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High-resolution Holocene South American monsoon history recorded by a speleothem from Botuverá Cave, Brazil

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ABSTRACT

A Holocene stalagmite from Botuverá Cave, southeastern Brazil was analyzed by LA-ICPMS for Mg/Ca, Sr/Ca, Ba/Ca. The observed variability in the record was demonstrated to be modulated by prior calcite precipitation, and, thus, is interpreted to reflect monsoon intensity. We find that the calcite $\delta^{18}O$ is strongly correlated with Sr/Ca, indicating that atmospheric circulation over South America and monsoon intensity have been tightly correlated throughout most of the Holocene, both directly responding to solar precession. Comparison with other contemporaneous high-resolution hydroclimate records reveals that SAMS has shown a degree of complexity during the Holocene not previously detected, with periods where the South American Convergence Zone (SACZ) expanded to cover most of the South American sub-continent, and coincident with periods of low-SST in the north Atlantic. We also detect periods where rainfall amount in northeastern and southeastern Brazil are markedly anti-phased, suggesting a north-south migration of SACZ, which it appears to be mediated by solar irradiance. The high-resolution nature of our record allow us to examine the effect that Holocene climate anomalies had upon SAMS dynamics and hydroclimate in southeastern Brazil, in particular the 8.2 ka event and the Little Ice Age. In addition to confirm the internal structure of the events, we also detect the possible consequences of the climatic anomalies upon ocean–atmosphere interactions through its effects upon SAMS.

1. Introduction

The South American Monsoon System (SAMS) refers to the austral summer season features of deep convective activity and large scale circulation over South America (Liebmann and Mechoso, 2011) from which one of most important biodiversity hotspot in the tropics, the Atlantic Rainforest, has relied upon during late Quaternary (Carnaval et al., 2009), and it is the main source of rainfall for the most densely-populated areas of South America. Because of its importance, an increasing number of studies have focused on deciphering the natural variability of SAMS on orbital to millennial time-scales and have established links to Northern Hemisphere climate (e.g. Cruz et al., 2005a, 2009; Stríkis et al., 2011; Wang et al., 2006). More recently, high-resolution paleoclimate records from South America have been able to reveal the modulation/coupling of SAMS by different (multi)decadal climatic modes, and/or solar oscillations (Apaéstegui et al., 2014a; Bird et al., 2011; Chiessi et al., 2009; Novello et al., 2012; Thompson et al., 2013; Vuille et al., 2012). Most of these reconstructions are focused on the last two millennia, and only Chiessi et al. (2009) cover a period of ∼4.5 ka during the last glacial maximum; yet, there is still no reconstruction of SAMS in subtropical South America providing evidence for hydroclimate modulation by multi-decadal climatic modes during the entire Holocene period when climate changed substantially from low to high phases of austral summer insolation. In this regard, it is necessary to obtain long, well-dated and

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highly resolved records of past SAMS's activity in an attempt to discuss the possible modulation of precession forcing on the high frequency precipitation variability. Such records also have the potential to provide valuable information on the coupling/decoupling of monsoonal systems with the different climatic modes, and/or reveal the possible influence from solar activity on climate instability or abrupt climate changes, providing a unique insight into the high-resolution paleoclimate dynamics during such events.

Oxygen-isotope records from stalagmites have provided many robust paleoclimate reconstructions spanning several thousands of years because variability in the carbonate $\delta^{18}O$ can be interpreted to reflect changes in the isotopic composition of local rainfall, which can be a function of moisture source, rainfall amount, or atmospheric equilibrium temperature (Lachniet, 2009). However, obtaining $\delta^{18}O$ records with high temporal resolution is complex and labor intensive (e.g. Treble et al., 2007), and is usually limited to samples with relatively high growth rates (>50 μm/yr), hampering our general understanding on how high-frequency climate modes and solar oscillations might have potentially impacted the different monsoonal systems in the world. This has led to the development of alternative rainfall proxies in stalagmites, among which, trace element variability is probably the most promising (Fairchild and Treble, 2009).

Trace element variability in stalagmites has been studied for several years (Fairchild and Treble, 2009), but the complexity and variety of geochemical processes to which they can be subjected in the epikarst hampers the establishment of a general model to explain trace element variations. Yet, the increasing knowledge on the geochemical processes modulating the abundance of some trace elements in the epikarst, as well as their incorporation into the speleothem calcite (Sinclair, 2011; Stoll et al., 2012; e.g. Treble et al., 2005; Tremaine and Froelich, 2013), along with the development and availability of different microbeam techniques, have permitted the construction of records with high spatial- and chronological resolution using laser ablation-ICPMS (Treble et al., 2003), secondary ionization mass-spectrometry (Smith et al., 2009) and micro-XRF (e.g. Borsato et al., 2007); thus allowing the construction of records with high-temporal resolution even from slow-growing stalagmites, which can complement complex $\delta^{18}O$ records.

Long trace element records can also provide additional information for the interpretation of speleothem $\delta^{18}O$ records where the isotopic composition of local precipitation and seepage, which is finally recorded by speleothems, can be modulated by more than one fractionation process (e.g. source and rainfall amount). This is the case of southern Brazil, where two isotopically distinct moisture sources, Amazonian and extratropical, dominate rainfall regimes during the summer and winter, respectively (Cruz et al., 2005a). Consequently, speleothem $\delta^{18}O$ cannot be used as a proxy of mean rainfall accumulation because the amount effect is not evident and is poorly correlated with $\delta^{18}O$ in the region (Cruz et al., 2005b; Vuille and Werner, 2005). If, however, the variability on the abundance of trace elements is demonstrated to be modulated by karst humidity and prior calcite precipitation, such as in caves from Southeastern Brazil (Karmann et al., 2007), then it is possible to build a more complete and precise hydroclimate reconstruction. Indeed, by examining the variability of both, trace element and $\delta^{18}O$ records, it can be possible to obtain information on changes in moisture sources and amount with high temporal resolution, providing a more detailed description of the climatic patterns and atmosphere dynamics modulating hydroclimate in the area.

Here, we present a high-resolution trace element record in a stalagmite from Botuverá Cave (southeastern Brazil) spanning most of the Holocene using LA-ICP-MS providing the most detailed record of Holocene hydroclimate yet available for this area. Paleoclimate records from this cave are, arguably, among the most robust climate reconstructions for South America (Cruz et al., 2006a, 2005b; Wang et al., 2006, 2007), but due to the slow growth rate exhibited by the collected stalagmites (2–10 μm/yr), construction of records of hydroclimate variability based on calcite $\delta^{18}O$ with high temporal-resolution is difficult. We present evidence supporting that the observed variability in trace elements is mostly modulated by changes in the karst humidity, thus rainfall amount. This allows us to identify the diverse set of climatic modes (e.g. AMO) and forcing mechanisms (e.g. solar variability) that have been modulating the strength of the South American Monsoon System, and determine that SAMS evolution throughout the Holocene has been the result from a complex interplay by different forcing mechanisms.

2. Samples and methods

Botuverá cave (Fig. 1, 27°13′S; 49°09′W, 230 m above sea level) is located in Santa Catarina State, Southern Brazil, and is hosted within carbonates and sediments from the Brusque Group (Auler, 2002), a succession of metavolcanosedimentary rocks from the Neoproterozoic with an age of c.a. 600 Ma (Basei et al., 2011). Sample BTV21a is a 22.5 cm long stalagmite collected in 2002. Visual inspection of the sample reveals that there are no evident changes in growth direction or long hiatuses, an observation supported also on the resulting age-model (Fig. 2). Modern climatic conditions in the area have been described elsewhere (Cruz et al., 2007). The stalagmite was sectioned and a linear age-model was developed from 13 U/Th ages measured at the Minnesota Isotope Laboratory, University of Minnesota, and at the Earth Observatory of Singapore, using the methods described in Shen et al. (2002).

Oxygen and carbon stable isotope analyses were carried out at the University of Minnesota following the procedures and quality control described in Wang et al. (2006). Trace element ratios were obtained by Laser-ablation ICP-MS using a Resonetics L-50 excimer laser-ablation workstation (ArF, $\lambda = 193$ ns, 23 ns FWHM, fluence of ~ 6 J/cm^2) at Centro de Geociencias, Universidad Nacional Autónoma de México (UNAM). Details on the analytical protocols used here are described in the supplemental material.

Spectral analyses were carried out on sub-annually interpolated time-series using the Redfit module (Schulz and Mudelsee, 2002) as incorporated in PAST v 3.03 (Hammer et al., 2001). Wavelet analysis was performed using a Morlet wavefunction using the protocols developed by Grinsted et al. (2004) for Matlab®.

3. Results

3.1. Chronology

Stalagmite BTV21a has approximately 90 ng/g of U and only ∼0.05 ng/g of Th, thus the average (^{232}Th/^{238}U) is 0.00018.[1] Ages were corrected for contributions from detrital material using a two-point isochron, assuming that the detrital material present in the stalagmite has a typical crustal ^{230}Th/^{232}Th $= (4.4 \pm 2.2) \times 10^{-6}$ and (^{232}Th/^{238}U) $= 1.2 \pm 0.5$ (McDonough and Sun, 1995) and, essentially, in secular equilibrium; i.e. (^{230}Th/^{238}U) and (^{234}U/^{238}U) $= 1.0 \pm 0.1$. Nevertheless, because of the very low Th concentration in the stalagmite, the difference between "corrected" and "raw" age is less than 5 yr, with the exception of the two uppermost samples, whose corrected age are 27.5 and 92 yr younger than the uncorrected age. All ages are in stratigraphic order (Fig. 2A, Table SP1) and show that the

[1] Round brackets denote activity ratios calculated using the decay constants from Cheng et al. (2000). We note that using the more recent values reported by Cheng et al. (2013a) does not yield significantly different activity ratios, ages or uncertainties.