that the range of measured stalagmite $\delta^{18}O$ values is consistent with equilibrium conditions for the likely temperatures of deposition, although past temperatures in Costa Rica over the past 100 ka are poorly constrained. We did not perform Hendy tests on the stalagmites, as considerable evidence suggests that stalagmites might fail a Hendy test yet still contain calcite deposited in oxygen isotopic equilibrium, because: (1) drilling of growth layers that thin away from the growth axis prohibits accurately obtaining age-equivalent calcite subsamples, particularly in speleothems were δ values vary rapidly on small spatial scales (Treble et al., 2005; Mickler et al., 2006; Lachniet, 2009a); (2) calcite along the growth axis (which is subsampled for paleoclimate reconstruction) may be deposited in equilibrium while contemporaneous calcite deposited on the stalagmite margins may be out of equilibrium (Spötl and Mangini, 2002; Dreybrodt, 2008) thus resulting in an erroneous 'failed' Hendy test; and (3) there may be a well-established climate-forced covariation in $\delta^{18}O$ and $\delta^{13}C$ values (Mickler et al., 2004; Lachniet, 2009a). Given the uncertainties above, we proceed with the caveat that the calcite was likely precipitated at or near oxygen isotopic equilibrium with drip waters, and represents variations in the past $\delta^{18}O$ variation in precipitation and cave drip waters.

Because $\delta^{18}O$ and rainfall amount in tropical precipitation are inversely correlated due to the 'amount' effect, we interpret the Costa Rica $\delta^{18}O$ variations as reflecting rainfall variability over the cave site. From this, we can infer that Central American rainfall amount has varied substantially on orbital and multi-millennial time scales, with driest periods around 58–63, 72–78, and 84–86 ka. Because cave temperatures are typically quite stable and reflect the mean annual temperature of the region, temperature variations and its effect on equilibrium fractionation between water and calcite is likely a minor forcing of stalagmite $\delta^{18}O$ variations (~0.2‰ per °C) (Kim and ONeil, 1997) relative to the large (>5‰) variations of $\delta^{18}O$ in rain water. Wettest periods (low $\delta^{18}O$ values) occurred at ca 7 ka (anomaly I), 27–40 ka (anomaly II), 67–72 ka (anomaly III), 78–84 ka (anomaly IV), and 87–96 ka (anomaly V). Rainfall amount in MIS 4 shows both the driest anomaly at ca 62 ka, and one of the wettest anomalies (anomaly III; Fig. 5). On the whole, MIS 5 was somewhat wetter than MIS 3, and the beginning of MIS 2 was also quite wet relative to the beginning of MIS 3. All isotope stages are characterized by apparently rapid and abrupt millennial-scale rainfall variability.

4. Data and discussion

4.1. Comparison to sea surface temperature and salinity records

The stalagmite records indicate substantial millennial to orbital-scale rainfall variability in Costa Rica (Fig. 5). In a concurrent study, we have shown that local rainfall variability is correlated with Antarctic temperature, highlighting an important climatic teleconnection between the tropical Pacific Ocean and the high southern latitudes (Johnson et al., in prep.). We further explore correlations between our extended Costa Rican record and other paleoclimate proxy records in the subsequent sections. To test our hypothesis that wettest conditions were associated with a warm tropical North Atlantic and/or a cold tropical Pacific, we compared our time series to SST proxy records from the neighboring oceans. Our comparison used the Mg/Ca SST and $\delta^{18}O$ records from *Globigerinoides ruber* (white variety) for core ODP-999A (Schmidt et al., 2004) in the Colombian Basin of the western Caribbean Sea near Panama and Costa Rica; the Mg/Ca record of *G. ruber* for core TR163-22 recovered near the Galapagos Islands in the eastern Pacific Ocean cold-tongue (Lea et al., 2006); and the alkenone SST record from MD02-2529 from the Costa Rican margin (Leduc et al., 2007). The Caribbean SST record from core ODP-999A was interpreted to reflect the mid-spring through early fall seasonal weighted temperatures (Schmidt et al., 2006b), and is in an area under the influence of the warm Caribbean Current. The timing of the Caribbean Mg/Ca calcification record during the warm season also coincides with the wet season in Costa Rica, so that the seasonality of the SST and $\delta^{18}O$ records should be directly comparable. We also calculated the Atlantic to Pacific SST gradient (ΔSST) by subtracting Pacific from Atlantic interpolated SSTs from the two records, once for the Costa Rican margin record and again for the cold-tongue record.

The Costa Rica rainfall time series is shown with the Caribbean and Pacific SST and ΔSST records in Fig. 6. Rainfall in Central America appears to be most strongly similar to the SST record from the tropical Atlantic: when SST is high, stalagmite $\delta^{18}O$ values are low and we infer wet periods. This relationship is consistent with data that suggests that the Caribbean exerts a stronger control than the Pacific on Central American rainfall, because positive SSTAs result in a longer wet season (Enfield and Alfaro, 1999), whereas ENSO only affects the wet season end date. Wettest conditions are found when Atlantic SST is greater than ~26.5 °C, which is close to the temperature required to initiate deep convection over the tropical ocean (Graham and Barnett, 1987). The driest interval in our record, between ca 45 and 62 ka, is associated with decreasing or relatively low Caribbean SSTs and intermediate Pacific SSTs. Both Caribbean and Pacific SSTs show a pronounced temperature increase from glacial to interglacial conditions, a characteristic that is not apparent in the rainfall proxy record in Central America.

The comparison between the Costa Rican rainfall $\delta^{18}O$ record and ΔSST is also shown in Fig. 6. The strongest similarity appears to be with the Caribbean to cold-tongue SST gradient, whereas the Caribbean to Costa Rican margin record (Leduc et al., 2007) appears less coupled to our rainfall record. Focusing on the Caribbean to cold-tongue gradient, periods of greatest ΔSST are associated with the wettest periods in Central America, particularly around 25–42, 63–72, and 85–95 ka. Our prominent wet anomaly (IV) at ca 80 ka, in contrast, is not associated with a large ΔSST. Thus, four of the five wet anomalies in our record coincide with an enhanced Caribbean to Pacific cold-tongue SST gradient. In contrast, the most pronounced dry anomaly in Central America between 45 and 61 ka is associated with relatively weak ΔSST. From this comparison, we observe that the general concordance of large (small) ΔSST and wet (dry) conditions in Costa Rica support our hypothesis that SSTAs exert a primary control on rainfall amount over Central America.

The coincidence of wet conditions with a large ΔSST is analogous to the modern climate, such as during a warm tropical North Atlantic and cold tropical Pacific state. During such conditions in the modern climate, rainfall amount is high and $\delta^{18}O$ values are low

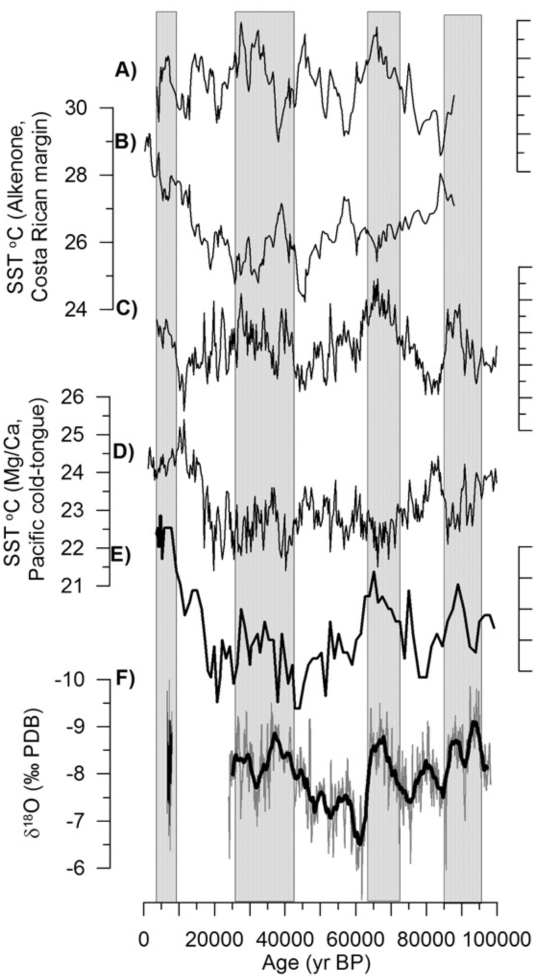

Fig. 6. Correlation of Central America rainfall and oceanographic proxies of SST. (A) Is SST difference across the isthmus from ODP-999A and MD02-2529; (B) is alkenone SST estimate of eastern Pacific Ocean (MD02-2529), offshore Costa Rica; (C) is the Caribbean to cold-tongue SST gradient (ODP-99A minus TR163-22); (D) is the Mg/Ca SST record (TR163-22) of the Pacific cold-tongue (Lea et al., 2006); (E) is the Mg/Ca-derived SSTs (ODP-999A) of the western Caribbean Sea (Schmidt et al., 2004); and (F) is the composite stalagmite $\delta^{18}O$ record from Costa Rica with a 45-pt running average. Four out of five of the wettest periods in Costa Rica coincide with an enhanced Caribbean to cold tongue SST gradient (transparent grey bars). Maximum wetness happens when the Caribbean is warm and the cold-tongue is cold, such as at ca 68 ka.

(Lachniet, 2009b). Our data are also consistent with the effects of ENSO on Costa Rican climate. Because the Pacific cold-tongue SSTs are strongly sensitive to ENSO, we suggest that those regional SSTAs are a stronger control on the position of the ITCZ and rainfall over Central America than the local SSTs recorded off the Costa Rican margin. Further, the Caribbean to Pacific cold-tongue SST gradient does not show a glacial–interglacial transition, a characteristic that is largely shared by our stalagmite $\delta^{18}O$ data. There does not appear to be a strong correlation in SSTs on the Costa Rican margin with those of atmospheric and sea surface temperatures at higher latitudes (Leduc et al., 2007), suggesting that the SST controls on rainfall over Central America are partly decoupled from high latitude changes in atmospheric air temperature.

Surprisingly, there is little broad correlation between Costa Rican rainfall and $\delta^{18}O$ in the Greenland Ice Sheet, or in $\delta^{18}O$ values in the subtropical North Atlantic Ocean (Fig. 7) (Shackleton et al., 2004), both of which record pronounced stadials and interstadials associated with Dansgaard/Oeschger (D/O) events. Such a finding is similar to the lack of clear D/O events in tropical Pacific Ocean sediment cores (Lea et al., 2006; Leduc et al., 2007). A comparison with a record of Heinrich events (HE) (Fig. 7) from offshore Brazil suggests that the strongest dry anomaly in Costa Rica is associated with Heinrich event 6, at which time increased river runoff in tropical South America is evident in the Ti/Ca ratios of marine sediments (Jaeschke et al., 2007). Rainfall also decreased during HE2, which was followed by a cessation of growth in stalagmite CT-5 (within the error of our chronology). The large amplitude of Heinrich event 6 in Central and South America suggests that the ITCZ was displaced southward during this time interval, and is consistent with water-hosing modeling studies (Vellinga and Wood, 2002). However, other Heinrich events do not appear to have had a strong impact on rainfall amount in Costa Rica, although such impacts on tropical hydrology are evident in proxy records of river runoff (Jaeschke et al., 2007) and stalagmite growth in the *nordeste* of South America (Wang et al., 2004). We suggest that HE 6 had a more pronounced effect on Costa Rican rainfall because of its larger amplitude and longer duration evident in the Brazil runoff record compared to other HEs. The comparisons to the ice core and marine records are subject to the caveat that age mismatches for the isotopic events are related to age model differences between the records. For example, the NGRIP SFCP04 chronology (Shackleton et al., 2004) presented in Fig. 7 has been updated with the GICC05 chronology, which we do not compare with our record because it only extends to ca 60 ka (Andersen et al., 2006; Svensson et al., 2006, 2008).

Based on these correlations, we suggest that our record is most consistent with a combined forcing of SSTAs in both ocean basins that is partly decoupled from extratropical North Atlantic temperature changes. The data support our hypothesis that SSTAs have forced

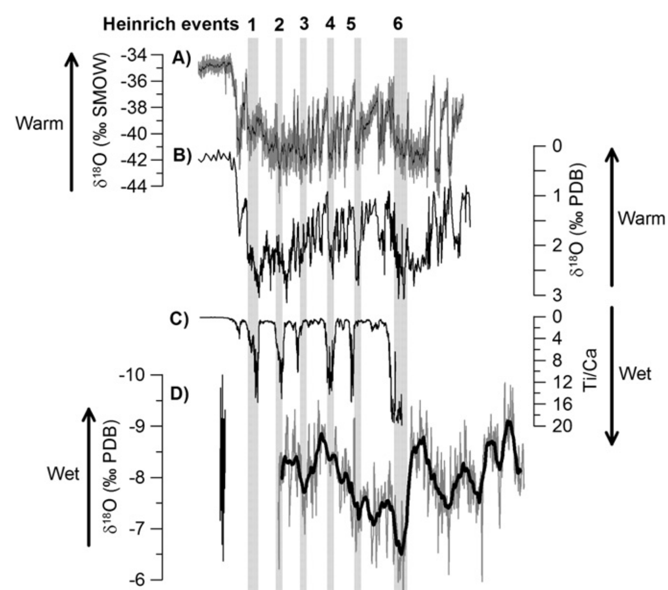

Fig. 7. Correlation of Costa Rican rainfall with proxy records of Heinrich events. (A) Is the $\delta^{18}O$ record from GRIP on the SFCP04 time scale (Shackleton et al., 2004); (B) is the $\delta^{18}O$ record of subtropical core MD95-2042 from off the Iberian margin (Shackleton et al., 2004) which shows a temperature response to Heinrich events in the North Atlantic Ocean; (C) is the Ti/Ca ratio of marine sediments GeoB 3910-2 offshore Brazil (Jaeschke et al., 2007). Higher ratios indicate enhanced freshwater runoff associated with a southward displacement of the ITCZ; (D) is the composite Costa Rican rainfall record. Pronounced drying in Costa Rica followed Heinrich events 6 and 2, and the driest interval of our record at ca 60 ka coincides with the strongest wet conditions on the Brazil margin. This relationship suggests that the ITCZ was displaced to the south during HE2 and 6, but that other Heinrich events did not appear to have had a strong influence on rainfall over Costa Rica.

Central American rainfall variability on orbital to multi-millennial time scales over the past glacial cycle, and differs from a more simple and direct SST temperature control on tropical rainfall amount, as suggested by other tropical stalagmite records (Wang et al., 2001; Burns et al., 2003). We suggest that the combined regional role of both the Caribbean Sea and Pacific Ocean SSTs control rainfall amount and $\delta^{18}O$ values over Central America.

To test the hypothesis that rainfall amount in Costa Rica is proportional to the freshwater export from the Atlantic Basin to the Pacific Ocean, we compared (Fig. 8) our rainfall record to salinity and salinity gradient proxy records ($\Delta\delta^{18}O_{sw}$) between the Caribbean Sea and Pacific Ocean, based on interpolated salinity reconstructions from the western Caribbean core ODP-999A (Schmidt et al., 2004) NE of Costa Rica, and tropical Pacific core MD02-2529 just offshore of the Osa Peninsula of Costa Rica (Leduc et al., 2007). The salinity of the Caribbean Sea is partly controlled by evaporation due to the trade winds (Benway et al., 2006), with higher $\delta^{18}O_{sw}$ during periods of enhanced trade wind evaporation. Caribbean salinity also appears to have varied inversely with North Atlantic deep water (NADW) production (Schmidt et al., 2004), such that periods of highest salinity are associated with decreased NADW production during stadial periods. The MD02-2529 core is located just offshore of Costa Rica in the lee of the Talamanca mountain range which receives copious river runoff. Variations in the MD02-2529 $\Delta\delta^{18}O_{sw}$ record was interpreted to primarily be a salinity signal (Leduc et al., 2007) related to rainfall over and near the core location. The $\delta^{18}O_{sw}$ records were corrected for SSTs using Mg/Ca

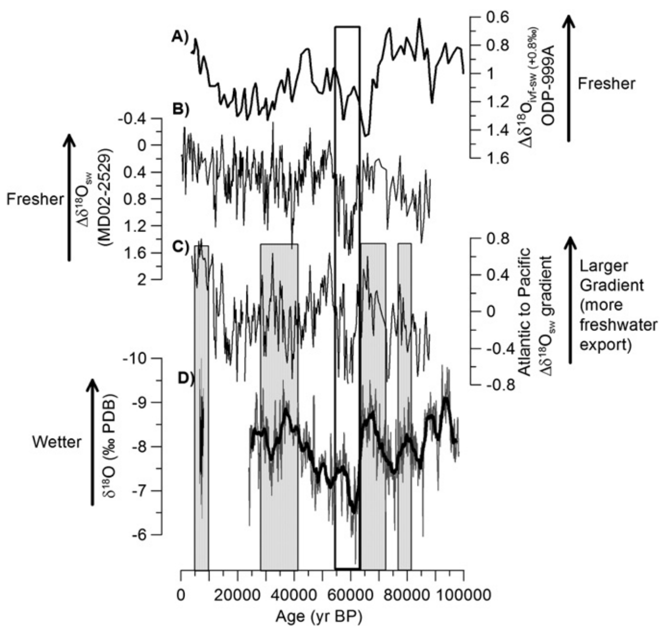

Fig. 8. Correlation of Central America rainfall with sea surface salinity proxy records from the Caribbean Sea and Pacific Ocean. (A) is the "$\Delta\delta^{18}O_{ivf-sw}$" record of (Schmidt et al., 2004) plus 0.8‰ (see text for details); (B) is the "$\Delta\delta^{18}O_{ivf}$" salinity proxy for the tropical eastern Pacific off the Costa Rican margin (Leduc et al., 2007). (C) Is the Caribbean to eastern Pacific salinity contrast, calculated from the interpolated Schmidt et al. and Leduc et al., records from (A) and (B). (D) Is the composite Costa Rican stalagmite $\delta^{18}O$ time series. The cross-isthmian SSS gradient in (C) may be interpreted as an indicator of freshwater export: a larger gradient is associated with a more saline Caribbean Sea and a less saline eastern Pacific, and implies enhanced export of freshwater across the isthmus. The comparison suggests that periods of wettest climate in Costa Rica coincide with periods of a large SSS gradient. Four of five prominent wet periods in Costa Rica (grey bars) are associated with an enhanced SSS gradient. The driest interval in Costa Rica at ca 68–72 ka is associated with both a reduced gradient and a prominent positive SSS anomaly off the Costa Rican margin (white bar), which suggests a decrease in the strength of the tropical hydrologic cycle and less freshwater delivery to the ocean.

data from *G. ruber* in the case of ODP-999A, and from alkenones in the case of MD02-2529 (Schmidt et al., 2006b; Leduc et al., 2007). Both records were corrected for the ice volume effect on $\delta^{18}O_{sw}$. For our calculation, the "$\Delta\delta^{18}O_{ivf-sw}$" record of ODP-999A (Schmidt et al., 2004) was modified by adding 0.8‰, which is the modern average $\delta^{18}O_{sw}$ of the Caribbean Sea, in order to be directly comparable to the "$\Delta\delta^{18}O_{sw}$" record of MD02-2529 (Leduc et al., 2007). Salinity anomalies in the eastern Pacific may have acted as a positive feedback on global climate change (Leduc et al., 2007). However, it is not the eastern Pacific salinity alone that is an indicator of freshwater export, but rather the sea surface salinity gradient across the isthmus that should be most strongly correlated to atmospheric moisture transport.

To test the relationship between moisture export and Costa Rican rainfall, we calculated the salinity gradient on either side of Central America by subtracting the Pacific from the Caribbean salinity records (Fig. 8C). Periods of enhanced freshwater export across Central America may be inferred during periods of largest SSS gradients across the isthmus (Benway et al., 2006). The most prominent dry $\delta^{18}O$ anomaly at ca 62 ka in our stalagmite record coincides with a large amplitude salinity increase in the eastern Pacific Ocean. This dry interval is also associated with a small SSS gradient across the isthmus, which suggests a decrease in moisture transport at this time. One of the wettest intervals in Costa Rica (anomaly III), between 63 and 72 ka, is associated with a pronounced positive ΔSSS anomaly, when the Atlantic Ocean gained salinity relative to the Pacific Ocean. Three other wet intervals in Costa Rica are associated with a large Caribbean to Pacific SSS gradient, in the early Holocene (anomaly I), at ca 25–40 (anomaly II), and at ca 80 ka (anomaly IV). In contrast, a clear positive ΔSSS anomaly at ca 55 ka happens when conditions are relatively dry over Costa Rica. Thus, all four of the wet anomalies in Costa Rica for the overlapping time interval coincide with large SSS gradients across the isthmus. From this, we infer that wet conditions on the Pacific Coast of Costa Rica are associated with enhanced export of freshwater across the isthmus, which would also have been associated with a stronger or more northerly position of the ITCZ.

It appears that enhanced (decreased) freshwater export is associated with wet (dry) conditions in Costa Rica. Our data are supported by satellite-based estimates of water vapor transport that show greatest easterly export over the Caribbean during June–July–August (Liu and Tang, 2005). This observation suggests that on millennial to orbital time scales greatest freshwater export is associated with a northward displacement of the ITCZ (Benway et al., 2006; Peterson and Haug, 2006; Leduc et al., 2007) when moisture is transported through prominent gaps in the cordillera (Xu et al., 2005). However, rainfall over the Pacific Coast of Central America is highest during the late wet season (August–November) when southeasterly trade winds over the Pacific Ocean cross the equator and curve to become southwesterlies (Poveda et al., 2006). These re-curved trade winds bring Pacific Ocean-derived rainfall to southern Central America with low $\delta^{18}O$ values (Lachniet, 2009b) that could contribute to rainfall and salinity variations in the Pacific Ocean in the absence of atmospheric freshwater export from the Atlantic Basin. Thus, because the origin of some of this moisture is from further south in the Pacific Ocean, some of the low salinity anomaly may have resulted in atmospheric transport from within the Pacific basin and not from export from the Atlantic Basin. Additional high-resolution salinity proxies from the equatorial Pacific Ocean are required to test for the influence of this Pacific-derived moisture in the eastern Pacific rainfall and salinity anomalies.

In the salinity and NADW proxy records from ODP-999A (Schmidt et al., 2004), cold glacial intervals (during MIS 2 and 4) were associated with more saline conditions than today and by inference enhanced moisture export relative to wet interstadial conditions (e.g. MIS 3 and 5). This relationship suggests a stadial southward displacement of the ITCZ and an interstadial northward displacement. However, the proxy for freshwater export presented here (the Caribbean to Pacific SSS gradient) does not show such a simple picture (Fig. 8). Rather, periods of greatest rainfall within the ITCZ are associated not simply with salinity in the Caribbean, but more coherently with the gradient between the Caribbean and the Pacific Ocean. Further, our rainfall proxy records suggests that the strength and/or location of the ITCZ may be highly variable in both stadial and interstadial periods. For example, rainfall in Costa Rica transitioned from very high (anomaly III) in early MIS 4 to very low in late MIS 4. Similarly, our wet anomaly II happens during MIS 2 and late MIS 3 when the interpretation of the Caribbean salinity record would suggest a southward displacement of the ITCZ. Our data also show a lack of a glacial–interglacial change in rainfall amount, as evident in the similar Holocene and Lateglacial $\delta^{18}O$ values. This is consistent with the lack of a deglacial paleosalinity difference in the Eastern Pacific Warm Pool region (Benway et al., 2006). Therefore, we forward the suggestion that the ITCZ in the Caribbean and eastern Pacific, as constrained by our Costa Rican rainfall record, is strongly controlled by the SST *gradient* across the isthmus. Some stadial–interstadial variations in Caribbean salinity have been associated with millennial-scale Dansgaard/Oschger events during MIS 3 (Schmidt et al., 2006a). Some of the pronounced rainfall variability in Costa Rica over MIS 3 may also relate to these D/O events, although we are unable to investigate this rigorously with our age control. Our results have implications for tropical–extratropical climate teleconnections, and suggest that the ITCZ is more than just a passive response to variations in NADW and thermohaline circulation anomalies (Vellinga and Wood, 2002; Schmidt et al., 2004).

Previous studies have documented a clear link between summer insolation, which is dominated by precession in the tropics, and rainfall proxy records from speleothems (Cruz et al., 2005; Wang et al., 2007) and lake deposits (Baker et al., 2001). Given that it is the SST gradient across the isthmus that appears to drive Costa Rican rainfall amounts, what role does precession play in multi-millennial rainfall variability in Central America? We compared our stalagmite record to monthly and seasonal insolation at 10°N, as well as to the speleothem rainfall proxy record from southern Brazil (Cruz et al., 2005). Integrated insolation over the January–June half-year shows a nice correspondence with monsoon strength in Central America (Fig. 9), with the wettest periods coinciding with high January–July insolation. This relationship suggests that winter and early wet season rainfall is most directly linked to insolation. Surprisingly, our record shows a negative correlation to August insolation (a proxy for full wet season insolation) which is opposite to that expected based on a direct insolation-monsoon strength mechanism.

By what mechanism(s) can the January–June half-year insolation forcing result in a change in wet season rainfall in Central America? We consider two possibilities for a direct and indirect control, respectively. First, it is possible that high winter insolation warms tropical North Atlantic and Caribbean SSTs, and 'primes' the ocean waters to contribute to a longer wet season the following summer. This is supported by evidence that warmer SSTs in the Caribbean promote decreased tropospheric stability and a higher rainfall probability over Central America (Enfield and Alfaro, 1999). Such speculation is also supported by the observation that rainfall anomalies in Central America are more strongly associated with SSTAs in the Caribbean Sea than the eastern Pacific Ocean (Enfield and Alfaro, 1999). The wet season starts early and ends late when the Caribbean is warm, and a longer and/or stronger wet season over Central America would be associated with low $\delta^{18}O$ values in

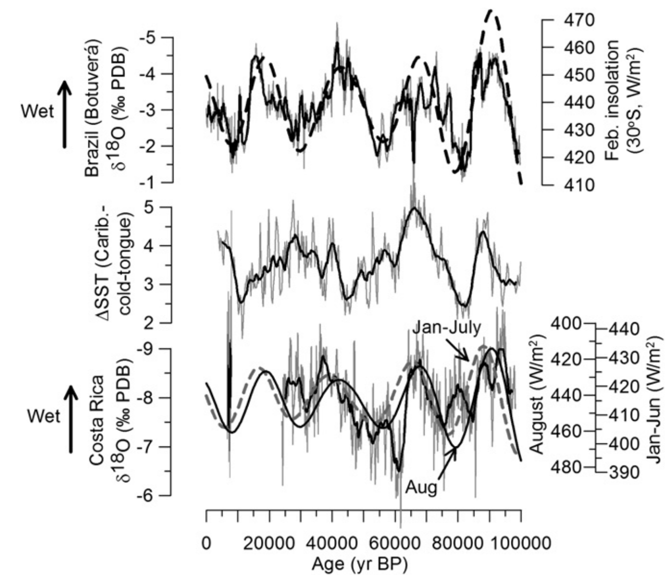

Fig. 9. Relationship between Costa Rican rainfall (bottom), insolation for 10°N in August (black line; note reversed scale) and integrated over January–July (dashed grey line), the ΔSST gradient across the isthmus (middle), and a rainfall proxy record for South America (top) that is linked to precessional variations in the austral summer (black dashed line). There is a positive relationship between the January and July half-year insolation and rainfall amount (see text for discussion).

our stalagmite record. This direct forcing would suggest that antecedent conditions in tropical SST are important for the following wet season rainfall.

High winter and January–July insolation may also drive an enhanced SST gradient across the isthmus (Fig. 9), either directly as above or indirectly by provoking cooler SSTs in the eastern equatorial Pacific. For example, results from the Zebiak–Cane ENSO model show that changes in tropical insolation have an effect on the mean climate state through variations in ENSO-like anomalies (Clement and Cane, 1999). In their model, an insolation decrease during the late summer (e.g. August) and early fall is associated with an enhanced El Niño-like climate state (i.e., warmer SSTs in the eastern equatorial Pacific). However, in the modern climate El Niño events are associated with decreased rainfall over the Pacific slope of Central America (Poveda et al., 2006), whereas our correlation in Fig. 9 suggests wet conditions when late summer insolation is low. Such an apparent contradiction may be reconciled by considering that tropical North Atlantic and Caribbean SSTAs are positively correlated with those in the eastern equatorial Pacific via the "atmospheric bridge"(Alexander et al., 2002), with maximum Caribbean warming following an El Niño event by one or two seasons (Enfield and Mayer, 1997; Giannini et al., 2001b). Even though El Niño months themselves are associated with high $\delta^{18}O$ values at zero lag in Central America (Lachniet, 2009b), little rain falls and the following wet season may be anomalously warm due to transfer of heat across the atmospheric bridge. Indeed, rainfall analyses indicate that the year following an El Niño event is typically wetter than normal near our study area (Waylen et al., 1994, 1996b), and would be associated with low $\delta^{18}O$ values. Furthermore, the speleothems may be biased to recording low $\delta^{18}O$ values as more calcite would be deposited during wet intervals (Lachniet, 2009a). We speculate that if low-frequency tropical North Atlantic and Caribbean SSTAs are controlled by SSTAs in the eastern tropical Pacific via the atmospheric bridge, they may be the dominant control on Central American rainfall on multi-millennial time scales. Further work is clearly needed to test these proposed mechanisms.

4.2. Comparison to the deuterium excess record of Greenland Ice

To explore further the role of the tropical hydrologic cycle in high latitude climate change, we compared our Costa Rican rainfall record to that of the deuterium excess ($d = \delta D - 8 \times \delta^{18}O$) in Greenland ice cores (Masson-Delmotte et al., 2005). Deuterium excess (d) is an indicator of condensation temperature, climatic conditions at the evaporating source, and changes in moisture source latitude (Armengaud et al., 1998; Hoffmann et al., 2001; Werner et al., 2001; Uemura et al., 2008) in snowfall reaching the high latitudes. Evaporation of the ocean surface in the warm and dry subtropics results in greater kinetic fractionation, leading to a high d value. Thus increases in Greenland d on orbital time scales are indicators of more southerly moisture sources, such as the tropics and subtropics (Armengaud et al., 1998; Werner et al., 2001). The δD value of Greenland Ice is also significantly correlated to SST in the 20–30°N band (White et al., 1997).

The GRIP d record (Masson-Delmotte et al., 2005) shows a striking correspondence to rainfall variations over Central America (Fig. 10) on an orbital time scale. Deuterium excess in Greenland shows greatest low latitude moisture delivery centered on the Holocene, and at ~32, 65, and 85 ka (Masson-Delmotte et al., 2005). Periods of high rainfall amount (low $\delta^{18}O$) in Costa Rica are associated with high d values in Greenland. Each of the five prominent wet anomalies in Costa Rica are associated with high d values in Greenland ice, and the driest interval in Costa Rica between ca 45 and 63 ka coincides with low d. Estimates of the change in source temperature (ΔT_{source}) are linked to the changing latitudinal position of moisture sources to Greenland, such that a warmer (lower latitude) moisture source correlates with higher d. The ΔT_{source} also shows a resemblance to the Central America rainfall variations. The correspondence between tropical rainfall and moisture delivery to Greenland is supported by modeling results, which show that the tropical Atlantic source area has its largest contribution during the summer wet season (Werner et al., 2001), although moisture delivery is strong year round. Taken together, the correspondence between tropical rainfall, d, and ΔT_{source} implicate a strong teleconnection between the low and high latitudes over the last glacial period.

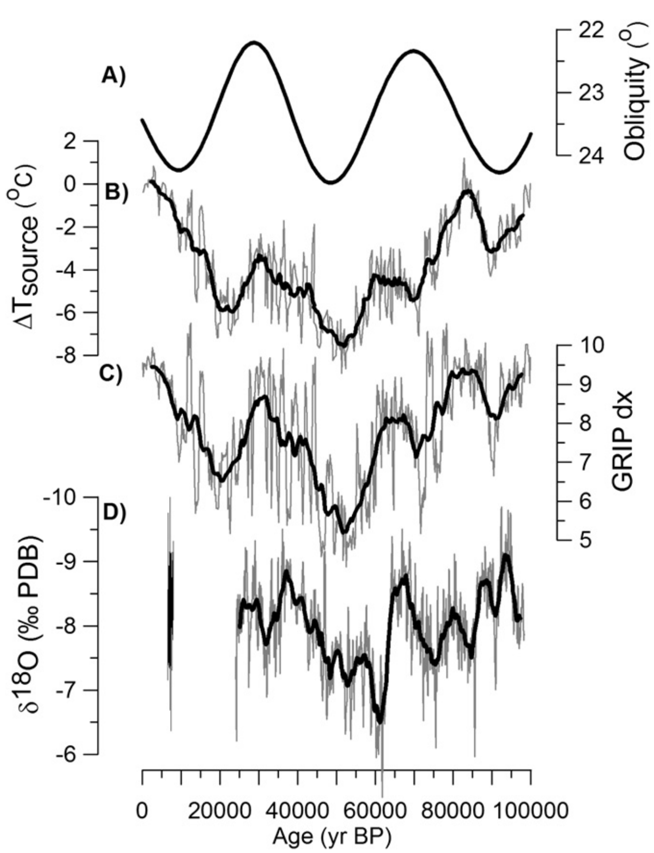

Fig. 10. Correlation plot of Costa Rica rainfall with ice core records of moisture source in Greenland. (A) Obliquity; (B) is inferred change in moisture source temperature (ΔT_{source}) for Greenland; (C) is Greenland ice deuterium excess (d_x, ‰ SMOW); and (D) is the composite Costa Rica rainfall proxy record ($\delta^{18}O$ ‰ PDB). There is a strong similarity between Costa Rican rainfall and GRIP deuterium excess records, which suggests a teleconnection between the high and low latitudes.

The d record from Greenland ice has been interpreted to be paced by obliquity variations (Fig. 10), which controls the low to high latitude temperature gradient and hence the strength of atmospheric transport (Loutre et al., 2004; Masson-Delmotte et al., 2005). The obliquity signal appears to have been strongest between 20 and 80 ka when ice sheet size was sub-maximal (Masson-Delmotte et al., 2005). Low obliquity should have resulted in warmer tropical SSTs, and enhanced sea surface evaporation and rainfall amount, a mechanism that is physically consistent with our proxy data from Central America. Such inferences for Greenland are supported by a very strong obliquity signal recorded in d in Antarctic ice (Vimeux et al., 1999; Stenni et al., 2003; Loutre et al., 2004), and further implicate the tropic-to-pole SST gradient as a dominant control on meridional atmospheric moisture transport. Although not a perfect correlation, our data are consistent with an obliquity forcing of moisture delivery to the high latitudes (Loutre et al., 2004). We suggest that orbital pacing of subtropical and tropical SSTs in the Atlantic Basin may have resulted in variations in the strength of the tropical hydrological cycle and associated delivery of moisture to the high latitudes. Enhanced low to high latitude temperature gradients during periods of low obliquity, in concert with increased Caribbean SSTs during wet periods in Central America, may have resulted in the greater delivery of subtropical moisture to Greenland due to enhanced strength of meridional atmospheric transport (Loutre et al., 2004). Thus, we show for the first time a link between tropical rainfall and moisture source in Greenland.

A possible climate mechanism linking the tropics to the high latitudes is variation in the strength of the North Atlantic subtropical high pressure cell, which delivers atmospheric moisture to both the tropics and the high latitudes (Lohmann and Lorenz, 2000). Such variations in moisture source may be related to persistent changes in the North Atlantic Oscillation (Hurrell et al., 2003), such as during an NAO neutral or NAO− state when moisture sources in the North Atlantic are more southerly (Sodemann et al., 2008a) and have higher d values (Sodemann et al., 2008b). More long-distance moisture transport from the southeastern North Atlantic is common during the NAO− phases (Sodemann et al., 2008a). Some of the differences between the GRIP deuterium excess and Costa Rican rainfall records may be explained by the complicated climate signal recorded in d: first, d variability in Greenland appears to be most related to winter NAO conditions (Sodemann et al., 2008b), whereas rainfall in Costa Rica happens during the summer; second, the Greenland d record is also related to condensation temperature over the ice sheet and thus contains a local temperature imprint; and third, air masses originating at low latitudes would also pick up moisture along their transport paths (Sodemann et al., 2008b) thus modifying d values due to extratropical processes.

Overall, our results show a highly variable tropical hydrologic cycle over the interval between 100 and 24 ka and the middle Holocene. Variations in SSTs in the Caribbean Sea and Pacific Ocean appear to exert a strong control on rainfall variability over Central

America, which in turn appear to modulate the advection of moisture to the higher latitudes. Orbital insolation may be a driving force behind the tropical rainfall variations on obliquity time scales, but the millennial-scale rainfall variations are likely linked to the complex interplay of cross-basin SST anomalies, and have implications for the Atlantic to Pacific Ocean salinity contrast. Our data suggest that variations in the latitudinal position and/or strength of the neotropical ITCZ is the dominant control on rainfall variability in Central America. Such variations in rainfall appear to be forced by SST gradients, both in the meridional and zonal sense. We suggest that our data are most consistent with an ITCZ forcing of tropical rainfall (Leduc et al., 2009) via variations in cross-isthmian sea surface temperature gradients. Our data also have implications for future moisture transport to the high latitudes, because of a projected strengthening of the hydrologic cycle due to global warming (IPCC, 2007). Such a change may result in the enhanced delivery of low latitude moisture to the high latitudes, which may be recorded in *d* of Greenland snow and ice.

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Appendix A. Supplemental material

Supplementary information for this manuscript can be downloaded at doi:10.1016/j.quascirev.2009.09.018.

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