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 δ18O monsoon rainfall proxy record from a U-Th-dated Costa Rican stalagmite (8840–4920 yr B.P.) documents an early Holocene dry period correlated with the high-latitude 8200 yr B.P. cold event. High δ18O 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, δ18O, 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 on 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.) δ18O 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 = 10⁶ m³·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 Bégo, 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 CaCO₃ and can be precisely dated by U-series isotopes (Richards and Dorale, 2003). In tropical regions characterized by strong vertical convection, rainfall δ18O 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 δ18O values during the wet season (R² = 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 ~12.0‰ variability.
Separation methods, modified from Chen et al. (1998), 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 $^{234}$U value of $-36\%\pm 1\%$. The reported uncertainties in the ratios are $2\sigma$ 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 smaller error bars) reported in calendar years before present (A.D. 2000–2002).

The $^{18}$O and $^{3}$He 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 $\sim 2$–5 yr of calcite deposition, so that aliasing of a seasonal cycle is precluded. The carbonate samples were reacted with $\mathrm{H}_2\mathrm{PO}_4$ 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 $^{18}$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 Pee Dee 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 $\pm$ 270 yr for ISO-1 (MSWD = 1.4) and 5160 $\pm$ 220 for ISO-2 (MSWD = 0.51), confirming acceptable robust isochron ages. Initial $^{230}$Th/$^{232}$Th ratios of $8.6 \times 10^{-6}$ ($R^2 = 1.0$) and 1.5 $\times 10^{-5}$ ($R^2 = 1.0$) were determined for ISO-1 and ISO-2, respectively, slightly larger than the "global" initial value of 4.4 $\times 10^{-6}$, and were used to correct their ages for "detrital" thorium; uncertainty of $\pm 50\%$ 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 VI 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 $\times 10^{-5}$ 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 $\sim 150$ yr. The stalagmite grew over $\sim 3920$ 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 $^{18}$O time series from stalagmite VI (Fig. 2) shows a distinct, high $^{18}$O anomaly between ca. 8300 and 8000 yr B.P. The $^{18}$O values rise from $-6.0\%$ at 8400 yr B.P. to

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

<table>
<thead>
<tr>
<th>Sample</th>
<th>Distance from base (mm)</th>
<th>$U$ (ppm)</th>
<th>$\pm 2\sigma$</th>
<th>$Th$ (ppm)</th>
<th>$\pm 2\sigma$</th>
<th>$^{230}$Th/$^{232}$Th (ppm)</th>
<th>$\pm 2\sigma$</th>
<th>$^{234}$U$_{calc}$ (ppm)</th>
<th>$\pm 2\sigma$</th>
<th>$^{230}$Th/$^{232}$U</th>
<th>$\pm 2\sigma$</th>
<th>Age (yr B.P.)</th>
<th>$\pm 2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0.1148</td>
<td>0.00064</td>
<td>0.00028</td>
<td>0.00003</td>
<td>654</td>
<td>78</td>
<td>196</td>
<td>14</td>
<td>0.0976</td>
<td>0.0820</td>
<td>9180</td>
<td>510</td>
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<tr>
<td>B</td>
<td>0</td>
<td>0.1590</td>
<td>0.00105</td>
<td>0.0012</td>
<td>0.00003</td>
<td>1998</td>
<td>577</td>
<td>187</td>
<td>8</td>
<td>0.0909</td>
<td>0.0334</td>
<td>8570</td>
<td>350</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0.1707</td>
<td>0.00005</td>
<td>0.0006</td>
<td>0.00003</td>
<td>4409</td>
<td>2412</td>
<td>181</td>
<td>12</td>
<td>0.0922</td>
<td>0.0073</td>
<td>8870</td>
<td>740</td>
</tr>
<tr>
<td>ISO-1</td>
<td>0</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>138</td>
<td>2</td>
<td>192</td>
<td>9</td>
<td>0.0860</td>
<td>0.0087</td>
<td>8280</td>
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</tr>
<tr>
<td>99</td>
<td>12</td>
<td>0.148</td>
<td>0.00065</td>
<td>0.00015</td>
<td>0.00002</td>
<td>138</td>
<td>2</td>
<td>192</td>
<td>9</td>
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<td>470</td>
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<tr>
<td>127</td>
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<td>0.120</td>
<td>0.00041</td>
<td>0.00281</td>
<td>0.00003</td>
<td>65</td>
<td>1</td>
<td>195</td>
<td>5</td>
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<td>0.0029</td>
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<tr>
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<td>0.00023</td>
<td>0.00091</td>
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<td>2</td>
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<td>540</td>
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<tr>
<td>128</td>
<td>87</td>
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<td>0.00389</td>
<td>0.00002</td>
<td>65</td>
<td>0</td>
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<td>0.0013</td>
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<td>640</td>
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<tr>
<td>85</td>
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<td>0.00108</td>
<td>0.00147</td>
<td>0.00002</td>
<td>171</td>
<td>2</td>
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<td>0.133</td>
<td>0.00045</td>
<td>0.00012</td>
<td>0.00002</td>
<td>1019</td>
<td>182</td>
<td>224</td>
<td>8</td>
<td>0.0554</td>
<td>0.0038</td>
<td>5020</td>
<td>350</td>
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<tr>
<td>125</td>
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<td>0.00159</td>
<td>0.00020</td>
<td>0.00002</td>
<td>559</td>
<td>61</td>
<td>213</td>
<td>9</td>
<td>0.0580</td>
<td>0.0042</td>
<td>5260</td>
<td>400</td>
</tr>
<tr>
<td>126</td>
<td>314.5</td>
<td>0.114</td>
<td>0.00056</td>
<td>0.00007</td>
<td>0.00002</td>
<td>297</td>
<td>19</td>
<td>217</td>
<td>13</td>
<td>0.0587</td>
<td>0.0041</td>
<td>5230</td>
<td>200</td>
</tr>
<tr>
<td>ISO-2</td>
<td>314.5</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>199</td>
<td>4</td>
<td>210</td>
<td>10</td>
<td>0.0574</td>
<td>0.0022</td>
<td>5160</td>
<td>220</td>
</tr>
</tbody>
</table>

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.

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**Figure 1. Age vs. depth plot for stalagmite VI.** 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).
-4.4‰ at 8050 yr B.P., then decline to -5.7‰ by 8000 yr B.P. The δ¹⁸O 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 δ¹⁸O 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 δ¹⁸O peak may shift by ~±150 yr based on uncertainties in the growth rate. We note that early Holocene δ¹³C 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 δ¹⁸O and δ¹³C values are poorly correlated ($R^2 = 0.48$).

**DISCUSSION**

Because the δ¹⁸O values of tropical rainfall are dominated by the “amount” effect, we interpret the δ¹⁸O 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 δ¹⁸O values were within 0.1‰ of modern values (Bard et al., 1990). Thus, the effect of lowered sea level, increased oceanic δ¹⁸O, and changes in moisture transport distance from the Caribbean at 8200 yr B.P. can be discounted as a primary factor controlling the δ¹⁸O values of sample V1. Further, unrealistic cave temperature variations of 5–12 °C on decadal time scales are required to explain the V1 δ¹⁸O variability. Although some of the early Holocene δ¹⁸O increase may be explained by cooler temperatures, most of the pronounced δ¹⁸O 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 δ¹³C 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) δ¹³C 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 δ¹⁸O 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 and Agassiz; arrow denotes meltwater routing ca. 8200 yr B.P. (5) GISP2 core location.
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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