A new perspective on the hydroclimate variability in northern South America during the Little Ice Age

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[1] An absolute dated speleothem oxygen isotope (δ^{18}O) record from northeastern Peru documents monsoon precipitation variability over northern South America during the past that 1000 years and indicates the annual precipitation in the 15th through the 18th centuries, the so-called Little Ice Age (LIA), was on average ~10% higher than during the 20th century. Over the 20th century recurrent modes of seasonal rainfall variability across northern South America were associated with discrete sea surface temperature anomaly patterns within the Atlantic and Pacific Oceans. Calling upon these SST-rainfall teleconnectivity patterns, and paleo-SST reconstructions that span the past 8 centuries, higher annual rainfall across northern South America during the LIA is attributed to cooler boreal spring SSTs in the tropical North Atlantic. Weaker co-variance between north Atlantic SSTs and the South American Monsoon System (SAMS) rainfall during the 20th century suggests that ENSO has become a more dominant influence than it was during the LIA.
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1. Introduction

[2] The annual cycle of precipitation over northern South America is monsoonal [*Vera et al.*, 2006]. A precipitation maxima occurs in austral summer in response to solar heating of the tropical landmass with its steep topographic relief, and the progressive movement of the Intertropical Convergence Zone (ITCZ), which accompanies the migration of deep atmospheric convection over the continent. The expression of seasonal rainfall is however, both spatially and temporally variable due in part to the topographic complexity that characterizes the continent and because of variable sea surface temperatures in both the Atlantic and in the Pacific that influence convective overturning within the tropical atmosphere [*Nogues-Paegle and Mo*, 1997; *Paegle et al.*, 2000; *Paegle and Mo*, 2002; *Vera et al.*, 2006; *Vuille and Keimig*, 2004; *Vuille and Werner*, 2005; *Walker*, 1928; *Zhou and Lau*, 2001]. The temporal and spatial complexity of atmospheric behavior means that any single station record of rainfall, be it from an observational station or from a long proxy reconstruction such as an ice core or speleothem, may not adequately resolve the continental scale hydrologic variations. Nonetheless, with a limited number of observational stations and a short instrumented record, proxy records are an important asset in assessing modes of climate change because they can extend the observational record significantly.

[3] In the effort to extend the record of hydroclimate variability for northern South America it has been postulated that down-core variations in detrital Ti accumulation in the sediments of the Cariaco Basin (~10°N on northern margin of Venezuela) track temporal variations in the amount of precipitation that fell over northern South America [*Haug et al.*, 2001; *Peterson and Haug*, 2006] and that precipitation over the continent has varied in response to changes in the annual cycle. This interpretation is motivated from observations that include: 1. Detrital Ti is eroded from the Andean highlands and carried by rivers to the coastal margins of South America, including the coastal margin of Venezuela; 2. the flux of Ti that is carried by South American rivers, including the Orinoco, increases at times of the year when river runoff is highest [*Peterson and Haug*, 2006], which is a function of the amount of precipitation that falls on northern South America [*Dai and Trenberth*, 2003]. Under present climate conditions the amount of precipitation that falls as rain over northern South America including the Amazon and Orinoco river basins (defined as −5 to 10 N) is highest between January and May with climatologic maxima in April (Figure 1). However, rainfall is highest over coastal Venezuela during June–August. It was on the basis of these modern observations that Peterson and Haug argued that when Ti accumulation in Cariaco Basin sediment was reduced in the past, there was less precipitation falling over northern South America [*Haug et al.*, 2001; *Peterson and Haug*, 2006]. Throughout the Holocene Ti accumulation closely followed the precessional changes in direct solar forcing and therefore, it appears that rainfall across northern South America was higher in the mid Holocene as compared to the late Holocene because summer season solar forcing was shifted further to the north [*Haug et al.*, 2001; *van Breukelen et al.*, 2008]. But a more recent and short-term departure in Ti accumulation occurred during the 16–18th centuries, a period often referred to as the "Little Ice Age" (LIA), that was not associated with a change in the seasonal solar insolation cycle. In their study of the LIA Ti excursion in the Cariaco Basin, *Peterson and Haug* [2006] called upon a shift in the annual cycle to explain the drop in Ti accumulation, but did not offer a discrete explanation for the disruption in the annual cycle.

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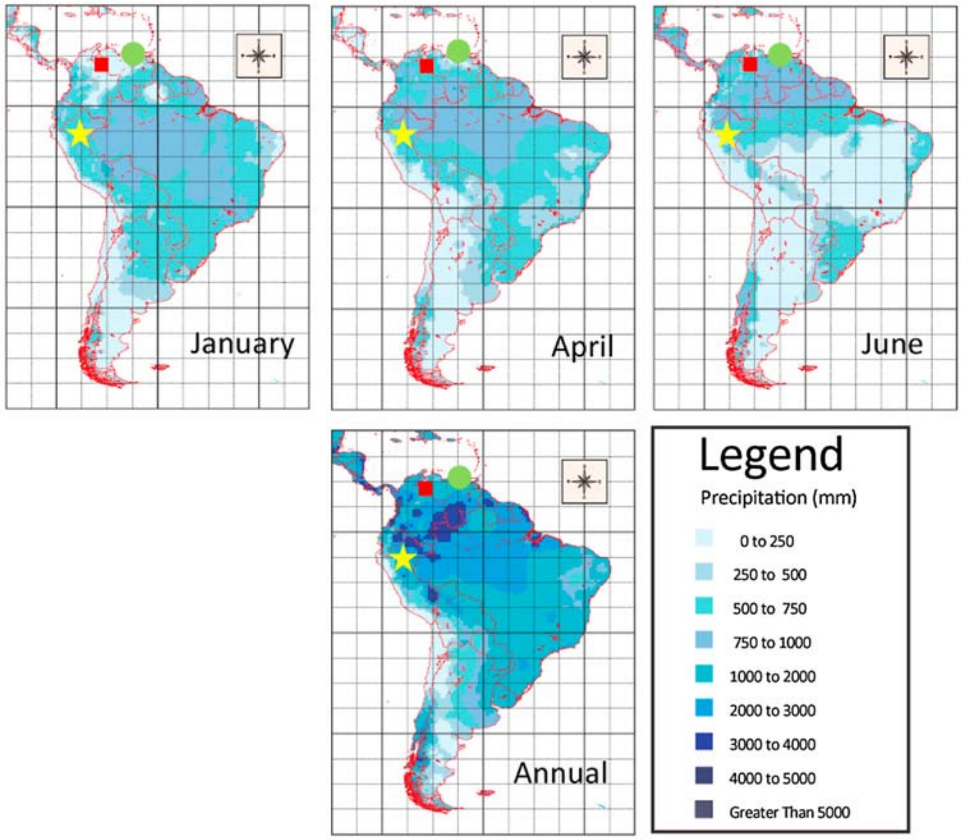

Figure 1. January, April, June and annual average rainfall climatology over South America [*Legates and Willmott*, 1990]. The yellow star marks the location of the CAS site, the red box marks Lake Mucubaji, Venezuela [*Polissar et al.*, 2006], the green circle is the Cariaco Basin.

In another study of hydrographic variability during the LIA, *Polissar et al.* [2006] found that in the high elevations of the Venezuelan Andes glaciers advanced during the LIA and interpreted this to be evidence of higher rather than lower precipitation. They attributed the higher precipitation to a steeper tropical lapse rate, possibly in response to variations in solar irradiance.

[4] Here we examine records of hydrologic variability over northern South America in the context of modern modes of variability that arise from forcing from within the Atlantic and from outside of the Atlantic. Our study incorporates new δ^{18}O data of precipitation derived from measurements of speleothem calcite that was collected in northeastern Peru (Figure 1). The speleothem δ^{18}O- rainfall estimates are based upon the relationship between rain water δ^{18}O and precipitation amount, the so-called "isotope amount effect", which is transmitted from the local aquifer to the speleothem during the precipitation of calcite. Observational records of precipitation from a network of tropical South America IAEA-GNIP stations, as well as simulations with atmospheric general circulation [*Vuille et al.*, 2003a, 2003b; *Yoshimura et al.*, 2008] and regional climate models equipped with stable isotope tracers [*Sturm et al.*, 2007], indicate the δ^{18}O of precipitation is negatively correlated with the amount of rainfall (or rainfall anomalies) that accompany changes in convective activity over the continent [*Sturm et al.*, 2007; *Vuille et al.*, 2003a, 2003b; *Vuille and Werner*, 2005].These studies also point to other less dominant site-specific influences on isotopic variability including, moisture source changes, seasonality of precipitation, evapotranspiration, moisture recycling and to a minor extent, temperature [*Vuille et al.*, 2003a, 2003b]. But the dominant influence on isotopic variations of annual rainfall is the amount effect. The slope of the interannual rainwater δ^{18}O versus the amount of precipitation in isotope enabled GCM simulations over the instrumental period falls between -0.4 and -0.8% per 100 mm increase in the mean annual precipitation [*Vuille et al.*, 2003a, 2003b; *Vuille and Werner*, 2005; *Yoshimura et al.*, 2008].

2. Study Area and Modern Climatology

[5] Two speleothems (CAS-A and CAS-D) were collected from Cascayunga cave in Northeast Peru along the eastern margin of the Andes Mountain range near the town of Cascayunga - (6°05′30″S, 77°13′30 W) (930 m) and Rioja - (6°03′46″S, 77°10′02″W) (841 m). Rainfall in this part of Peru is modulated by the annual solar cycle that influences convective activity over the continent and regulates winds. The Atlantic Ocean is the main source of moisture. Moisture crosses the continent primarily between the Guiana Highlands and the Brazilian Altiplano. The westward moisture transport at lower elevations is then turned southward along the Andes cordillera. During austral summer convective motion and high rainfall occurs over central Brazil and this is referred to as the South Atlantic Convergence Zone (SACZ) [*Vera et al.*, 2006].

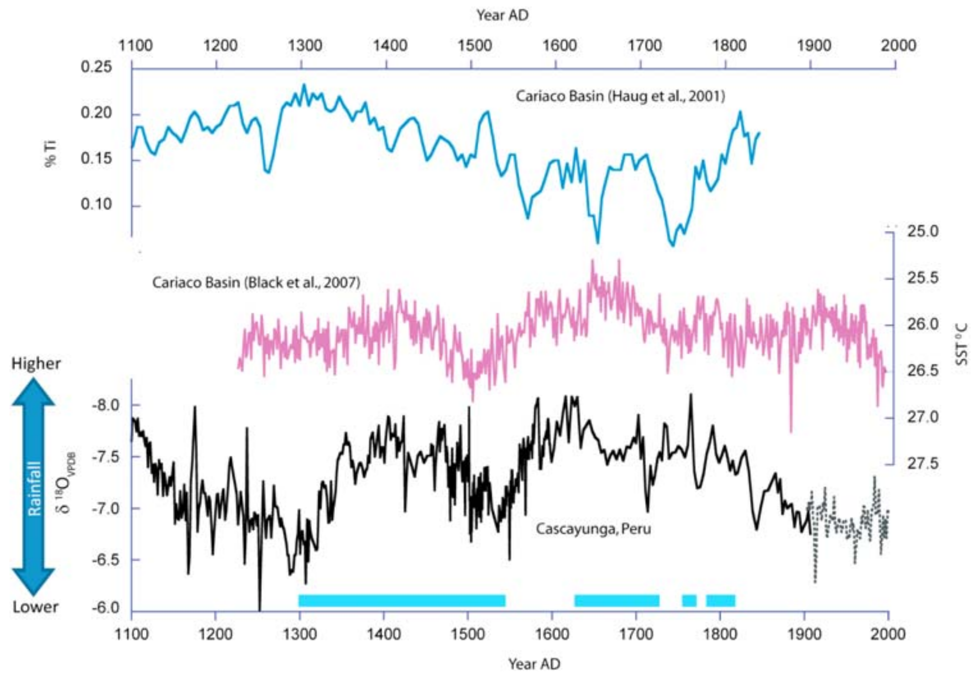

Figure 2. Cariaco Basin Titanium Record (blue); Cariaco SST (red); CAS speleothem rainfall δ^{18}O (black, the dashed line indicates CAS A, solid line is CAS D). Time of glacial advance in the Venezuelan Andes are indicated with blue bars [*Polissar et al.*, 2006].

[6] Importantly however, the maximum runoff from the large rivers such as the Orinoco, as well as from the Amazon occurs several months later due to the transport time between the Andean highlands and the coastal margins. For this reason, the sediment load that is carried by the Orinoco and other major rivers flowing towards the coastal basins of northern South America are most strongly influenced by the amount of rain that falls during austral summer, not in winter when the rainfall is at its highest over coastal Venezuela [*Dai and Trenberth*, 2003]. The Cascayunga cave site lies at a location where the annual rainfall is dominated by summer season (January–April) precipitation. It is therefore strategically located to record changes in the amount of rainfall during the summer monsoon season, the period when the major river basins receive the most rainfall and the river systems are charged. Over the latter half of the 20th century the region of Peru where the Cascayunga cave is located received an average annual rainfall of ~1973 mm [±807 mm].

3. Materials and Method

[7] A total of seven U-series dates were measured for CAS-D. This speleothem spans 540 AD to ~1900 AD. For the present study the top 14 cm was analyzed, covering the period between 1050 AD to 1900 AD (Table S1 of Text S1 of the auxiliary material).[1] For CAS-A there is only one U-Th age (1917 AD) which was taken at 0.5 cm from the top. A second datum of 2006 AD is applied to the top of the speleothem, which was actively growing when collected. Together these two speleothems provide a continuous time series covering the past 1000 years. The ^{230}Th dates were obtained at the Minnesota Isotope Laboratory, University of Minnesota using a Thermo-Finnigan Element equipped with a double-focusing sector-field magnet in reversed Nier-Johnson geometry and a single MasCom multiplier in peak-jumping mode (Table S1 of Text S1). The chemical procedures used to separate uranium and thorium for ^{230}Th dating are similar to those described by *Edwards et al.* [1987]. The procedures of charactering multiplier and instrumental approaches were similar to those described by *Cheng et al.* [2000] and *Shen et al.* [2002]. We used the half-life values reported by *Cheng et al.* [2000]. An age model was developed by linearly interpolating ages between ^{230}Th dates (Figure S1 of Text S1).

[8] Samples for oxygen isotope measurement were taken from the Cascayunga speleothems every 50 microns using a micro drill attached to an automated X-Y-Z stage. For the CAS-D speleothem every fifth sample was analyzed isotopically. For the CAS-A speleothem every sample was analyzed. The δ^{18}O measurements were made with an online, common acid bath system attached to a VG Prism II IRMS. The samples were analyzed isotopically relative to a working standard calibrated to VPDB via measurement of NIST standards. A calcite standard (ULTISS) was used in conjunction with the speleothems samples to monitor the analytical precision throughout the study. The average $\delta^{18}O_{VPDB}$ of 58 Ultiss samples analyzed during the present study was −2.00 ‰ with a standard deviation of ±0.11‰.

4. Results and Discussion

[9] Over the last 1000 years the CAS speleothems δ^{18}O record exhibits variability of more than 1.5‰ (Figure 2). The δ^{18}O values from the LIA sections between 1300 and 1900 AD are an average of ~1.0‰ lower than those from the 20th century. Taking a value for the modern regional

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL041051.

isotope-rainfall amount effect of 0.8‰ to 0.4‰ implies an increase in the amount of rainfall at Cascayunga of ~10–20% during the LIA compared to the 20th century. The latter half of the 16th and the 17th centuries stand out as the wettest period. Cooler temperatures within the cave during the LIA would have increased the speleothem δ^{18}O slightly (~0.2‰ per °C) and therefore may have offset some δ^{18}O decrease associated with increased rainfall. On the other hand, a steeper atmospheric lapse rate during the LIA may mean that the modern δ^{18}O-rainfall relationship underestimates the amount of rainfall increase. Taking into account both the cooler cave temperatures and a steeper lapse rate, the 1.0‰ lower δ^{18}O values during the LIA implies a substantial increase in the amount of rainfall during the LIA.

[10] A number of studies have documented the dynamical links between SST anomalies in both the Atlantic and Pacific and atmospheric anomalies that affect rainfall across northern South America [*Giannini et al.*, 2001; *Hastenrath and Greischar*, 1993; *Mechoso et al.*, 1990; *Uvo et al.*, 1998]. SST anomalies within the Pacific associated with ENSO have had dominant influence on the interannual variations in rainfall during the 20th century. But tropical Pacific SST anomalies are not the only influence on rainfall variability over South America. *Paegle and Mo* [2002] used an EOF analysis to describe four primary spatial patterns of rainfall variability over South America that arise from sea surface temperature anomalies within the Atlantic as well as the Pacific. During the late 20th century satellite-based estimates of rainfall variability and rain gauge data indicate that approximately 12% of the interannual rainfall variability over northern South America was related to ENSO [*Guevara*, 2006; *Paegle and Mo*, 2002]. El Niño disrupts atmospheric convection and reduces the amount of rainfall over the northern portions of the continent. This brings about enriched isotopic values of precipitation. On the other hand, La Niña is associated with enhanced convection and increased rainfall that is more isotopically depleted [*Paegle and Mo*, 2002; *Vera et al.*, 2006; *Vuille et al.*, 2003b; *Vuille and Werner*, 2005; *Yoshimura et al.*, 2008]. Changes in atmospheric temperatures also influence the isotopic composition of rainfall associated with El Niño and La Niña, but the dominant influence remains the amount effect [*Vuille et al.*, 2003b; *Vuille and Werner*, 2005]. The other major influence on the SAMS are the tropical Atlantic SSTAs, which account for another ~10% of the composite variance in interannual summer season rainfall variability during the 20th century [*Paegle and Mo*, 2002]. In particular, anomalously warm north, and cool south equatorial Atlantic SST anomalies are associated with reduced rainfall over northern South America. But due to the shortness of the instrumental record, it is difficult to know how persistent or how dominant the Pacific and the Atlantic SST influences have been in the past.

[11] Drawing upon the modern teleconnection patterns, the precipitation increase documented by the speleothem isotopic values in the 16 and 17th centuries could reflect a predominantly La Niña-like hydroclimate response to Pacific SSTs. Yet, while there is not yet a continuous SST record from the tropical Pacific covering the past 500 years, the existing data from the Pacific do not indicate there were more frequent or a more persistent La Niña-like climate in the Pacific during the LIA [*Cobb et al.*, 2003; *Graham et al.*, 2007; *Newton et al.*, 2006]. Hence, it would appear that ENSO was not the dominant influence on multidecadal SAMS variability during the 16–17th centuries. Anomalously cool SSTs in the north equatorial Atlantic and warmer SSTs to the south could however, explain the enhanced precipitation across northern South America, including Venezuela [*Guevara*, 2006; *Paegle and Mo*, 2002]. In fact, such a record is documented from the Cariaco Basin [*Black et al.*, 2007]. Boreal spring SSTs were ~1°C cooler in the northwestern equatorial Atlantic during the 16th and 17th centuries, coinciding with the precipitation increases observed at Cascayunga (Figure 2). Prior to the 20th century the temporal patterns of cooler SSTs correspond to periods of lower δ^{18}O/high rainfall. On a multi-decadal-scale (≥20 year) the correlation between SST variability in the Cariaco Basin and δ^{18}O at Cascayunga (CASD record) is 0.53 (Tables S2 and S3 of Text S1), suggesting that the tropical Atlantic SST variability was a significant influence on the rainfall variability over northern South America prior to the 20th century. In this view, the multidecadal to century-scale hydroclimate variability over northern South America during the LIA mimicked that portion of the modern interannual variability that is associated with tropical Atlantic SST variability. The relationship breaks down in the 20th century, which may imply a strengthened ENSO influence.

[12] The rainfall variability that is documented in the Cascayunga δ^{18}O reconstruction requires a reconsideration of how detrital Ti accumulation in the Cariaco Basin has been interpreted previously to reflect precipitation changes over northern South America during the LIA [*Peterson and Haug*, 2006]. During the 20th century cool SSTAs in the north equatorial Atlantic during boreal spring were associated with higher rainfall across northern South America and increased runoff from the major rivers that carry Ti from the Andean highlands to coastal Venezuela and the Cariaco Basin. Anomalously cool boreal spring SSTs in the North Atlantic during the LIA and higher rainfall as reflected in the CAS record should therefore have been associated with higher river runoff and a greater flux of Ti. But the Ti accumulation in the Cariaco Basin decreased during the LIA, reaching minimum values at times when rainfall at Cascayunga was highest (Figure 2). *Polissar et al.* [2006] produced a record of glacial advances in the Venezuelan Andes that compliments the Cascayunga results and indicates precipitation was also higher over the Venezuelan Andes during the LIA. Polissar et al argued that alpine glaciers advanced during the LIA because of the combined effects of a steepened adiabatic lapse rate and enhanced vapor transport via stronger northeasterly trade winds associated with cooler SSTs in the North Atlantic [*Black et al.*, 1999, 2007]. The cooler SSTs would have lowered the absolute humidity at sea level. The steepened lapse rate would have also lowered the dew point and enhanced vapor condensation as tropical air masses rose over the Andes. In this way precipitation would have increased from the low to higher elevations.

[13] In order to reconcile the hydroclimate reconstructions from speleothem δ^{18}O and glacial records from Venezuela with the Ti accumulation history from the Cariaco Basin, we propose an alternative interpretation of the Ti variability in the Cariaco Basin over the past millennia. The primary source of detrital titanium to the Cariaco Basin is the Tuy River [*Peterson and Haug*, 2006]. This river is

short (~250 km) and has an extremely high gradient, dropping from its source area at nearly 3000 meters to sea level in just 250 km. Most of the titanium that the Tuy River carries originates at high elevations where steep slopes expose Fe and Ti-rich terrain. Generally, increased precipitation over this terrain would be associated with enhanced erosion and higher sediment discharge into the rivers that flow off of the steep terrain. However, during the LIA a steepened tropospheric lapse rate meant that precipitation that fell at higher elevations was in the form of snow rather than as rain. Consequently, erosion in the source region would have been reduced as the terrain was covered in snow and ice. Titanium accumulation within Cariaco Basin clearly decreased at times when glaciers were advancing within the Andes. We therefore propose that precipitation associated with the SAMS increased during the LIA and that this was a response to cool boreal spring SSTs in the North Atlantic. The pattern of interdedadal co-variability between SSTAs in Cariaco Basin and the rainfall variability reflected in the Cascayunga breaks down during the late 19th century, at the end of the LIA (Figure 2 and Tables S2 and S3 of Text S1). We tentatively suggest that this transition reflects a strengthening influence of ENSO on rainfall variability over northern South America during the 20th century that was less dominant during the LIA.

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