https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions
Open Access

Spatiotemporal ITCZ dynamics during the last three millennia in Northeastern Brazil and related impacts in modern human history

Giselle Utida[1]*, Francisco W. Cruz[1], Mathias Vuille[2], Angela Ampuero[1], Valdir F. Novello[3], Jelena Maksic[4], Gilvan Sampaio[5], Hai Cheng[6,7,8], Haiwei Zhang[6]; Fabio Ramos Dias de Andrade[1], R. Lawrence Edwards[9]

[1]Instittuto de Geociências, Universidade de São Paulo, Rua do Lago, 562, Cidade Universitária, São Paulo-SP, 05508-090, Brazil

[2]Department of Atmospheric and Environmental Sciences, University at Albany, SUNY, Albany, NY, USA

[3]Geo- and Environmental Research Center, University of Tübingen, Tübingen, Germany

[4]Division of Impacts, Adaptation and Vulnerabilities (DIIAV), National Institute for Space Research (INPE), São Jose dos Campos-SP, Brazil

[5]General Coordination of Earth Science (CGCT), National Institute for Space Research (INPE), Sao Jose dos Campos-SP, Brazil

[6]Institute of Global Environmental Change, Xi'an Jiaotong University, Xi'an, China

[7]State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

[8]Key Laboratory of Karst Dynamics, MLR, Institute of Karst Geology, CAGS, China

[9]Department of Earth Sciences, University of Minnesota, Minneapolis, MN, USA

*Corresponding author: giselleutida@hotmail.com

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions
Open Access

Abstract

Changes in tropical precipitation over the past millennia have usually been associated with latitudinal displacements of the Intertropical Convergence Zone (ITCZ). Recent studies provide new evidence that contraction and expansion of the tropical rainbelt may also have contributed to ITCZ variability on centennial time scales. Over tropical South America few records point to a similar interpretation, which prevents a clear diagnosis of ITCZ changes in the region. In order to improve our understanding of the equatorial rainbelt variability, our study presents a reconstruction of precipitation for the last 3200 years from the Northeast Brazil (NEB) region, an area solely influenced by ITCZ precipitation. We analyze oxygen isotopes in speleothems that serve as a faithful proxy for the past location of the southern margin of the ITCZ. Our results, in comparison with other ITCZ proxies, indicate that the range of seasonal migration, contraction and expansion of the ITCZ was not symmetrical around the equator. A new NEB ITCZ pattern emerged based on the comparison between two distinct proxies that characterize the ITCZ behavior during the last 2500 years, with an ITCZ zonal pattern between NEB and the eastern Amazon. In NEB, the period related to the Medieval Climate Anomaly (MCA) was characterized by an abrupt transition from wet to dry conditions. These drier conditions persisted until the onset of the period corresponding to the Little Ice Age (LIA), representing the longest dry period over the last 3200 years in NEB. The ITCZ was apparently forced by teleconnections between Atlantic Multidecadal Variability and Pacific Decadal Variability that controlled the position, intensity and width of Walker cell over South America changing the ITCZ zonally, and sea surface temperature changes in both the Pacific and Atlantic, stretching/weaking the ITCZ-related rainfall meridionally over NEB. Wetter conditions started around 1500 CE in NEB. During the last 500 years, our speleothems document the occurrence of some of the strongest drought events for the last millennia, which drastically affected population and environment of NEB

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions

during the Portuguese colonial period. The historical droughts were able to affect the karst system, and led to significant impacts over the entire NEB region.

Keywords: Holocene, speleothems, stable isotopes, droughts, Portuguese colony

1. Introduction

Northeastern Brazil (NEB) is one of the areas in South America (SA) most vulnerable to the impacts of climate change. The semi-arid conditions in NEB are strongly affected by precipitation variability, and since the 18th century the region has experienced more frequent drought events. Today the frequent droughts put ~57 million people, ~27% of the Brazilian population, at risk of experiencing water scarcity (Marengo and Bernasconi, 2015; Lima and Magalhães, 2018). Aside from native people, the region has been occupied since the Portuguese colonization in the 16th century, and the ensuing intense agricultural activity has been responsible for a large-scale degradation of the Caatinga biome, the typical vegetation of NEB's semi-arid areas. This land mismanagement and the increasing frequency of regional droughts has put some of these areas at great risk of desertification (Marengo and Bernasconi, 2015; Sampaio et al., 2020). Advancing our knowledge about NEB's climate and recurrence of extreme events in a long-term context is therefore of great importance to better anticipate the impacts of these intense and abrupt drought events.

The Intertropical Convergence Zone (ITCZ) is one of the key elements responsible for precipitation over NEB, which is also indirectly affected by the South American Summer Monsoon (SASM). When the ITCZ is in its southernmost position during austral autumn, northern areas of NEB experience increased precipitation (Schneider et al., 2014), while the precipitation in the southern areas of NEB occurs mainly during austral summer in response to climatic conditions in the tropical South Atlantic (Vera et al., 2006; Vuille et al., 2012).

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Although these systems are independent and arise in different seasons, the position of the ITCZ affects SASM intensity and its development through moisture influx to the continent (Vuille et al., 2012; Schneider et al., 2014).

On orbital to centennial timescales, weakened precipitation in NEB has been associated with enhanced subsidence over NEB during intense SASM periods (Cruz et al., 2009; Orrison et al., 2022), giving rise to a zonal dipole between the western Amazon and NEB (Cruz et al., 2009; Novello et al., 2018). This mode also operates today on interannual and seasonal time scales (Lenters and Cook, 1997; Sulca et al., 2016).

More recent studies suggested that these variations on millennial and centennial timescales in NEB may also have been caused by contraction or expansion of the ITCZ affecting the precipitation over South America (Utida et al., 2019; Chiessi et al., 2021). These ITCZ dynamics would be forced by changes in tropical Atlantic and Pacific SST and related atmospheric circulation changes (e.g., Lechleitner et al., 2019; Utida et al., 2019; Chiessi et al., 2021; Steinman et al., 2022). These results suggest complex ITCZ dynamics operating over NEB; a region where the lack of studies complicates the paleoclimate interpretations for the last millennia.

In comparison with the ITCZ, the SASM has received more attention from recent studies, mainly due to its larger area of influence in SA, extending from the tropical Andes to the Amazon and southeastern SA (e.g., Apaéstegui et al., 2018; Azevedo et al., 2019; Della Libera et al., 2022). The spatiotemporal precipitation variability over tropical SA during the Common Era (CE) was evaluated based on a network of high-resolution proxy records (Novello et al., 2018; Campos et al., 2019; Orrison et al., 2022). These studies point to an association between SASM variability and the latitudinal displacement of the ITCZ, although changes in the latitude of the ITCZ during the last millennia are not well established.

Previous studies based on oxygen and hydrogen isotopes from paleorecords obtained in NEB have served as useful proxies for ITCZ precipitation in the region (Cruz et

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past Discussions

al., 2009; Utida et al., 2019, 2020), while carbon isotopes have been used to interpret soil erosion/production and vegetation cover (Utida et al., 2020; Novello et al., 2021; Azevedo et al., 2021). Building on these recent advances, we present an ITCZ precipitation reconstruction based on stalagmite records from the state of Rio Grande do Norte (RN), located at the modern southernmost limit of the ITCZ in eastern South America (Fig 1). By using oxygen and carbon isotopes obtained from these stalagmites, we reconstruct precipitation and vegetation/soil cover over the last 3,200 years over NEB. These data are essential to fill the gap of high-resolution records in NEB and to improve the interpretation of ITCZ dynamics over SA and how they are related to SASM variability during the CE.

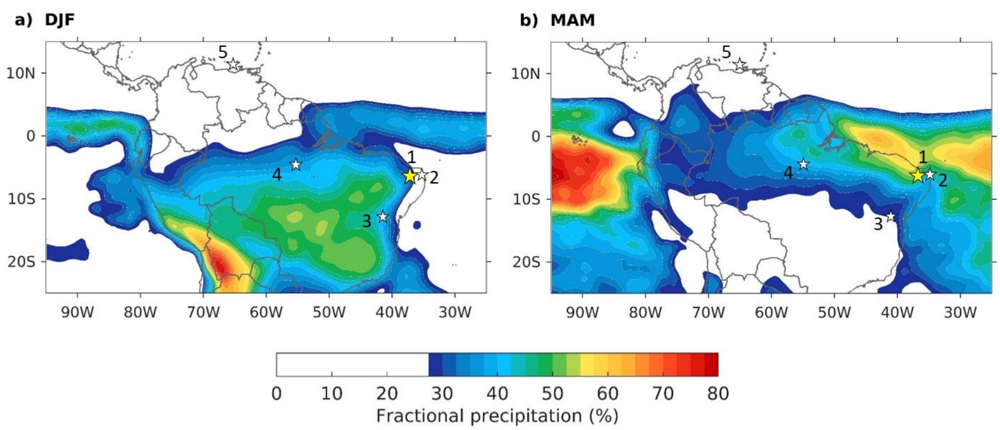


Figure 1 – Location and precipitation climatology of study sites during the austral summer (DJF - December to February) and autumn (MAM - March to May). Color shading of regions above 27.5% of annual precipitation highlights the extent of the (a) SASM over the continent and (b) the ITCZ over the ocean. Precipitation data from the Global Precipitation Measurement (GPM) mission, with averages calculated over period 2001–2020. 1) Trapiá and Furna Nova Cave (yellow star, this study), 2) Boqueirão Lake (Utida et al., 2019), 3) Diva de Maura Cave (Novello et al., 2012), 4) Paraíso Cave (Wang et al., 2017), 5) Cariaco Basin (Haug et al., 2001).

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

2. Regional settings

2.1. Study area

We study stalagmites from two caves located in the Rio Grande do Norte State, in northern NEB (Fig 1), Trapiá and Furna Nova Cave. The caves were developed in the Cretaceous carbonate rocks of the Jandaíra Formation, Potiguar Basin, close to the Apodi River valley (Pessoa-Neto, 2003; Melo et al., 2016). The exposed karst pavements extend over several kilometers and include a series of small canyon-like caves that usually are no more than 40 m deep (Silva et al., 2017). We collected speleothems in Trapiá and Furna Nova caves. Trapiá Cave (5°33'45.43"S, 37°37'15.92"W) is a 2330 m long cave with 29 m of bedrock above the cave cavity. This cave is located 90 km from the Atlantic coast and ~ 50 m above sea level, with temperature and relative humidity at the chamber of 28.5°C and 100%, respectively. Furna Nova Cave (5°2'3.22"S, 37°34'16"W) is located 60 km north of Trapiá Cave, 45 km from the Atlantic coast and ~95 m above sea level. The cave is 239.3 m long, with 29.8 m of bedrock above the cave cavity. Its temperature and relative humidity at the speleothem chamber are 25°C and 95.0%, respectively.

The annual mean temperature is around 28ºC (INMET - National Institute of Meteorology – Instituto Nacional de Meteorologia – data from 1961-1990) and average precipitation is approximately 730 mm/year, concentrated in the period between March and May, during the southernmost position of the ITCZ (Agência Nacional de Águas – ANA - National Agency of Waters, 2013; Ziese et al., 2018). Caatinga dry forest is the typical vegetation of the region. It is adapted to short rainy seasons of 3 to 4 months in length and tolerates large interannual variations in precipitation. It is characterized by sparse dry forest, dominated by arboreal deciduous shrubland (Erasmi et al., 2009).

2.2. Climatology

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

The drylands of NEB extend from 2.5°S to 16.1°S, and from 34.8°W to 46°W, with an area of about 1,542,000 km^2, representing 18.26% of Brazilian territory (Marengo and Bernasconi, 2015). Although the whole area is classified as semi-arid and has faced intense droughts, especially influenced by El Niño, there are significant differences in climatic systems between the northern and southern sectors of NEB. Furthermore, the NEB eastern coastal sector is characterized by a different rainfall seasonality, receiving more rainfall across the year, as the climate in this region is modulated by the sea breeze circulation and easterly wave disturbances during June and July (Gomes et al., 2015; Marengo and Bernasconi, 2015; Utida et al., 2019).

Northern NEB (N-NEB), where the studied caves are located, receives most of its precipitation from March to May, when the seasonal migration of the ITCZ reaches its southernmost position (Fig 2a) (Schneider et al., 2014; Utida et al., 2020), and ITCZ-related precipitation extends across the equator southward to NEB (Fig 1).

In N-NEB, we analyzed precipitation data of Pedra das Abelhas Station – RN (Fig 2a), from 1911 to 2015 (n=103). In order to exclude possible extreme events with a known forcing, we excluded the most significant years of El Niño - Southern Oscillation (ENSO) (39 years), according to Araújo et al. (2013). The results (Fig S1) reveal that in the majority of years (interquartile range) the total rainy season persists from February to April, with precipitation varying from 100 to 180 mm/month, and minor contributions occurring in January and May (50-70 mm/month). During the driest years (25% of quantiles), the rainy season persists also from February to April, but the maximum precipitation is below 90 mm/month, while during the wettest years (75% of quantiles), the rainy season starts in January with more than 100 mm/month and lasts until May with almost 150 mm/month, reaching values higher than 250 mm around March. These data show that years with increased precipitation amounts are characterized by a longer rainy season, while the precipitation deficit during drought years is primarily the result of a shorter rainy season. The

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

anomalous length of the rainy season can be attributed to variations in the meridional SST gradient in the tropical Atlantic that result in a shift of the ITCZ to the north or south of its climatological position (e.g.,Andreoli et al., 2011; Marengo and Bernasconi, 2015; Alvalá et al., 2019).

In S-NEB, the precipitation occurs mainly during summer, from December to February (Fig 1a and 2b). This regional seasonality difference with N-NEB is evident in the spatial correlation map between GPCC precipitation anomalies (Schneider et al., 2011) and $\delta^{18}O$ anomalies obtained from IAEA-GNIP (International Atomic Energy Agency - Global Network of Isotopes in Precipitation) for Fortaleza and Brasília (the closest IAEA station to Diva de Maura Cave) stations. The reddish areas on the map indicate significant negative correlations during the austral summer (DJF) and autumn (MAM) between the local precipitation $\delta^{18}O$ signals and the regional precipitation amount. Overall, the spatial correlations indicate that in both areas the amount effect is the dominant effect on the isotopic composition of rainfall (Dansgaard, 1964). However, the isotopic signal varies seasonally and as a function of the two different circulation systems. The negative spatial correlation observed over N-NEB suggests precipitation is dominated by ITCZ dynamics, similar to the conditions over Fortaleza, while the negative spatial correlation over S-NEB (Fig 2b) is a result of the rainfall influenced by the SASM (Fig 1) (Vera et al., 2006), such as in Brasília city, in central Brazil. Therefore, precipitation and the associated isotopic signal are the result of ITCZ dynamics in N-NEB, while they are influenced by the SASM in the S-NEB. Accordingly, their rainfall seasonality is also different (Fig 2), with a NDJFM peak in the south (Brasília) and a MAM rainfall peak in the north (Fortaleza).

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

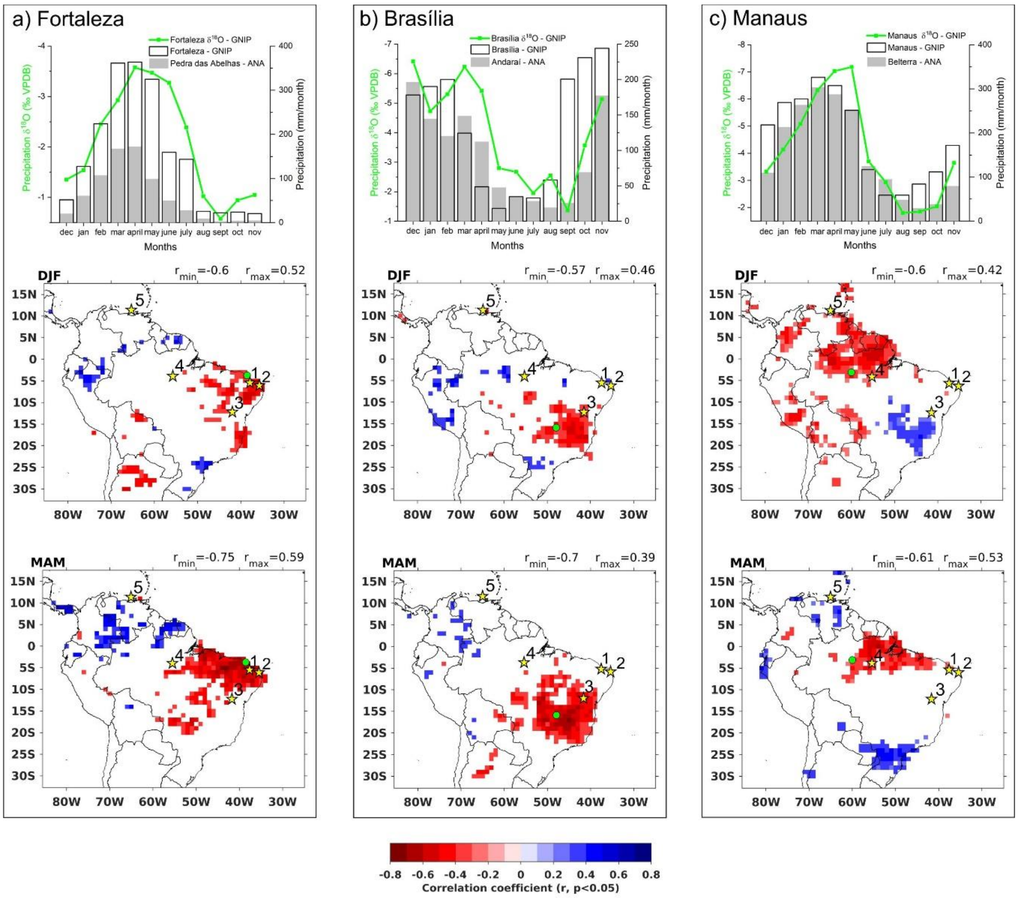


Figure 2 – NEB correlation map between regional precipitation amount and oxygen isotope ratios for GNIP stations (IAEA-WMO, 2021) (green dots) and precipitation amount for ANA stations: (a) Fortaleza GNIP station and precipitation at Pedra das Abelhas station in northern NEB, (b) Brasília GNIP station and precipitation at Andaraí station (star 3) in southern NEB, c) Manaus GNIP station and precipitation at Belterra station (star 4) in the eastern Amazon. The maps show the spatial correlation between $\delta^{18}O$ anomalies at GNIP stations and GPCC gridded precipitation anomalies for December to February (DJF) and March to May (MAM) for Fortaleza, Brasília and Manaus GNIP stations (Ziese et al., 2018). The $\delta^{18}O$ values and precipitation for each station were obtained from GNIP IAEA/WMO database. The reference period for analysis is 1960-2016. Stars indicate the site locations:

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past Discussions

1) Trapiá Cave, Furna Nova Cave and Pedra das Abelhas ANA Station, 2) Boqueirão Lake (Utida et al., 2019), 3) Diva de Maura Cave (Novello et al., 2012) and Andaraí ANA Station, 4) Paraíso Cave (Wang et al., 2017) and Belterra ANA Station, 5) Cariaco Basin (Haug et al., 2001).

Another important region in SA affected by the ITCZ behavior is the eastern Amazon, west of the NEB, where the Paraiso speleothem isotope record was retrieved (Fig 1 and Fig 2). This region is characterized by increased precipitation during DJFMAM and a peak in rainfall and a $\delta^{18}O$ minimum in MAM (Fig 2c) as a result of precipitation received from the ITCZ in both summer and autumn. It can be depicted by the negative correlation between $\delta^{18}O$ at the Manaus GNIP station and rainfall over the upstream equatorial region under direct ITCZ influence. In addition, there is only a minor influence through water recycling over the Amazon Basin, due to its proximity to the coast (Wang et al., 2017).

3. Materials and Methods

Four stalagmites were collected in northern NEB caves, two at Trapiá Cave, TRA5 and TRA7 that are 178 and 270 mm long, respectively (Fig S2), and two at Furna Nova, FN1 and FN2 with a length of 202 and 95 mm, respectively (Fig S3). The stalagmite FN1 was previously studied by Cruz et al. (2009) for chronology and oxygen isotopes. Utida et al. (2020) also studied TRA7 for chronology and carbon isotopes. These samples are part of the speleothem collection of the Geoscience Institute at the University of São Paulo.

Chronological studies on speleothems were based on U-Th geochronology performed at the Laboratories of the Department of Earth and Environmental Sciences, College of Science and Engineering, University of Minnesota (USA), and at the Institute of Global Environmental Change, Xi'an Jiaotong, University of Xi'an (China), using an

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

inductively coupled plasma-mass spectrometry (MC-ICP-MS Thermo-Finnigan NEPTUNE) technique, according to Cheng et al. (2013). Age models of speleothem TRA5 and FN2 were based on 12 and 10 uranium U/Th dates, respectively (Table S1 and S2). The FN1 chronology is based on 10 previously published U/Th results obtained by Cruz et al. (2009) plus 8 additional new dates obtained for this study (Table S1). Speleothem TRA7 has 27 U/Th ages that were presented in Utida et al. (2020). The individual age models for all speleothems were constructed by the software COPRA (Breitenbach et al., 2012) through a set of 2,000 Monte Carlo simulations, where a random age within the ±1σ age interval was chosen each time.

For oxygen and carbon isotope analysis of the speleothems, around 200 μg of powder was drilled for each sample, consecutively at intervals of 0.1 mm (TRA5), 0.3 mm (TRA7) and 0.15 mm (FN2), with a Micromill micro-sampling device. These samples were prepared using an online automated carbonate preparation system and analyzed by a GasBench interfaced to a Thermo Finnigan Delta V Advantage at the Laboratory of Stable Isotopes (LES) at the Geoscience Institute of the University of São Paulo. Isotopes are reported in delta notation ($\delta^{18}O$ and $\delta^{13}C$) relative to the Vienna Pee Dee Belemnite (VPDB) standard, with uncertainties in the reproducibility of standard materials < 0.1‰. The isotopic profiles of TRA5, TRA7, FN1 and FN2 stalagmites consist of 443, 885, 1215 and 651 isotope samples, respectively. These datasets provide an average resolution of ~1 year per sample for TRA5 and ~ 4 years for the other speleothem records. TRA7 $\delta^{13}C$ results were presented by Utida et al. (2020) and FN1 $\delta^{18}O$ results by Cruz et al. (2009) using the same methods. Cruz et al. (2009) do not provide FN1 $\delta^{13}C$ results, which were not included in this study.

Different textural characteristics of speleothem TRA5 and FN2 were identified in intervals which were analyzed for mineralogical composition based on approximately 20 mg samples with X-ray powder diffraction in a Bruker D8 diffractometer (Cu Ka, 40 kV, 40 mA,

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

step 0.02°, 153 s/step, scanning from 3 to 105° 2θ) at the NAP Geoanalítica Laboratory of the University of São Paulo. Qualitative and quantitative mineralogical analyses were performed with *Match!* and *FullProf* software, using the Crystallographic Open Database (Grazulis et al., 2009). Crystallographic data for the mineral phases were taken from Pokroy et al. (1989) for aragonite and from Paquette and Reeder (1990) for calcite. Mineralogical results of TRA7 and FN1 were obtained by Utida et al. (2020) using the same method. All results are presented in weight proportion (wt %). The $\delta^{18}O$ results of speleothems were calibrated according to the percentage of calcite identified for the interval applying the aragonite–calcite fractionation offset of 0.85‰ ± 0.29‰ (Zhang et al., 2014). The $\delta^{13}C$ results were not corrected because the original aragonite–secondary calcite fractionation factor is negligible (~0.1-0.2‰) (Zhang et al., 2014). Even considering the original aragonite-original calcite mean fractionation factor of 1.1‰ (Zhang et al., 2015), the range of $\delta^{13}C$ RN stalagmites is very large (>8‰) and the correction would not affected the main interpretation.

The intra-site correlation model (*iscam*) was used to construct a composite record (Fohlmeister, 2012). It combined the climate records to obtain a unique age model and oxygen isotopic record, corrected only for mineralogical composition for speleothems from Rio Grande do Norte, which here is referred to as the RN Composite. The age-depth modeling software was adjusted to calculate 1000 Monte-Carlo simulations on absolute age determinations to find the best correlation between oxygen isotope records from Trapiá and Furna Nova speleothems, reproducing adjacent archives. The results estimate the error of the age-depth model by indicating the 68%, 95% and 99% confidence intervals obtained from evaluation of a set of 2000 first order autoregressive processes (AR1) for each record. This method allows significantly reducing the age uncertainty within the overlapping periods and it can be tested if the signal of interest is indeed similar in all the records (Fohlmeister, 2012). The age data were assumed to have a Gaussian distribution and were calculated

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

pointwise. The composite result was detrended and normalized, according to the *iscam* method. The performance of the *iscam* results is affected by low quality of chronological control, low resolution and hiatuses. Therefore, the following intervals were removed from the stalagmite records before constructing the RN Composite: FN1 0-12 mm and 187-202 mm, FN2 0-6 mm, TRA5 0-37mm and TRA7 222-227 mm. In addition, the FN1 record was divided into two portions: FN1a 12.14-136.99 mm and FN1b 140.15-186.87 mm that are separated by a hiatus. The chronological age-depth relationship in the overlapping parts of the individual stalagmites was modified and improved according to the *iscam* results of the composite record.

4. Results

4.1. Chronology and mineralogy

The RN record covers the last 5000 years, four stalagmites cover the last 3250 years, and two of these stalagmites cover partially between 3000 and 1260 Before Common Era (BCE), with the exception of one hiatus at 2100 -1720 years BCE (Fig 3, Table S1 and S2).

Stalagmite TRA7 from Trapiá Cave was deposited from 3000 to 2180 BCE (Fig S4) with a low deposition rate (DR) of approximately 0.05 mm/yr. After a hiatus of 1880 years, it resumed deposition from at 300 BCE until 1940 CE with a DR of 0.18 mm/yr. The TRA5 stalagmite deposition occurred continuously from 1490 to 1906 CE (Fig S4) with a DR of 0.33 mm/yr.

Stalagmite FN1 from Furna Nova was deposited over the last 3,600 years, with a hiatus from 125 to 345 BCE and another one of approximately 100 years between 1525 and 1662 CE (Fig S4), with an average DR of 0.09 mm/yr. The FN2 stalagmite deposited continuously from 1226 BCE to 7 CE, except for a hiatus between 189 and 45 BCE (Fig S4) with a DR of 0.20 mm/yr.

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

The mineralogy of the stalagmites from Trapiá Cave is formed by layers of crystals with mosaic and columnar fabrics, composed exclusively of calcite, except for the base portion of TRA7 from 173 to 270 mm (3,000 BCE to 130 CE), which is described as an interbedded needle-like crystals texture, composed of 87.1 to 99% of aragonite (Fig S2, Table S3). The same needle-like morphology is present in most of the Furna Nova Cave stalagmites, composed of aragonite with a weight proportion greater than 85% in FN1, extending from 0 to 83 mm (160 to 1,340 CE) and from 128 to 183 mm (1,730 BCE to 80 CE). In the FN2 sample this weight proportion is greater than 93.4% (1265 BCE to 35 CE). The only interval composed of 100% calcite is from 95 to 125 mm in FN1 (Fig S3, Table S3). These speleothem samples show no sign of dissolution or recrystallization.

4.2. Stalagmite $\delta^{18}O$ and $\delta^{13}C$

The oxygen isotope ratios of the RN record vary from 0.6‰ to -4.5‰, with mean values for each speleothem of -2.8‰ for TRA7, -3.5‰ for TRA5, -2.4‰ for FN1 and -1.5‰ for FN2. Similarities among the stalagmites are evident, especially around 1500 CE when $\delta^{18}O$ values abruptly decrease in TRA7 and TRA5, while in FN2 this period features a hiatus.

These values were slightly changed by the correction for aragonite–calcite fractionation ($\delta^{18}O_{C-A}$) (Zhang et al., 2014), according to their aragonite weight proportion (Table S3, Fig 3b). The isotopic correction due to mineralogy for the stalagmites from Furna Nova Cave resulted in changes of less than 0.1‰ of their mean values. The mean correction for TRA7 equals an enrichment of 0.5‰ during the first 1800 years. Values from TRA5 were corrected along the entire sample by adding 0.85‰, as it is composed of 100% calcite. Therefore, the mean values increased from -3.5‰ to -2.7‰.

Four main phases describe the $\delta^{13}C$ dataset (Fig 3a). The oldest phase from 3000 to 2160 BCE is characterized by $\delta^{13}C$ values close to zero. After a hiatus (2170-1270 BCE)

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions

there is a short interval of stability with $\delta^{13}C$ values around -4‰ that lasts from 1270 to 840 BCE and is followed by a $\delta^{13}C$ enrichment that reaches a value of zero at 30 CE. Between 30 and 1500 CE there is a trend toward more negative $\delta^{13}C$ values, varying from 0 to -8.8‰. This interval is marked by a valley at 190 CE with $\delta^{13}C$ values of -7.2‰ and a peak at 1000 CE with $\delta^{13}C$ values of 0.22‰. The youngest period, from 1500 to 1930 CE is more stable than the previous one, with $\delta^{13}C$ values averaging around - 6.4‰.

4.3. Composite

Combining the $\delta^{18}O$ results from the four RN stalagmites allows establishing a continuous record covering the last ~3200 years, the RN Composite (Fig 4). The correlation coefficient (r) between each measured $\delta^{18}O$ stalagmite time series is >0.59, significant at the 95% level (Fig S5). The composite provides an average temporal resolution of ~2 years. The entire stable isotope time series is composed of 2495 $\delta^{18}O$ measurements, corrected according to mineralogical composition.

5. Discussion

5.1. Paleoclimate interpretation

The $\delta^{18}O$ RN Composite allowed us to reconstruct precipitation changes influenced by the ITCZ position in N-NEB and its convective intensity. This interpretation is based on the spatial correlation between $\delta^{18}O$ at GNIP stations and GPCC precipitation (Fig 2). Highest precipitation amounts occur between March and May and they coincide with more depleted $\delta^{18}O$ precipitation signals, consistent with the amount effect (Dansgaard, 1964).

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions
Open Access
EGU

Hence, the most negative $\delta^{18}O$ values in RN stalagmites reflect an increased rainfall amount, as a consequence of ITCZ position close to N-NEB (Cruz et al., 2009; Utida et al., 2019).

A generally drier climate prevailed in NEB after the 4.2 ky BP (Before Present) event in the Mid-Holocene, which led to the development of a sparse vegetation cover, the Caatinga (De Oliveira et al., 1999; Utida et al., 2020; Chiessi et al., 2021). These conditions favored soil erosion during rainfall events and reduced soil thickness (Utida et al., 2020). When erosion events remove most of the soil cover, there is an increase in the carbon contribution from local bedrock (mean $\delta^{13}C$ of 0.5 ‰), which leads to higher $\delta^{13}C$ values in the stalagmites (Utida et al., 2020). On the other hand, more negative $\delta^{13}C$ values in stalagmites are associated with increased soil coverage and soil production. In NEB soils have a $\delta^{13}C$ average around -25 ‰, which suggests a dominant influence from C3 plants with $\delta^{13}C$ values ranging between -32‰ and -20‰ (Pessenda et al., 2010). Therefore, the $\delta^{13}C$ stalagmite results are interpreted as changes in soil production/erosion and the density of vegetation coverage (e.g., Utida et al., 2020; Azevedo et al., 2021; Novello et al.,2021).

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions

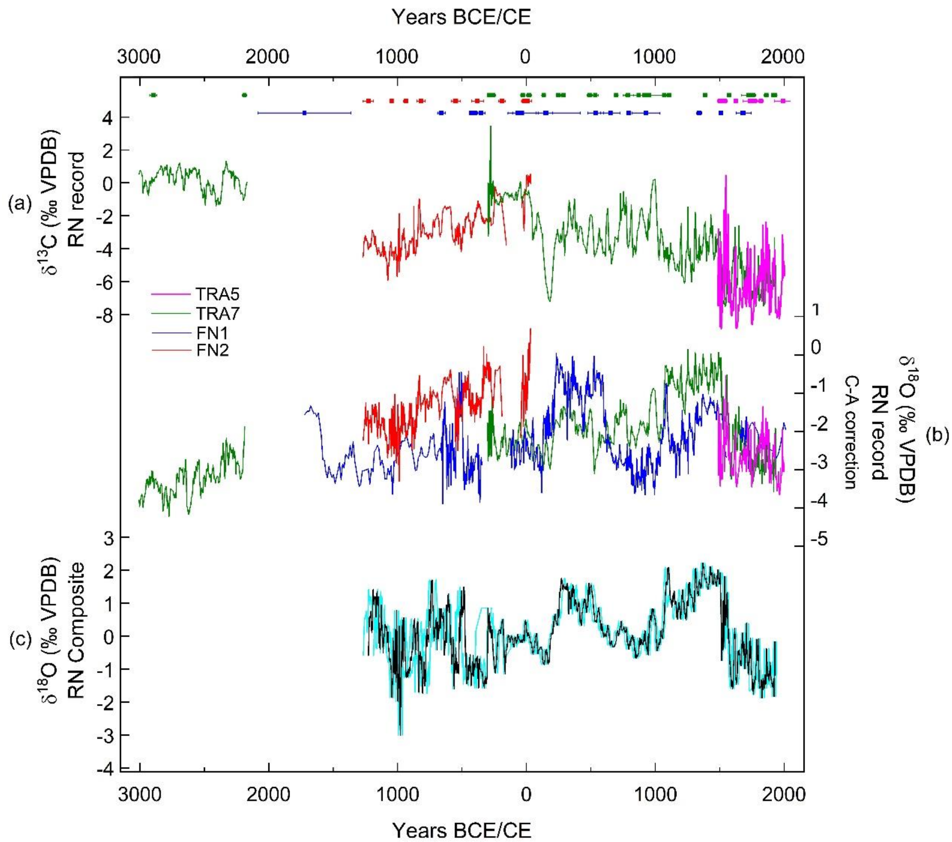


Figure 3 – Rio Grande do Norte stalagmite isotope record. a) Raw data of δ^{13}C. (b) Oxygen isotope results corrected for calcite-aragonite fractionation ($\delta^{18}O_{C\text{-}A}$), according to weight proportion of mineralogical results. c) δ^{18}O composite constructed using stalagmite records from NEB (black line). Cyan lines denote the age model confidence interval of 99%. Dots with error bars are U/Th ages of each stalagmite, according to their color.

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions

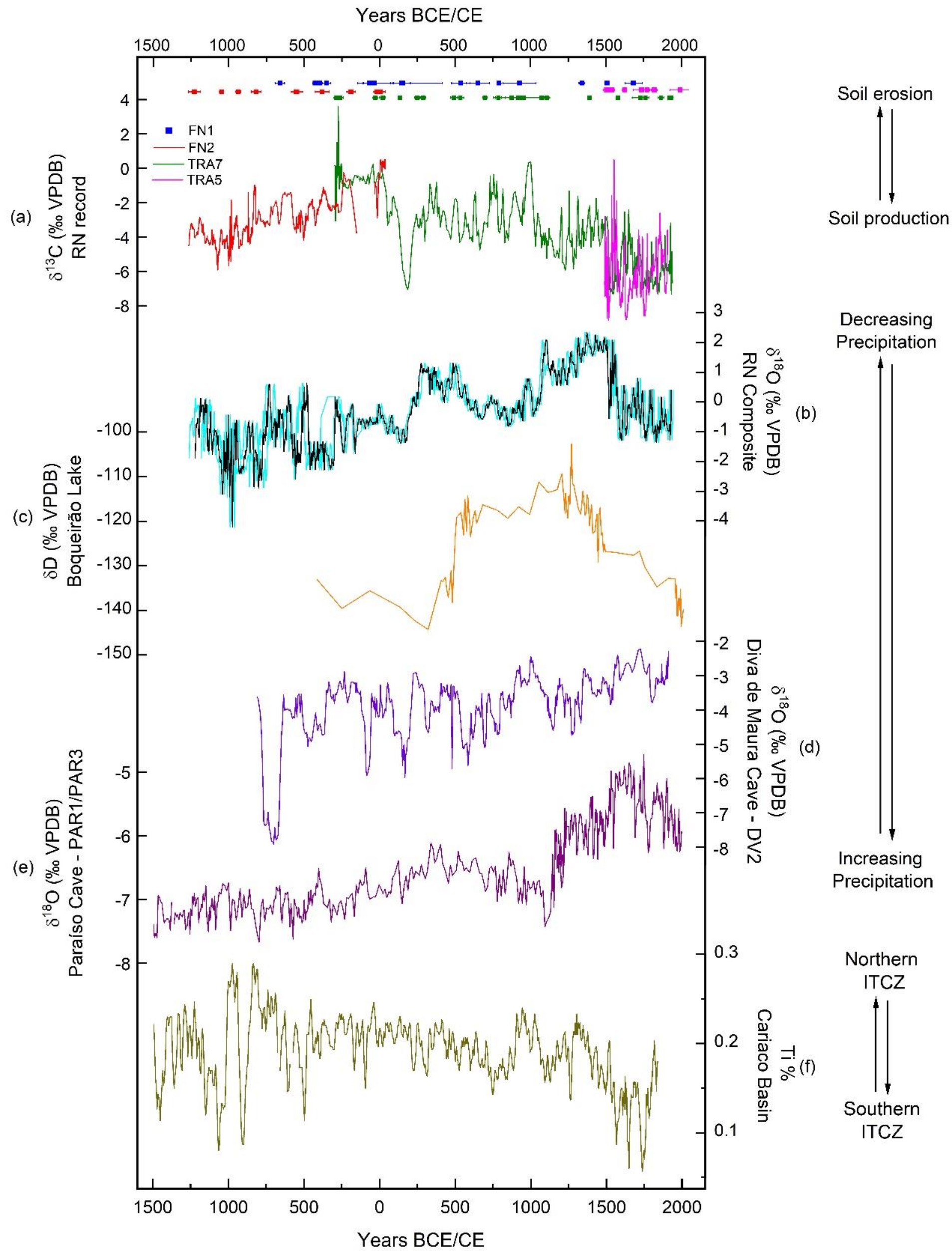


Figure 4 – Comparison of a composite record of: a) carbon isotope ratios and b) oxygen ratios obtained from RN stalagmites. Cyan lines denote confidence interval of 99%. Colored squares are speleothem U/Th age results. c) Boqueirão Lake δD record (Utida et

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past Discussions

al., 2019). d) DV2 speleothem oxygen isotope record from Diva de Maura cave, southern NEB (Novello et al., 2012). e) PAR01 and PAR03 $\delta^{18}O$ records from Paraíso cave, eastern Amazon (Wang et al., 2017). f) Ti record of Cariaco Basin (Haug et al., 2001).

The oldest period covered by the RN Composite, from 1060 to 480 BCE, reflects increased precipitation in N-NEB as suggested by negative $\delta^{18}O$ anomalies during most of this period, although a tendency from lower to higher $\delta^{13}C$ values is observed, possibly led by surface soil erosion (Fig 4). This period is also characterized by successive dry and wet multidecadal periods that could favor soil production but did not contribute much to the carbon isotopic composition of speleothems because it was eroded during drier years, as described in Utida et al. (2020). The association of erosion processes with $\delta^{13}C$ is rather clear from 480 BCE to 0 CE when their values reach the bedrock signature at about -1‰ to +1‰, which was caused by intense ITCZ rainfall as suggested by the more negative values of $\delta^{18}O$. During the following period, the $\delta^{13}C$ values are slightly more negative but still high from 200 CE to 1500 CE, when the climate was mostly dry. This relationship is contrary to what is observed in the last 500 years, during the period equivalent to the Little Ice Age (LIA) (here from 1500 to 1800 CE) and in the last two centuries, that is marked by very negative values of $\delta^{13}C$ in response to wet climatic conditions as indicated by lower $\delta^{18}O$ values. The more negative $\delta^{13}C$ during the LIA are probably related to denser vegetation that favored both soil production and stability above the cave. Due to the high range of $\delta^{13}C$ results (more than 11‰), we assumed that the Prior Calcite Precipitation effect would be negligible in our results. In addition, the more positive $\delta^{13}C$ signal occur around 280 BCE when the climate conditions were not the driest in the last 5000 years.

During the last 2500 years, the RN Composite shows similar characteristics as the lower-resolution δD lipids obtained in Boqueirão Lake sediments (Fig 1 and 4). From 500 to

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

1500 CE, enriched δD lipids obtained in Boqueirão Lake sediments (N-NEB) were interpreted as the beginning of a long dry phase (Utida et al., 2019), although the beginning of the dry period is slightly delayed when compared with the RN speleothem isotope record. This difference might be related to a strong influence of eolian and fluvial sedimentary dynamics in Boqueirão Lake. Furthermore, the later location might also be affected by different climatic conditions given its location in the eastern coastal sector of NEB (Zular et al., 2018; Utida et al., 2019).

It is important to note that the RN record exhibits a climatic signal that is distinctly different from the from DV2 speleothem record from Diva de Maura Cave in S-NEB (Novello et al., 2012). The general trend toward more positive values seen in both stalagmites, resulting from insolation forcing (Cruz et al., 2009; Novello et al., 2012), explains the persistent dry conditions in the entire NEB region since 4.2 BP. However, the DV2 record does not document the same multidecadal and centennial-scale climate variability as recorded in the RN speleothem record (Fig 4). As demonstrated by the spatial correlation maps between δ^{18}O values and regional precipitation (Fig 2), the S-NEB and N-NEB regions are influenced by distinct rainfall regimes whose peaks of precipitation arise during the summer monsoon season and the autumn ITCZ, respectively. Our data provide evidence for this interpretation of differences in seasonality in northeastern Brazil during the last millennia.

When considering conditions over the eastern Amazon, we see that the RN Composite shares some similarities with the Paraiso stalagmite record, but there are also important differences (Wang et al., 2017) (Fig 4). From the δ^{18}O peak around 250 CE to the end of the drought period near 1500 CE, precipitation in both areas seems to share many similar characteristics, assumed to be mostly driven by the ITCZ (Fig. 1). However, during the event around 1100 CE, centered in the Medieval Climate Anomaly (MCA), and the period from 1500 to 1750 CE, Paraiso is antiphased with the RN record and in phase with the

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Cariaco Basin (Haug et al., 2001), which suggests a zonal behavior of precipitation shifts in the ITCZ domain. Even though the Paraiso and Cariaco sites are located in different hemispheres, the observed in-phase climate relationship during the LIA suggests that their isotopic signatures were both sensitive to the same rainfall changes over northern South America (Fig 2).

The Bond 2 Event is recorded in the RN Composite, marked by increased precipitation around 1000 BCE, when the ITCZ was displaced toward the south. This southerly ITCZ displacement might be attributed to persistent lower temperatures in the North Atlantic (Bond et al., 2001; Broccoli et al., 2006) caused by the slowdown of the Atlantic Meridional Overturning Circulation (Jackson et al., 2015).

There is a relationship between the $\delta^{18}O$ values in our RN speleothems and Atlantic Multidecadal Variability (AMV) (Lapointe et al., 2020), which reinforces the idea of an ITCZ displacement toward the warmer hemisphere (Fig 5). Studies suggest that warm AMV forces the ITCZ to shift meridionally (Knight et al., 2006, Levine et al., 2018), while model simulations also suggest weakening of ITCZ from February to July during warm AMV (Maksic et al., 2022). Although there are some decoupling intervals between our results and the AMV during the last two millennia, the driest periods from 200 to 580 CE and 1100 and 1500 CE occurred during long relatively warm AMV anomalies which would force a northward ITCZ displacement and low precipitation variability over NEB.

Analyzed observed precipitation anomaly patterns during the mean states defined by the overlapping periods of AMV and Pacific Decadal Variability (PDV) show that dry conditions over N-NEB and eastern Amazon are present when both AMV and PDV are in warm phases, or when AMV is cold and PDV is in warm phases (Kayano et al., 2020, 2022). On the other hand, when AMV and PDV are both in cold phase, precipitation over Amazon is anti-phased with NEB, resulting in decreased precipitation over the Amazon and increased precipitation over NEB. Our analysis corroborates with this and points to

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

increasing precipitation over N-NEB and decreasing precipitation over eastern Amazon, between 1500 and 1750 CE, when both AMV and PDV are in cold phase (Fig 4). This sign reversal is assigned to perturbations of the regional Walker cell's produced by teleconnection between the Atlantic and Pacific (Kayano et al., 2022, He et al., 2021).

Steinmann et al. (2022), suggested a southward displacement of the ITCZ during the Common Era toward the southern hemisphere in response to changes in the Pacific and Atlantic meridional SST gradients. Indeed, our RN Composite is dynamically consistent with these SST gradient changes and in agreement with the hypothesis of a north-south oscillation of the latitudinal ITCZ position in the tropical Atlantic during the last millennia, modulating precipitation over N-NEB. When the tropical South Atlantic and tropical eastern Pacific are anomalously warm (cold) the ITCZ is displaced to the south (north), resulting in increasing (decreasing) precipitation over NEB, as observed during the LIA (Fig 5). The abrupt changes in N-NEB precipitation around 1100 and 1500 CE occur approximately synchronous with the SST gradient changes, confirming how sensitive the RN speleothems respond to changes in the ITCZ latitudinal position (Fig 5). According to Steinmann et al. (2022), during the LIA period warm SST in the eastern tropical Pacific and in the tropical South Atlantic would promote a southward displacement of the ITCZ. This is supported by other records from the western Amazon and the tropical Andes that document an intensified SASM during the LIA, fueled by the southern location of the ITCZ (e.g., Vuille et al., 2012; Apaéstegui et al., 2018), which is also very well recorded in other archives around the tropics (Leichleitner et al., 2017; Campos et al., 2019; Orrison et al., 2022; Steinmann et al., 2022).

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past
Discussions

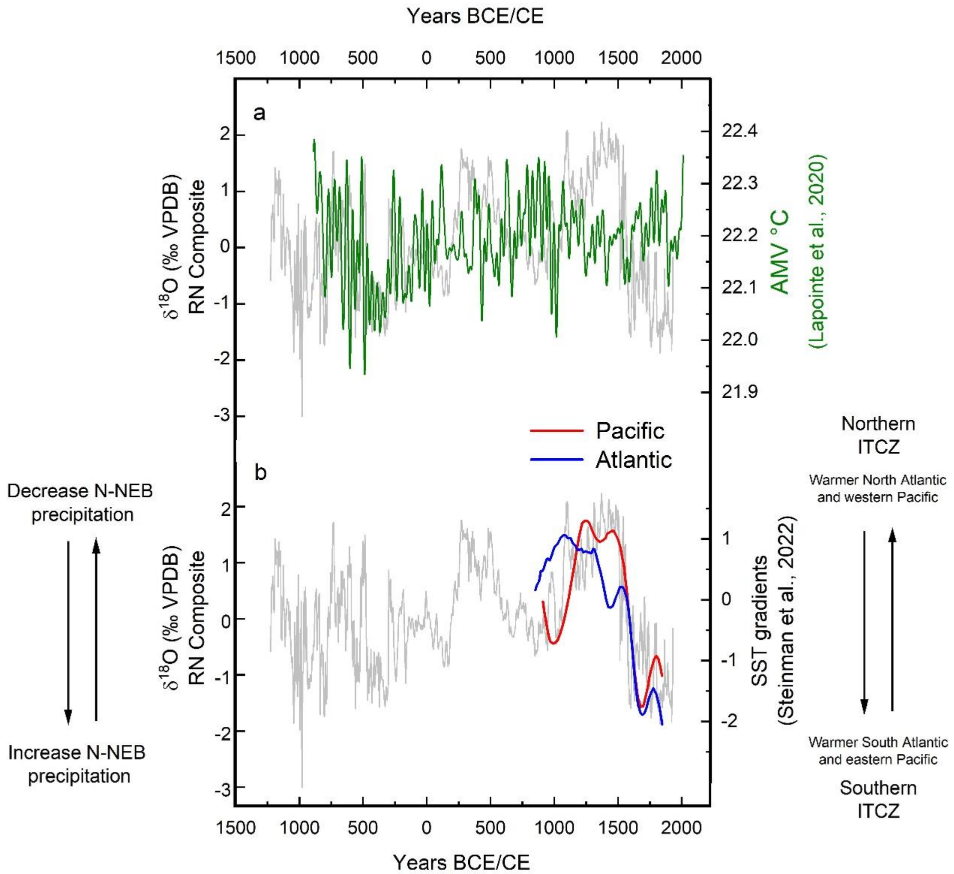


Figure 5 - δ^{18}O RN Composite compared with (a) Atlantic Multidecadal Variability (Lapointe et al., 2020) and (b) Pacific and Atlantic Sea Surface Temperature gradients calculated according to Steinman et al. (2022). Atlantic: 2σ range of 1,000 realizations of the Atlantic meridional SST gradient (north – south). Pacific: median of 1,000 realizations of the Pacific zonal SST gradient (west – east).

5.2. The use of RN δ^{18}O as a recorder of extreme dry events

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

In NEB, the low water availability has been one of the major challenges faced by its people during the last centuries (Marengo and Bernasconi, 2015; Marengo et al., 2021; Lima and Magalhães, 2018). On the other hand, the last 500 years were the wettest of the last two millennia, according to our results (Fig 4). Superimposed on these long-term negative $\delta^{18}O$ anomalies, distinct peaks are recorded in the higher resolution TRA5 $\delta^{18}O$ record from 1500 to 1850 CE (Fig 6). The highest peaks correspond to extreme drought events, such as the ones centered around 1546 and 1564 CE (points 1 and 2 of Fig 6). They can be associated with observed historical droughts that took place in 1553 and 1559 CE. These were the first two events recorded in Brazil by the Portuguese Jesuits that led to a reported reduction in riverflow in the tributaries of the main rivers of NEB (Serafim Leite, 1938; Hue et al., 2006; Lima and Magalhães, 2018).

Another relevant drought according to TRA5 is centered around 1620 CE (point 3 of Fig 6). This drought is recorded in historical documents and lasted from 1614 to 1615 CE, although it did not have the same socioeconomic impact as the two prior droughts (Lima and Magalhães, 2018). In fact, from the middle of the 16th to the middle of the 17th century there are few historical drought records (point a of Fig 6). One hypothesis to explain this hiatus is the low population density of the NEB territory, resulting in poor historical documentation of such events. However, according to the TRA5 record, between the event 2 ~1564 CE and event 4 ~1717 CE (Fig 6), the only drought peak occurs in 1620 CE, confirming an almost 150-year long period of relative climate stability with prevailing wet conditions in NEB. These favorable conditions certainly helped with the initial population establishment at the beginning of 16th century, and led to the peak era of sugar cane production in NEB around 1650 CE along coastal areas (Taylor, 1970).

During the 18th century NEB experienced a significant increase in rural population, characterized by the establishment of large cattle farms (Fausto, 2006). In this period, three droughts are documented in the TRA5 record (Fig 6). The $\delta^{18}O$ excursion around 1717 CE (point 4 in Fig 6) can be associated with the drought that lasted from 1720 to 1727 CE; the first big drought in NEB, which according to historical documents, caused the mortality of wildlife and cattle, and affected the agricultural productivity. Entire indigenous tribes died of starvation as a consequence of this drought and a related smallpox (variola) epidemic, which also killed other ethnic groups, especially the native population and black people enslaved during that period (Alves, 1929).

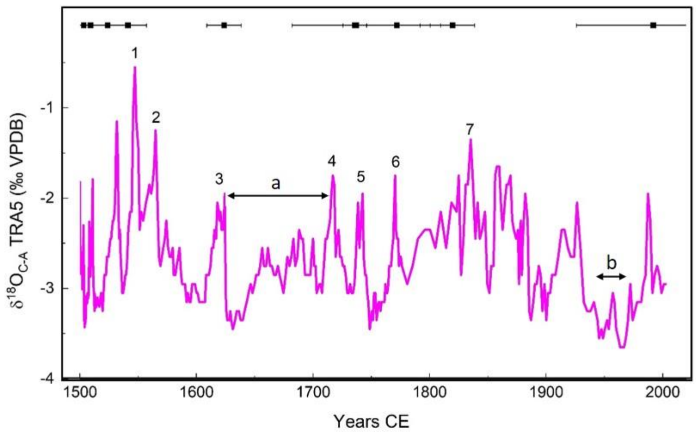
The following event around 1740 CE (point 5 in Fig 6) was also recorded in historical documents, but did not seem to be associated with major impacts. However, all of these droughts were probably responsible for a drop in sugar-cane exports to Europe during the first half of the 18th century (Galloway, 1975).

Another drought occurred from 1776 to 1778 CE, and is imprinted in our record around 1770 CE (point 6 in Fig 6). This event was again accompanied by a variola outbreak probably spread by lowering in sanitary conditions and increased people agglomeration. The association between this disease and droughts might explain the economic and health crisis, since people started to migrate to the cities looking for treatment and food, leading the Governor to transfer infected people to isolated lands, resulting in thousands of deaths (Rosado, 1981). Finally, the most recent peak in our data displays an event around 1835 CE (point 7 of Fig 6), associated with a drought that lasted from 1833 to 1835, reaching the northernmost areas of NEB, and leading to the largest human migration to other Brazilian regions (Lima and Magalhães, 2018).

Our TRA5 stalagmite data record some of the most important droughts that occurred in NEB between the 16th and the 18th centuries, demonstrating the potential of stalagmite studies in monitoring abrupt and extreme climate events through time. However, the speleothems do not record all documented historical dry events, as some droughts may not have affected the Trapiá Cave region or they were not strong or long enough to affect the isotopic signal of the groundwater storage in the epikarst.

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Although the TRA5 speleothem chronology is not so precise during the last ~150 years, we observe that the wet period from 1940s to 1970s (point b of Fig 6) is coincident with the mid-20th Century break in global warming that has been discussed to be forced by aerosol emissions (e.g., Booth et al., 2012; Undorf et al., 2018). Our data suggest an increased precipitation in this period that is supported by a trend in decreasing values of $\delta^{18}O$ in corals from the northeast coast of N-NEB that is interpreted as an ITCZ southward displacement caused by decreasing SST gradient between North and South Atlantic (Pereira et al., 2022).



NEB Drought events (yr CE)

#Event	Historical	TRA5
1	1553	1546
2	1559	1564
3	1614-1615	1620
4	1720-1727	1717
5	1744-1748	1740
6	1776-1778	1770
7	1835-1833	1835

Figure 6 – $\delta^{18}O_{C-A}$ record from TRA5 speleothem and its U/Th ages and errors represented by black dots and lines at the top of the graph. The numbers in the graph represent the occurrence of historical drought years compiled from Lima and Magalhães (2018). a - middle of the 16th to the middle of the 17th century. b - 1940s to 1970s period.

6. Conclusions

We present the first high-resolution record for the ITCZ in N-NEB that covers the last 3200 years and also records the major historical droughts that took place in NEB during the

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

last 500 years. Based on two distinct proxies, we describe the regions' paleoclimate variability for the last 2500 years and its connections to remote forcing mechanisms such as the AMV and changes in Pacific and Atlantic SST gradients.

The N-NEB record presents a trend toward drier conditions as is also being observed in the Diva de Maura Cave in S-NEB, interpreted as an ITCZ withdrawal and SASM weakening, respectively. These data suggest a trend toward increased aridity over NEB from 3000 BP to the present, although the two records are influenced by distinctly different climate systems with different precipitation seasonality.

During the last millennia, ITCZ dynamics in the tropical Atlantic – South America sector cannot be explained solely by north-south ITCZ migrations or one single forcing mechanism. We propose a zonally non-uniform behavior of the ITCZ during the event centered around 1100 CE and the drought period between 1500 and 1750 CE, when the RN record is anti-phased with the Paraiso cave record from the eastern Amazon. This zonal behavior would be forced by the interactions between AMV and PDV modes that changed the regional Walker cell position and ITCZ intensity/width and thus affecting precipitation variability between eastern Amazon and N-NEB.

The historical droughts recorded in the RN stalagmite suggest that much of the socioeconomic development of the NEB, which occurred after 1500 CE, benefitted from conditions that were unusually humid in a long-term context. During the last 500 years the technological development, infrastructure, civilization and population growth relied on more abundant resources. On the other hand, our data also shows how short, abrupt drought events significantly affected human population and other life forms, especially when associated with anthropogenic changes in the environment. These droughts induced an environment favorable for spreading of disease, starvation, lack of water, environmental degradation and crowding of people seeking help, among other problems. These events demonstrate the social and environmental impacts associated with extreme events in this vulnerable environment and our speleothem work documents the enormous potential of these archives to reconstruct the drought history in this region.

Acknowledgments

We thank Alyne Barros M. Lopes, Osmar Antunes and Christian Millo (LES-IGc-USP, Brazil) for their support during the analyses. We thank M.E.D.-L.G, J.C.R., E.A.S.B, V.A. and W.D. for their support in U/Th analysis. We are grateful to Leda Zogbi and Diego de Medeiros Bento for the Trapiá cave and Furna Nova maps. We thank Jocy Brandão Cruz, Diego de Medeiros Bento, José Iatagan Mendes de Freitas, Darcy José dos Santos, Uilson Paulo Campos (CECAV/RN), Antônio Idaelson do Nascimento and Geilson Góes Fernandes for all support in the field trip, information and data about the caves. This work was supported by the FAPESP, Brazil through PIRE NSF-FAPESP [2017/50085-3 to F.W.C], as well as the fellowships to G.U. [2020/02737-4], V.F.N [2016/15807-5], J.M. [2018/23522-6] and A.A. [2020/09258-4]. The NSF, United States support through grants [AGS-1303828 and OISE-1743738] to MV and 1103403 to R.L.E and H.C. is acknowledged. The NSFC, China support through grant [NSFC 41888101] to H.C. and [NSFC 42261144753] to H.Z. is acknowledged, G.U. is grateful to CAPES for the PhD and PosDoc fellowships through the Programa de Pós-Graduação em Geoquímica e Geotectônica at Universidade de São Paulo, Brazil.

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

References

Alvalá, R.C.S., Cunha, A.P.M.A., Briton, S.S.B., Seluchi, M.E., Marengo, J.A., Moraes, O.L.L., Carvalho, M.A.: Drought monitoring in the Brazilian Semiarid region, An. Acad. Bras. Ciênc., 91 (1), e20170209, https://doi.org/10.1590/0001-3765201720170209, 2019.

Alves, J.: História das secas (século XVII a XIX). Fundação Waldemar Alcântara, Fortaleza, https://colecaomossoroense.org.br/site/wp-content/uploads/2018/07/HIST%C3%93RIA-DAS-SECAS.pdf, last access: 22 March 2022. 2003.

ANA – Agência Nacional de Águas, Sistema Nacional de Informações sobre Recursos Hídricos: http://www.snirh.gov.br/hidroweb/apresentacao, last access: 01 February 2022, 2013.

Andreoli, R. F. S., de Souza, R.A.F., Kayano, M.T., Candido, L.A.: Seasonal anomalous rainfall in the central and eastern Amazon and associated anomalous oceanic and atmospheric patterns, Int. J. Climatol., 32, 1193–1205, https://doi.org/10.1002/joc.2345, 2011.

Apaéstegui, J., Cruz, F.W., Vuille, M., Fohlmeister, J., Espinoza, J.C., Sifeddine, A., Strikis, N., Guyot, J.L., Ventura, R., Cheng, H., Edwards, R.E.: Precipitation changes over the eastern Bolivian Andes inferred from speleothem ($\delta^{18}O$) records for the last 1400 years, Earth Planet. Sci. Lett., 494, 124–134, https://doi.org/10.1016/j.epsl.2018.04.048, 2018.

Araújo, R.G., Andreoli, R.V., Candido, L.A., Kayano, M.T., de Souza, R.A.F.: Influence of El Niño-Southern Oscillation and Equatorial Atlantic on rainfall over northern and northeastern regions of South America, Acta Amaz., 43, 4, 469-480, https://doi.org/10.1590/S0044-59672013000400009, 2013.

Azevedo, V., Strikis, N.M., Novello, V.F., Roland, C.L., Cruz, F.W., Santos, R.V., Vuille, M., Utida., G., de Andrade, F.D., Cheng, H., Edwards, R.L.: Paleovegetation seesaw in Brazil since the Late Pleistocene: A multiproxy study of two biomes, Earth Planet. Sci. Lett., 563, 116880, https://doi.org/10.1016/j.epsl.2021.116880, 2021.

Bond, G., Kromer, B., Beer, Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G.: Persistent Solar Influence on North Atlantic Climate During the Holocene, Science, 294, 2130-2136, https://doi.org/10.1126/science.1065680, 2001.

Booth, B.B.B., Dunstone, N.J., Halloran, et al., P.R., Andrews, T., Bellouin, N.: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability, Nature, 484, 228-232, https://doi.org/10.1038/nature10946, 2012.

Breitenbach, S.F.M., Rehfeld, K., Goswami, B., Baldini, J.U.L., Ridley, H. E., Kennett, D. J., Prufer, K.M., Aquino, V.V., Asmerom, Y., Polyak, V.J., Cheng, H., Kurths, J., Marwan, N.: COnstructing Proxy Records from Age models (COPRA), Clim. Past, 8, 1765–1779, https://doi.org/10.5194/cp-8-1765-2012, 2012.

Broccoli, A. J., Dahl, K.A., Stouffer, R.J.: Response of the ITCZ to Northern Hemisphere cooling, Geophys. Res. Lett., 33, L01702, https://doi.org/10.1029/2005GL024546, 2006.

Campos, J.L.P.S., Cruz, F.W., Ambrizzi, T., Deininger, M., Vuille, M., Novello, V.F., Strikis, N.M.: Coherent South American Monsoon Variability During the Last Millennium Revealed Through High-Resolution Proxy Records, Geophys. Res. Lett., 46, 8261–8270, https://doi.org/10.1029/2019GL082513, 2019.

Cheng, H., Edwards, R.L., Shen, C-C., Polyak, V.J., Asmerom, Y., Woodhead, J., Hellstrome, J., Wang, Y., Kong, X., Spötlg, C., Wang, X., Alexander Jr. E.C.: Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values and U-Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry, Earth Planet. Sci. Lett., 371-372, 82-91, https://doi.org/10.1016/j.epsl.2013.04.006, 2013.

Chiessi, C. M., Mulitza, S., Taniguchi, N.K., Prange, M., Campos, M.C., Häggi, C., Schefuß, E., Pinho., T.M.L., Frederichs, T., Portilh-Ramos, R.C., Souza, S.H.M., Crivellari, S., Cruz, F.W.: Mid- to late-Holocene contraction of the Intertropical Convergence Zone over northeastern South America, Paleocean. Paleoclim., 36, e2020PA003936, https://doi.org/10.1029/2020PA003936, 2021.

Cruz, F.W., Vuille, M., Burns, S.J., Wang. X., Cheng, H., Werner, M., Edwards, R.L., Karman, I., Auler, A.S., Nguyen, H.: Orbitally driven east-west antiphasing of South American precipitation, Nat. Geosci., 2, 210-214, https://doi.org/10.1038/ngeo444, 2009.

Dansgaard, W.: Stable isotopes in precipitation, Tellus XVI, 4, 436-468, https://doi.org/10.1111/j.2153-3490.1964.tb00181.x, 1964.

De Oliveira, P.E., Barreto, A.M.F., Suguio, K.: Late Pleistocene-Holocene climatic and vegetational history of the Brazilian Caatinga: the fossil dunes of the middle São Francisco River, Palaeogeogr. Palaeoclimatol. Palaeoecol., 152, 319-337, https://doi.org/10.1016/S0031-0182(99)00061-9, 1999.

Della Libera, M.E., Novello, V.F., Cruz, F.W., Orrison, R., Vuille, M., Maezumi, S.Y., de Souza, J., Cauhy, J., Campos, J.L.P.S., Ampuero, A., Utida., G., Stríkis, N.M., Stumpf, C.F., Azevedo, V., Zhang, H., Edwards, R.L., Cheng. H.: Paleoclimatic and paleoenvironmental changes in Amazonian lowlands over the last three millennia, Quat. Sci. Rev., 279, 107383, https://doi.org/10.1016/j.quascirev.2022.107383, 2022.

Erasmi, S., Maurer, F., Petta, R.A., Gerold, G., Barbosa, M.P.: Interannual variability of the Normalized Difference Vegetation Index over Northeast Brazil and its relation to rainfall and El Niño Southern Oscillation, Geo-Öko, 30, 3-4, 185-206, 2009.

Fausto, B.: História do Brasil, 12th ed., Editora Universidade de São Paulo, São Paulo, 660 pp., ISBN 85-314-0240-9, 2006.

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past Discussions

Fohlmeister, J.: A statistical approach to construct composite climate records of dated archives, Quat. Geochronol., 14, 48-56, https://doi.org/10.1016/j.quageo.2012.06.007, 2012.

Galloway, J.H.: Northeast Brazil 1700-50: The agricultural crisis re-examined, J. Hist. Geogr., 1, 1, 21-38, https://doi.org/10.1016/0305-7488(75)90073-0, 1975.

Gomes, H.B., Ambrizzi, T., Herdies, D.L., Hodges, K., da Silva, B.F.P.: Easterly Wave Disturbances over Northeast Brazil: An Observational Analysis, Adv. Meteorol., 176238, https://doi.org/10.1155/2015/176238, 2015.

Grazulis, S., Chateigner, D., Downs, R.T., Yokochi, A.F.T., Quirós, M., Lutterotti, L., Manakova, E., Butkus, J., Moeck., P., Le Bail., A.: Crystallography Open Database – an open-access collection of crystal structures, J. Appl. Crystallogr., 42, 726-729, https://doi.org/10.1107/S0021889809016690, 2009.

Haug, G., Hughen, K.A., Sigman, D.M., Peterson, L.C., Röhl, U.: Southward migration of the Intertropical Convergence Zone through the Holocene, Science, 293, 5533, 1304-1308, https://doi.org/10.1126/science.1059725, 2001.

He, Z., Dai. A., Vuille, M.: The Joint Impacts of Atlantic and Pacific Multidecadal Variability on South American Precipitation and Temperature, J. Clim., 34, 7959-7981, https://doi.org/10.1175/JCLI-D-21-0081.1, 2021.

Hue, S. M.: Primeiras Cartas do Brasil 1551-1555: Introdução e notas, Jorge Zahar Editor, Rio de Janeiro, 147 pp., ISBN 8571109079, 2006.

IAEA/GNIP - Global Network of Isotopes in Precipitation, The GNIP Database, https://nucleus.iaea.org/wiser, last access: 20 August 2021.

INMET - Instituto Nacional de Meteorologia, Banco de Dados Meteorológicos para Ensino e Pesquisa, http://www.inmet.gov.br/, last access 5 November 2021.

Jackson, L. C., Kahana, R., Graham, T., Ringer, M.A., Woollings, T., Mecking, J.V., Wood, R.A.: Global and European climate impacts of a slowdown of the AMOC in a high

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

resolution GCM, Clim. Dyn., 45, 3299–3316, https://doi.org/10.1007/s00382-015-2540-2, 2015.

Kayano, M.T., Andreoli, R.V., de Souza, R.A.: Pacific and Atlantic multidecadal variability relations to the El Niño events and their effects on the South American rainfall, Int. J. Clim., 40(4), 2183-2200, https://doi.org/10.1002/joc.6326, 2020.

Kayano, M.T., Cerón, W.L., Andreoli, R.V., Souza, R.A.F., Avila-Diaz, A., Zuluaga, C.F., Carvalho, L.M.V.: Does the El Niño-Southern Oscillation Affect the Combined Impact of the Atlantic Multidecadal Oscillation and Pacific Decadal Oscillation on the Precipitation and Surface Air Temperature Variability over South America?, Atmos., 13, 231, https://doi.org/10.3390/atmos13020231, 2022.

Knight, J.R., Folland, C.K., Scaife, A.A.: Climate impacts of the Atlantic Multidecadal Oscillation, Geophys. Res. Let., 33, L17706, https://doi.org/10.1029/2006GL026242, 2006.

Lapointe, F., Bradley, R.S., Francus, P., Balascio, N.L., Abbott, M.B., Stoner, J.S., St-Onge, G., De Coninck, A., Labarre, T.: Annually resolved Atlantic Sea surface temperature variability over the past 2,900 y, PNAS, 117, 44, 27171–27178, https://doi.org/10.1073/pnas.2014166117, 2020.

Lechleitner, F. A., Breitenbach, S.F.M., Rehfeld, K., Ridley, H.E., Asmerom, Y., Prufer, K.M., Marwan, N., Goswami, B., Kennett, D.J., Aquino, V.V., Polyak, V., Haug, G.H., Eglinton, T.I., Baldini, J.U.L.: Tropical rainfall over the last two millennia: Evidence for a low-latitude hydrologic seesaw, Sci. Rep., 7, 45809, https://doi.org/10.1038/srep45809, 2017.

Lenters, J. D., Cook, K. H.: On the origin of the Bolivian High and related circulation features of the South American climate, J. Atmos. Sci., 54, 656–677, https://doi.org/10.1175/1520-0469(1997)054<0656:OTOOTB>2.0.CO;2, 1977.

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Levine, A.F.Z., Frierson, D.M.W., McPhaden, M.J.: AMO Forcing of Multidecadal Pacific ITCZ Variability, J. Clim., 31, 5749–5764, https://doi.org/10.1175/JCLI-D-17-0810.1, 2018.

Lima, J.R., Magalhães, A.R.: Secas no Nordeste: registros históricos das catástrofes econômicas e humanas do século 16 ao século 21, Parcer. Estratég., 23, 46, 191-212, 2018.

Maksic J., Shimizu, M.H., Kayano, M.T., Chiessi, C.M., Prange, M., Sampaio, G.: Influence of the Atlantic Multidecadal Oscillation on South American Atmosphere Dynamics and Precipitation, Atmos., 13, 11, 1778, https://doi.org/10.3390/atmos13111778, 2022.

Marengo, J.A., Bernasconi, M.: Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections, Clim. Chang., 129, 103-115, https://doi.org/10.1007/s10584-014-1310-1, 2015.

Marengo, J.A., Galdos, M.V., Challinor, A., Cunha, A.P., Marin, F.R., Vianna, M.S., Alvala, R.C.S., Alves, L.M., Moraes, O.L., Bender, F.: Drought in Northeast Brazil: A review of agricultural and policy adaptation options for food security, Clim. Resil. Sustain., 1, 17, https://doi.org/10.1002/cli2.17, 2021.

Melo, A.C.C., Castro, D.L., Bezerra, F.H.R., Bertotti, G.: Rift fault geometry and evolution in the Cretaceous Potiguar Basin (NE Brazil) based on fault growth models, J. South Am. Earth Sci., 71, 96-107, https://doi.org/10.1016/j.jsames.2016.07.006, 2016.

Novello, V.F., Cruz, F.W., Karmann, I., Burns, S.J., Stríkis, N.M., Vuille, M., Cheng, H., Edwards, R.L., Santos, R.V., Frigo, E., Barreto, E.A.S.: Multidecadal climate variability in Brazil's Nordeste during the last 3000 years based on speleothem isotope records, Geophys. Res. Lett., 39, L23706, https://doi.org/10.1029/2012GL053936, 2012.

Novello, V.F., Cruz, F.W., Moquet, J.S., Vuille, M., de Paula, M.S., Nunes, D., Edwards, R.L., Cheng, H., Karmann, I., Utida, U., Stríkis, N.M., Campos, J.L.P.S.: Two Millennia of South Atlantic Convergence Zone Variability Reconstructed from Isotopic Proxies, Geophys. Res. Lett., 45, https://doi.org/10.1029/2017GL076838, 2018.

Novello, V.F., Cruz, F.W., Vuille, M., Campos, J.L.P.S., Stríkis, N.M., Apaéstegui, J., Moquet, J.S., Azevedo, V., Ampuero, A., Utida, G., Wang, X., Paula-Santos, G.M., Jaqueto, P., Pessenda, L.C.R., Breecker, D.O., Karmann, I.: Investigating δ^{13}C values in stalagmites from tropical South America for the last two millennia, Quat. Sci. Rev., 255, 106822, https://doi.org/10.1016/j.quascirev.2021.106822, 2021.

Orrison, R., Vuille, M., Smerdon, J.E., Apaéstegui, J., Azevedo, V., Campos, J.L.P.S., Cruz, F.W., Della Libera, M.E., Stríkis, N.M.: South American Monsoon variability over the last millennium in paleoclimate records and isotope-enabled climate models, Clim. Past, 18, 2045–2062, https://doi.org/10.5194/cp-18-2045-2022, 2022.

Paquette, J., Reeder, R.J.: Single-crystal X-ray structure refinements of two biogenetic magnesian calcite crystals, Am. Mineral., 75, 1151-1158, 1990.

Pereira, N.S., Clarke, L.J., Chiessi, C.M., Kilbourne, K.H., Crivellari, S., Cruz, F.W., Campos, J.L.P.S., Yu, T.-L., Shen, C.-C., Kikuchi, R.K.P., Pinheiro, B.R., Longo, G.O., Sial, A.N., Felis, T.: Mid to late 20th century freshening of the western tropical South Atlantic triggered by southward migration of the Intertropical Convergence Zone, Palaeogeogr. Palaeoclimatol. Palaeoecol., 597, 111013, https://doi.org/10.1016/j.palaeo.2022.111013, 2022.

Pessenda, L.C.R., Gouveia, S.E.M., Ribeiro, A.S., De Oliveira, P.E., Aravena, R.: Late Pleistocene and Holocene vegetation changes in northeastern Brazil determined from carbon isotopes and charcoal records in soils, Palaeogeogr. Palaeoclimatol. Palaeoecol. 297, 597-608, https://doi.org/10.1016/j.palaeo.2010.09.008, 2010.

Pessoa-Neto, O.C.: Estratigrafia de sequências da plataforma mista neogênica na Bacia Potiguar, margem equatorial brasileira, Revista Bras. Geociênc., 33, 3, 263-278, 2003.

Pokroy, B., Fieramosca, J. S., Von Dreele, R. B., Fitch, A. N., Caspi, E. N., Zolotoyabko, E.: Atomic structure of biogenic aragonite, Chem. Mater., 19, 3244-3251, https://doi.org/10.1021/cm070187u, 1989.

Rosado, J. V.-U., (org): Memorial da Seca. Brasília, Coleção Mossoroense, nº 163, Centro Gráfico do Senado Federal/ESAM, https://colecaomossoroense.org.br/site/acervo-oswaldo-lamartine/, last access: 25 August 2022, 1981.

Sampaio, P.R.F., Saraiva Jr, J.C., Portela, J.C., da Silva, J.F.: Agricultural areas to desertification in RN and mitigating measures: the case of settlements Milagres and Terra da Esperança, HOLOS, 36, 7, e5902, https://doi.org/10.15628/holos.2020.5902, 2020.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Ziese, M.: GPCC Full Data Reanalysis Version 6.0 at 1.0Â°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data, https://doi.org/10.5676/DWD_GPCC/FD_M_V7_100, 2011.

Schneider, T., Bischoff, T., Haug, G.H.: Migrations and dynamics of the intertropical convergence zone, Nature, 513, 7516, 45-53, https://doi.org/10.1038/nature13636, 2014.

Serafim Leite, S.J.: História da Companhia de Jesus no Brasil, Tomo II (Século XVI - A Obra), Civilização Brasileira, Rio de Janeiro, 658 pp. 1938.

Silva, O.L., Bezerra, F.H.R., Maia, R.P., Cazarin, C.L.: Karst landforms revealed at various scales using LiDAR and UAV in semi-arid Brazil: Consideration on karstification processes and methodological constraints, Geomorphol., 295, 611-630, https://doi.org/10.1016/j.geomorph.2017.07.025, 2017.

Steinman, B.A., Stansell, N.D., Mann, M.E., Cooke, C.A., Abbott, M.B., Vuille, M., Bird, B.W., Lachniet, M.S., Fernandez, A.: Interhemispheric antiphasing of neotropical precipitation

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

Climate of the Past Discussions
Open Access EGU

during the past millennium, PNAS, 119, 17, e2120015119, https://doi.org/10.1073/pnas.2120015119, 2022.

Sulca, J., Vuille, M., Silva, Y., Takahashi, K.: Teleconnections between the Peruvian Central Andes and Northeast Brazil during Extreme Rainfall Events in Austral Summer, J. Hydrometeorol., 17, 499-515, https://doi.org/10.1175/JHM-D-15-0034.1, 2016.

Taylor, K.S.: The Economics of Sugar and Slavery in Northeastern Brazil, Agric. Hist., 44 3, 267-280, 1970.

Undorf, S., Bollasina, M.A., Hegerl, G.C.: Impacts of the 1900–74 Increase in Anthropogenic Aerosol Emissions from North America and Europe on Eurasian Summer Climate, J. Clim., 31, 8381-8399, https://doi.org/10.1175/JCLI-D-17-0850.1, 2018.

Utida, G., Cruz, F.W., Etourneau, J., Bouloubassi, I., Schefuß, E., Vuille, M., Novello, V., Prado, L.F., Sifeddine, A., Klein, V., Zular, A., Viana, J.C.C., Turcq, B.: Tropical South Atlantic influence on Northeastern Brazil precipitation and ITCZ displacement during the past 2300 years, Sci. Rep., 9, 1698, https://doi.org/10.1038/s41598-018-38003-6, 2019.

Utida, G., Cruz, F.W., Santos., R.V., Sawakuchi, A.O., Wang, H., Pessenda, L.C.R., Novello, V.F., Vuille, M., Strauss, A.M., Borella, A.C., Stríkis, N.M., Guedes, C.C.F., De Andrade, F.D., Zhang., H., Cheng, H., Edwards, R.L.: Climate changes in Northeastern Brazil from deglacial to Meghalayan periods and related environmental impacts, Quat. Sci. Rev., 250, 106655, https://doi.org/10.1016/j.quascirev.2020.106655, 2020.

Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C.R., Nogues-Paegle, J., Silva Dias, P.L., Zhang, C.: Toward a Unified View of the American Monsoon Systems, J. Clim., 19, 4977-5000, https://doi.org/10.1175/JCLI3896.1, 2006.

Vuille, M., Burns, S.J., Taylor, B.L., Cruz, F.W., Bird, B.W., Abbott, M.B., Kanner, L.C., Cheng, H., Novello, V.F.: A review of the South American monsoon history as recorded

https://doi.org/10.5194/cp-2023-2
Preprint. Discussion started: 16 February 2023

in stable isotopic proxies over the past two millennia, Clim. Past, 8, 1309–1321, https://doi.org/10.5194/cp-8-1309-2012, 2012.

Wang, X., Edwards, R.L., Auler, A.S., Cheng, H., Kong, X., Wnag, Y., Cruz, F.W., Dorale, J.A., Chiang, H.-W.: Hydroclimate changes across the Amazon lowlands over the past 45,000 years, Nature, 541, 204-207, https://doi.org/10.1038/nature20787, 2017.

Zhang, H., Cai, Y., Tan, L., Cheng, H., Qin, S., An, Z., Edwards, R.L., Ma, L.: Large variations of $\delta^{13}C$ values in stalagmites from southeastern China during historical times: implications for anthropogenic deforestation, Boreas, 44, 511-525, https://doi.org/10.1111/bor.12112, 2015.

Zhang, H., Cai, Y., Tan, L., Qin, S., An, Z.: Stable isotope composition alteration produced by the aragonite-to-calcite transformation in speleothems and implications for paleoclimate reconstructions, Sediment. Geol., 309, 1-14, https://doi.org/10.1016/j.sedgeo.2014.05.007, 2014.

Ziese, M., Rauthe-Schöch, A., Becker, A., Finger, P., Meyer-Christoffer, A., Schneider, U.: GPCC Full Data Daily Version 2018 at 1.0°: Daily Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data [datset], https://doi.org/10.5676/DWD_GPCC/FD_D_V2018_100, 2018.

Zular, A., Utida, G., Cruz, F.W., Sawakuchi, A.O., Wang, H., Bícego, M. Giannini, P.C.F., Rodrigues, S.I., Garcia, G.P.B., Vuille, M., Sifeddine, A., Zocatelli. R., Turcq, B., Mendes, V.R.: The effects of mid-Holocene fluvio-eolian interplay and coastal dynamics on the formation of dune-dammed lakes in NE Brazil, Quat. Sci. Rev., 196, 137–153, https://doi.org/10.1016/j.quascirev.2018.07.022, 2018.