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Regional-scale climate influences on temporal variations of rainwater and cave dripwater oxygen isotopes in northern Borneo

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Abstract

This study investigates the relationship between large-scale climate variability, rainfall oxygen isotopic composition ($\delta^{18}O$), and cave dripwater $\delta^{18}O$ at Gunung Mulu and Gunung Buda National Parks in northern Borneo (4°N, 115°E) on intraseasonal to interannual timescales. A 3-yr timeseries of rainfall $\delta^{18}O$ contains prominent seasonal and interannual variability. The seasonal cycle in rainfall $\delta^{18}O$ is defined by lighter values of − 10‰ during late boreal summer and heavier values of − 4‰ during late boreal winter, and is poorly correlated to local precipitation, which displays very weak seasonality. Seasonally-varying moisture trajectories likely play a key role in the observed seasonal cycle of rainfall $\delta^{18}O$, driving enhanced fractionation during boreal summer and less fractionation during boreal winter. Dripwater $\delta^{18}O$ timeseries display 2‰ seasonal cycles that follow the rainfall $\delta^{18}O$ seasonal cycles, with a mean $\delta^{18}O$ value equivalent to the mean $\delta^{18}O$ of rainfall. Large surveys of cave dripwaters conducted during three fieldtrips to Gunung Mulu/Buda reveal a system-wide response to rainfall $\delta^{18}O$ seasonality that supports a relatively short (less than 6months) response time for most drips. During the weak 2005/2006 La Niña event, sustained positive precipitation anomalies are associated with rainfall $\delta^{18}O$ values that are 4 to 5‰ lighter than previous years' values, consistent with the tropical "amount effect" observed in both models and data. Dripwater $\delta^{18}O$ values are 1 to 2‰ lighter during the weak La Niña event. The importance of the "amount effect" in driving intraseasonal rainfall $\delta^{18}O$ anomalies at our site is supported by an 8‰ increase in rainfall $\delta^{18}O$ that occurred over the course of two weeks in response to a pronounced decrease in regional convective activity. Dripwater discharge rates underwent a ten-fold decrease during the extended dry period, but dripwater $\delta^{18}O$ values remained constant. This study supports the interpretation of stalagmite $\delta^{18}O$ records from Gunung Mulu/Buda as paleo-precipitation records that are sensitive to the location and strength of deep convection in the West Pacific Warm Pool.

Keywords: stalagmite; rainfall; dripwater; oxygen isotopes; paleoclimate; West Pacific Warm Pool

1. Introduction

Stalagmite oxygen isotopic records have provided long, high-resolution, absolutely-dated climate reconstructions from many regions of the globe. Such reconstructions have played a particularly important role

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in the tropics, where high-resolution, absolutely-dated paleoclimate archives are scarce. Indeed, tropical stalagmite oxygen isotopic ($\delta^{18}O$) records conclusively link precipitation variability in southeastern Asia (Wang et al., 2001), the Arabian Sea (Burns et al., 2003), and the eastern Mediterranean (Bar-Matthews et al., 1999) to abrupt climate change events recorded in the Greenland ice cores (Grootes et al., 1993). Millennial-scale variability in stalagmite $\delta^{18}O$ records points to precessional forcing as the dominant control on orbital-scale tropical hydrology (Fleitmann et al., 2003; Yuan et al., 2004; Cruz et al., 2005a,b; Dykoski et al., 2005; Cruz et al., 2006; Wang et al., 2006; Partin et al., 2007), while centennial-scale variability in stalagmite $\delta^{18}O$ records that span the last millennium document tropical hydrological effects associated with the 'Medieval Warm Period' and the 'Little Ice Age' (Burns et al., 2002; Fleitmann et al., 2004; Lachniet et al., 2004).

Despite the increasingly important role that stalagmite $\delta^{18}O$ records play in global climate change studies, their interpretation with respect to large-scale climate dynamics is often ambiguous. In the tropics, stalagmite $\delta^{18}O$ records are largely interpreted as rainfall $\delta^{18}O$ reconstructions, with a minor role for relatively small temperature changes that occur in the tropics. Potential controls on rainfall $\delta^{18}O$ variability include temperature-dependent changes in the vapor-liquid fractionation factor, changes in the water vapor source region, and the cumulative effect of Raleigh fractionation that occurs as vapor condensation proceeds (Dansgaard, 1964; Rozanski et al., 1993; Gat, 1996). An empirical relationship referred to as the 'amount effect' exists between rainfall $\delta^{18}O$ and rainfall amount in the tropics, and likely arises from more extensive rainout (and therefore larger rainfall $\delta^{18}O$ depletions) and/or less evaporative enrichment of raindrops during wet periods. On regional scales, atmospheric general circulation models equipped with stable isotope tracers have reproduced the strong inverse relationship between the amount of precipitation and the $\delta^{18}O$ of rainfall throughout the tropics (Jouzel et al., 1987; Hoffmann et al., 1998; Cole et al., 1999; Noone and Simmonds, 2002; Vuille et al., 2005; Brown et al., 2006). However, both models and data highlight the importance of variable moisture sources and trajectories in contributing to significant seasonal and interannual rainfall $\delta^{18}O$ variability in the tropics, especially in regions characterized by monsoonal circulation and/or proximity to large-scale atmospheric fronts (Araguas-Araguas et al., 1998; Cole et al., 1999; Cruz et al., 2005a,b; Vuille and Werner, 2005; Vuille et al., 2005). Detailed on-site analyses of the relationship between large-scale climate and local rainfall $\delta^{18}O$ are critical to accurate climatic interpretations of many terrestrial paleoclimate reconstructions based on ice core, tree ring, or stalagmite $\delta^{18}O$, but few such studies exist.

Even if the climate-rainfall $\delta^{18}O$ relationship is well-constrained, cave hydrology adds an additional layer of complexity to the interpretation of stalagmite $\delta^{18}O$ records. The climate-related rainfall $\delta^{18}O$ signal must be transmitted through the dynamic karst system, which involves mixing in the epikarst, possible evaporative fractionation, and highly variable groundwater flow rates. Dripwater residence times vary from several months in tropical regions (Cruz et al., 2005a,b; Johnson et al., 2006) to decades in semi-arid regions (Ayalon et al., 1998), depending on the recharge and mixing characteristics of a given cave system. Prolonged rainfall anomalies can cause temporal variability in dripwater residence times (McDonald et al., 2004), while different dripwater pathways contribute to spatial heterogeneity in residence times (Ayalon et al., 1998). Quantitative calibrations of high-resolution stalagmite $\delta^{18}O$ records to the instrumental climate record (e.g. Fleitmann et al., 2004; Treble et al., 2005b) provide the most direct measure of climatic influences on stalagmite $\delta^{18}O$, but such calibrations are exceedingly rare and may be impossible to undertake at some sites. Therefore, detailed site-specific investigations of the relationship between large-scale climate, rainfall $\delta^{18}O$ variability, cave hydrology, and dripwater $\delta^{18}O$ variability are critical to accurate interpretations of stalagmite $\delta^{18}O$ variability.

In this study we investigate the large-scale climatic controls on rainfall and dripwater $\delta^{18}O$ variability in northern Borneo, where climate is dominated by monsoonal variability and the El Niño-Southern Oscillation. As no GNIP (http://isohis.iaea.org) rainfall $\delta^{18}O$ data exist from Borneo, this study is key to accurate interpretations of several new stalagmite $\delta^{18}O$ reconstructions that extend through the Last Glacial Maximum from the site (Partin et al., 2007). A 3-yr-long on-site rainfall and dripwater monitoring program is supplemented with intensive sampling during three fieldtrips in 2003, 2005, and 2006 to provide constraints on both spatial and temporal variability in rainwater and dripwater $\delta^{18}O$. The resulting $\delta^{18}O$ timeseries are compared against local rainfall as well as gridded datasets of precipitation and wind in an attempt to isolate the climatic controls on rainfall and dripwater $\delta^{18}O$ across synoptic, seasonal, and interannual timescales.

2. Geologic setting

The research site is located in the adjoining Gunung Mulu and Gunung Buda National Parks (4°N, 115°E), in