“High-resolution paleoclimate reconstruction of the last 9000 years based on speleothem isotope records from northeastern Venezuela”

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Dissertação apresentada ao Programa Geociências (Geoquímica e Geotectônica) para a obtenção do título de Mestra em Ciências.

Área de concentração: Geoquímica dos Processos Exógenos

Orientador: Prof. Dr. Francisco William da Cruz Junior

SÃO PAULO
2022
M. Medina, Nathalie Melissa
High-resolution paleoclimate reconstruction of the last 9000 years based on speleothem isotope records from northeastern Venezuela / Nathalie Melissa M. Medina; orientador Francisco William da Cruz Junior. -- São Paulo, 2022.
102 p.

Dissertação (Mestrado - Programa de Pós-Graduação-em Geoquímica e Geotectônica) -- Instituto de Geociências, Universidade de São Paulo, 2022.

1. Inter-tropical Convergence Zone. 2. Holocene. 3. Venezuela. 4. Speleothems. 5. Cariaco Basin. I. da Cruz Junior, Francisco William, orient. II. Título.
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Dissertação de Mestrado

Nº 889

COMISSÃO JULGADORA

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SÃO PAULO
2022
RESUMO

Medina, N.M.M., 2022, High-resolution paleoclimate reconstruction of the last 9000 years based on speleothem isotope records from northeastern Venezuela [Master’s Thesis], São Paulo, Instituto de Geociências, Universidade de São Paulo, 102 p.

 Existem poucos registros paleoclimáticos de alta resolução disponíveis de regiões localizadas sob influência direta da Zona de Convergência Inter-tropical (ZCIT) na América do Sul, sendo a Bacia de Cariaco uma das áreas com maior número de estudos. O presente trabalho é baseado em registros isotópicos de alta resolução de δ¹⁸O e δ¹³C de espeleotemas de duas cavernas localizadas nas adjacências da Bacia de Cariaco, os quais cobrem a maior parte dos últimos 9,0 ka, durante o Holoceno. Os dados isotôpicos obtidos indicam oscilações climáticas em escalas de tempo multidecenal a secular, ainda pouco estudadas na região da ZCIT, que são comparadas a outros registros isotópicos de alta resolução no Atlântico Norte, Caribe e região tropical da América do Sul. Os dados isotôpicos sugerem que as condições climáticas mais frias no Atlântico Norte durante os eventos Bond estão associadas com mudanças na precipitação no nordeste da Venezuela, assim como na produtividade primária na Bacia de Cariaco. Entretanto, a relação climática com registros caribenhos depende da magnitude destes eventos e da fase de insolação vigente. O clima predominantemente úmido é observado na Venezuela e Caribe durante o Holoceno médio entre 8,1-6,5 ka, enquanto condições mais secas ocorrem no evento de maior magnitude, Bond (4), por volta de 5,5 ka. Já em eventos de menor intensidade e de mais curta duração, como o Bond 3, a comparação entre registros isotópicos sugere um estreitamento da ZCIT entre Venezuela e Barbados, que resultou em condições mais secas a norte em Cuba e a sul no Peru. O registro de espeleotema da caverna Caripe, nordeste da Venezuela, difere significativamente do registro das concentrações de titânio da Bacia de Cariaco durante os últimos 2300 anos. Durante este período, é observado o predomínio de uma relação climática antífásica com os registros caribenhos e em fase com os registros mais a sul, no domínio do Sistema de Monção Sul Americana (SMSA). Contrário ao que foi descrito em estudos anteriores da Bacia de Cariaco, os dados de espeleotemas indicam um clima mais seco na região
costeira da Venezuela no período correspondente a Anomalia Climática do Período Medieval (900-1100 CE). Já o período da Pequena Idade do Gelo, foi marcado pela não deposição de espeleotema, possivelmente associada a condições mais secas e o deslocamento mais a sul da ZCIT, que intensificou o regime de chuvas do SMSA em parte do continente sul-americano.

**Palavras chave:** Zona de Convergência Inter-tropical, Holoceno, Venezuela, espeleotemas, Bacia de Cariaco, paleoclima, isótopos estáveis, América do Sul, Caribe, Ciclos Bond.
ABSTRACT

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Few high-resolution paleoclimate proxy records exist in the region located under the direct influence of the Inter-tropical Convergence Zone (ITCZ) in South America (SA); most of them retrieved from the Cariaco Basin (CB) off the coast of Venezuela. Here we present new high-resolution $\delta^{18}$O and $\delta^{13}$C records of speleothems collected in caves in the region adjacent to the CB in Venezuela, covering the Mid and Late Holocene. We document previously undetected multidecadal- to secular-scale climate variability in the core region of the ITCZ, which is being compared to other high-resolution records from the North Atlantic (NA), Caribbean and southern tropical South America. We show that the northeastern Venezuelan Holocene hydroclimate variability and the input of nutrients, productivity and oxygen demand in the CB has primary (but not exclusively) responded to NA climate (Bond cycles). However, the magnitude of those events and the background insolation conditions might have been the main determinants. Increased Northern Hemisphere (NH) insolation during the Mid-Holocene likely led to mostly in-phase relation between Venezuela and eastern Caribbean records (i.e. wet conditions occurred between 8.1-6.5 ka despite coinciding with Bond 5, due to the enhanced NH insolation and northward position of the ITCZ, whereas dry conditions were observed during the strongest of the Bond Cycles (4) around 5.5 ka). In addition, the comparison between the speleothem record of this study and other ones suggest that ITCZ stayed between Venezuela and Barbados as a narrower band during weaker and shorter events such as the Bond 3 with drying conditions observed to the north in Cuba and to the south in Peru. Our NE Venezuela record from Caripe Cave considerably differs from the Cariaco Basin Ti record during the last 2.3 ka. Pointing to non-previously reported relations to Caribbean and southern hemisphere tropical high-resolution records. During this period an out-phase relation is observed between Venezuela and Caribbean records and rather appears to be closely related to the South American Monsoon System (SAMS).
dynamics. Contrary to results from previous studies in Cariaco, our results point out to drier conditions during Medieval Climate Anomaly (MCA, 900-1100 CE) close to the coast in Venezuela. No speleothem deposition occurred during most of Little Ice Age (LIA) which might be related to dryer conditions in response to a southward position that led to major moisture income to the SASM domain.

Key words: Inter-tropical Convergence Zone, Holocene, Venezuela, speleothems, Cariaco Basin, paleoclimate, stable isotopes, South America, Caribbean, Bond Cycles.
1. INTRODUCTION

1.1. What is the ITCZ?

The Inter-tropical Convergence Zone (ITCZ) is defined as a narrow or confined latitudinally low-pressure band of atmospheric deep convective clouds along the equator, where northerly and southerly trade winds converge and most of the rain of the Earth falls (Philander et al., 1996; Waliser & Gautier, 1993). During a year cycle the ITCZ migrates meridionally depending on the amount of solar radiation received on Earth by season and by latitude. Similarly, on longer time scales, paleo-records (Deplazes et al., 2013; Haug et al., 2001; Lea et al., 2003;) and modeling studies (Broccoli et al., 2006; Chiang & Bitz, 2005) have revealed that the ITCZ migrates, with some exceptions, towards a differentially warming hemisphere (Schneider, Bischoff, & Haug, 2014; Adam, Bischoff, & Schneider, 2016). Although the solar radiation has a maximum at the equator, the ITCZ location is not uniform around the globe. Currently, over the central Atlantic and Pacific oceans, the ITCZ migrates between 9°N in boreal summer and 2°N in boreal winter. And over the Indian Ocean and adjacent land surfaces, between 20°N in boreal summer and 8°S in boreal winter. Then, mean position of the ITCZ around the Earth’s middle situates further north at 6°N (Schneider et al., 2014).

The explanation for this asymmetry is the northwards heat transport across the equator by the Atlantic Meridional Overturning Circulation (AMOC). Compensated by the southward atmospheric heat transport achieved by shifting the tropical circulation northward of the equator (Marshall et al., 2014).

Given that there is no unambiguous definition for the ITCZ in reason of the number of different variables used to describe it, in addition to the confusion derived from the extrapolation of the ITCZ concept to land (Nicholson, 2018); two parameters have been frequently used to track the ITCZ position. The latitude of maximum precipitation (above a specific quantile) and minimum outgoing longwave radiation (OLR) in each longitude (Gu & Zhang, 2002; Mamalakis et al., 2021). Reminding that quantity of OLR is inversely related to the deep convective cloudiness (Poveda et al., 2006), as the cloud cover hamper the emission of electromagnetic radiation from the Earth and its atmosphere out to the space. However, continuing research based on observations and simulations has intended to unify the above parameters into a formula to describe the position...
of the ITCZ and its rainfall intensity: the atmospheric energy balance equation (Schneider, Bischoff & Haug, 2014). Defined as the absorbed solar radiation at the top of the atmosphere, minus the outgoing longwave radiation and any ocean energy uptake owing to transport or storage in the oceans (Schneider, Bischoff & Haug, 2014).

The ITCZ must be seen as an atmosphere-ocean interplay coupled by the trade winds near the surface. Which are especially important over the Atlantic and Pacific Oceans, where the continents are less influential (Philander et al., 1996).

The Hadley cell meridional overturning circulation is the atmospheric process controlling zonal-mean ITCZ position. While the belt of ocean currents (Meridional Overturning Circulation-MOC) has a key role in transporting large amounts of heat and salt around the world and thus in determining the inter-hemispheric heat balance (Manabe and Stouffer, 1999).

Hadley cells rise tropical air masses to the upper troposphere through evaporation (Schneider, Bischoff & Haug, 2014; Davis, et al., 2016). As the sun-warmed ocean heats the overlying air, air becomes less dense due to an increase in the particle’s kinetic energy and rises. As air rises, loses temperature and its capacity of retaining moisture, becomes supersaturated and some of its water vapor condenses into water droplets. Those condensed water droplets form clouds. When enough moisture has condensed and the droplets have grown too heavy to stay suspended by air currents, fall as rain. This rising air near the ocean surface is replaced by air masses from north and south of the equator which are deflected to the west due to the Coriolis effect, creating the easterly trade winds. Trade winds blow southwest toward the equator in the Northern Hemisphere (northeasterlies), and northwest toward the equator in the Southern Hemisphere (southeasterlies). In the upper troposphere, air masses detrain from clouds and diverge in the Northern and Southern hemispheres and subside at approximately 30°N and 30°S, respectively, in the extra-tropics at the subtropical highs. From here, air masses flow back to the equator through warm and moist surface zonal winds (Schneider, Bischoff & Haug, 2014; Davis, et al., 2016). Because these trade winds converge near the equator, the tropical rain belt occurring over the ocean is known to meteorologists as the Inter-tropical Convergence Zone. Whereas, the expression of the convectively equatorial active zone over the
inland area is observed as rather scattered cloud masses known as the equatorial trough (Riehl, 1979).

The AMO (Manabe and Stouffer, 1999) is manifested in the Atlantic Ocean as the AMOC. As is described by Kuhlbrodt et al., (2007), the AMOC consist of four main branches: the wind-driven processes that transport cold depth water near to the surface through upwelling at the Southern Ocean; the surface currents that accumulate warm and less saline waters on their path through the tropical waters toward northern high latitudes; the Southern (Antarctic Bottom Water, AABW) and the North Atlantic Deep Water (NADW) formation branches; together with the deep currents closing the loop.

Since the AMOC effectively contributes to the warming of the North Atlantic it is reasonable to think that a change in some of this branches would have its strongest response around this region (Vellinga & Wood, 2002; Schmittner et al., 2005). However, significant changes may occur over the entire globe. Various climate reconstructions/simulations of past and future scenarios, shows that increasing meltwater input into the North Atlantic may cause a slowdown of the AMOC (negative AMOC phase) or even the collapse of the oceanic heat transport (Vellinga & Wood, 2002; Schmittner et al., 2005). Not only triggering colder and drier conditions in much of the Northern Hemisphere, but also a relatively warmer Southern Hemisphere, stronger northeasterly winds, southward shift of the ITCZ over the Atlantic and eastern Pacific Basins, and enhanced precipitation in South America and Africa monsoon regions (Vellinga & Wood, 2002).

1.2. High Resolution Western Atlantic ITCZ Paleorecords: Cariaco Basin Sedimentary and Stable Isotope Records in Speleothems

Since the recovery of the first sediments cores from Cariaco Basin (CB) in 1957 (Peterson et al., 2000b), several proxy data sets were analyzed. Some of them reaching a temporal depth of up to 600,000 years BP (Gibson & Peterson, 2014; Peterson et al., 2000b), covering over five glacial cycles, with an extraordinary sampling interval of up to 5 years for the last 14 ka (Haug et al., 2001). Hence, CB located at 10°N has become the biggest source of information of northern South American paleoclimate and a worldwide reference to the ITCZ position. However, the spatial distribution of ITCZ rainfall over continental northern South
America remained more speculative. Until the high-resolution $\delta^{18}$O speleothem record from Caracos Cave located in the eastern Andean Cordillera at 6°N came into light, revealing the complementary picture of ITCZ variability for a period spanning almost the entire last glacial cycle (Ramirez, 2018).

CB off the coast of Venezuela is an east-west trending pull apart basin that actually consist of two small sub-basins reaching depths of ~1400 mbsl, separated by a shallower central saddle of ~900 mbsl. Surrounding this structural depression to the north, the much shallower Tortuga Bank that extends from the Margarita Island to the east, to Cabo Cordera to the west, acts like a barrier that limits the exchange of waters with the rest of the Caribbean (Fig. 1) (Peterson et al., 2000b; Sweere et al., 2016). This key feature in combination with the large sedimentation rates (0.3 to >1 mm/year) make the CB a particularly sensitive repository to high-latitude climatic events. Such as the expansion and demise of polar ice sheets during glacial-interglacial transitions accompanied by dramatic sea level changes. And the trigger of a rapid tropical feedback through atmospheric-ocean teleconnections (Chiang & Bitz, 2005; Lea et al., 2003). Indeed, the correlation between Greenland temperatures (ice core $\delta^{18}$O in ‰; Wolff et al., 2010) to past changes in CB ventilation (Mo in cps, Gibson & Peterson, 2014), upwelling (gray scale from 0-255; Hughen et al., 2000 and total reflectance in L*; Deplazes et al., 2013), surface productivity (alkenone concentration in µg/g sediment, Herbert & Schuffert, 2000) and sea surface temperatures (Mg/Ca in mmol/mol; Lea et al., 2003) point to a link between NH cooling and the strengthening of trade wind-driven upwelling in a situation analogous to the nowadays boreal winter dry season (December-January-February).

Like northern Venezuela, central Colombia also experiences a dry season during boreal winter due to the southward shift of the ITCZ. However, Ramirez, (2018) showed that during the Last Glacial Cycle there was a prevalence of an antiphased relationship with the Cariaco Basin at orbital (Marine Isotopes Stages) and millennial (Greenland Stadials and Interstadials) scales. Exceptions were observed in extreme cold events known as Heinrich Stadials (HS) in which both, the Cariaco Basin and central Colombia experienced a shortfall of precipitation. Providing evidence to the southward displacement of the ITCZ, already suggested by the enhancement of the South American Monsoon System (SAMS)
(Cruz et al., 2009; X. Wang et al., 2004), weakening of the AMOC (Bohm et al., 2015; McManus et al., 2004; Mulitza et al., 2017) and a suite of water-hosing modeling studies (Kageyama et al., 2013).

Dry (wet) periods were observed in the Caracos speleothem stable-isotope record as enriched (depleted) δ¹⁸O values. Whilst, in the CB were interpreted/observed in the lithology and geochemistry proxies as oxic (anoxic) bottom waters, colder (warmer) sea surface temperatures, and as lighter (darker), inorganic-biogenic (organic-carbon-rich), typically bioturbated (laminated) sediments. Besides, high detrital Fe and Ti abundances during periods of warm interstadials are thought to indicate increased terrigenous input to the Cariaco Basin, implying higher rainfall and increased runoff from the local watersheds. Namely of the small drainages of Cumaná, Neverpi, Unare and Tuy rivers (Fig. 1) (Deplazes et al., 2019; González et al., 2008; Haug et al., 2001; Peterson et al., 2000).

The coherence of the above-mentioned proxies has certainly probed to reflect ITCZ past meridional migrations in close synchronicity with NH climate in orbital to millennial time scales. Particularly for the Holocene, the consistency between the variability observed in the numerous proxy records from the CB is less apparent. Still, the Ti concentrations in sediments (Haug et al., 2001) have been used in several proxy comparisons and modeling studies as unequivocally evidence for the southward displacement of the ITCZ, following the gradual decrease in local insolation since the mid-Holocene, leading to rainfall diminution in northern Venezuela. Other Holocene data from the CB such of oxygen balance (Gibson & Peterson, 2014) and sediment color (Deplazes et al., 2013) instead shows a marked cyclicity pattern during the Mid Holocene. And for the Late Holocene, an opposite scenario to the Ti interpretation is exposed by progressively darker sediments approaching the present (Hughen et al., 2000), which might indicate a greater terrigenous input by increased river discharges expected by an ITCZ directly overhead. Then, the present study aims to reconcile the exposed discrepancies by providing new independent high-resolution δ¹⁸O and δ¹³C hydroclimate proxies from stalagmites collected in two caves located just 20 km of the Cariaco Basin. And contribute to northern South America hydroclimate reconstructions by giving important time windows of the Holocene period.
2. CONCLUSIONS

Precipitation in northeastern Venezuela is subjected to the geographic location that mainly determines the exposure to the moisture carrying trade winds. Whereas, isotopic composition imprint on rainfall represents more regional mechanisms. Based on the available data, we suggest that on monthly scales, $\delta^{18}O$ isotopic variability mainly responds to the amount effect related to the latitudinal migration of the ITCZ convective activity. Which in turn is associated to the evaporative enrichment of the raindrops during the dry months from January to March leading to heavier $\delta^{18}O$ values. And enhanced Rayleigh distillation during the wet season from May to December inducing lighter $\delta^{18}O$ values in precipitation (Frölich et al., 2002; Rozanski et al., 1993). More data are needed for further supporting this hypothesis and the possible influence of local sources of moisture during the last month of the year.

The negative correlation between annual weighted $\delta^{18}O$ values and precipitation totals point to the amount effect. However, the non-significance ($p$-value=0.1759>0.05) might be related to the few data included in the correlation. Again, we highlight the need for producing more continuous meteorological data with information on the isotope composition of water. As well as conducting parallel monitoring surveys of dripping waters and calcite precipitates in Venezuelan Caves of paleoclimatic interest.

Covariation between $\delta^{18}O$ and $\delta^{13}C$-speleothem values in northeastern Venezuela and molybdenum concentration in CB sediments points to a close relation between hydroclimate, vegetation density/soil cover and oxygen balance in the CB. We suggest that wet conditions and increased delivery of organic matter-rich terrigenous-sediments likely led to necessary reductive conditions to accumulate Mo in CB sediments through the increase in primary productivity and $O_2$ consumption. Those observations were accompanied by minor, almost negligibly variations in Ti and sediment reflectance. Except for the last 2300 yrs, in which the relation to $\delta^{18}O$ and CB Ti concentration in sediments considerable differs.

Venezuelan records are strategically located to track the mean position of the ITCZ during important climate perturbations. An attempt that has been previously assessed indirectly by Caribbean (Fensterer et al., 2012, 2013; Mangini et al.,
and tropical SH paleorecords (Apaéstegui et al., 2014; Bird et al., 2011; Novello et al., 2012; Stríkis et al., 2011; Vuille et al., 2012). We show that Holocene hydroclimate variability in Venezuela has primary (but not exclusively) responded to NA climate (Bond cycles) (Bond et al., 2001) with repercussions in the Cariaco Basin dynamics (Black et al., 1999; Gibson & Peterson, 2014; Haug et al., 2001; Hughen et al., 2000). The magnitude of those events as depicted by the concentration of HSG in the sub-polar NA sediments and the background insolation conditions might have been the main determinants. Increased NH insolation during the Mid-Holocene likely led to mostly in-phase relations between Alfredo Jahn and eastern Caribbean records. Contrasting the invariable convective activity observed over Central America (Serrato Marks et al., 2021; Winter et al., 2020). Whereas, during the Late-Holocene and out-phase relation is observed between Caripe and Caribbean records. During this particular period Caripe record appears to be closely related to the SAMS dynamics.

Apparent wet conditions are observed during peak Bond Cycle 5 in Cuba (Fensterer et al., 2013) and Venezuela, suggesting an ITCZ overhead and warmer Caribbean SSTs (LoDico et al., 2006). Conversely, between 5.8 and 5.2 ka, cold and windy NH climate in sync with the strongest of the Bond events (Bond 4) (Bond et al., 2001; Jackson et al., 2005b; Oppo et al., 2003), induced the southward displacement of the ITCZ and enhancement of the SAMS (Bustamante et al., 2016). Wet conditions in Venezuela and the southern Lesser Antilles (Mangini et al., 2007) were observed during the relative weak Bond Cycle 3, suggesting a subtle displacement of the mean position of the ITCZ, hence diminished convection in the SAMS region.

The Late Holocene Caripe record shows two distinct periods. From 350 BCE to 870 CE the convection was high and relatively stable, with variability apparently related to the Diva de Maura record from the NEB (Novello et al., 2012) likely also forced by the AMO in a common 40-yr periodicity. During the last 1000 years, instead, Caripe closely resembled the SAMS paleorecords in timing and direction (Apaéstegui et al., 2014; Bird et al., 2011; Della Libera et al., 2022). Relatively higher δ¹⁸O values during the MCA reflects a further north position of the ITCZ. And lower values during the first part of the LIA point to mean ITCZ position over
the Guianas, which apparently by this time was enough to drive important moisture influx to the SAMS domain.
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