Tropical response to the 8200 yr B.P. cold event? Speleothem isotopes indicate a weakened early Holocene monsoon in Costa Rica

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ABSTRACT

A δ^{18}O monsoon rainfall proxy record from a U-Th–dated Costa Rican stalagmite (8840–4920 yr B.P.) documents an early Holocene dry period correlative with the high-latitude 8200 yr B.P. cold event. High δ^{18}O values between ca. 8300 and 8000 yr B.P. demonstrate reduced rainfall and a weaker monsoon in Central America. A relatively wetter and more stable monsoon was established ca. 7600 yr B.P. The early Holocene dry event suggests a tropical-extratropical teleconnection to the 8200 yr B.P. cold event and a possible association of isthmian rainfall anomalies with high-latitude climate changes. The likely source of such a tropical anomaly is a decrease in Atlantic thermohaline circulation and atmospheric perturbations associated with drainage of proglacial lakes and freshwater discharge into the North Atlantic. A weaker monsoon at 8200 yr B.P. may be linked to wetland contraction and a decrease in methane observed in Greenland ice cores.

Keywords: Costa Rica, tropics, paleoclimate, 8200 yr B.P. event, stalagmite, δ^{18}O, Holocene, Central American monsoon, Intertropical Convergence Zone, U-Th dating.

INTRODUCTION

The tropics export atmospheric moisture and heat to higher latitudes and support ~40% of the world's population. Yet few isotopic paleoclimate records exist from tropical regions, and important details regarding their climatic response to regional and global forcing remain unresolved. Specifically, the dependence of monsoonal precipitation to changes in sea-surface temperatures (SSTs) and thermohaline circulation (THC) during the last deglaciation remains unconstrained in Central America, but a high-resolution record of such change would provide insight into monsoon climate dynamics. To test the relationship between tropical monsoon rainfall and high-latitude climate changes, we developed a U-Th–dated (8840–4920 yr B.P.) δ^{18}O proxy record of monsoon rainfall from stalagmite V1, Venado Cave, Costa Rica (10.6°N, 84.8°W).

The 8200 yr B.P. event is the most pronounced Holocene climate anomaly noted in Greenland ice-core records, when air temperature decreased by 6 ± 2 °C and snow accumulation was reduced by 20% (Alley et al., 1997). The 8200 yr B.P. event is thought to have resulted from rapid drainage of a large volume of freshwater at a rate as high as 5.2 Sv (1 Sv = 10^6 $m^3 \cdot s^{-1}$) from glacial lakes Agassiz and Ojibway to the North Atlantic Ocean via the Hudson Strait (Clark et al., 2002; Barber et al., 1999; Teller et al., 2002). Freshwater influx inhibited THC, cooled SSTs by 1.5–3 °C, and provoked regional climatic changes. For example, European temperatures decreased over an ~200 yr period, and hydrologic change was noted from northern Europe to North Africa (von Grafenstein et al., 1998; Baldini et al., 2002; Magny and Bégeot, 2004). Atmospheric reorganizations are noted in paleoclimatic records from North America (Dean et al., 2002). In the tropics, Gasse (2000) noted low African lake levels, and Hughen et al. (1996) demonstrated enhanced trade winds over the Cariaco Basin. For the 8200 yr B.P. event, no significant monsoon rainfall anomalies have been documented from the American monsoon region. Consequently, the hemispheric- to global-scale climatic teleconnections of the 8200 yr B.P. event are still largely unresolved.

Located in the humid inner tropics, Costa Rica is under the climatic influence of the Intertropical Convergence Zone, which is characterized by deep vertical convection and copious rainfall. The annual migration of the zone results in wet and dry seasons and is designated the Central American Monsoon (Giannini et al., 2000). Climate data from nearby Ciudad Quesada indicate monthly rainfall of 90–290 mm during the January to April dry season, 320–550 mm during the May to December wet season, and mean annual precipitation of 4540 mm (Food and Agriculture Organization of the United Nations, 1985). Mean annual temperature at Venado Caves is ~25.0 °C; boreal winter (December-January-February) is ~2 °C cooler than summer, and average relative humidity is 89%. Although no seasonal measurements of Venado Cave microclimate are available, cave climate is commonly more humid and stable than aboveground climate (Poulson and White, 1969). Our observations in numerous humid tropical caves show wet-season relative humidity near 100% and temperature within 0.5 °C of regional mean temperatures. Hydrologically, Venado Cave is located in a shallow local groundwater-flow system, ensuring a fast transit time of rainfall to the stalagmite site.

Speleothems are ideal paleoclimate proxies because they incorporate rainfall-derived oxygen into precipitated $CaCO_3$ and can be precisely dated by U-series isotopes (Richards and Dorale, 2003). In tropical regions characterized by strong vertical convection, rainfall δ^{18}O values are inversely correlated with rainfall via the ''amount effect'' (Rozanski et al., 1993). Precipitation from stations in Costa Rica and Panama (International Atomic Energy Agency/World Meteorological Organization, 1998) demonstrate lower monthly mean δ^{18}O values during the wet season ($R^2 = 0.80$, $p < 0.01$) (and higher mean values during the dry season) and a seasonal variability of ~8.0‰, whereas Costa Rican surface waters exhibit larger ~12‰ variability

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TABLE 1. STALAGMITE V1 U-Th ISOTOPE DATA AND CALCULATED AGES

Sample	Distance from base (mm)	U (ppm)	±2σ	Th (ppm)	±2σ	^{230}Th/^{232}Th (ppm)	±2σ	$\delta^{234}U_{initial}$	±2σ	(^{230}Th/^{238}U)	±2σ	Age (yr B.P.)	±2σ
A	0	0.1148	0.00064	0.00028	0.00003	654	78	196	14	0.0976	0.0820	9180	510
B	0	0.1590	0.00057	0.00012	0.00003	1998	577	187	8	0.0909	0.0034	8670	350
C	0	0.1797	0.00094	0.00006	0.00003	4409	2412	181	12	0.0922	0.0073	8870	740
ISO-1	0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	**8840**	**270**
99	12	0.148	0.00065	0.00151	0.00002	138	2	192	9	0.0860	0.0037	7620	470
127	22	0.120	0.00041	0.00281	0.00003	66	1	195	5	0.0939	0.0029	7640	714
84	36	0.074	0.00023	0.00091	0.00002	143	2	202	5	0.1059	0.0042	9420	540
128	87	0.174	0.00052	0.00399	0.00002	65	0	213	4	0.0903	0.0013	7200	640
85	208	0.242	0.00108	0.00147	0.00002	171	2	206	6	0.0634	0.0018	5570	250
124	314.5	0.133	0.00045	0.00012	0.00002	1019	182	224	8	0.0554	0.0038	5020	350
125	314.5	0.116	0.00159	0.00020	0.00002	559	61	213	9	0.0580	0.0042	5260	400
126	314.5	0.114	0.00056	0.00037	0.00002	297	19	217	13	0.0587	0.0041	5230	400
ISO-2	314.5	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	**5160**	**220**
86	346	0.150	0.0008	0.0007	0.00002	199	4	210	10	0.0574	0.0022	5060	250

Note: ISO-1 is age derived from isochron subsamples A, B, C, and ISO-2 is age derived from isochron subsamples 124, 125, and 126. N.A.—not applicable.

(Lachniet and Patterson, 2002). Conversely, the correlation between surface temperature and rainfall $\delta^{18}O$ values is poor ($R^2 = 0.11$, $p = 0.12$). At ~25 °C, cave temperature variation of 1 °C should have a minor 0.20‰ effect on speleothem $\delta^{18}O$ values (Kim and O'Neil, 1997), considerably less than the observed seasonal rainfall $\delta^{18}O$ variation. Also, evaporation is expected to be minor in poorly ventilated tropical caves with relative humidity near 100%, such as Venado. Thus, speleothem $\delta^{18}O$ values faithfully record variations in oxygen isotope values of rainfall on time scales of years to millennia (Burns et al., 2001), and we interpret the stalagmite V1 $\delta^{18}O$ stratigraphy from Venado Cave as a rainfall proxy.

METHODS

Stalagmite V1 (352 mm tall) was collected from ~150 m within Venado Cave, ~10 m beneath the surface. The stalagmite was halved, and thin sections were prepared to evaluate crystal fabrics. We made a total of eight U-Th age determinations from carbonate (~0.3 g) drilled parallel to growth banding that included two 3-point isochrons. Chemical separation methods, modified from Chen et al. (1986), were described in Polyak and Asmerom (2001). U and Th isotopes were measured on a Micromass Sector 54 thermal-ionization mass spectrometer with an ion-counting Daly filter. The NBL-112 U standard was measured with every batch; we obtained the commonly accepted $\delta^{234}U$ value of −36‰ ± 1‰. The reported uncertainties in the ratios are 2σ of the mean and include uncertainties related to the initial $^{230}Th/^{232}Th$ correction, which is constrained somewhat by the isochron method. Th isotopes for subsamples 127, 84, and 86 were analyzed twice, and final ages are weighted means. An age model was constructed by using a fifth-order polynomial visually weighted to follow the most robust age determinations (isochrons and those with small error bars) reported in calendar years before present (A.D. 2000–2002).

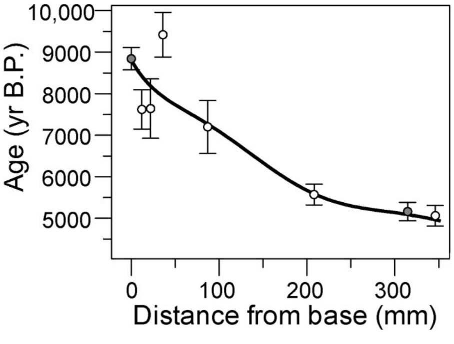

Figure 1. Age vs. depth plot for stalagmite V1. Filled circles are ages derived from three-point isochrons. Solid black line is fifth-order polynomial best-fit age model, visually weighted to most robust age determinations (isochron-based ages and those with smallest error bars).

The $\delta^{18}O$ and $\delta^{13}C$ values were determined for 296 subsamples drilled with a 0.5-mm-diameter bit along the stalagmite growth axis at intervals from 0.13 to 2.0 mm. Each subsample integrates ~2–5 yr of calcite deposition, so that aliasing of a seasonal cycle is precluded. The carbonate samples were reacted with H_3PO_4 in a Finnigan Kiel-III automated carbonate preparation device coupled to Finnigan MAT 252 (Syracuse University) and Finnigan Delta+ XL (University of Massachusetts) isotope ratio mass spectrometers. Precision is better than 0.1‰ for $\delta^{18}O$, determined through daily analysis of NBS-18, NBS-19, and an internal carbonate standard. All results are presented in per mil notation relative to the Vienna Peedee belemnite standard.

RESULTS

Thin sections confirm continuous growth along the drip axis. U-Th analyses and ages are shown in Table 1. Isochrons ISO-1 (0.0 mm from base) and ISO-2 (314.5 mm) consisted of subsamples A, B, and C, and 124, 125, and 126, respectively. Final weighted ages and mean square of weighted deviates (MSWD) statistics (Ludwig, 2003) are 8840 ± 270 yr for ISO-1 (MSWD = 1.4) and 5160 ± 220 for ISO-2 (MSWD = 0.51), confirming acceptable robust isochron ages. Initial $^{230}Th/^{232}Th$ ratios of 8.6×10^{-6} ($R^2 = 1.0$) and 1.5×10^{-5} ($R^2 = 1.0$) were determined for ISO-1 and ISO-2, respectively, slightly larger than the "global" initial value of 4.4×10^{-6}, and were used to correct their ages for "detrital" thorium; uncertainty of ±50% was assumed. Because of low ^{230}Th and moderate ^{232}Th concentrations, the nonisochron ages were sensitive to the initial $^{230}Th/^{232}Th$ ratio correction, a likely indication of variable initial $^{230}Th/^{232}Th$ ratios. Because we observed no silicate detritus in thin section or U-series leachates, a carbonate material with a higher than global ratio is the likely "detrital" contamination source (Asmerom et al., 1997). Nonisochron subsample ages were corrected with an initial $^{230}Th/^{232}Th$ ratio of $1.0 \times 10^{-5} \pm 50\%$, selected on the basis of the isochron results. The stalagmite V1 age model (Fig. 1) is within the error bars of all samples except 99 and 84, which likely have a component with a variable initial $^{230}Th/^{232}Th$ ratio. For example, a negligible correction to the $^{230}Th/^{232}Th$ ratio places subsample 99 within error bars, whereas an initial correction of 3.2×10^{-5} places subsample 84 within error bars. Due to a lack of annual laminae over the early Holocene growth interval, we are not able to constrain better the ages of subsamples 84 and 99. As a result, the age model during this period may deviate from the true ages by ~±150 yr. The stalagmite grew over ~3920 yr with a mean extension rate of 0.09 mm/yr over the interval 8840 and 4920 yr B.P., after which calcite deposition ceased, likely after cave plumbing changes interrupted drip-water delivery to the stalagmite.

The $\delta^{18}O$ time series from stalagmite V1 (Fig. 2) shows a distinct, high $\delta^{18}O$ anomaly between ca. 8300 and 8000 yr B.P. The $\delta^{18}O$ values rise from −6.0‰ at 8400 yr B.P. to

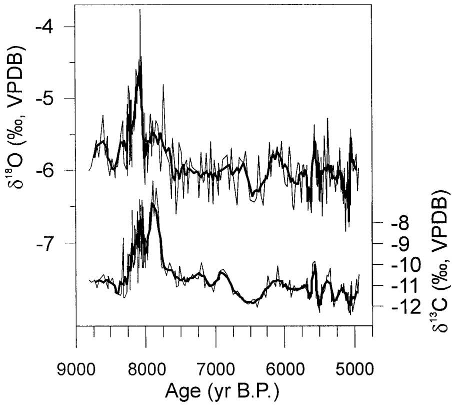

Figure 2. δ^{18}O time series for stalagmite V1. High δ^{18}O anomaly between ca. 8300 and 8000 yr B.P. is interpreted as dry interval. Wetter and more stable middle Holocene monsoon was established by ca. 7600 yr B.P. VPDB—Vienna Peedee belemnite.

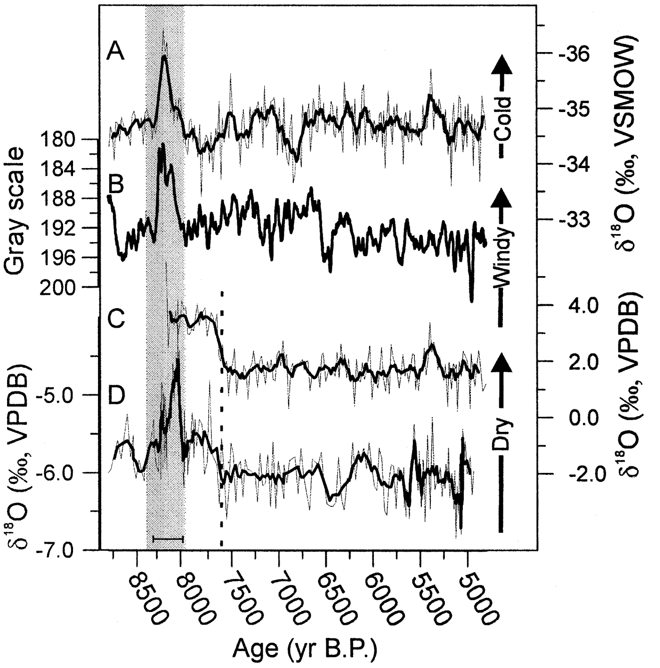

Figure 3. Comparison of Venado Cave monsoon record to other paleoclimate proxy records. A: δ^{18}O values from GISP2 ice. B: Cariaco sediment-core gray scale as indicator of trade-wind intensity (revised age model of Hughen et al., 1998, available at www.ngdc.noaa.gov/paleo). C: Lake Chichancanab, Mexico, gastropod δ^{18}O record. D: Stalagmite V1 δ^{18}O time series. Shaded bar indicates ~400 yr duration of 8200 yr B.P. event. Horizontal error bar (±150 yr) indicates uncertainty in timing of early Holocene dry event in Costa Rica. Vertical dashed line represents establishment of monsoon in Central America. All records indicate that early Holocene was anomalous compared to middle Holocene. Colder conditions in Greenland coincide with enhanced trade winds over tropical Atlantic and reduction in strength of Central American monsoon. VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

−4.4‰ at 8050 yr B.P., then decline to −5.7‰ by 8000 yr B.P. The δ^{18}O values reach a relatively stable middle Holocene mean of −6.1‰ by 7600 yr B.P., ~1.7‰ lower than peak values. The early Holocene δ^{18}O anomaly is unprecedented over the ~3920 yr V1 growth interval and is twice the amplitude of middle Holocene variability. The absolute timing of the early Holocene δ^{18}O peak may shift by ~±150 yr based on uncertainties in the growth rate. We note that early Holocene δ^{13}C values are higher than the middle Holocene values but are within the range expected for speleothems formed beneath C3 rainforest vegetation (−14‰ to −6‰; Richards and Dorale, 2003) and that δ^{18}O and δ^{13}C values are poorly correlated ($R^2 = 0.48$).

DISCUSSION

Because the δ^{18}O values of tropical rainfall are dominated by the ''amount'' effect, we interpret the δ^{18}O variations in stalagmite V1 as indicators of rainfall amount, with lower (higher) values indicating wetter (drier) conditions. Sea level ca. 8200 yr B.P. was lower by ~20 m than at present, and marine δ^{18}O values were within 0.15‰ of modern values (Bard et al., 1990). Thus, the effect of lowered sea level, increased oceanic δ^{18}O, and changes in moisture transport distance from the Caribbean at 8200 yr B.P. can be discounted as a primary factor controlling the δ^{18}O values of sample V1. Further, unrealistic cave temperature variations of 5–12 °C on decadal time scales are required to explain the V1 δ^{18}O variability. Although some of the early Holocene δ^{18}O increase may be explained by cooler temperatures, most of the pronounced δ^{18}O anomaly between 8300 and 8000 yr B.P. is best explained by a centennial-scale weakening of the monsoon. Monsoon weakening clearly postdates our robust basal isochron age of 8840 ± 270 yr B.P., but uncertainties in our chronology do not permit evaluation of potential leads and lags in the climate system. A relatively stable monsoon was established ca. 7600 yr B.P. and persisted until at least 4900 yr B.P. Additionally, the δ^{13}C data support our interpretation of dry conditions ca. 8200 yr B.P., in that delivery of isotopically light biogenic carbon to the stalagmite was reduced.

Figure 3 shows the stalagmite V1 record plotted against other paleoclimate records. We suggest that the early Holocene dry event in stalagmite V1 is a tropical manifestation of the 8200 yr B.P. event in the North Atlantic region (Fig. 4). During this time, North Atlantic cooling is evident in decreased GISP2 (Greenland Ice Sheet Project 2) δ^{18}O values (Stuiver et al., 1995) and reduced snow accumulation in Greenland (Alley et al., 1997). Cariaco basin sediments indicate stronger trade winds at 8200 yr B.P. (Hughen et al., 1996), and our data demonstrate decreased precipitation in Central America. Rising sea level filled Lake Chichancanab ca. 8200 yr B.P. (Hodell et al., 1995), but initiation of a humid climate ca. 7600 yr B.P. in both Mexico and Costa Rica suggests a common middle Holocene timing for monsoon development in Central America.

A weaker Central American monsoon is likely related to global atmospheric and/or oceanographic reorganization during the 8200 yr B.P. event. For example, strengthening and/or a southward displacement of the North Atlantic anticyclone would have resulted in decreased strength and/or a southward displacement of the Intertropical Convergence Zone (Giannini et al., 2000), keeping the western tropical Atlantic both windy (Hughen et al., 1996) and dry (Hastenrath, 1984). A suppressed monsoon could have also resulted from a basin-wide reduction in SSTs at 8200 yr B.P., such as noted off subtropical West Africa (deMenocal et al., 2000). Cooler tropical SSTs result in delayed onset and early end dates of the Caribbean rainy season (Enfield and Alfaro, 1999) and may have indirectly resulted in higher δ^{18}O values in our stalagmite via a temperature forcing of decreased rainout. However, evidence is equivocal for basin-wide tropical SST depression at 8200 yr B.P. (Manabe and Stouffer, 1995; Rühlemann et al., 1999). Modern climatic variability is dominated by the El Niño–Southern Oscillation

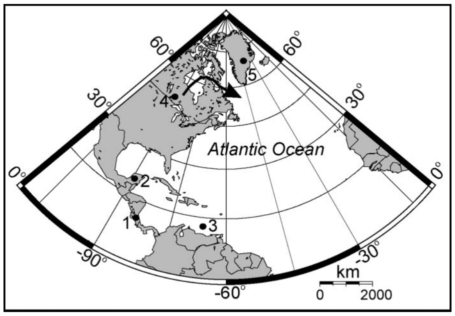

Figure 4. Map showing (1) Venado Cave, Costa Rica, (2) Lake Chichancanab, Mexico, (3) Cariaco Basin, Caribbean Sea, (4) approximate location of glacial lakes Ojibway and Agassiz; arrow denotes meltwater routing ca. 8200 yr B.P., (5) GISP2 core location.

(ENSO), and Waylen et al. (1996) noted that increased trade winds result in enhanced orographic rainfall on the Caribbean slope of Costa Rica, while drier conditions exist on the Pacific slope. Such a forcing acts contrary to the evidence of dry and windy conditions in the Caribbean. However, Venado Cave is located midway between the coasts, and the relationship of greater rainfall with enhanced trade winds is weak over our site. Further, ENSO variability was likely reduced before 5000 yr B.P. (Rodbell et al., 1999), such that modern climate may not be an analog for the early Holocene. Our data also suggest that tropical drying at 8200 yr B.P. may have resulted in contraction of wetlands and possibly contributed to decreased methane concentrations observed in Greenland ice (Alley et al., 1997).

The results of our study have several implications for global climate. Tropical rainfall anomalies at times of high-latitude climate change indicate that monsoonal regimes are linked to extratropical climate. Modeling studies have shown that North Atlantic THC is sensitive to high-latitude freshwater forcing, such that freshwater flux as small as 0.06 Sv could weaken THC (Manabe and Stouffer, 1995; Rahmstorf, 1995; Renssen et al., 2001). Melting of high-latitude ice sheets in a greenhouse world may force a shutdown in THC (Clark et al., 2002) with potentially catastrophic results for global climate. Our data suggest that such a change may result in a weaker monsoon in Central America. Because Central American communities rely upon monsoon rainfall for agriculture, drinking water, and supplying freshwater for the strategically important Panama Canal, such a rainfall decrease may have adverse socioeconomic impacts.

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