Millennial-scale precipitation changes in southern Brazil over the past 90,000 years

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[1] A U-Th dated 90,000 year-long speleothem oxygen isotope record from southern Brazil anti-correlates remarkably with the cave calcite records from eastern China, but positively correlates with the speleothem record from northeastern Brazil, suggesting an interhemispheric anti-phasing of rainfall on both millennial and orbital timescales, likely related to displacement in the mean position of the intertropical convergence zone and associated asymmetry in Hadley circulation. The phase relationships among these records are consistent with the hypothesis that abrupt climate events during the last glacial period are triggered by oceanic circulation changes in the high latitudes and enhanced by tropical feedbacks.
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1. Introduction

[2] Millennial-scale climate events were first revealed in the Greenland ice cores [e.g., *Dansgaard et al.*, 1993] and similar events were later identified elsewhere around the world [*Voelker and Workshop Participants*, 2002]. The mechanism of these changes is not yet resolved [*Broecker*, 2003]. Change in Atlantic meridional overturning circulation (AMOC) is a possible trigger for these events [*Broecker et al.*, 1990]. Rapid cooling in the north could produce a southern warming through the bipolar seesaw mechanism [*Broecker*, 1998], although exact phase relationships between distant paleoclimate records may be complex [*Blunier and Brook*, 2001; *Stocker and Johnsen*, 2003]. Climate change in the North Atlantic would also drive latitudinal intertropical convergence zone (ITCZ) migration, causing tropical rainfall shifts [e.g., *Chiang et al.*, 2003]. However, it has been argued that such changes could be initiated in the tropics and propagated worldwide through an El Niño-Southern Oscillation (ENSO)-like mechanism [*Cane*, 1998]. Persistent ENSO phenomenon, the so-called Super-ENSO, may influence global climate on millennial and orbital timescales through teleconnection patterns [*Clement and Cane*, 1999], driving a similar climatic seesaw between two hemispheres [*Stocker*, 1998].

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[3] The AMOC and Super-ENSO scenarios may result in different patterns of low-latitude precipitation change during abrupt climate events, analogous to today's (Figure 1). For example, modern El Niño events induce drought in northeastern Brazil and high precipitation in southern Brazil [*Ropelewski and Halpert*, 1987; *Lau and Zhou*, 2003]. If these patterns hold for millennial timescales, the Super-ENSO mechanism would generate anti-phased precipitation between the two regions. On the other hand, the AMOC mechanism causes ITCZ migration and associated Hadley changes [e.g., *Zhang and Delworth*, 2005; *Broccoli et al.*, 2006]. Similar to modern seasonal observations, the precipitation in these two regions may shift in concert on millennial timescales, both out of phase with northern low-latitude precipitation. If so, we can distinguish between these two mechanisms if we can determine the sense of precipitation phasing between the two Brazilian sites.

[4] In order to establish the pattern and phasing of low-latitude precipitation, we need records with accurately and precisely known chronologies. Here we report a new record from southern Brazil and compare it with the records from eastern China [*Wang et al.*, 2001; *Yuan et al.*, 2004; *Wang et al.*, 2005] and northeastern Brazil [*Wang et al.*, 2004]. By applying U-Th dating methods at all three localities, we can precisely characterize their phase relationships based on their independent and absolutely-dated chronologies and test hypotheses about abrupt climate change.

2. Methods, Sample, and Climate Setting

[5] We previously obtained a speleothem record for the last 36 thousand years (ky) from Caverna Botuverá (27°13'S, 49°09'W, 250 m above sea level), southern Brazil [*Wang et al.*, 2006]. The record is relatively short and, though precisely dated, has hiatuses over several critical time intervals, such as the period between 17 and 11 ky before the present (B.P.). *Cruz et al.* [2005] also reported Botuverá data, covering a much longer time span; however, the millennial-scale events were not well constrained. Here we report an oxygen isotope (δ^{18}O) record from another sample (BTV3A) collected from Caverna Botuverá (Figure 1). The new data are extensive and precise enough so that we can characterize abrupt climate events and correlate them with other contemporaneous records.

[6] BTV3A is a 24 cm-long calcite stalagmite. 16 subsamples were dated with U-Th methods by inductively coupled plasma mass spectrometry (ICP-MS) [*Shen et al.*, 2002]. The sample grew continuously for the last 90 ky without detectable hiatuses. All dates are in stratigraphic order, with a typical relative 2σ error of about 0.5%. 239 oxygen isotopic analyses were made on this sample

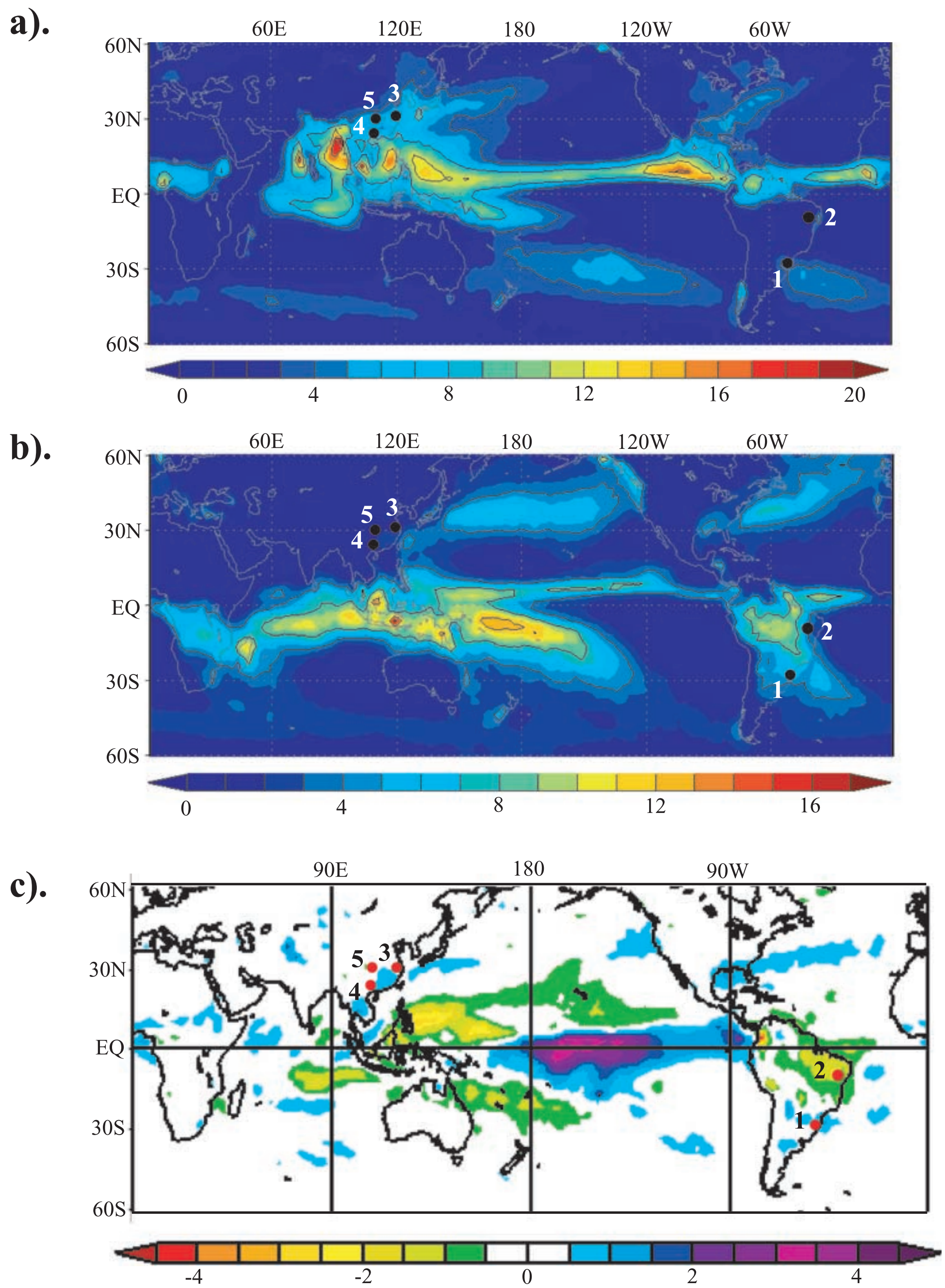

Figure 1. (a) Global long term mean precipitation (mm/day) derived from years 1979 to 2000 averaged from June to August (JJA). (b) Same as Figure 1a but from December to February (DJF). (c) Composite anomaly of precipitation rate (mm/day) during winter (Nov-Mar) associated with 8 El Niño events (1957–1958, 1965–1966, 1968–1969, 1972–1973, 1982–1983, 1986–1987, 1991–1992 and 1997–1998) from 1948 to the present. Anomalies are defined as the difference from the 1968–1996 means. Images are from website http://www.cdc.noaa.gov/. Numbers in the figure indicate cave locations mentioned in text: 1, Caverna Botuverá; 2, northeastern Brazil caves (10°10'S, 40°50'W); 3, Hulu Cave (32°30'N, 119°10'W); 4, Dongge Cave (25°17'N, 108°5'W); and 5, Shanbao Cave (31°40'N, 110°26'W).

(Tables S1 and S2).[1] The chronology is established using linear interpolation between dates (Figure 2). Procedures on sampling, chemical separation and mass spectrometric measurements are similar to those described by *Wang et al.* [2006].

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2007gl031149.

[7] Climate in southern Brazil is largely affected by the South American Summer Monsoon (SASM), a large-scale atmospheric circulation system over the continent [*Zhou and Lau*, 1998]. During austral summer, the ITCZ moves southward and deep convection forms over most of tropical South America (Figure 1b). Although not directly affected by the ITCZ, southern Brazil receives a large amount of water vapor derived from the Amazon basin by a south-

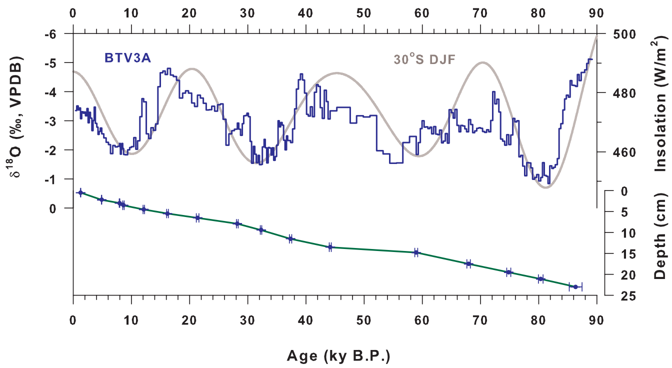

Figure 2. The δ^{18}O time series of calcite stalagmite BTV3A with reversed scale over the last 90 ky (blue curve). Gray curve presents 30°S insolation integrated over December, January and February (DJF) [*Berger*, 1978]. BTV3A age versus depth profile (dark green curve). Also shown are ICP-MS ^{230}Th dating points and 2σ error bars.

eastward low-level jet (LLJ) [*Vera et al.*, 2006]. However during winter, regional precipitation is mainly created by mid-latitude cyclones with distinct moisture from the nearby subtropical Atlantic [*Vera et al.*, 2002]. Meteorological data for the last 50 years indicate a positive relationship between monsoonal rainfall amount in southern Brazil and the SASM activity associated with sea surface temperature (SST) in the neighboring ocean [*Liebmann et al.*, 2004]. When the SASM is intensified, rainfall increases in this region and is characterized by low δ^{18}O because of a large recycled moisture contribution from remote Amazonian source [*Vuille and Werner*, 2005].

3. Results and Record Comparisons

[8] The BTV3A δ^{18}O values fluctuate significantly throughout the whole profile, with an amplitude as large as 4‰ (Figure 2). The record broadly follows local summer insolation variation, confirming the *Cruz et al.* [2005] conclusions, but with more precise dating control. Low calcite δ^{18}O values appear to have occurred in phase with 30°S summer insolation maxima produced by the Earth's precession cycle. Additionally, the record successfully captures millennial-scale events that punctuate this orbital pattern during the last glacial period. Short term δ^{18}O dips (−3 to −5‰ VPDB) are observed at about 87.0 ky, 76.6 ky, 72.5 ky, 66.0 ky, 60.3 ky, 47.6 ky, 43.5 ky, 42.1 ky, 39.4 ky, 35.4 ky, 30.1 ky, 16.7 ky, and 12.1 ky B.P., coinciding with known cold episodes over Greenland, such as the Younger Dryas and those that correlate with Heinrich events [e.g., *Dansgaard et al.*, 1993], and weak East Asian Monsoon (EAM) events recorded in eastern China caves [*Wang et al.*, 2001]. The abrupt drop in δ^{18}O associated with these events is large, with up to 2‰ amplitude.

[9] Previous studies demonstrated that speleothem samples from Botuverá cave were deposited under isotopic equilibrium conditions [*Cruz et al.*, 2005; *Wang et al.*, 2006]. Their calcite δ^{18}O was subsequently suggested to be a good proxy of local meteoric water. Most recently, a trace element study on a Botuverá stalagmite shows that variations of Mg(Sr)/Ca ratios are in general positively correlated with the δ^{18}O change along the growth axis [*Cruz et al.*, 2007], which confirms that Botuverá δ^{18}O is dominated by the monsoonal rainfall amount [*Wang et al.*, 2006]. Similar to speleothem δ^{18}O in eastern China as a proxy of EAM intensity, Botuverá δ^{18}O record largely reflects change in the SASM activity. Low (high) Botuverá speleothem δ^{18}O indicates intensified (weakened) SASM activity, more (less) Amazon moisture contribution and higher (lower) rainfall in southern Brazil.

[10] Using their individual chronologies, we compare the Botuverá δ^{18}O record with the eastern China δ^{18}O profile, which is a combination of records from Hulu [*Wang et al.*, 2001], Dongge [*Yuan et al.*, 2004; *Wang et al.*, 2005], and Shanbao caves (Y. Wang and R. L. Edwards, unpublished data, 2007) (Figures 1 and 3). All records are precisely established with a relative 2σ error in age of about 0.5–1%. Within dating errors, the comparison shows a remarkable anti-correlation between records on both orbital and millennial scales. Throughout the whole profile, the lower Botuverá δ^{18}O coincides precisely with the higher δ^{18}O in the eastern China speleothems, and vice versa, which indicates a rainfall seesaw between the two low-latitude regions. We also compare our Botuverá δ^{18}O record to the record of speleothem growth periods from northeastern Brazil [*Wang et al.*, 2004], an indicator of pluvial phases in this currently semi-arid region (Figures 1 and 3). Although the latter may not be a complete data set, a striking positive phase relationship stands out between the two records. For instance, northeastern Brazil speleothem resumes growth around 87 ky, 72 ky, 66 ky, 48 ky, 39 ky, 16 ky and 12 ky B.P., when δ^{18}O values are relatively low in the southern Brazil sample. The correlation between these three records therefore suggests that on millennial timescales, rainfall changes in southern Brazil and northeastern Brazil are in phase, and both anti-correlate with precipitation variation in eastern China.

4. Mechanisms on the Abrupt Climate Events

[11] Thus, the observed pattern is consistent with the AMOC mechanism driving ITCZ migration and associated Hadley cell changes and inconsistent with the pattern envisioned for the Super-ENSO hypothesis. Recent model-based simulations successfully illustrate that, with melt-water discharge, cooling in the North Atlantic can induce significant responses in the tropics [e.g., *Chiang et al.*, 2003; *Zhang and Delworth*, 2005], such as weakened monsoon and reduced rainfall in eastern China [*Wang et al.*, 2001] and increased precipitation in northeastern Brazil

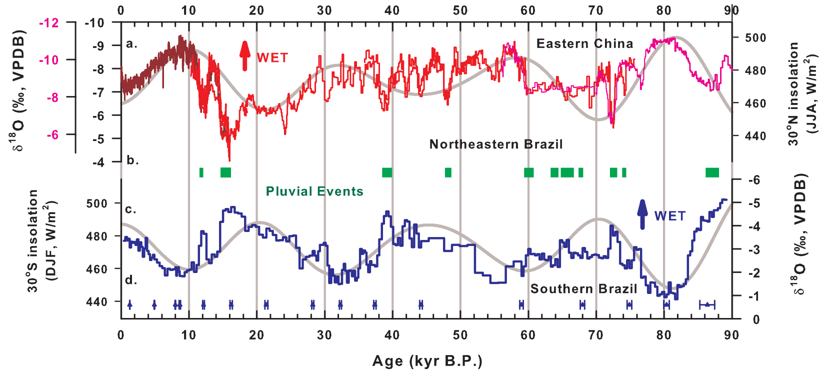

Figure 3. Comparisons of speleothem records. (a) A combined profile of the eastern China δ^{18}O records (Dongge Cave, dark red [*Yuan et al.*, 2004; *Wang et al.*, 2005]; Hulu Cave, red [*Wang et al.*, 2001]; and Shanbao Cave, pink (Y. Wang and R. L. Edwards, unpublished data, 2007)). Contemporaneous Dongge and Hulu stalagmites have virtually identical δ^{18}O values, while Shanbao values are offset by about -1‰, but with a similar pattern to Hulu (see replicated portions). (b) Northeastern Brazil growth periods (green) [*Wang et al.*, 2004]. (c) Southern Brazil δ^{18}O record (Caverna Botuverá, blue). (d) The 2σ age error bars for the BTV3A record (blue). Note scales for speleothem δ^{18}O are all reversed, increasing downwards. All three chronologies are established independently with uranium-thorium methods, with typical 2σ errors of about 0.5–1%. Also shown are 30°N and 30°S summer insolation (JJA and DJF, respectively, gray curves) [*Berger*, 1978].

[*Wang et al.*, 2004]. AMOC changes may lead to SST anomalies in the southern Atlantic due to the bipolar seesaw mechanism [*Broecker*, 1998, *Knutti et al.*, 2004]. Similar to today's climate [*Liebmann et al.*, 2004], a warm (cold) SST anomaly over the subtropical South Atlantic during glacial stadials (interstadials) would produce an intensified (weakened) SASM, and therefore, high (low) rainfall in southern Brazil. Moreover, substantially weakened AMOC and increased sea ice coverage in the northern high latitudes result in a southward ITCZ shift [*Chiang et al.*, 2003] and would subsequently alter Hadley circulation [*Lindzen and Hou*, 1988]. Such modification produces intensified uplift of moist air in the southern low latitudes but strong subsidence in the north [*Lindzen and Hou*, 1988], and therefore, may also contribute to the anti-correlation of the intensities of the two monsoon systems and the mirror-image rainfall pattern between southern Brazil and eastern China.

[12] ENSO originates in the tropical Pacific, but its climate impacts are global in extent [*Ropelewski and Halpert*, 1987; *McPhaden et al.*, 2006]. In the tropical Atlantic region, northeastern Brazil experiences dramatic decrease of precipitation during El Niño years, probably because of strong atmospheric subsidence [*Lau and Zhou*, 2003, Figure 1c]. However, heavy rains and flooding are almost simultaneously observed in southern Brazil due to significant enhancement of the SASM and LLJ east of the Andes, probably coupled with sinking motion over northern Brazil caused by the El Niño anomaly [*Lau and Zhou*, 2003, Figure 1c]. Persistent ENSO behavior with high frequency and severe intensity, i.e. Super-ENSO, is suggested to be the mechanism propagating millennial-scale abrupt climate events around the world [*Cane*, 1998], possibly applicable on orbital scales as well [*Clement and Cane*, 1999]. Super-ENSO may modulate freshwater balance between the tropical Atlantic and Pacific, and subsequently the AMOC [*Schmittner and Clement*, 2002]. However, results from field studies are controversial. Salinity in the western tropical Pacific warm pool is elevated during glacial stadials, indicating a phenomenon analogous to the modern warm phase (El Niño) [*Stott et al.*, 2002], whereas wet periods in northeastern Australia suggest less frequent El Niño events when the North Atlantic is cold [*Turney et al.*, 2003]. Recent work in both the tropical western Atlantic and eastern Pacific shows that when the north Atlantic was cold, sea surface salinity increased [*Schmidt et al.*, 2006; *Leduc et al.*, 2007] associated with cooling and reduced rainfall in the regions [*Peterson et al.*, 2000]. Moreover, both northeastern Brazil and southern Brazil are observed to be wetter at times of high-latitude cooling. This in-phase relationship of rainfall change between the two Brazilian locations on millennial timescales does not favor the above Super-ENSO mechanism because their rainfall patterns would be out of phase if the modern ENSO behavior does not change substantially with time [*Clement and Cane*, 1999; *Tudhope et al.*, 2001]. On the contrary, together with observations in low latitude Pacific regions, the patterns are consistent with shifts in the mean ITCZ position, linked to AMOC changes.

5. Conclusions

[13] There is no doubt that the tropics play a critical role in global heat and water vapor transport. However, if the modern climate observations are a good analogue for the past, the Super-ENSO patterns do not appear to be the dominant feature during millennial-scale events. Instead, they may be strongly modulated by AMOC changes and associated ITCZ migration [*Zhang and Delworth*, 2005; *Koutavas et al.*, 2006]. Through air-sea dynamics, abrupt climate events initiated in the North Atlantic eventually telecommunicate to the low latitudes.

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