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Key Points:
- A new and expanded network of speleothem records from eastern Brazil recorded the movement of the South Atlantic Convergence Zone over the last 2,000 years
- The new network shows that precipitation did not vary in phase throughout the entire monsoon domain during the last millennium over Brazil
- Variations in location and intensity of the South Atlantic Convergence Zone represent a main driver of hydrologic variability over Brazil

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2

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Two Millennia of South Atlantic Convergence Zone Variability Reconstructed From Isotopic Proxies

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Abstract Most reconstructions of the South American Monsoon System (SAMS) over the last two millennia are based on $\delta^{18}O$ records from locations at high-elevation sites in the Andes, which are not influenced by the South Atlantic Convergence Zone (SACZ). Yet the SACZ is a key driver of SAMS variability over much of Brazil. Here we use two new $\delta^{18}O$ records from speleothems sampled in the central and southwestern portions of the SACZ core to show that the SAMS was not varying in phase over the entire tropical continent during the last two millennia. In fact, speleothem records located to the northeast of the SACZ record precipitation variations that are antiphased with similar records on the opposite side of the SACZ, in particular during the Little Ice Age period, while records close to the core of the SACZ axis show no significant departure from the mean state during this period.

Plain Language Summary The South American Monsoon System (SAMS) is responsible for most rainfall occurring over tropical South America. Within this monsoon system the South Atlantic Convergence Zone (SACZ) is considered a key driver of SAMS variability over Brazil. By analyzing the chemical composition of stalagmites we can track the history of rainfall in the region where these stalagmites grew. Using stalagmites from caves in the SACZ region of Brazil that formed during the last two millennia, we can reconstruct the behavior of the SACZ, and consequently the rainfall distribution over Brazil during this period, which includes global climate changes that significantly affected human history, such as the Medieval Climate Anomaly and the Little Ice Age. Understanding the nature of these past changes in climate is fundamental for putting current climate changes in a longer-term perspective and for differentiating between natural and anthropogenic causes of current and future climate change.

1. Introduction

The South American monsoon is of great importance for social and economic purposes, supplying water for agriculture, hydropower production, industry, sanitation, and human consumption. Past changes in the South American Monsoon System (SAMS) have affected vegetation dynamics in a region that includes the Amazon and Atlantic rainforests and the Brazilian savanna (cerrado and caatinga). In addition, changes in the amount and distribution of rainfall have been linked with the migration, rise, and demise of pre-Columbian populations in South America (Iriarte et al., 2016). Finally, a detailed understanding of the sensitivity of the SAMS to past changes in radiative forcing is fundamental for improving future projections of climate change in the region, on which robust mitigation and adaptation policies can be based.

In a review of the SAMS over the last two millennia, Vuille et al. (2012) investigated the coherent behavior of tropical precipitation in the region based on a limited set of stable oxygen isotopic records from the Andes and SE Brazil. Since then many additional high-resolution isotopic records have become available, in particular from the eastern and south-central Amazon, which afford a more detailed analysis of the spatiotemporal variability of the SAMS during the past two millennia. In particular, a series of speleothem records covering a latitudinal range from NE to SE Brazil now allow a more detailed analysis of changes in intensity and location of the South Atlantic Convergence Zone (SACZ), which is a key feature of the SAMS.

The prevailing view in the literature considers SAMS variability over the last two millennia to be driven primarily by changes in the interhemispheric temperature gradient in the Atlantic, whereby cold Northern

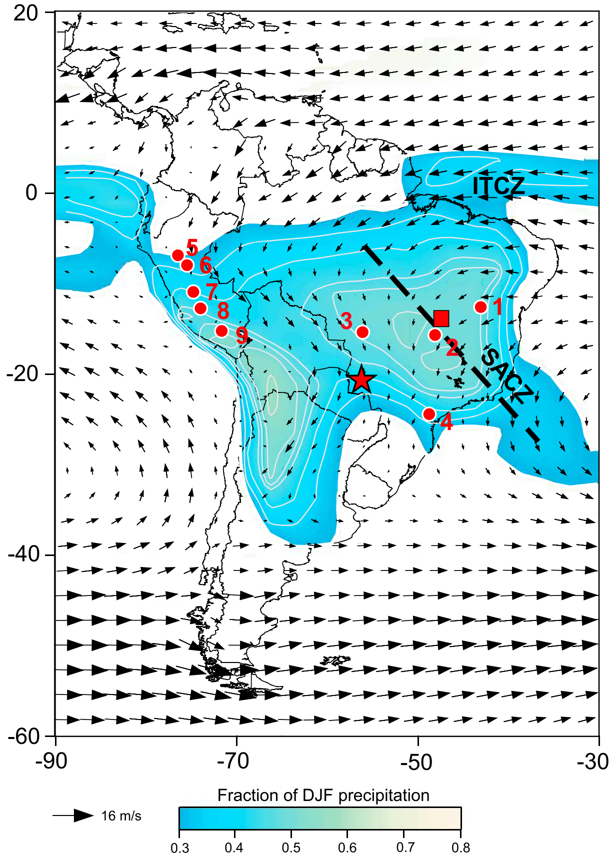

Figure 1. Map of South America with location of paleoclimate records discussed in text, austral summer (December–February, DJF) 850 hPa wind field and fractional DJF precipitation. Color shading indicates regions where fraction of total annual precipitation falling during austral summer (DJF) > 0.3, which is congruent with the extent of the SAMS over the continent; contour interval is 0.05. Wind data are from ERA-Interim (Dee et al., 2011) and precipitation data from GPCC (Schneider et al., 2011), with averages calculated over period 1979–2014. The red star indicates our speleothem site in Mato Grosso do Sul State (MS—record based on the stalagmites JAR4 + JAR1); the red square indicates our site in Goiás State (GO—record based on the stalagmites SBE3 + SMT5). Others sites include (1) caves from Iraquara city (Novello et al., 2012), (2) Tamboril cave (Wortham et al., 2017), (3) Pau d'Alho and Curupira caves (ALHO6 + CUR4 stalagmites; Novello et al., 2016), (4) Cristal cave (Vuille et al., 2012), (5) Cascayunga cave (Reuter et al., 2009), (6) Palestina cave (Apaéstegui et al., 2014), (7) Laguna Pumacocha (Bird et al., 2011), (8) Huagapo cave (Kanner et al., 2013), and (9) Quelccaya Ice Cap (Thompson et al., 2013). Figure modified from Novello et al. (2016).

Hemisphere temperature anomalies are responsible for a southward shift of the Intertropical Convergence Zone (ITCZ), funneling more moisture toward the core SAMS domain over the tropical continent, while the opposite is the case during periods of anomalously warm Northern Hemisphere temperature (Bird et al., 2011; Vuille et al., 2012). This forcing mechanism has been used to explain the moisture deficit during the Medieval Climate Anomaly (MCA) as well as the predominantly wet conditions during the Little Ice Age (LIA) period in South America (Bird et al., 2011; Novello et al., 2012, 2016; Vuille et al., 2012). However, this interpretation was based primarily on paleoclimate records from the Peruvian Andes (Apaéstegui et al., 2014; Bird et al., 2011; Kanner et al., 2013; Reuter et al., 2009; Thompson et al., 2013; Vuille et al., 2012). New paleoclimate records from others regions of the SAMS domain show a more nuanced picture with less distinct climate departures during LIA and MCA (Novello et al., 2012; Wortham et al., 2017).

Here we present two new high-resolution paleoclimate records based on $\delta^{18}O$ from stalagmites, collected at two different study sites located in central and southwestern Brazil, both influenced by the SAMS and its subcomponent, the SACZ. Combining these new data sets with the previously published paleoclimate records allows us to establish a set of paleoclimate benchmarks along a transect from NE to SW Brazil, perpendicular to the prevailing SACZ axis. Investigating the spatiotemporal variability in precipitation along this transect affords us the unique opportunity to explore the dynamics of SAMS and SACZ variability over the last two millennia.

2. Samples, Study Sites, and Isotopic Interpretation

2.1. Records Located to the Southwest of the SACZ Position (State of Mato Grosso do Sul)

We obtained two new $\delta^{18}O$ records from stalagmites sampled in a cave of southwestern Brazil, namely, stalagmites JAR4 and JAR1 (Figure S1), both collected in Jaraguá cave. The sample JAR4 is ~13 cm long and grew continuously between ~1190 and 2000 CE. Its isotopic profile consists of 238 $\delta^{18}O$ values linearly interpolated between 20 U/Th dates (Table S1), which provides a resolution of ~1 data point every three years. The sample JAR1 is a ~28-cm-long stalagmite that provides a continuous isotopic record between ~442 and 1451 CE with 423 $\delta^{18}O$ data linearly interpolated between 15 U/Th ages (Table S1), providing a resolution of approximately three years.

Jaraguá cave is located in Bonito city (21°05′S, 56°35′W, ~570 m above sea level) in the state of Mato Grosso do Sul, southwestern Brazil (the description of the cave is in Text S1). The climate in Bonito City is tropical with a three-month long dry season during austral winter, with annual precipitation of 1,400 mm and with mean temperature over austral winter and summer of ~20 and 26 °C, respectively. A separate $\delta^{18}O$ record derived from different stalagmites obtained in Jaraguá cave covering the last deglaciation was previously published in Novello et al. (2017). In the latter article, using a monitoring of environmental parameters, the authors showed that the amount effect exerts the main control on the $\delta^{18}O$ fractionation at our study site on both seasonal and interannual timescales and that the cave atmosphere does not have a significant influence on the isotopic fractionation during stalagmite formation. In addition, the $\delta^{18}O$ profiles of the two stalagmites overlap between ~1191 and 1451 CE, confirming a similar isotopic fractionation on both samples (Figure 2). Thus, we interpret the $\delta^{18}O$ profile in the JAR4 and JAR1 stalagmites as varying primarily in response to changes in rainfall amount, with more negative $\delta^{18}O$ values reflecting more precipitation, and vice versa. We are confident that this interpretation is robust for the past two

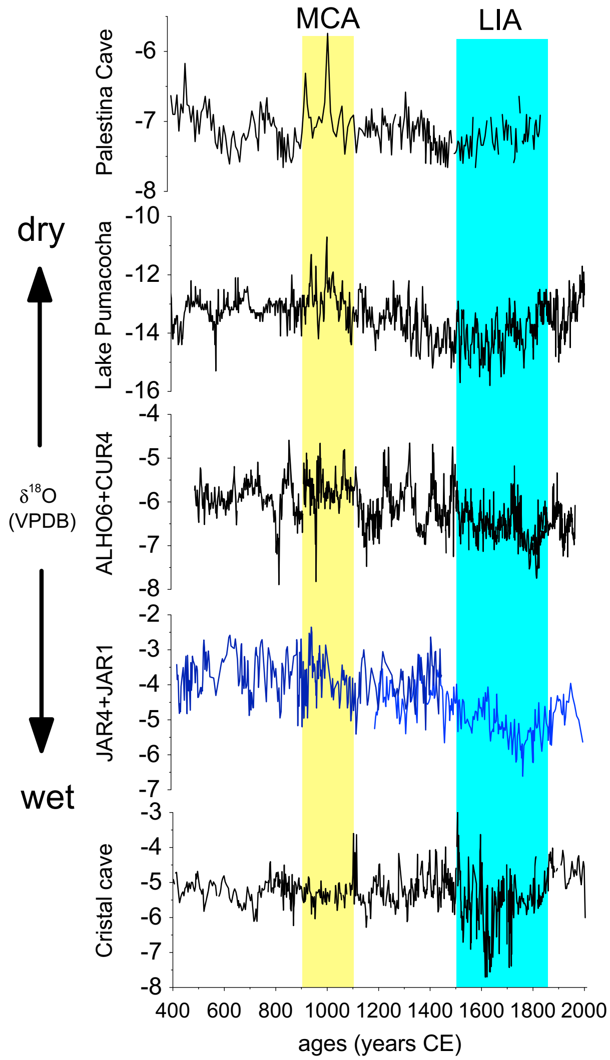

Figure 2. Comparison between the δ^{18}O records that show wet conditions during the LIA period: Cristal cave, located in southeastern Brazil, JAR4 + JAR1 stalagmite (this study), ALHO6 + CUR4 stalagmites in midWest Brazil (Novello et al., 2016), Lake Pumacocha (Bird et al., 2011), and Palestina cave (Apaéstegui et al., 2014) from the Peruvian Andes.

millennia, as significant changes in seasonality of precipitation or changes in moisture source are unlikely to have occurred during this time interval (Vuille et al., 2012).

2.2. Records Located to the Northeast of the SACZ Position (State of Goiás)

Additional speleothem records were obtained in central Brazil, where δ^{18}O was sampled on two stalagmites, the stalagmite SBE3 from São Bernardo cave and the stalagmite SMT5 from São Matheus cave (Figure 1). Both caves are located in the same karstic region, and their entrances are within approximately 10 km of one another. We sampled a 37-cm-long portion on stalagmite SBE3 for isotopic analyses, covering a period between ~1123 and 2010 CE. The isotopic profile of SBE3 consists of 1116 δ^{18}O values constrained by 11 U/Th ages (Table S1), providing a subannual resolution. The isotopic profile of stalagmite SMT5 contains 576 δ^{18}O values, constrained by 4 U/Th ages (Table S1) and sampled over 17 cm of the speleothem. This interval covers the period between 264 and 1201 CE, resulting in an average resolution close to annual.

The São Bernardo and São Mateus caves (13.81°S, 46.35°W, ~631 m above sea level) are located in the Terra Ronca State Park (PETER) in the state of Goiás (GO), near the border to Bahia State (BA); the description of the caves and monitoring information of them are presented in Text S2. The climate in this region is tropical semihumid with a mean annual precipitation of ~1,270 mm. The rainy season extends from October to April, while rainfall is basically absent between May and September. The mean annual temperature is 24.0 °C with the monthly mean ranging between 22.5 (July) and 25.8 °C (October; Moquet et al., 2016).

The most recent 140 years of the SBE3 record were published by Moquet et al. (2016), which, together with the monitoring performed in the São Bernardo cave, demonstrates that the δ^{18}O record covaries with the amount of rainfall associated with SACZ activity in the central region of Brazil on interannual time scales. Therefore, the oxygen isotopic signature of speleothems from this cave is being used in this study to reconstruct past SACZ activity.

3. Methodology

3.1. Geochronology

The chronology of the stalagmites was established based on ages obtained using U/Th dating. These analyses were performed at the Minnesota Isotope Laboratory using a multicollector-inductively coupled plasma-mass spectrometry technique (Thermo-Finnigan NEPTUNE), according to the procedures described in Cheng et al. (2013).

3.2. Stable Isotope Analyses

Stable isotope analyses were carried out at the Stable Isotope Laboratory of the Geosciences Institute of the University of São Paulo (LIESP-CPGeo-IGc-USP) using a Thermo-Finnigan Delta Plus Advantage mass spectrometer. Oxygen isotope results are expressed in δ notation, with the per mil deviation from the Vienna Peedee Belemnite standard. $\delta^{18}O = [((^{18}O/^{16}O)\ \text{sample}/(^{18}O/^{16}O)\text{Vienna Peedee Belemnite}) - 1] \times 1,000$. The reproducibility of the standard is approximately 0.1‰ for δ^{18}O. Approximately 100 to 200 μg of powder was drilled for each measurement along a profile following the growth axes of the stalagmites.

3.3. Mineralogical Analyses

The mineralogical analyzes were carried out in the X-ray diffraction laboratory of the Geosciences Institute at the University of São Paulo (LDRX-GMG-IGc USP) using a Bruker D8 Advance Da Vinci diffractometer with

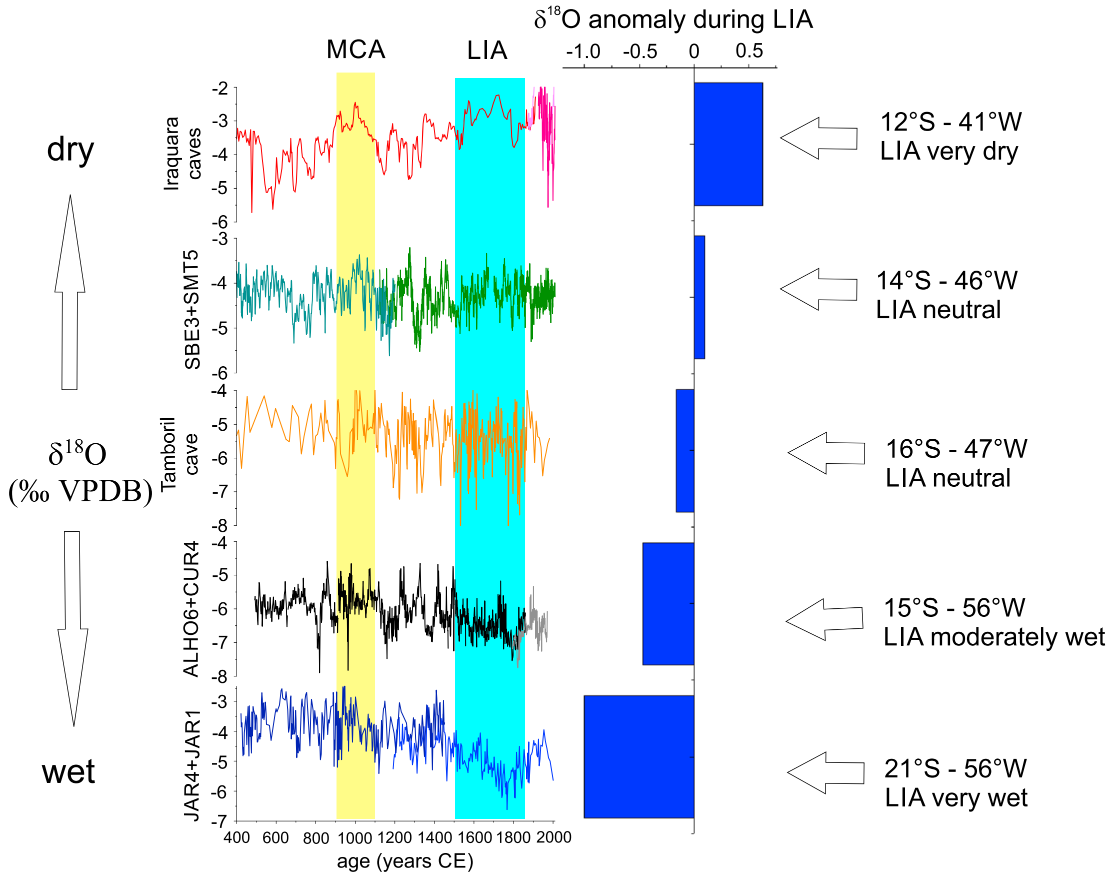

Figure 3. Comparison of the LIA signal in $\delta^{18}O$ records from the SACZ region: Iraquara caves (Novello et al., 2012); SBE3 + SMT stalagmites (GO, this study); Tamboril cave (Wortham et al., 2017); ALHO6 + CUR4 (Novello et al., 2016), and JAR4 + JAR1 stalagmite (MS, this study). The blue bars show the standardized departure of $\delta^{18}O$ values in individual records during LIA period (1500–1850 CE), compared to long-term mean (492–1971 CE, period common to all records).

LYNXEYE detector and TWIN-TWIN optics. For phase identification, the laboratory uses the SUITE Diffracplus program and the PDF-2 (ICDD) version 2009 and COD (Crystallographic Open Database).

4. Results

The sampled stalagmites have a very regular stratigraphy marked by conical layers that vary slightly from white to light gray color without evidence of growth gaps. The mineral habit is of fine fibrous crystals that form divergent bundles that cross the layers, evidencing continuous growth. Their dominant mineralogical composition of aragonite was confirmed by X-ray diffraction analysis of three samples along each stalagmite. All samples showed composition of at least 96% of aragonite and calcite varying around 1 to 4%. However, we believe that this small percentage of calcite in all samples is due to the recrystallization of aragonite into calcite during the sampling of the powder for the X-ray analysis, which was performed using a manual electric drill that increases the temperature and pressure on the sampling point.

The $\delta^{18}O$ record from Jaraguá cave (based on the stalagmites JAR4 and JAR1) varies between −6.6 and −2.3‰ with a mean value of −4.2‰ (Figure 2). The $\delta^{18}O$ profile displays a slight trend toward lighter $\delta^{18}O$ values between 400 and 1400 CE, superimposed on multiple ~1–2‰ oscillations. After 1400 CE the values start to drop until 1770 CE. Thereafter, the tendency is reversed and the values increase again until 1950 CE. From 1950 to 2000 CE the $\delta^{18}O$ values progressively decrease again.

The $\delta^{18}O$ record from central Brazil (based on the stalagmites SBE3 and SMT5) does not show a trend and is characterized by a smaller range of variability, reaching values between −5.5 and −3.1‰ (Figure 3). Based on the calibration between $\delta^{18}O$ and summer precipitation (November-December-January-February) proposed for this region by Moquet et al. (2016), this $\delta^{18}O$ range of 2.4‰ corresponds to a variability of ~317 mm in seasonal rainfall. The record shows some abrupt wet events, such as the extended wet periods between 680–780 CE and 1290–1350 CE, and shorter events occurring around 1050, 1175, and 1490 CE.

5. Discussion

The wet period documented in the JAR4 + JAR1 record during the LIA period between 1500 and 1850 CE is consistent with the wet conditions reported for all other records located to the southwest of the mean position of the SACZ axis (Figure 2), such as Pau d'Alho and Curupira caves (ALHO6 + CUR4 stalagmites) in midwest Brazil (Novello et al., 2016) and Cristal cave (CR1 stalagmite) in southeastern Brazil (Vuille et al., 2012). Similarly, the δ^{18}O records of Laguna Pumacocha (Bird et al., 2011), Quelccaya ice cap (Thompson et al., 2013), Cascayunga cave (Reuter et al., 2009), Huagapo Cave (Kanner et al., 2013), and Palestina cave (Apaéstegui et al., 2014) in the Peruvian Andes also exhibit negative δ^{18}O anomalies during this time period. The δ^{18}O record from Iraquara caves (Novello et al., 2012), located to the northeast of the mean position of the SACZ, on the other hand, indicates that dry conditions prevailed in this region during the LIA period (Figure 3). Hence, our δ^{18}O proxy network indicates a moist/dry dipole modulated by the positioning of the SACZ. This notion is consistent with the data from our new SBE3 + SMT5 record and the δ^{18}O record from Tamboril cave (Wortham et al., 2017), which are both located near the node of this dipole (Figure 1). These two sites likely experienced continuous SACZ influence at all times, hence displaying neutral moisture conditions during the LIA period and no trend over the last millennium (Figure 3).

The absence of a trend in the δ^{18}O record from central Brazil was previously discussed in Wortham et al. (2017). The authors suggested that this δ^{18}O record from central Brazil may be disconnected from the main SAMS variability since their Tamboril δ^{18}O record did not show the same tendency for more negative δ^{18}O values during the LIA as the records from SE Brazil and the Peruvian Andes. As we document here, however, the absence of a trend in the δ^{18}O records from central Brazil is fully consistent with the notion of the SACZ transitioning between two extremes states (NE versus SW) over centennial timescales. Records such as Tamboril that are located in the center of this region will be influenced by the SACZ at all times, hence experiencing much subdued variability.

Although the records in the core of the SACZ (SBE3 + SMT5, ALHO6 + CUR4, and Tamboril) did not exhibit a significant change in the mean state during MCA and/or LIA, they do show strong multidecadal to centennial-scale variability during the transition period from MCA to LIA (between 1100 and 1500 CE; Figure 3). This is in stark contrast to the other isotopic records located far away from the SACZ core (Palestina cave, Lake Pumacocha, Cristal cave—Figure 2, and JAR4 + JAR1 and Iraquara caves—Figure 3), which all show rather stable conditions at this time (Figure 3).

The records composed by stalagmites JAR4 + JAR1 and SBE3 + SMT5 are strategically located to assess climate variability along a transect perpendicular to the SACZ axis (Figure 1). During the LIA positive precipitation anomalies became more pronounced along this transect (decrease in δ^{18}O), from anomalously dry conditions in the northeast at 12°S/41°W to unusually wet conditions in southwestern Brazil at 21°S/56°W (Figure 3). The record from Iraquara caves in the northeast displays a standardized anomaly of +0.66‰ during the LIA period (averaged over 1500–1850 CE). The other records along this transect show increasingly more negative values when moving toward the southwest. For example the SBE3 + SMT5 and Tamboril cave records located at 14°S/46°W and 16°S/47 W° contain standardized anomalies of 0.02‰ and −0.27‰, during this same time period, respectively. At Pau d'Alho and Curupira caves (15°S/56°W), the standardized δ^{18}O anomaly is significantly more negative (−0.54‰), exceeded only by the most negative value of −1.12‰ in the most southwestern location (JAR4 + JAR1 record at 21°S/56°W; Figure 3). These values suggest that the region of transition from increased toward decreased precipitation during the LIA was located near the sites of the SBE3 + SMT5 and Tamboril cave records. Vuille et al. (2012) pointed out that dry conditions prevailed over the SAMS domain during the MCA period, in particular over the Andes region, as a consequence of a more northerly position of the ITCZ. None of the records that are under significant SACZ influence show a significant change in the mean state during the MCA (900–1100 CE), although they are all anomalously positive during this time period. Thus, we posit that the SACZ was shifted southward during the LIA, resulting in enhanced rainfall at sites located near its southern limit of influence. The increased aridity during the MCA on the other hand is first and foremost a consequence of a northward withdrawal of the ITCZ that limited moisture influx over the SAMS domain. The reduced moisture convergence over the South American continent likely weekend convective activity over the entire SACZ domain, leading to drier conditions throughout eastern Brazil.

Based on the arguments above, we infer that the ITCZ plays an important role for the moisture influx to the SAMS system, yet the intensity and positioning of the SACZ are what determine the spatial precipitation distribution over the south-central part of the SAMS. Although the rainfall dipole during the LIA between southwestern and northeastern Brazil is consistent with the El Niño–Southern Oscillation (ENSO) footprint in the region (Garreaud et al., 2009), Vuille et al. (2012) discarded the possibility of a major role for ENSO in modulating the SAMS during the LIA period. The main argument against a major ENSO influence at the time is related to the synchronous wet conditions during the LIA in the Peruvian Andes and southeast Brazil, even though the canonical ENSO impact in these two regions is the exact opposite.

The formation of the SACZ is associated with maximum precipitation extending from the Amazon toward southeastern Brazil with a northwest-southeast orientation, while at the same time suppressing convection over the northeast coast of Brazil (Carvalho et al., 2004; Grimm & Saboia, 2015). Thus, the intensity and location of the SACZ provide a more robust mechanism to explain the moisture distribution over the south-central part of the SAMS domain than the explanation invoking only a role for the ITCZ position; in this sense, the SACZ modulates the ITCZ signal imprinted on the SAMS. In addition, convective heating over the core monsoon region, including the region of our study site in southwest Brazil, which occurs in association with increased SAMS rainfall, is associated with upper-level convergence, subsidence, and reduction of precipitation over the northeastern portions of the SAMS domain (Lenters & Cook, 1997; Novello et al., 2012), where the Iraquara caves are located.

6. Conclusions

Using a new and expanded data set of isotopic proxies recording SAMS variability, we show that the SACZ has shifted significantly during the past two millennia, leading to drier and wetter conditions on either side of this system. Hence, we expand on previous interpretations of SAMS variability, which were based solely on records from the Andes and southeastern Brazil and indicated that the SASM varied in phase over the entire region, in response to shifts of the oceanic ITCZ (Vuille et al., 2012). The displacement of the SACZ was particularly pronounced during the LIA, leading to dry conditions in the northeastern portions of the SAMS domain, while wet conditions prevailed to the southwest. Our results clearly document that over eastern and central Brazil variations in the location and intensity of the SACZ represent a main driver of centennial-scale hydrologic variability. Our interpretation also offers a consistent framework to explain the diverging records over eastern Brazil during the LIA period, ranging from dry (northeastern Brazil) to neutral (central-east Brazil) to wet (southeastern Brazil) conditions.

Future efforts to improve our understanding of SACZ variability over the past millennia will require detailed studies analyzing the relative importance of internal versus external forcing in determining the positioning and intensity of the SACZ, and how this convergence zone interacts with ocean-atmosphere feedbacks on long time scales. For this purpose our new data set can serve as an ideal test bed for climate model simulations over the last millennium (e.g., Rojas et al., 2016), but it also provides a valuable new contribution from the undersampled southern hemisphere for global paleoclimate reconstructions during the late Holocene.

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