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Caribbean and Pacific moisture sources on the Isthmus of Panama revealed from stalagmite and surface water δ^{18}O gradients

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[1] We test the hypothesis that the Pacific Ocean contributes moisture to the Intertropical Convergence Zone (ITCZ) over southern Central America, by spatial analysis of surface water δ^{18}O values from Panama and Costa Rica. The δ^{18}O values decrease with distance from the Caribbean Sea to the isthmian divide then gradually increase from the divide toward the Pacific slope, which suggests a contribution of both Caribbean and Pacific sourced moisture to the isthmus. We estimated the Pacific moisture contribution for Pacific slope regions of 22% to 64%. The δ^{18}O values from stalagmites from five cave systems demonstrate decreasing δ^{18}O values with distance from the Caribbean, implicating the Atlantic Basin as a dominant moisture source. Constraining modern moisture sources is important for the interpretation of stable isotopic proxy records of past rainfall, because of the combined influence of Pacific and Atlantic ocean-atmosphere phenomena on ITCZ rainfall over the Isthmus of Panama. **Citation:** Lachniet, M. S., W. P. Patterson, S. Burns, Y. Asmerom, and V. Polyak (2007), Caribbean and Pacific moisture sources on the Isthmus of Panama revealed from stalagmite and surface water δ^{18}O gradients, *Geophys. Res. Lett.*, *34*, L01708, doi:10.1029/2006GL028469.

1. Introduction

[2] The tropical hydrological cycle plays a key role in regulating global climate through the export of heat and moisture to higher latitudes. Freshwater export from the Atlantic to the Pacific Ocean over the Isthmus of Panama is a key driver of the thermohaline circulation (THC) [*Zaucker et al.*, 1994]. Because of its global importance, the isthmus has been targeted for paleoclimatic study using speleothems, a proxy for rainfall amount and moisture source in tropical and monsoon regions [*Burns et al.*, 2003]. However, in order to understand the δ^{18}O variations in stalagmites, it is necessary to constrain the modern controls on stable isotope values of moisture over the isthmus.

[3] The objective of this study is to quantify moisture sources to the Intertropical Convergence Zone (ITCZ) over southern Central America. The northeast trade winds advect moisture evaporated from the Caribbean Sea and tropical north Atlantic Ocean, and traverse the isthmus approximately perpendicular to its axis in southern Central America. However, the contribution of moisture from the Pacific Ocean to the ITCZ over Central America remains poorly constrained. Knowledge of moisture sources is important because oceanographic changes in the Atlantic and Pacific Basins may operate on various time scales and ocean-atmosphere interactions. For example, the dominant source of modern interannual rainfall variability on the isthmus is Pacific Ocean sourced El Niño/Southern Oscillation (ENSO) [*Poveda et al.*, 2006]. Lower frequency variability on interdecadal scales has been documented due to the Atlantic Multidecadal Oscillation (AMO) [*Knight et al.*, 2005], and on Quaternary time scales through thermohaline circulation variations associated with Heinrich and Dansgaard/Oeschger events [*Alley and Clark*, 1999].

[4] We test the hypothesis that Pacific-sourced moisture is a significant contributor to rainfall budgets to the Pacific coast of southern Central America (Panama and Costa Rica), using δ^{18}O data of surface waters collected from throughout the isthmus (Figure 1). We also investigate the cross-isthmian isotope gradients from δ^{18}O analyses of surface waters (n = 227) and U-series dated stalagmites (n = 3300) from five isthmian caves. Because stalagmites incorporate rainfall-derived δ^{18}O values into speleothem calcite, they may be considered archives of past rainfall. Our results indicate that the Caribbean Sea is a dominant source of moisture to the Isthmus, but that Pacific-sourced moisture contributes significantly to Pacific coastal sites in Costa Rica and Panama.

[5] Although surface waters are an imperfect data source for constraining stable isotope hydrology, they have several distinct advantages over precipitation. First, numerous samples may be collected from large areas to increase spatial sampling density relative to a few rainfall collection sites. Second, surface waters integrate rainfall over large areas and thus provide a weighted average δ^{18}O value for the drainage basin above the collection site. Third, base flow to rivers sampled at the end of the dry season (as in the Panama data) approximate δ^{18}O values of mean annual rainfall and groundwater recharge, the water source feeding cave stalagmites. Therefore, in this study we rely on the established database of surface water δ^{18}O values for Panama and Costa Rica, from which we provide preliminary estimates of moisture source contribution to rainfall over the isthmus. Because of the humid climate in southern Central America, evaporation of surface waters is minimal (discussed below), and the spatial variability of surface waters should reflect broad-scale spatial δ^{18}O variability in rainfall.

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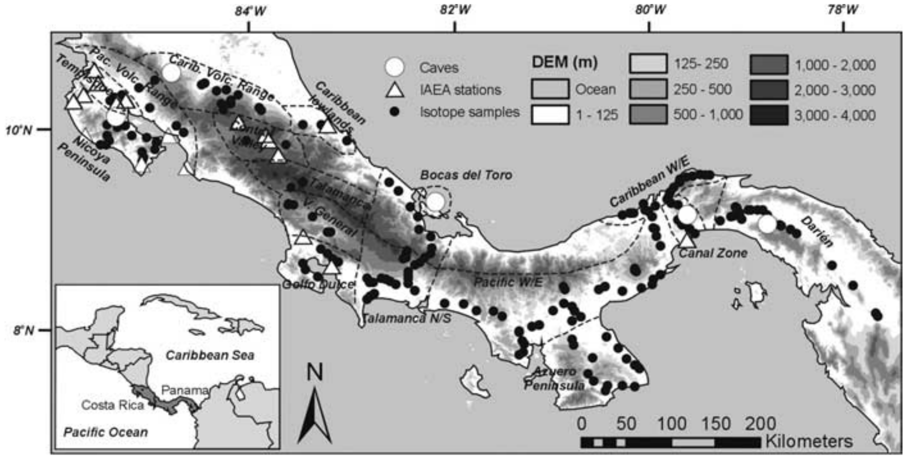

Figure 1. Site map of surface water δ^{18}O samples, IAEA stations, and cave locations on the Isthmus of Panama. Physiographic regions are shown in dashed lines. Inset is Central America and NW South America.

1.1. Modern Climate

[6] The climate of southern Central America is dominated by the annual migration of the ITCZ [*Hastenrath*, 2002; *Poveda et al.*, 2006]. The Pacific coast has the strongest rainfall seasonality, typically with a 7–8 month wet season during boreal summer when moist convection dominates, and a 4–5 month dry season during boreal winter when trade wind subsidence and clear skies prevail. In contrast the Caribbean coast experiences year-round precipitation, with greatest rainfall during periods of enhanced trade winds and associated orographic lifting over the cordilleras. Temperature seasonality is low [*Poveda et al.*, 2006]. Rainfall on the Caribbean slope is typically higher than on the Pacific slope, although a simple rainfall gradient is an oversimplification. For example, on the Caribbean slope annual rainfall totals are 3300 mm/yr in Cristóbal (Panama) and 3530 mm/yr in Limón (Costa Rica), whereas Pacific rainfall amounts are 1793 mm/yr in Balboa (Panama) [*Windsor*, 1990] and 1640 mm/yr at Liberia (Costa Rica) [*Bergoeing*, 1998]. Orographic rainfall in the high cordilleras may reach up to 5000 mm.

[7] The northeast trade winds blow strongly over the Isthmus during the winter dry season, and the wind direction is affected by topographic gaps in the Cordillera, such that winds are northerly through the Panama Canal Zone and northeasterly across Costa Rica and its larger cordilleras. At the northernmost extent of the ITCZ in boreal summer (May–October), cross-equatorial winds from the southern hemisphere recurve to become southwesterly and advect Pacific sourced moisture to the Isthmus [*Poveda et al.*, 2006]. Wind data from the Panama Canal Zone show northerly winds from December to July and southerly winds from August to November [*Windsor*, 1990]. During September the northeast trades weaken allowing the penetration of Pacific moisture associated with enhanced southwesterly flow [*Hastenrath*, 2002].

[8] The Temporal weather systems (*temporales*) originate as disturbances in the eastern Pacific ITCZ and provide substantial precipitation to the Pacific Coast in September and June [*Hastenrath*, 2002]. When the ITCZ is located farther north, the *temporales* are more frequent and contribute rainfall to Pacific Coast stations [*Hastenrath*, 2002], such as during the La Niña cool phase of the Southern Oscillation. Wet spells on the Pacific Coast of the isthmus may produce twice as much rainfall as the average day, however the contribution from Pacific-sourced *temporales* vs. Caribbean-sourced trade wind transport remains unknown. Also, surges of cold high latitude air masses in the Boreal winter may penetrate as far south as Panama and Costa Rica [*Schultz et al.*, 1998] and bring rainfall to the Caribbean side of the isthmus.

[9] The formation of strong tropical depressions in the Atlantic Basin may reverse the cross-isthmian pressure gradient, allowing the advection of Pacific moisture over the isthmus [*Waylen and Harrison*, 2005]. Although the southern isthmus is usually outside of the direct effects of hurricanes, the passage of hurricanes and tropical depressions increases rainfall and flooding on the Pacific Coast [*Poveda et al.*, 2006]. Further, development of strong cyclonic depressions off the southwest coast of Mexico also enhances anomalous westerly flow and wet spells on the Pacific Coast of Central America [*Pena and Douglas*, 2002].

[10] The AMO is defined as the detrended anomaly of averaged SSTs in the north Atlantic Ocean (0 to 70°N) [*Gray et al.*, 2004], and is associated with an ~65 year periodicity [*Knight et al.*, 2005]. The warm phase of the AMO promotes enhanced hurricane formation [*Zhang and Delworth*, 2006] and indirectly increases precipitation on the Pacific Slope of the isthmus.

[11] ENSO is the dominant source of interannual rainfall variability on the Isthmus. During El Niño years, rainfall decreases on the Pacific slope of Costa Rica and Panama [*Waylen and Harrison*, 2005]. El Niño events also tend to decrease the number of tropical depressions forming in the Atlantic Basin, which further decreases Pacific-sourced moisture to the Isthmus [*Waylen and Harrison*, 2005]. Cooling of SSTs during La Niña are associated with enhanced onshore flow and rainfall to the Pacific slope [*Poveda et al.*, 2006]. Because of the combined forcings of SSTs on isthmian rainfall, the rainfall response to the AMO and ENSO may interact on varying time scales.

1.2. Stable Isotope Values in Southern Central America

[12] Previous work has noted a general decrease in surface water δ^{18}O values in Panama and Costa Rica with

Table 1. Locations of Cave Sites and Mean δ^{18}O Values of Eight Stalagmites From the Isthmus of Panama[a]

Cave/Region	Mean δ^{18}O, ‰ VPDB	σ, ‰	Count	Distance From Caribbean, km	Stalagmite Age
Bocas del Toro, Caribbean Coast of Panama	−4.3	0.27	73	1	∼8 ka to present
Chilibrillo Cave, Panama Canal Zone	−5.5	0.65	484	30	∼2.2 to 0.7 ka
Pueblo Nuevo Cave, Darien of Panama	−6.8	0.75	543	41	∼4 to 1.3 ka
Pueblo Nuevo Cave, Darien of Panama	−6.6	0.67	301	41	∼4 to 1.1 ka
Venado Cave, Caribbean slope of Costa Rica	−5.8	0.50	297	134	∼3.7 to 1.1 ka
Terciopelo Cave, Nicoya Peninsula, Costa Rica	−8.1	0.54	437	200	∼36 to 27 ka
Terciopelo Cave, Nicoya Peninsula, Costa Rica	−8.3	0.52	371	200	∼8.1 to 6.9 ka
Nicoa Cave, Nicoya Peninsula, Costa Rica	−8.1	0.57	794	200	∼5 ka to present

[a]A decrease in stalagmite δ^{18}O values with distance from the Caribbean Sea is apparent. See Figure 3 for δ^{18}O histograms.

distance from the Caribbean Sea [*Lachniet and Patterson*, 2002, 2006], which was interpreted to reflect rainout and isotopic depletion of air masses advected by the trade winds. A stepwise multiple regression of surface water δ^{18}O in Panama containing the variables distance from the Caribbean, latitude, longitude, median stream elevation, and stream length explains 74% of the isotopic variability [*Lachniet and Patterson*, 2006]. The dominant control on temporal δ^{18}O values of rain in Panama and Costa Rica (Global Network for Isotopes in Precipitation: The GNIP Database, Release 3, 1998, available from IAEA/WMO at http://isohis.iaea.org) is the amount effect. However, the limited temporal (generally less than 2 years) and spatial coverage inhibit detailed understanding of moisture sources to the isthmus.

2. Methods

[13] We collected surface waters from Costa Rica (1999, n = 63) and Panama (2001, n = 162) (Figure 1); for additional details see *Lachniet and Patterson* [2002, 2006]. We analyzed the water samples for δ^{18}O and δD values, with precisions of ±0.1‰ δ^{18}O and ±3‰ δD. The surface water data were grouped by geographic regions and are available at http://isohis.iaea.org/. We also analyzed eight stalagmites for δ^{18}O values at regular intervals along their growth axes (n = 3300), with age control provided by U-series dating. Caves in Bocas del Toro represent the Caribbean Coast end member, and caves from the Nicoya Peninsula of Costa Rica represent the Pacific Coast end member, whereas Pueblo Nuevo and Chilibrillo Caves in Panama, and Venado Cave in Costa Rica are located midway across the isthmus (Table 1). Stalagmite δ^{18}O values were determined by phosphoric acid reaction on Kiel II and III devices coupled to Finnigan MAT 252 and Delta + XL mass spectrometers at Syracuse University and the University of Massachusetts-Amherst respectively. δ^{18}O values are reported relative to VSMOW for waters and VPDB for carbonates, with precisions of ±0.1‰ δ^{18}O.

[14] δ^{18}O data were linearly regressed against distance from the Caribbean in two sets, for samples less than and greater than 100 km distance from the Caribbean. The 100 km distance was chosen because δ^{18}O values show a clear inflection in slope near there and it represents the approximate isthmian divide distance. Mean and standard deviations for δ^{18}O and distance from the Caribbean for the regions were calculated.

[15] We estimated the percentage contribution of Pacific-sourced moisture for five coastal regions: the Tempisque lowlands, Nicoya Peninsula, Pacific side of the northern volcanic ranges in Costa Rica, and the Golfo Dulce Basin in Costa Rica, and the Azuero Peninsula in Panama (Figure 1). These regions were chosen because of their proximity to the Pacific Ocean. We used a two end-member mixing model to estimate the percentage of Pacific-sourced moisture for the five regions by differencing the average regional δ^{18}O value (Figure 2) from a value linearly extrapolated from the isotopic gradients based on the regional means, and assuming a lightly distilled Pacific-source rainfall of −4.0‰. This value is consistent with estimates of Pacific rainfall in the Panama Bight [*Benway and Mix*, 2004]. The linear extrapolation would underestimate the δ^{18}O decrease if modeled just by Rayleigh distillation, so we take the extrapolation to be a conservative estimate. To estimate the Pacific-source

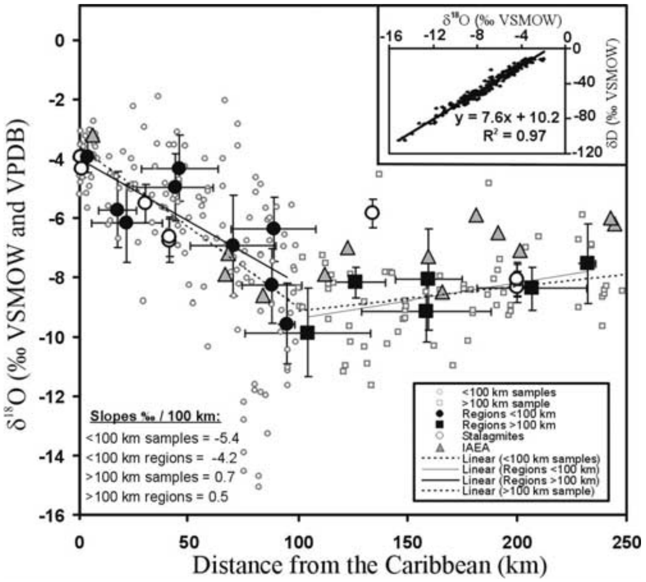

Figure 2. Plot of surface water δ^{18}O values as a function of distance from the Caribbean Sea (grey open circles <100 km, grey open squares >100 km), with regional averages (<100 km black closed circles; >100 km black closed squares), IAEA stations (grey diamonds), and stalagmite δ^{18}O values (open circles). Error bars are the standard deviation of both δ^{18}O and distance from the Caribbean, and the standard deviation of stalagmite δ^{18}O values. Two clear trends are apparent: a decrease of ∼4 to 5‰ 100 km^{-1} from the Caribbean Coast to ∼100 km distance, and an increasing trend of ∼0.5 to 0.7‰ from ∼100 km distance to the Pacific Coast. Inset is Costa Rica and Panama surface water line. The slope and intercept are consistent with tropical precipitation relatively unaffected by surface evaporation.

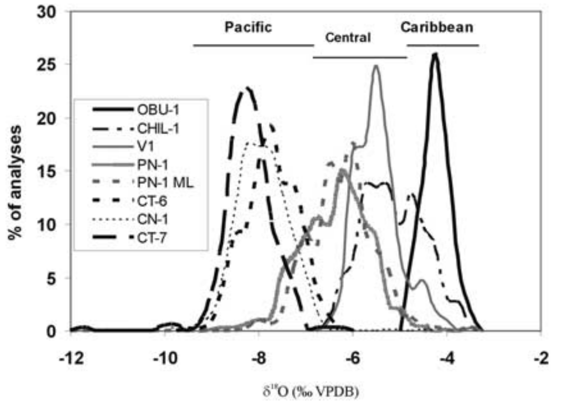

Figure 3. Histogram of 3300 stalagmite δ^{18}O values demonstrate a decrease from −4‰ VPDB on the Caribbean slope to −8‰ VPDB on the Pacific slope. The overlap in δ^{18}O values of stalagmite CT-6 (~36 to 27 ka) with Holocene stalagmites CN-1 and CT-7 suggest that rainfall amount was similar during these times.

contribution, we varied the percentages of Pacific (−4.0‰) and Caribbean (estimated from the best fit slope of −4.2‰ 100 km^{-1}) moisture to match the observed regional average δ^{18}O values.

3. Results

[16] The southern Central America surface water line (Figure 2) is defined as δD = 7.6 × δ^{18}O + 10.2. The slope and intercept of the surface water line are typical of tropical rainfall in Panama and Costa Rica [*Lachniet and Patterson*, 2002, 2006], and Africa and Bolivia [*Gonfiantini et al.*, 2001], and are very similar to the global meteoric water line [*Rozanski et al.*, 1993]. The similarity of the surface water line and meteoric water lines from tropical regions indicates that surface water values have not been modified significantly by evaporation, except for a few individual rivers with high δ^{18}O and δD values.

[17] Surface water δ^{18}O values are highest near the Caribbean Coast at −4‰, a value that is close to that of the first rainfall derived from a cloud formed from recent evaporation of the ocean surface. Lowest surface water δ^{18}O values are found along the highest altitudes of the Isthmian divide, averaging −7 to −10‰, and decreasing to −15% in the Talamanca mountains at 3500 m altitude. Values then increase slightly along the Pacific coast regions, particularly on the Nicoya, Osa, and Azuero Peninsulas of the isthmus, to values of −7 to −8‰. Two isotopic gradients are identified: a decrease in δ^{18}O with distance from the Caribbean for samples collected less than 100 km from the Caribbean, with an average gradient of −5.4‰ 100 km^{-1}, and a modest but perceptible increase in δ^{18}O values for samples collected from 100 to 250 km from the Caribbean Sea, with an average gradient of +0.5 to +0.7‰ 100 km^{-1}. There is considerable scatter in δ^{18}O values as a function of distance, some of which is related to the variable width of the isthmus, the variable height of the cordilleras air masses traverse, and the variable sample collection locations and drainage basin parameters. The overlap of surface water δ^{18}O data from Costa Rica and Panama suggests a common climate process controls isotope values in both countries despite the different collection dates (1999 in Costa Rica and 2001 in Panama).

[18] Rainfall weighted δ^{18}O values are slightly higher but overlap the surface water field (Figure 2). The mean annual δ^{18}O value at Estrada on the Caribbean Coast is −3.2‰, whereas Pacific Coast sites have annual means between −6 and −8.5‰, supporting the general decrease in δ^{18}O values with distance from the Caribbean. The limited number of stations does not allow identification of isotope gradients across the isthmus.

[19] Analysis of δ^{18}O values of eight stalagmites recovered from five cave systems in Panama and Costa Rica substantiate the decrease in δ^{18}O values with distance from the Caribbean (Figures 2 and 3 and Table 1). The δ^{18}O values are highest on the Caribbean Coast of Panama (−4.3 ± 0.27‰ for stalagmite OBU-1), and lowest on the Nicoya Peninsula of Costa Rica (stalagmites CN-1, CT-6, and CT-7, −8.1 ± 0.57, −8.1 ± 0.54, and −8.3 ± 0.54‰ respectively), while caves intermediate in location (Pueblo Nuevo, Chilibrillo, and Venado), have intermediate δ^{18}O values. Stalagmite V1 from Venado Cave shows higher than expected values considering its distance from the Caribbean, which we discuss in our interpretations below.

4. Interpretation

[20] The general decrease in surface water δ^{18}O values with distance from the Caribbean is interpreted to reflect rainout and orographic distillation of Caribbean-sourced air masses borne by the trade winds. A linear regression for the entire data set yield a slope of −2.3‰ 100 km^{-1}. For samples <100 km from the Caribbean, δ^{18}O values decrease by −4.2 to −5.4‰ 100 km^{-1} (for regions and raw data respectively), then increase by 0.5 to 0.7‰ 100 km^{-1} from the divide to the Pacific Coast. Because rainfall amount decreases from the Caribbean to Pacific slope, the amount effect can not explain the between-site δ^{18}O differences, although it is the dominant control on at-a-site δ^{18}O variability [*Lachniet and Patterson*, 2002, 2006]. As the incoming Caribbean moisture has relatively low δ^{18}O values as it reaches the Pacific slope, the δ^{18}O increase there must reflect some physical process. Stream water evaporation along the relatively drier Pacific Coast is one possible mechanism. Considering that these waters do not show pronounced evaporative effects (e.g. a low deuterium excess), however, a more likely explanation is enhanced contribution of lightly-distilled Pacific-sourced rainwater with higher δ^{18}O values. Therefore, we interpret the increasing δ^{18}O trend at sites >100 km to reflect an enhanced contribution of Pacific-sourced moisture relative to sites on the Caribbean slope, which itself is undergoing rainout with increasing distance from the Pacific.

[21] The results of our mixing model suggest the input of variable amounts of Pacific-sourced moisture, and are 40, 64, 50, 22, and 23% for the Pacific volcanic range, Tempisque lowlands, Nicoya Peninsula, Golfo Dulce Basin, and the Azuero Peninsula, respectively. The average of these values is 40% Pacific moisture contribution. Slightly higher percentages (51, 71, 60, 35, and 38, respectively; average of 51%) are calculated if the −5.4‰ 100 km^{-1} gradient of the <100 km surface water samples is used.

Surprisingly, we calculated lower Pacific contributions for the southern Azuero Peninsula and Golfo Dulce regions, where stronger cross-equatorial southwesterlies would imply an enhanced Pacific component. Our model assumptions may account for the discrepancy. For example, the calculated Pacific contribution would be underestimated if the cross-isthmian δ^{18}O gradient were actually larger than we assumed, which is a likely possibility given the greater rainfall amounts at the southern sites relative to the northern sites. Alternatively, a lower δ^{18}O value of Pacific rainfall at the wetter southern sites may also explain the discrepancy. Further, because seasonal variations in surface water δ^{18}O values should follow rainfall δ^{18}O values with a muted amplitude and lagged response, the timing of sampling may also result in error in the calculated percentage contributions of Pacific water. The δ^{18}O data do not indicate a substantial input of Pacific-sourced moisture to the Caribbean slope, suggesting effective blocking by the isthmian cordillera.

[22] The mean δ^{18}O values from the IAEA stations are highest on the Caribbean Coast (−3.2‰ at Estrada), and are lower in the Cordilleras and for stations along the Pacific Coast (−6 to −8‰). The IAEA station's mean annual δ^{18}O values overlap, but are slightly higher than, the surface water δ^{18}O values. This offset most likely represents the fact that the surface waters were collected downstream from where the waters initially fell as precipitation nearer the isthmian divide, where δ^{18}O values are lower.

[23] δ^{18}O values in stalagmites reflect the amount of rainfall over the site and the air mass history, which is related to the intensity and position of the ITCZ. The decrease in stalagmite δ^{18}O values with distance from the Caribbean (Figure 3), is interpreted to reflect air mass rain out and isotopic distillation. Highest stalagmite δ^{18}O values are found on the Caribbean slope (−4‰ VPDB), and lowest on the Nicoya Peninsula (−8‰ VPDB). Unfortunately, the density of cave locations on the isthmus is not sufficient to constrain Caribbean vs. Pacific rainout gradients as we have done with the surface water data. The similarity of the surface water and stalagmite δ^{18}O decrease with distance from the Caribbean Sea suggests that the δ^{18}O-distance gradient has been maintained, at least in broad detail, over the late Quaternary. The three stalagmites from Barra Honda National Park indicate overlapping mean δ^{18}O values, despite the age difference of CT-6 which grew ∼36–27 ka relative to the two Holocene stalagmites (CN-1 and CT-7). These data provide suggestive evidence that rainfall amounts and gradients were similar during the Holocene and between ∼36 and 27 ka. The higher than expected average δ^{18}O value for Venado Cave is likely related to the early Holocene high δ^{18}O values (dry conditions) observed in this stalagmite [*Lachniet et al.*, 2004] that may not be representative of late Holocene or modern climate conditions, and may also reflect an isotopic value of recycled moisture along the Caribbean trough [*Lachniet and Patterson*, 2002].

5. Implications for Paleoclimatology

[24] The contribution of Pacific-sourced moisture to the Isthmus has important implications for the interpretation of speleothem δ^{18}O time series. The combined influence of Caribbean and Pacific SST variability may lead to a complex rainfall response to ocean-atmosphere phenomena such as the AMO and ENSO. For example, during El Niño (La Niña) events, rainfall is decreased (increased) on the Pacific Slope of Costa Rica [*Waylen et al.*, 1996], whereas warm (cold) SSTs in the Caribbean Sea result in enhanced (reduced) rainfall. Thus, maximum rainfall on the Pacific slope most likely occurs when La Niña events in the Pacific Basin are coupled with high SSTs of the positive AMO phase in the Atlantic Basin. Therefore, the δ^{18}O signal preserved in stalagmite proxies should reflect ocean-atmosphere interactions in both ocean basins. From this, we predict substantial interannual isotopic variability (derived from ENSO) superimposed upon longer-term multidecadal to millennial-scale climate oscillations associated with the AMO and THC fluctuations in the Atlantic Ocean. Determination of which basin is the dominant control on isthmian rainfall on Quaternary time scales remains debatable, and will be investigated by time series analysis of U-series dated stalagmites.

[25] Comparison of stalagmite δ^{18}O time series recovered from both sides of the isthmus may reveal cross-isthmian rainout gradients over time, and provides the possibility to reconstruct variations in atmospheric circulation through the late Quaternary. For example, assuming that the Caribbean slope stalagmites only sample Caribbean-sourced rainfall and the Pacific slope stalagmites sample rainfall from both the Pacific and Atlantic Oceans, periods of greatest δ^{18}O differences between the Caribbean and Pacific slopes would indicate a proportional decrease in Pacific-sourced moisture, and vice versa. Nearly equal values would suggest a decreased component of Caribbean-sourced rainfall in Pacific slope stalagmites.

[26] Our results also have implications for the reconstruction of salinity variations in the western Caribbean and eastern Pacific Oceans near the isthmus. Presently, the Caribbean Sea is saltier than the Pacific Ocean by ∼1 salinity unit because of high ocean evaporation rates and associated trade wind transport of fresh water across the Isthmus, where the moisture is condensed to rain over the Pacific Ocean. This cross-isthmian transport may play a key role in stimulating thermohaline circulation in the North Atlantic Ocean, which has prominent forcings on regional and global climate via atmospheric and oceanic teleconnections [*Alley and Clark*, 1999]. For example, sediment cores recovered from either side of the isthmus indicate varying cross-isthmian freshwater transport over the late Quaternary [*Benway et al.*, 2006]. Based on salinity/δ^{18}O relationships in the Panama Bight, [*Benway and Mix*, 2004] estimated a freshwater contribution with a δ^{18}O value of −8.5‰ to the eastern tropical Pacific off Panama, that is nearly identical to values we measured in surface waters draining the Pacific slope of Panama. Their calculations suggested a contribution of ∼50% Pacific moisture [*Benway and Mix*, 2004], nearly identical to our results presented here. Further, salinity in the eastern tropical Pacific during the late Glacial (15–25 ka) is statistically identical to the Holocene [*Benway et al.*, 2006], suggesting similar rainfall amounts in the region. Similarly, we observe no large difference between stalagmite δ^{18}O values from a MIS3 stalagmite (CT-6) and Holocene stalagmites (CN-1 and CT-7), providing indications that such a relationship was also present over the isthmus. We note that our estimates are preliminary, involve

assumptions, and should be further investigated with additional collection of rain, surface water, and groundwater samples on the isthmus. A better understanding of the temporal variation in moisture sources will also be critical for generating credible predictions of future precipitation under various global warming scenarios.

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