Abrupt variations in South American monsoon rainfall during the Holocene based on a speleothem record from central-eastern Brazil

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ABSTRACT

Well-dated high-resolution oxygen isotope records of speleothems in central-eastern Brazil spanning from 1.3 to 10.2 kyr B.P. reveal that the occurrence of abrupt variations in monsoon precipitation is not random. They show a striking match with Bond events and a significant pacing at ~800 yr, a dominant periodicity present in sea surface temperature records from both the North Atlantic and equatorial Pacific Oceans that is possibly related to periods of low solar activity (high ^{14}C based on the atmospheric $\Delta^{14}C$ record). The precipitation variations over central-eastern Brazil are broadly antiphased with the Asian and Indian Monsoons during Bond events and show marked differences in duration and structure between the early and late Holocene. Our results suggest that these abrupt multicentennial precipitation events are primarily linked to changes in the North Atlantic meridional overturning circulation (AMOC). Anomalous cross-equatorial flow induced by negative AMOC phases may have modulated not only the monsoon in South America but also affected El Niño–like conditions in the tropical Pacific during the Holocene.

INTRODUCTION

Ever since Bond et al. (1997) published their paper on rapid climate change events in the North Atlantic region, the Holocene has been recognized as an epoch marked by abrupt climate fluctuations on millennial to centennial time scales at high latitudes. Based on the striking correlation between ice-rafted debris (IRD) records in North Atlantic sediment cores and tropical rainfall, the Bond IRD events have been used to link shifts in the intensity of the Atlantic thermohaline circulation to changes in sea surface temperature (SST) and related precipitation anomalies over regions affected by the Indian and Asian Monsoons (Fleitmann et al., 2003; Wang et al., 2005; Cheng et al., 2009).

Although the magnitude of millennial-scale cold events in the Holocene is much less pronounced than during the last glacial period (O'Brien et al., 1995; Bond et al., 1997), they nonetheless produce a large deficit in monsoonal rainfall over the Northern Hemisphere. This is indicated by the striking match between the Bond events and less tropical and subtropical precipitation over regions in Oman (Fleitmann et al., 2003), Asia (Wang et al., 2005), and northernmost South America (Haug et al., 2001). Despite strong evidence that intense cold conditions over the Northern Hemisphere also produced wetter conditions within the South America monsoon system (SAMS) region during the 8.2 kyr B.P. meltwater pulse cooling event (Cheng et al., 2009) and the Little Ice Age (Bird et al., 2011), it is not clear whether other similar abrupt events during the Holocene, for example, the events at 1.4, 2.7, 4.2, 5.5, 7,4, and 9.2 kyr B.P., exerted a similar influence on South American monsoon precipitation and glacial advances.

One of the first attempts to associate abrupt centennial- to millennial-scale variations in SAMS precipitation with Bond events was that of Baker et al. (2001, 2005), who proposed that lake-level fluctuations at Lake Titicaca (Bolivia and Peru) were positively correlated with the record of IRD pulses over the North Atlantic during the Holocene. Ekdahl et al. (2008) showed that patterns of lake-level variations inferred from diatom stratigraphy of lakes near Lake Titicaca were similar to those observed by Baker et al. (2001, 2005). The physical mechanism linking changes in the hydrologic cycle over the tropical Andes with climate variations in the North Atlantic, however, remains speculative. Over the tropical lowlands, precipitation changes may result from variations in the latitudinal gradients of tropical SST primarily related to trade wind strength (Arz et al., 2001) and related changes in the intensity or core location of tropical convection. However, there are significant discrepancies in the timing and amplitude between the different records that make these assumptions somewhat inconclusive. This is particularly true for large regions directly affected by the SAMS in Brazil, where almost no data are available from high-resolution, well-dated paleoprecipitation records.

Our results are based on a high-resolution speleothem isotope record that extends back to 10.2 ka; the record is from a cave located in the northern portion of Minas Gerais State, Brazil, where precipitation is exclusively due to SAMS activity. This new record allows us to reconstruct the history of monsoon precipitation over central-eastern Brazil on multidecadal to centennial time scales, and climatic forcings, in particular the impact of negative North Atlantic SST anomalies during Bond events.

SAMPLES AND METHODS

Two stalagmites were collected from the 2200-m-long Lapa Grande cave (LG3 and LG11, hereafter Lapa Grande record) in northern Minas Gerais State (14°25′22″S; 44°21′56″W), central-eastern Brazil (Fig. 1). The cave developed in low metamorphic grade limestones of the Mesoproterozoic to Neoproterozoic Bambuí Group. The samples were collected at ~560 m distance from the entrance in a locale with more restricted cave ventilation.

The present-day climate at the study site is tropical semihumid, according to the Köppen-Geiger classification, with a mean annual precipitation of 958 mm (recorded from A.D. 1953–2005 at a meteorological station located 1 km from the cave; http://www2.ana.gov.br). The regional precipitation is due to activity of the South Atlantic Convergence Zone (SACZ), which is one of the main features of the SAMS during the austral summer, associated with intense convective activity in the Amazon region (Garreaud et al., 2009). The SACZ extends southeastward from the core of the continent to the South Atlantic (Vera et al., 2006) (Fig. 1). Once the monsoon season comes to an end, rainfall basically ceases from May to October.

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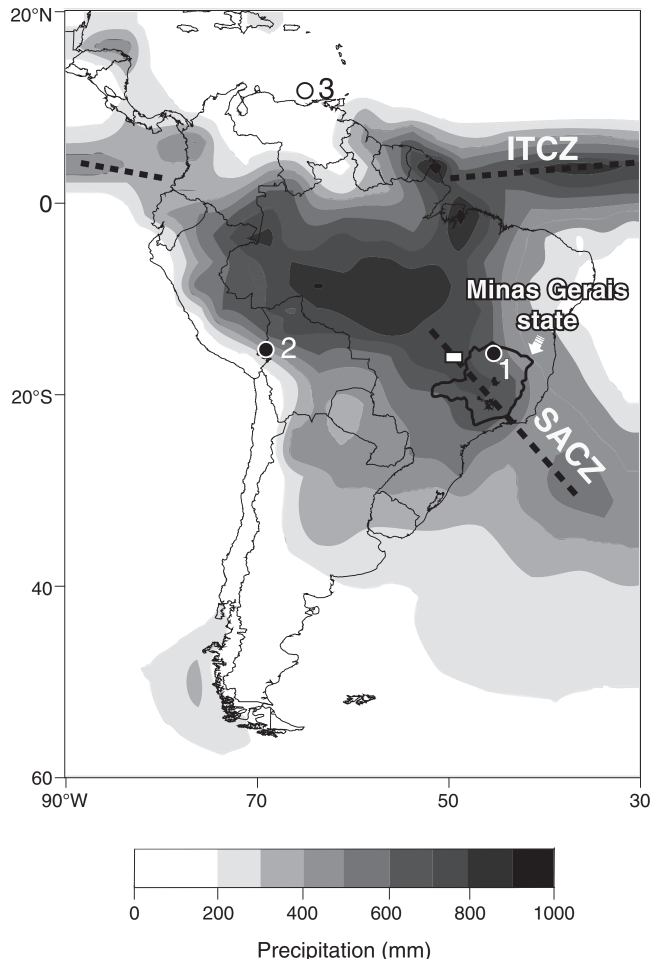

Figure 1. Long-term mean (A.D. 1979–2000) precipitation (in mm) for December–February (DJF) from the Climate Prediction Center Merged Analysis of Precipitation. Numbers on map indicate study site and other paleoclimate records: 1—Lapa Grande Cave in Minas Gerais State, central-eastern Brazil; 2—Lake Titicaca, Bolivia and Peru (Baker et al., 2001); 3—Cariaco Basin, Venezuela (Haug et al., 2001). White square indicates location of Brasília International Atomic Energy Agency–Global Network of Isotopes in Precipitation station. ITCZ—Intertropical Convergence Zone; SACZ—South Atlantic Convergence Zone.

The speleothems were dated by the U-Th method using inductively coupled plasma–mass spectrometry (ICP-MS) techniques at the University of Minnesota following the procedures described by Shen et al. (2002). Most dates, 24 in total, yield errors (2σ) <1% (Table DR1 in the GSA Data Repository[1]). Oxygen isotope ratios are reported as $\delta^{18}O$ relative to the Vienna Peedee belemnite standard (for methods and analytical procedures, see the Data Repository). The Lapa Grande record spans from 1.3 to 10.2 kyr B.P., with a hiatus from 6.3 to 5.9 kyr B.P.. The early and middle Holocene is represented by stalagmite LG11, while the middle to late Holocene is represented by stalagmite LG3. The isotope profile is composed of 600 $\delta^{18}O$ samples, yielding a temporal resolution between 1 and 40 yr (10 yr on average) and exhibiting a large range of ~4.5‰ throughout the Holocene. The wide range of temporal resolution is due to large differences in growth rates observed along the speleothem long axis, which varies from 0.01 to 0.35 mm/yr. Hence some of the events that appear to be very brief might in fact result from the coarse temporal sampling during some time intervals.

[1]GSA Data Repository item 2011314, analytical methods, Figures DR1–DR4, and Table DR1, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

RESULTS AND DISCUSSION

Model experiments suggest that the $\delta^{18}O$ in precipitation is primarily controlled by the "amount effect" over areas such as northern Minas Gerais, where precipitation is fundamentally the result of SAMS activity (Vuille et al., 2003). This interpretation is confirmed by the strong negative correlation between monthly rainfall amount with monthly weighted mean $\delta^{18}O$ at the International Atomic Energy Agency–Global Network of Isotopes in Precipitation station in Brasília between 1963 and 1987 ($R^2 = 0.64$), where precipitation is climatologically identical to the study region (Fig. DR1A in the Data Repository). Relatively low correlation coefficients between $\delta^{18}O$ and $\delta^{13}C$ along the speleothem growth axes suggest that stalagmites LG3 ($r^2 = 0.13$) and LG11 ($r^2 = 0.24$) were deposited in approximate isotopic equilibrium according to the Hendy test (Fig. DR1B).

The novel characteristics of this new record are abrupt fluctuations in $\delta^{18}O$ punctuating the entire Holocene, with some differences in the structure and duration of events between the early and middle Holocene (considered here to extend from 10 to 7 kyr B.P. and from 7 to 4 kyr B.P., respectively) and the late Holocene (after 4 kyr B.P.). The Lapa Grande $\delta^{18}O$ record shows strong events of increased precipitation centered at 9.2, 8.2, 7.4, 7.0, 6.6, 5.2, 4.0, 3.2, 2.7, 2.3, 2.2, and 1.9 kyr B.P. During the early and middle Holocene the duration of these events was ~300 yr with amplitudes varying from 0.9‰ to 1.5‰. The strongest wet events, in terms of duration and more negative values of $\delta^{18}O$, correspond to Bond event 4 and the 8.2 kyr B.P. event, respectively (Fig. 2). Soon after the 8.2 kyr B.P. event, a dry event with similar amplitude (~1.5‰) and duration (~0.3 k.y.) occurred at 7.8 kyr B.P., an event without any equivalent in the paleoclimate records from South America. These abrupt events recorded in Brazil present isotopic amplitudes that are 2 to 3 times larger than documented in the Dongge Cave speleothem records (eastern China), where the largest event took place at 8.2 kyr B.P. with only a ~0.5‰ shift (Wang et al., 2005).

Late Holocene abrupt events are equivalent to those observed in the early and middle Holocene in terms of their amplitude; however, they are much more short-lived, not lasting longer than 100 yr. The longest event occurred at 2.7 kyr B.P. and lasted ~100 yr, followed by other abrupt shorter fluctuations of <~50 yr (3.2, 2.3, 2.2, and 1.9 kyr B.P.), which are constrained by 2–8 data points (see Fig. DR2). These results suggest significant differences in the mechanism controlling multidecadal to centennial SAMS variability between the early to middle Holocene and late Holocene.

Figure 2 presents a comparison of the Lapa Grande isotope record with IRD pulses in the North Atlantic expressed in terms of percentage of hematite-stained grain variations and with other paleomonsoon records from South America and eastern China. Abrupt negative shifts of $\delta^{18}O$ in the Lapa Grande record show a striking match with Bond events during the early and middle Holocene, consistent with the notion of a SAMS intensification during cold events in the Northern Hemisphere (Baker et al., 2001, 2005; Ekdahl et al., 2008; Cheng et al., 2009). These abrupt decreases in $\delta^{18}O$ values, associated with increased precipitation in central-eastern Brazil, closely correspond with an anomalously cold North Atlantic during Bond events 6, 5, and 4, and during the 8.2 kyr B.P. event (Fig. 2). However, it is important to note that other significant wet events, albeit with shorter duration, occurred at 7.1 and 6.6 kyr B.P. at times of low IRD input to the North Atlantic, apparently unrelated to Bond events.

Conversely, the impact of these events seems to produce a different rainfall response over tropical South America during the late Holocene. Even though negative excursions of $\delta^{18}O$ in our speleothems are still

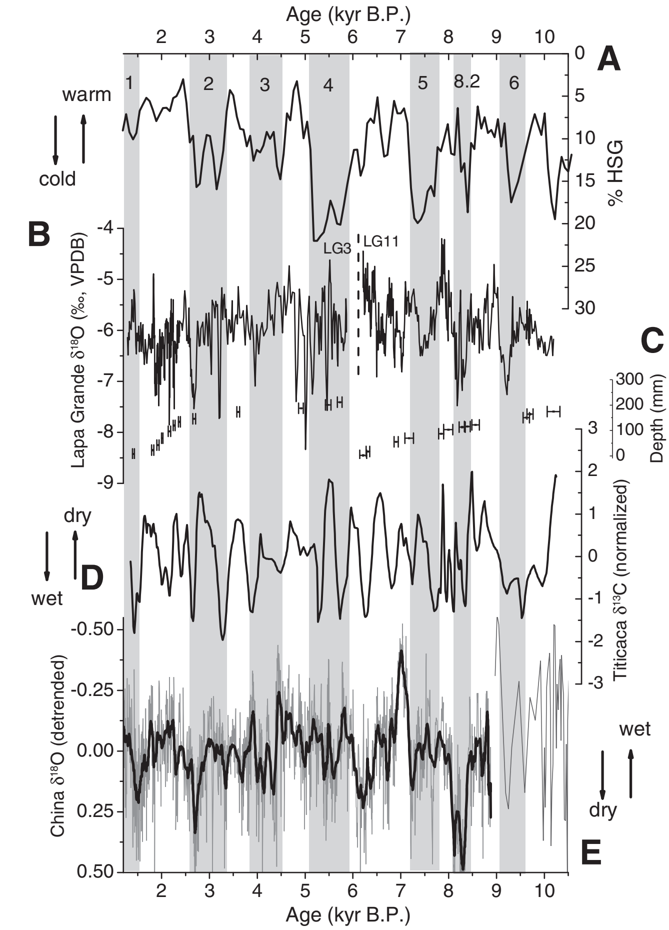

Figure 2. A: Hematite-stained quartz grain (HSG) record from North Atlantic marine core VM 29-191 (Bond et al., 2001). B: Composite $\delta^{18}O$ record from stalagmites LG3 and LG11, Lapa Grande Cave, central-eastern Brazil. Vertical dashed line marks area that is not represented by either LG3 or LG11 isotope profiles. VPDB—Vienna Peedee belemnite. C: Age-depth (in mm, relative to top) relations. Horizontal error bars indicate typical U/Th dating errors for speleothems. D: Detrended $\delta^{13}C$ record from Lake Titicaca (Bolivia and Peru; Baker et al., 2005). E: Detrended DA (light gray) and D4 (dark gray) stalagmite $\delta^{18}O$ record from Dongge Cave, eastern China (Wang et al., 2005; Yuan et al., 2004). A 20 yr running mean of DA $\delta^{18}O$ time series is in black. Bond events 1–6 and 8.2 kyr B.P. event are indicated by gray bars.

coherent with Bond events 2 and 4, a change in the temporal structure of the events is apparent. For example, the Lapa Grande record shows no response to Bond events 1 and 3.

Anomalously cold conditions in the North Atlantic region apparently affected SAMS precipitation over part of the continent, as indicated by the large coherence in both amplitude and duration of wet events in Brazil with periods of high lake levels of Titicaca inferred from $\delta^{13}C$ of organic matter in sediments (Fig. 2C) (Baker et al., 2005). The relationship also appears to have been valid during periods of strong reductions in SAMS paleoprecipitation that occurred synchronously in Bolivia and central-eastern Brazil within age errors.

The Lapa Grande paleoprecipitation record shows a prominent antiphased relationship with Asian Monsoon precipitation as recorded in the Dongge speleothem record (Wang et al., 2005) (Fig. 2). Low Asian Monsoon activity over eastern China during Bond events 6, 5, and 2 (9.2, 7.4, and 3.1–2.7 kyr B.P.) and the 8.2 kyr B.P. event coincided with an intensification of the SAMS over central-eastern Brazil (Fig. 2.).

Differences in the climate response to typical Northern Hemisphere cold events throughout the Holocene might be the result of glacial boundary conditions that persisted until ca. 7 kyr B.P. (Carlson et al., 2008). The longer duration of abrupt wet events recorded in central-eastern Brazil during the early Holocene is probably related to the rapid meltdown of the remaining Laurentide ice caps, potentially reducing the strength of the AMOC (Carlson et al., 2008; Fleitmann et al., 2008; Bernal et al., 2011). This mechanism may have exerted a strong influence on meridional SST gradients in the tropical Atlantic, thereby increasing monsoonal rainfall in southern tropical South America. However, after ca. 7 kyr B.P., the absence of significant ice would have reduced the potential effectiveness of such a meltwater-driven mechanism.

Our record of variations in SAMS precipitation shows some consistencies with the Ti record from the Cariaco Basin, an extensively used proxy record for rainfall distribution within the area influenced by the Intertropical Convergence Zone (ITCZ) (Fig. DR2). Despite the amplitude of climate oscillations in northern Minas being much larger than those recorded in the Cariaco Basin, abrupt events recorded during the early and middle Holocene are generally synchronous within age errors (e.g., Bond events 6 and 4, and the 8.2 kyr B.P. event), as are some of the shorter events that occurred during the late Holocene. In addition, the generally antiphased pattern of tropical precipitation between hemispheres is evident when comparing speleothem records from Brazil and China, for example ca. 2.7 and 2.3 kyr B.P., during Bond event 2, suggesting an intrinsic control on SAMS precipitation activity through the mean latitudinal position of the ITCZ. Some incongruities between South America and Central America are in part due to a stronger influence of El Niño/La Niña Southern Oscillation (ENSO) in certain regions such as Central America and the Caribbean during the late Holocene (Haug et al., 2001; Lachniet et al., 2004). In contrast, central-eastern Brazil is not significantly influenced by ENSO (Garreaud et al., 2009).

A spectral analysis of the composite stalagmites LG3 and LG11 shows that the most prominent periodicity observed in the Lapa Grande paleoprecipitation record during the early and middle Holocene is at ~820 yr (Figs. DR2 and DR4). The same periodicity is described in the Cueva del Diablo record, southwestern Mexico (Bernal et al., 2011), and for SST variations in the eastern equatorial Pacific (Marchitto et al., 2010), where warmer SST are observed during Bond events. In order to highlight the importance of this cycle during the early and middle Holocene, a sine function with a wavelength of 820 yr is compared with the $\delta^{18}O$ time series in Figure DR3. Multidecadal periodicities peaking at 60 and 110 yr are identified in our records from both the spectral analysis and the wavelet spectrum, suggesting an influence of the Atlantic Multidecadal Oscillation (Timmermann et al., 2007; Chiessi et al., 2009) on monsoon precipitation in central-eastern Brazil (Fig. DR3).

Bond et al. (2001) argued that most of the North Atlantic SST oscillations are likely tied to solar activity; hence, at least part of the Bond events could be driven by variations in solar activity. Indeed, the events at 9.2, 8.2, 7.5, 5.2, 2.7, and 2.3 kyr B.P. coincide with periods of low solar activity (high ^{14}C based on atmospheric $\Delta^{14}C$ and cosmogenic ^{10}Be deposition on the Greenland ice sheet) centered on 9.4, 8.2, 7.4, 5.4, 2.7, and 2.3 kyr B.P. (Bond et al., 2001). However, variations in solar irradiance alone cannot explain all these interhemispheric changes in monsoon rainfall. For example, none of the speleothem records from Brazil and China shows a significant covariance with solar activity during the events at 4.0 and 3.2 kyr B.P. (Fig. DR4).

Abrupt increases (decreases) in South American monsoon (Asian and Indian monsoon) rainfall have been related to lower SST in the North Atlantic, an intensification of the northeast trade winds, and a southward displacement of the ITCZ, invoking an intensification of cross-equatorial flow. At the same time of increased SAMS, warm SST is observed in the eastern equatorial Pacific (Marchitto et al., 2010). These results may have important implications for the notion of the establishment of El Niño–like conditions in the eastern tropical Pacific because atmospheric circulation changes forced by negative anomalies of SST in the Atlantic Ocean are partly controlled by the strength of the AMOC (Timmermann et al., 2007).

In this context, our results demonstrate that the slowdown of the AMOC associated with freshwater pulses in the North Atlantic can promote abrupt changes in monsoonal precipitation in South America, potentially influenced by feedback processes.

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REFERENCES CITED

Arz, H.W., Gerhardt, S., Pätzold, J., and Röhl, U., 2001, Millennial-scale changes of surface- and deep-water flow in the western tropical Atlantic linked to Northern Hemisphere high-latitude climate during the Holocene: Geology, v. 29, p. 239–242, doi:10.1130/0091-7613(2001)029<0239:MSCOSA>2.0.CO;2.

Baker, P.A., Seltzer, G.O., Fritz, S.C., Dunbar, R.B., Grove, M.J., Tapia, P.M., Cross, S.L., Rowe, H.D., and Broda, J.P., 2001, The history of South American tropical precipitation for the past 25,000 years: Science, v. 291, p. 640–643, doi:10.1126/science.291.5504.640.

Baker, P.A., Fritz, S.C., Garland, J., and Ekdahl, E., 2005, Holocene hydrologic variation at Lake Titicaca, Bolivia/Peru, and its relationship to North Atlantic climate variation: Journal of Quaternary Science, v. 20, p. 655–662, doi:10.1002/jqs.987.

Bernal, J.P., Lachniet, M., McCulloch, M., Mortimer, G., Morales, P., and Cienfuegos, E., 2011, A speleothem record of Holocene climate variability from southwestern Mexico: Quaternary Research, v. 75, p. 104–113, doi:10.1016/j.yqres.2010.09.002.

Bird, B.W., Abbott, M.B., Vuille, M., Rodbell, D.T., Stansell, N.D., and Rosenmeier, M.F., 2011, A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes: Proceedings of the National Academy of Sciences, v. 108, p. 8583–8588, doi:10.1073/pnas.1003719108.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., and Bonani, G.A., 1997, A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates: Science, v. 278, p. 1257–1266, doi:10.1126/science.278.5341.1257.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., and Bonani, G., 2001, Persistent solar influence on North Atlantic climate during the Holocene: Science, v. 294, p. 2130–2136, doi:10.1126/science.1065680.

Carlson, A.E., LeGrande, A.N., Oppo, D.W., Came, R.E., Schmidt, G.A., Anslow, F.S., Licciardi, J.M., and Obbink, E., 2008, Rapid early Holocene deglaciation of the Laurentide ice sheet: Nature Geoscience, v. 1, p. 620–624, doi:10.1038/ngeo285.

Cheng, H., Fleitmann, D., Edwards, L.R., Wang, X., Cruz, F.W., Auler, A.S., Mangini, A., Wang, Y., Kong, X., Burns, S.J., and Matter, A., 2009, Timing and structure of the 8.2 kyr B.P. event inferred from $\delta^{18}O$ records of stalagmites from China, Oman, and Brazil: Geology, v. 37, p. 1007–1010, doi:10.1130/G30126A.1.

Chiessi, C.M., Mulitza, S., Pätzold, J., Wefer, G., and Marengo, J.A., 2009, Possible impact of the Atlantic Multidecadal Oscillation on the South American summer monsoon: Geophysical Research Letters, v. 36, L21707, doi:10.1029/2009GL039914.

Cruz, F.W., Vuille, M., Burns, S.J., Wang, X., Cheng, H., Werner, M., Edwards, L.R., Karmann, I., Auler, A.S., and Nguyen, H., 2009, Orbitally driven east-west antiphasing of South American precipitation: Nature Geoscience, v. 2, p. 210–214, doi:10.1038/ngeo444.

Ekdahl, E.J., Fritz, S.C., Baker, P.A., Risgby, C.A., and Coley, K., 2008, Holocene multidecadal- to millennial-scale hydrologic variability on the South American Altiplano: The Holocene, v. 18, p. 867–876, doi:10.1177/0959683608093524.

Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., and Matter, A., 2003, Holocene forcing of the Indian Monsoon recorded in a stalagmite from southern Oman: Science, v. 300, p. 1737–1739, doi:10.1126/science.1083130.

Fleitmann, D., Mudelsee, M., Burns, S.J., Bradley, R.S., Kramers, J., and Matter, A., 2008, Evidence for a widespread climatic anomaly at around 9.2 ka before present: Paleoceanography, v. 23, PA1102, doi:10.1029/2007PA001519.

Garreaud, R.D., Vuille, M., Compagnucci, R., and Marengo, J., 2009, Present-day South American climate: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 281, p. 180–195, doi:10.1016/j.palaeo.2007.10.032.

Haug, G., Hughen, K., Sigman, D.M., Peterson, L.C., and Röhl, U., 2001, Southward migration of the Intertropical Convergence Zone through the Holocene: Science, v. 293, p. 1304–1308, doi:10.1126/science.1059725.

Lachniet, M., Burns, S.J., Piperno, D.R., Asmerom, Y., Polyak, V.J., Moy, C.M., and Christenson, K., 2004, A 1500-year El Niño/Southern Oscillation and rainfall history for the Isthmus of Panama from speleothem calcite: Journal of Geophysical Research, v. 109, D20117, doi:10.1029/2004JD004694.

Marchitto, T.M., Muscheler, R., Ortiz, J.D., Carriquiry, J.D., and van Geen, A., 2010, Dynamical response of the tropical Pacific Ocean to solar forcing during the early Holocene: Science, v. 330, p. 1378–1381, doi:10.1126/science.1194887.

O'Brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., and Whitlow, S.I., 1995, Complexity of Holocene climate as reconstructed from a Greenland ice core: Science, v. 270, p. 1962–1964, doi:10.1126/science.270.5244.1962.

Shen, C.-C., Edwards, R.L., Cheng, H., Dorale, J.A., Thomas, R.B., Moran, S.B., Weinstein, S.E., and Edmonds, H.N., 2002, Uranium and thorium isotopic and concentration measurements by magnetic sector inductively coupled plasma mass spectrometry: Chemical Geology, v. 185, p. 165–178, doi:10.1016/S0009-2541(01)00404-1.

Timmermann, A., and 13 others, 2007, The influence of a weakening of the Atlantic Meridional Overturning Circulation on ENSO: Journal of Climate, v. 20, p. 4899–4919, doi:10.1175/JCLI4283.1.

Vera, C., and 12 others, 2006, Toward a unified view of the American monsoon systems: Journal of Climate, v. 19, p. 4977–5000, doi:10.1175/JCLI3896.1.

Vuille, M., Bradley, R.S., Werner, M., Healy, R., and Keimig, F., 2003, Modeling $\delta^{18}O$ in precipitation over the tropical Americas: 1. Interannual variability and climatic controls: Journal of Geophysical Research, v. 108, no. D6, 4174, doi:10.1029/2001JD002038.

Wang, Y., Cheng, H., Edwards, R.L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M.J., Dykoski, C.A., and Li, X., 2005, The Holocene Asian Monsoon: Links to solar changes and North Atlantic climate: Science, v. 308, p. 854–857, doi:10.1126/science.1106296.

Yuan, D., and 12 others, 2004, Timing, duration, and transitions of the Last Interglacial Asian monsoon: Science, v. 304, p. 575–578, doi:10.1126/science.1091220.

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