Multidecadal climate variability in Brazil's Nordeste during the last 3000 years based on speleothem isotope records

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Received 2 October 2012; revised 25 October 2012; accepted 30 October 2012; published 12 December 2012.

[1] We present the first high resolution, approximately ∼4 years sample spacing, precipitation record from northeastern Brazil (hereafter referred to as 'Nordeste') covering the last ∼3000 yrs from ^{230}Th-dated stalagmites oxygen isotope records. Our record shows abrupt fluctuations in rainfall tied to variations in the intensity of the South American summer monsoon (SASM), including the periods corresponding to the Little Ice Age (LIA), the Medieval Climate Anomaly (MCA) and an event around 2800 yr B.P. Unlike other monsoon records in southern tropical South America, dry conditions prevailed during the LIA in the Nordeste. Our record suggests that the region is currently undergoing drought conditions that are unprecedented over the past 3 millennia, rivaled only by the LIA period. Using spectral, wavelet and cross-wavelet analyses we show that changes in SASM activity in the region are mainly associated with variations of the Atlantic Multidecadal Oscillation (AMO) and to a lesser degree caused by fluctuations in tropical Pacific SST. Our record also shows a distinct periodicity around 210 years, which has been linked to solar variability. **Citation:** Novello, V. F., et al. (2012), Multidecadal climate variability in Brazil's Nordeste during the last 3000 years based on speleothem isotope records, *Geophys. Res. Lett.*, *39*, L23706, doi:10.1029/2012GL053936.

1. Introduction

[2] The rainfall associated with the South American Summer Monsoon (SASM) and the Intertropical Convergence Zone (ITCZ) supplies more than 70% of tropical South American's annual precipitation and is fundamental for sustaining the water regime of several basins such as the São Francisco River, which is responsible for most of the water supply used in irrigation over the semi-arid area in Northeast Brazil and for producing hydroelectric power.

[3] Precipitation variability on decadal to multidecadal timescales in northeastern Brazil (hereafter 'Nodeste') is strongly modulated by variations in SST and sea level pressure (SLP) anomalies in the North Atlantic and by tropical Atlantic SST gradients [*Folland et al.*, 2009; *Knight et al.*, 2006]. Much of the variance on multidecadal time scales appears to be linked to the Atlantic Multidecadal Oscillation (AMO), whose periodicity varies from 50 to 70 years and reflects variability in the meridionally overturning oceanic circulation [*Knight et al.*, 2006]. In the 20th century periods of high rainfall in the Nordeste coincided with the negative AMO phase (1900s–1920s, 1960s–1980s), while the positive phase of this mode (1930s–1950s) saw below average precipitation [*Knight et al.*, 2006]. A more detailed analysis of multidecadal Atlantic climate variability and it's influence on NE Brazil, however, has been hampered by the limitation of the instrumental time series to less than 100 years at most sites in Brazil. This lack of observational data severely restricts our ability to evaluate the impact of Pacific-Atlantic climate interactions on decadal and multi-decadal rainfall variability over NE South America. This is particularly worrisome as NE Brazil is considered to be extremely vulnerable regarding future climate change impacts, with extreme heat and drought occurrences projected to increase substantially, in a region which is already under severe water stress [e.g., *Urrutia and Vuille*, 2009]. It is therefore not clear how natural climate variability might dampen or reinforce anthropogenically induced drought and heat extremes over this region over the coming decades.

[4] Since historical data sets are too short, high resolution paleoclimatic proxies offer the only alternative to properly constrain multidecadal rainfall variability in the region. Very little is known how multidecadal Atlantic variability has affected the region over the past millennia and during key climate events such as the Little Ice Age (LIA, 1400 to 1700 A.D.), the Medieval Climate Anomaly (MCA, 950 to 1250 A.D.) and the 2800 B.P. event. The conditions in the tropical Atlantic are linked to changes in precipitation during the last two millennia not only in the region influenced directly by the ITCZ such as the Cariaco Basin in Venezuela [*Haug et al.*, 2003] or West Africa [*Shanahan et al.*, 2009] but also over most of tropical South America within the region influenced by the SASM, such as the Peruvian Andes [*Bird et al.*, 2011], the Amazon basin [*Reuter et al.*, 2009] and southern and central Brazil [*Vuille et al.*, 2012]. However, none of these studies focus on past changes in precipitation on multidecadal timescales associated with the AMO

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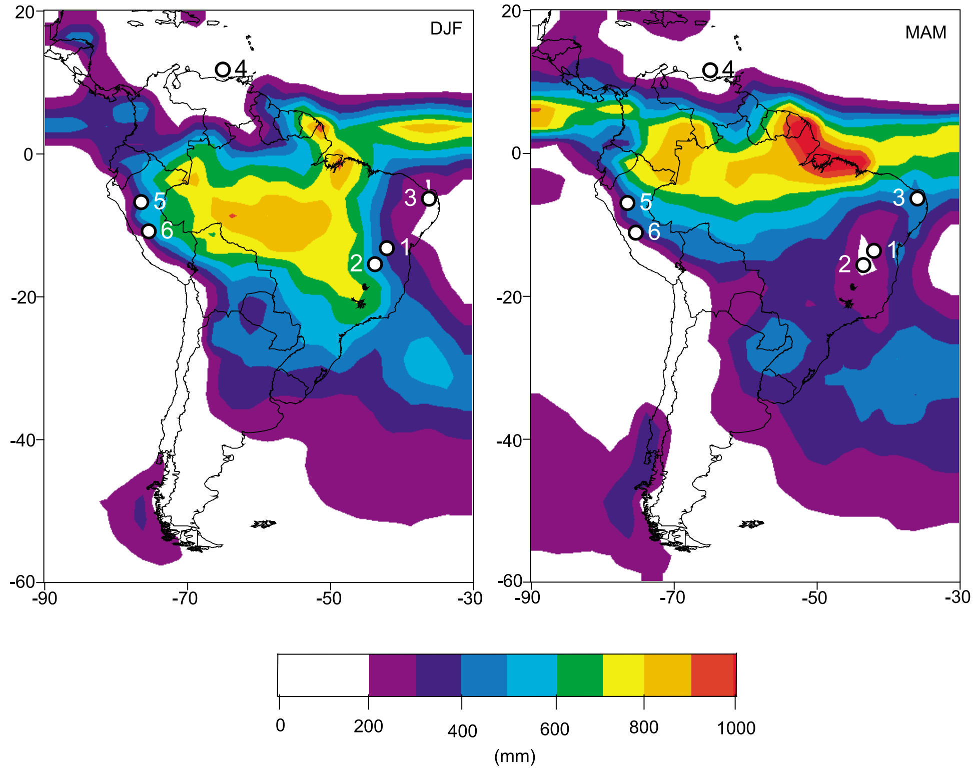

Figure 1. Long-term mean (A.D. 1979–2000) precipitation (in mm) for (left) December–February (DJF) and (right) March–May (MAM) from the Climate Prediction Center Merged Analysis of Precipitation (CMAP). Numbers on map indicate study site and other paleoclimate records: 1, Diva Cave and Torrinha Cave; 2, Lapa Grande Cave in Minas Gerais State central-eastern Brazil [*Stríkis et al.*, 2011]; 3, Rio Grande do Norte record [*Cruz et al.*, 2009]; 4, Cariaco Basin, Venezuela [*Haug et al.*, 2003]; 5, Cascayunga Cave [*Reuter et al.*, 2009]; 6, Pumacocha record [*Bird et al.*, 2011].

and none of them are representative of NE Brazil. The present study represents the first continuous high-resolution reconstruction of paleo-precipitation for the last 3000 years in NE Brazil based on precisely dated $\delta^{18}O$ records in stalagmites from the Nordeste. The limited observational studies discussed above suggest that this new record is ideally located to determine the past influence of multidecadal oscillations such as the PDO and AMO and how they modulated ITCZ location and SASM intensity and hence precipitation variability over NE Brazil.

2. Samples, Methods, Study Site and Calibration

[5] This study uses three stalagmite samples collected in the Diva de Maura, Torrinha and Lapa Doce cave systems, which are located nearby Iraquara City in Bahia State, in the southern portion of the Nordeste region (Figure 1).

[6] The DV2 sample is a 25-cm-long stalagmite (Figure S1 in Text S1 in the auxiliary material) collected in Diva Cave (12° 22′S, 41° 34′W) which grew continuously during most of the last 2850 years (Figure S2 in Text S1), except for the last century.[1] Its isotopic profile consists of 540 $\delta^{18}O$ samples, linearly interpolated between 13 U-Th dates, yielding errors (2σ) <1% (Table S1 in Text S1). This yields an average resolution of ∼5 years in between two $\delta^{18}O$ samples and a mean growth rate of 0.05 mm/yr. The missing modern portion of the DV2 isotope record is complemented with the stalagmites TR5 (Figure S1 in Text S1) and LD12 (Figure S1 in Text S1) that cover the last 130 years. The TR5 chronology is based on 9 U-Th dates and its relatively fast growth rates, ranging between ∼0.3 and 0.9 mm/yr, together with the LD12 chronology based on 6 U-Th dates, allow obtaining a resolution between ∼4 months and 2 yrs.

[7] The stalagmites were dated based on U-Th geochronology at the University of Minnesota, using an inductively coupled plasma-mass spectrometry (ICP-MS) technique following the procedures described by *Cheng et al.* [2009]. Oxygen isotope ratios are reported as $\delta^{18}O$, relative to the Vienna Peedee Belemnite standard (see Text S1 in the auxiliary material for details of methods and analytical procedures).

[8] The climate in the study region is semi-arid with mean annual precipitation of approximately 700 mm and is located along the eastern limit of the region influenced by the SASM [*Vera et al.*, 2006]. Rainfall during the mature phase of the SASM between the months of November and February contributes approximately 75% (518 mm) of total annual precipitation. The remaining 25% of precipitation occurs between March and May; a period when the Intertropical Convergence Zone (ITCZ) is at its southernmost position (Figure 1).

[9] Model experiments suggest that on seasonal to interannual timescales the $\delta^{18}O$ in precipitation is primarily controlled by the "amount effect" over central-eastern South America, where precipitation is fundamentally the result of

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053936.

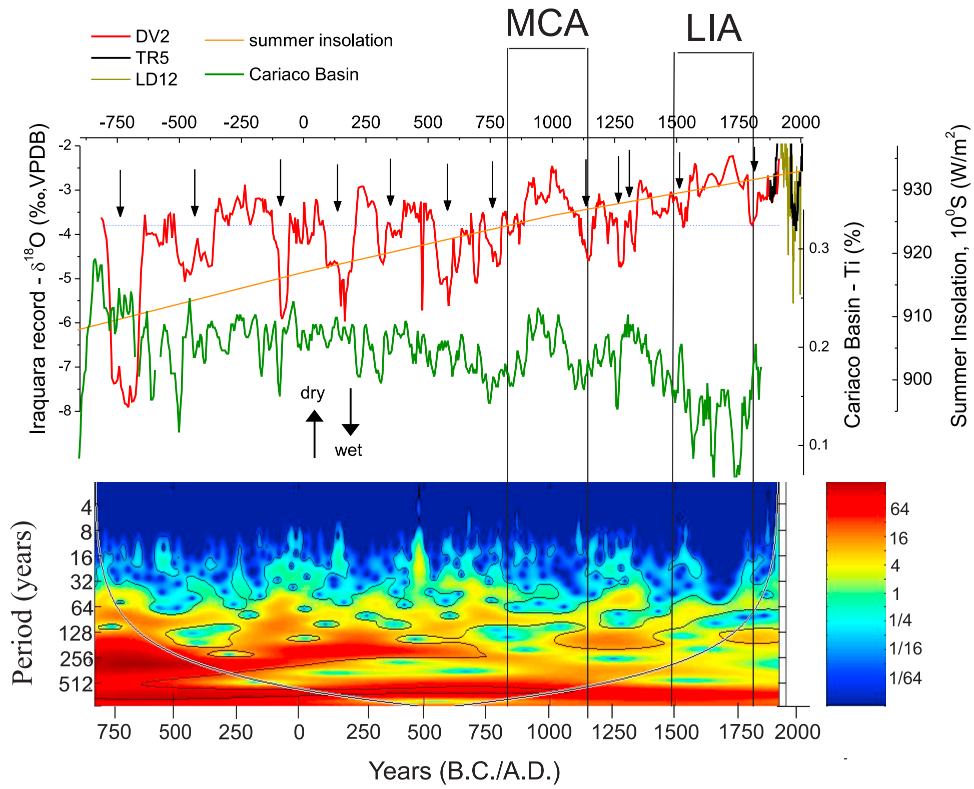

Figure 2. (top) Iraquara δ^{18}O record composed by DV2 (red), TR5 (black) and LD12 (brown) stalagmites. The wet events are indicated by vertical arrows. In green and orange are the sedimentary %Ti record of the Cariaco Basin and the February insolation curve at 10°S, respectively. (bottom) Wavelet power spectrum of DV2 speleothem records using Morlet wave function, the color index indicates the energy intensity of the periodicities in the time series and the black line indicates 95% significance level.

SASM activity or directly influenced by the ITCZ [*Vuille et al.*, 2003]. Observational data from the Global Network of Isotopes in Precipitation program of the International Atomic Energy Agency (GNIP-IAEA) confirm the strong negative correlation between weighted values of monthly rainfall and monthly δ^{18}O at stations in central and northeastern Brazil, such as Brasilia (R^2 = 0.65), Fortaleza (R^2 = 0.85) and Ceará-Mirim (R^2 = 0.69), respectively (Figure S3 in Text S1). Given that the precipitation regime in the study area is quite similar to the one at Brasilia station it is reasonable to assume that most of the isotopic fractionation is primarily related to total rainfall amount, which is characterized by more negative values during the wet season and more positive ones during the dry season.

[10] The δ^{18}O and δD values of rainwater collected at a station near the cave during this study show a close similarity between the local and the global meteoric water line (GMWL), despite the limited number of available data. In addition, the δ^{18}O and δD values of drip water from Torrinha and Fumaça caves, both located in the same region; fall on or very near to the local meteoric water line (Figure S4 in Text S1). This feature suggests a direct association of dripwater with the isotopic composition of rain, which is corroborated by very similar average values of δ^{18}O between the rainwater (−2.4‰) and Fumaça Cave drip (−2.6‰) and the mean rainfall δ^{18}O values estimated from isotope enabled GCMs for the region [*Vuille et al.*, 2003]. The climatic signal embedded in our speleothems is also evident when comparing the modern δ^{18}O profiles and the observational data from rain gauges located close to the caves (Figure S5 in Text S1). Hence we interpret these new oxygen isotope records mainly as a proxy for SASM activity in the region, consistent with other studies performed in different portions of South America, such as the Peruvian Andes [*Reuter et al.*, 2009; *Bird et al.*, 2011], southeastern [*Cruz et al.*, 2005] and central Brazil [*Stríkis et al.*, 2011].

[11] Spectral analysis techniques were performed on annually interpolated DV2 δ^{18}O time series. Wavelets analysis [*Torrence and Compo*, 1998] is used to display the frequency variability of the δ^{18}O time series, while cross-wavelet analysis [*Grinsted et al.*, 2004] is utilized to test the correlation significance between our speleothem record and other reconstructed records on multi-decadal timescales.

3. Results and Discussion

[12] The δ^{18}O values of stalagmites from the Nordeste (DV2, TR5 and LD12) vary between −7.8 and −1.8‰ (mean of −3.8‰) over the last ~3000 years, with significant variability observed at multi-decadal and centennial time scales (Figure 2). Superimposed on the high-frequency variations is a long-term trend to higher values from the oldest to the more recent portions of the δ^{18}O time series, which may be related to the gradual increase of summer insolation at 10°S. This relationship is similar to what was observed in low resolution speleothem records from the northern portion of the Nordeste region, where a significant decrease in mean precipitation is associated with a high phase in summer

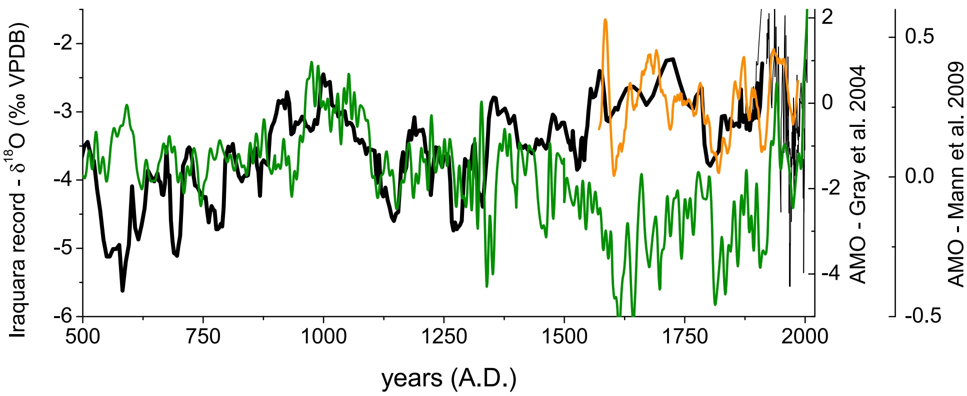

Figure 3. Comparison between Iraquara δ^{18}O record and AMO reconstruction of the *Gray et al.* [2004] in orange and *Mann et al.* [2009] in green.

insolation [*Cruz et al.*, 2009]. Spectral analysis of δ^{18}O in the DV2 record indicates significant periodicities centered on 210–330, 125–168, 96, 76, 65, 40, 22 and 15 years, within 95% statistical confidence (Figure S6 in Text S1). The most prominent periodicity is observed at 210 years (in wavelet analysis; Figure 2), which closely corresponds to the solar cycle of Vries-Suess [*Wagner et al.*, 2001]. The same periodicity has been identified in several tropical regions where precipitation is associated with oscillations in Atlantic SST [*Shanahan et al.*, 2009]. This periodicity is very prominent in DV2 during ~850 B.C. to 750 A.D. as well as in the other abrupt wet events highlighted with arrows in Figure 2. The most prominent wet event is observed at 811–642 B.C. and characterized by a striking negative shift in δ^{18}O of 4.3‰, coincident with the 2.8 ky event or Bond event 2, previously identified in speleothem records from central-eastern Brazil [*Stríkis et al.*, 2011]. Other important wet events also occur at the following intervals: 528–352 B.C., 130–57 B.C., 74–218 A.D., 299–398 A.D., 527–637 A.D., 729–803 A.D., 1097–1174 A.D., 1264–1293 A.D., 1309–1341 A.D., 1504–1545 A.D. and 1792–1833 A.D. They are marked by abrupt negative fluctuations of δ^{18}O ranging from 1.0 to 2.2 ‰, but decreasing to values below 1.0 ‰ during the last millennium. Periodicities of ~125–168 and 98 years are present throughout most of the DV2 record, but especially prominent during the intervals ~625-260 B.C., 700–1120 A.D., a period corresponding to the MCA, and particularly at 1550–1780 A.D. during the LIA.

[13] Today the oxygen isotope ratios are at levels above −2.5‰, which is equivalent to MCA and LIA values which represent the driest periods recorded in the last 3000 years in the region. Hence, when interpreted in terms of wet or dry conditions, our record suggests that the region is currently undergoing drought conditions that are unprecedented over the past 3 millennia, except for the LIA period. These periods between ~890-1154 A.D. and ~1538-1803 A.D., respectively are defined in our record by abrupt increases in δ^{18}O values of about 1.5 to 2.2‰ in just a few years. These centennial-scale events are marked by the dominance of dry conditions occasionally interrupted by shorter-term wet events with decadal-scale length centered around 1147, 1280 and 1330 A.D. The LIA's drought peak occurs at ~1715 A.D. and is followed by a wet period centered at ~1803 A.D. that lasted only a few decades until a new dry period took hold from 1890 to 1959 A.D., if we consider that the hiatus in 1920–1959 is a consequence of a drought period. Afterwards a wet phase occurred until ~1985 A.D. when the region again became drier, consistent with a change in AMO polarity (Figure S8 in Text S1).

[14] Figure 3 presents a comparison between the Nordeste speleothems and the reconstructed AMO published by *Mann et al.* [2009] and *Gray et al.* [2004]. In general higher (lower) δ^{18}O values tend to coincide with the positive (negative) phase of the AMO, which is consistent with the tendency for negative precipitation anomalies in the Nordeste during periods of warmer SST in the tropical North Atlantic [*Knight et al.*, 2006]. This phase relationship is maintained with the tree ring reconstruction by *Gray et al.* [2004] between 1470 and 1930 A.D. and also with the instrumental data reconstruction after 1860 A.D. During the same time interval, however, higher δ^{18}O values coincide with a negative phase of the AMO index in the reconstruction by *Mann et al.* [2009]. The multidecadal signal is represented in the wavelet analysis by a 76 to 50 year band centered at 65 years that is persistent and statistically significant in the entire DV2 record. This feature is also evident in the cross-wavelet analysis between the δ^{18}O DV2 record and the AMO reconstruction [*Gray et al.*, 2004], which confirms the strong coherence at periodicities from 50 to 90 years that persists throughout the interval between 1550–1910 A.D., the period when the two time series are coeval (Figure S7 in Text S1). In addition, the modern portion of the Iraquara record is marked by a rather dry period in the Nordeste during a positive phase of the AMO between 1920 and 1959, evidenced by a depositional hiatus observed in the TR5 stalagmite and high δ^{18}O values in the LD12 stalagmite (Figure S8 in Text S1). The coherent and continued influence of the AMO recorded in our record is in agreement with results by *Chiessi et al.* [2009] from a sedimentary record from the La Plata River, confirming that the AMO has a major impact on SASM/SACZ activity on multi-decadal time scales.

[15] Furthermore, there is also a clear concentration of power at periodicities of ~40, 22 and 15 years during which wet events are expressed by rather negative δ^{18}O values (Figure 2), which suggest an influence of NAO and PDO modes on Nordeste precipitation. This result is consistent with the ~14 years periodicity observed in instrumental data [*Folland et al.*, 2009; *Kayano and Andreoli*, 2007].

[16] In addition, there is a good match between the DV2 speleothem and the Cariaco Basin Ti record (Figure 2), although a shift in the phase relationship is observed from MCA to LIA events. For instance, high values in both $\delta^{18}O$ and Ti of these records during the MCA suggest that the climate was dry in the southern portion of the Nordeste, while it was relatively wet in the drainage basin of Cariaco Basin. In contrast, the high $\delta^{18}O$ and low Ti values imply that the climate was dry in both regions during the LIA. The drier conditions in the Nordeste observed during the MCA are consistent with a more northerly position of the ITCZ, which might reduce precipitation in the southern regions affected by the SASM and ITCZ regimes. However, conditions observed during the LIA are more difficult to explain since drier conditions occurred in the Nordeste at the same time that the ITCZ is presumably displaced to the south of its current mean position [*Reuter et al.*, 2009; *Bird et al.*, 2011; *Vuille et al.*, 2012]. Changes in meridional Atlantic SST gradients therefore are unlikely to be the main cause for the aridity observed in the Nordeste during the LIA.

[17] Instead this phase shift in the relationship between DV2 and other paleoclimate records from South America during the LIA might reflect the intensification of the Bolivian High-Nordeste Low pressure system due to increased SASM rainfall and related convective heating over the SW portion of the Amazon region [*Lenters and Cook*, 1997]. This mechanism, associated with increased upper level convergence, subsidence and a deficit in summer precipitation over northeastern Brazil during periods of enhanced SASM activity, has been invoked to explain the antiphasing between precipitation in Nordeste rainfall and most of tropical South America on orbital time scales [*Cruz et al.*, 2009]. A similar mechanism may also be dominant during the LIA, as illustrated by wet conditions in the main SASM region [*Reuter et al.*, 2009; *Bird et al.*, 2011; *Vuille et al.*, 2012] but dry conditions at our cave site in the Nordeste.

[18] The PDO on the other hand is unlikely to play a major control in the establishment of the LIA dry period in Nordeste, given the lack of dominant ~40 and 22 year periodicities in the $\delta^{18}O$ spectra of DV2 (Figure 2). This is consistent with modern climatology in which the PDO influence is weak in this region [*Garreaud et al.*, 2009]. Cross-Wavelet analysis performed between DV2 and the reconstructed PDO index [*MacDonald and Case*, 2005] shows a statistically significant correlation restricted to 1220–1370 A.D., a relatively wet period in the Nordeste (Figure S9 in Text S1).

[19] The 2.8 ky event in the North Atlantic [*Bond et al.*, 2001], which lasted approximately 100 years, shows the strongest amplitude of $\delta^{18}O$ observed in the entire Iraquara speleothem record. We interpret this excursion as indicative of an abrupt increase in precipitation in the Nordeste (Figure 2). This event was previously recorded in other areas of South America, such as central Brazil [*Stríkis et al.*, 2011]. These precipitation changes might be related to persistent, lower SST's in the North Atlantic and a southerly displacement of the Atlantic ITCZ [*Broccoli et al.*, 2006].

4. Summary

[20] The Iraquara speleothem record suggests that the region is currently undergoing drought conditions that are unprecedented over the past 3 millennia, rivaled only by the LIA period. It further documents that abrupt wet events have occurred over the past 3 millennia with a periodicity of approximately 210 years. The most remarkable such event occurred in ~2800-2650 B. P., likely in response to cold conditions in the North Atlantic. The AMO seems to be the most persistent mode modulating precipitation in the Nordeste, with a significant periodicity peaking at 65 years. The influence of the Pacific Ocean on Nordeste rainfall on multidecadal timescales is more limited but may have a role to play during episodic wet events recorded in the Iraquara record. The deficit in monsoonal precipitation observed during the MCA is consistent with other studies performed in tropical South America and likely caused by a persistent northerly position of the ITCZ. However, our new record indicates that SASM activity over the Nordeste does not behave linearly in response to the SST's amplitude in the tropical Atlantic. In fact the climate is also dry in the Nordeste during the LIA even though the ITCZ mean position is considered to be located further to the south. This climate response is in direct juxtaposition to other regions within the SASM influence. These results suggest that changes in precipitation over tropical South America are not merely a function of the meridional ITCZ displacement, but also sensitive to an east-west dipole in zonal circulation (the Bolivia High - Nordeste Low system) triggered by strong convective activity over the core monsoon region [*Cruz et al.*, 2009]. During such periods, which include the LIA, the ITCZ influence over the Nordeste is limited by the large-scale subsidence over the region, which develops in response to strong convective activity over the Amazon further to the west, and results in extended dry periods over northeastern Brazil.

[21] **Acknowledgments.** We thank Luis Mancine for their support during the stable isotope data acquisition at the Universidade de Brasília and Osmar Antunes for their support at Universidade de São Paulo. We are grateful to IBAMA/C. Mendes for permission to collect stalagmite samples. This work was supported by the Fundação de Amparo a Pesquisa do Estado de São Paulo, Brazil (FAPESP grants 2006/06761-0 and 2011/ 39450394 to F.W.C and fellowship to V.F.N.) and also by grants 2013CB955902, CNSF 41230524, U.S. NSF grants 0502535 and 3961103404 to RLE and HC and 1003690 to MV. The paper was significantly improved after the comments by two anonymous reviewers.

[22] The Editor thanks the two anonymous reviewers for their assistance in evaluting this paper.

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