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Invited review

Nature and causes of Quaternary climate variation of tropical South America

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ABSTRACT

This selective review of the Quaternary paleoclimate of the South American summer monsoon (SASM) domain presents viewpoints regarding a range of key issues in the field, many of which are unresolved and some of which are controversial. (1) El Niño-Southern Oscillation variability, while the most important global-scale mode of interannual climate variation, is insufficient to explain most of the variation of tropical South American climate observed in both the instrumental and the paleoclimate records. (2) Significant climate variation in tropical South America occurs on seasonal to orbital (i.e. multi-millennial) time scales as a result of sea-surface temperature (SST) variation and ocean–atmosphere interactions of the tropical Atlantic. (3) Decadal-scale climate variability, linked with this tropical Atlantic variability, has been a persistent characteristic of climate in tropical South America for at least the past half millennium, and likely, far beyond. (4) Centennial-to-millennial climate events in tropical South America were of longer duration and, perhaps, larger amplitude than any observed in the instrumental period, which is little more than a century long in tropical South America. These were superimposed upon both precession-paced insolation changes that caused significant variation in SASM precipitation and eccentricity-paced global glacial boundary conditions that caused significant changes in the tropical South American moisture balance. As a result, river sediment and water discharge increased and decreased across tropical South America, lake levels rose and fell, paleolakes arose and disappeared on the Altiplano, glaciers waxed and waned in the tropical Andes, and the tropical rainforest underwent significant changes in composition and extent.

To further evaluate climate forcing over the last glacial cycle (~125 ka), we developed a climate forcing model that combines summer insolation forcing and a proxy for North Atlantic SST forcing to reconstruct long-term precipitation variation in the SASM domain. The success of this model reinforces our confidence in assigning causation to observed reconstructions of precipitation. In addition, we propose a critical correction for speleothem stable oxygen isotopic ratios, which are among the most significant of paleoclimate proxies in tropical South America for reconstruction of variation of paleo-precipitation (or SASM intensity). However, it is already well known that any particular $\delta^{18}O$ value observed in speleothem carbonate is affected by two processes that have nothing to do with changes in precipitation amount—the influence of temperature on carbonate-water isotopic fractionation in the cave and the influence of changing $\delta^{18}O$ of seawater. Quantitatively accounting for both "artifacts" can significantly alter the interpretations of speleothem records. In tropical South America, both adjustments act in the same direction and have the tendency to increase the true amplitude of the paleo-hydrologic signal (but by different amounts in glacial and inter-glacial stages). These corrections have even graver implications for the interpretation of tropical Northern Hemisphere speleothem records (e.g. Chinese speleothems) where the combined adjustments tend to decrease or even eliminate the "true" signal amplitude.
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1. Introduction

Several reviews have been published concerning the Quaternary paleoclimate of tropical South America, including a recent edited volume on the topic (Vimeux et al., 2009). Thus, it would not be interesting, nor is it our intention, to produce an exhaustive recapitulation of the subject. Instead, in this selective review, we take the opportunity to offer our viewpoints and conclusions regarding a range of topics that we chose, because we believe they are key issues in the field yet still represent unsettled science.

We mostly limit our discussion to *tropical* South America and, more restrictively, to tropical South America from the Andes eastward and south of the equator (Fig. 1). This area incorporates most of South America (and most of the Amazon basin), which is after all dominantly a tropical and Southern Hemisphere continent. This region is highlighted, because it lies largely within the influence of the South American summer monsoon (SASM), the largest and most significant climate feature of South America (Jones and Carvalho, 2013), a nearly continental-scale circulation that is responsible for much of the precipitation that falls from the Amazon River south to the La Plata Basin (Marengo et al., 2012a). The large changes in precipitation reconstructed on paleoclimate time scales throughout this domain are products of temporal changes in SASM intensity that are likely extrinsically forced by temporally variable insolation, greenhouse gas concentrations, glacial boundary conditions, and remote ocean–atmosphere interactions. The central questions of this review are: what is the history of the SASM and these extrinsic forcings?

Paleoclimate scientists are limited to proxy measurements that are imperfect recorders of a small number of climate variables in relatively few sites. However, in most of the tropics, including tropical South America, the instrumental record is itself limited by being short, sparse, incomplete, and imperfect. For example, Manaus is the only station in the entire Amazon basin having a century of weather data. A major issue is that this short and sparse instrumental record cannot capture low-frequency and long-term variation, therefore it records a relatively narrow amplitude of variation that neither fully characterizes the recent past nor the likely near future. Thus, we believe that lessons learned from studying the paleoclimate record of tropical South America provide insight into both past and future climates.

2. Modern climate of tropical South America and its relevance to the interpretation of Quaternary climate

The dynamics of past climates cannot be fully understood by simply extending what has been observed during the instrumental period, because most of the climate signals that are reconstructed from paleoclimate archives were of greater amplitude, longer duration, larger spatial footprint, and lower frequency than any that have been observed in the instrumental period. Thus, it is possible, even likely, that the origins of climate variation on "paleoclimate" time scales also were different than any that have been directly observed. Here we offer our own observations about both the importance, but also the limitations, of studies of modern climate variability as a means for deducing the origins and mechanisms of

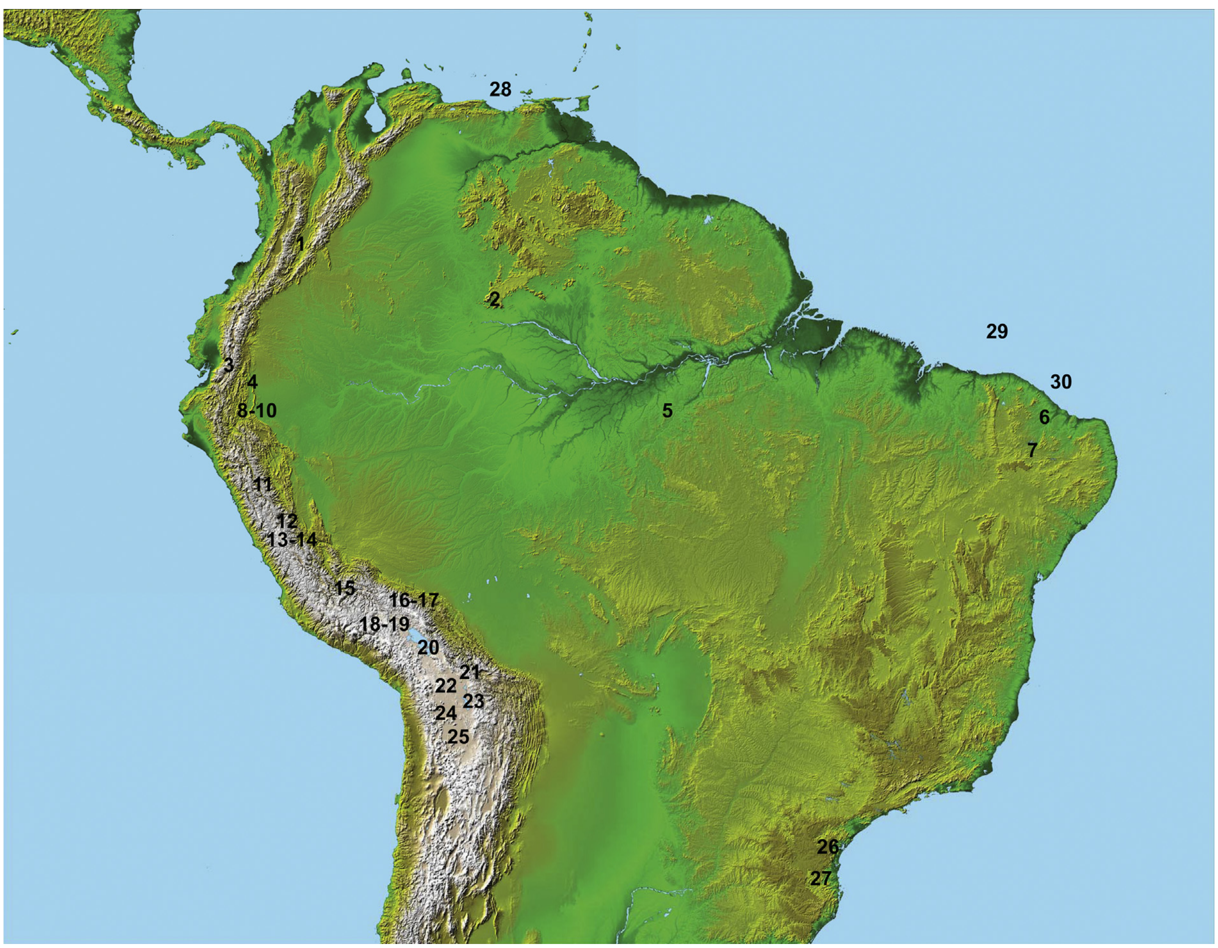

Fig. 1. Map of tropical South America showing the location of sites discussed in the text. See Table 1 for additional site information.

Table 1
List of sites mentioned in the text. Site numbers correspond to Fig. 1.

Site#	Archive	Record	Proxies	Reference	Lat.	Long °W	Elev. (m)
1	Lake	Sabana de Bogatá, Colombia	Pollen	Torres et al., 2013; Marchant et al., 2002	4.83°N	74.2	2550
2	Lake	Hill of Six Lakes, Brazil	Pollen	Bush et al., 2004	0.30°N	66.67	75
3	Lake	Pallcacocha, Ecuador	RedScale	Rodbell et al., 1999; Moy et al., 2002	2.77°S	79.23	4200
4	Speleothem	Santiago, Ecuador	$\delta^{18}O$	Mosblech et al., 2012	3.02°S	78.13	980
5	Speleothem	Paraíso, Brazil	$\delta^{18}O$	Cheng et al., 2013	4.07°S	55.45	
6	Speleothem	Rio Grande, Brazil	$\delta^{18}O$	Cruz et al., 2009	5.6°S	37.73	100
7	Groundwater	Maranhao, Brazil	Noble gas	Stute et al., 1995	7°S	41.5	400
8	Speleothem	Diamante,Perú	$\delta^{18}O$	Cheng et al., 2013	5.73°S	77.5	960
9	Speleothem	El Condor,Perú	$\delta^{18}O$	Cheng et al., 2013	5.93°S	77.3	860
10	Speleothem	Tigre Perdido, Perú	$\delta^{18}O$	van Breukelen et al., 2008	5.93°S	77.31	1000
11	Ice Core	Huascaran, Perú	$\delta^{18}O$	Thompson et al., 1995	9°S	77.5	6050
12	Lake	Pumacocha, Perú	$\delta^{18}O$	Bird et al., 2011	10.70°S	76.06	4300
13	Lake	Junin, Perú	$\delta^{18}O$	Seltzer et al., 2000	11.02°S	76.12	4082
14	Speleothem	Pacupahuain,Perú	$\delta^{18}O$	Kanner et al., 2012, 2013	11.24°S	75.82	3800
15	Lake	Pachuca, Perú	Diatoms	Hillyer et al., 2009	13.6°S	73.49	3095
16	Ice Core	Quelccaya, Perú	$\delta^{18}O$	Thompson and Mosley-Thompson, 1984	13.93°S	70.83	5670
17	Lake	Consuelo, Perú	Pollen	Bush et al., 2004	13.95°S	68.99	1360
18	Lake	Umayo, Perú	Diatoms, $\delta^{18}O$	Ekdahl et al., 2008; Baker et al., 2009	15.44°S	70.1	3880
19	Lake	Lagunillas,Perú	Diatoms	Ekdahl et al., 2008	15.44°S	70.44	4220
20	Lake	Titicaca, Bolivia/Perú	$\delta^{13}C$	Baker et al., 2001; Fritz et al., 2007	16°S	68.5	3810
21	Ice Core	Illimani, Bolivia	$\delta^{18}O$	Ramirez et al., 2003	16.62°S	67.77	6350
22	Ice Core	Sajama, Bolivia	$\delta^{18}O$	Thompson et al., 1998	18°S	69	6540
23	Lake	Poopo, Bolivia	Shorelines	Placzek et al., 2006	18.55°S	67.08	3685
24	Lake	Coipasa, Bolivia	Diatoms	Sylvestre et al., 1999	19.38°S	68.13	3656
25	Lake	Uyuni, Bolivia	Gamma	Baker et al., 2001; Fritz et al., 2004	20°S	68	3653
26	Wetland	Volta Vehla, Brazil	Pollen	Behling and Negrelle, 2001	26.07°S	48.63	5
27	Speleothem	Botuverâ, Brazil	$\delta^{18}O$	Cruz et al., 2005; Wang et al., 2006	27.22°S	49.15	230
28	Marine	Cariaco, Venezuela	Color	Peterson et al., 2000; Haug et al., 2001	10.5°N	65	0
29	Marine	CDH-86, Brazil	XRF	Nace et al., 2014	0.33°S	44.21	0
30	Marine	GEOB-3912, Brazil	XRF	Arz et al., 1998	3.67°S	37.43	0

past climate variation. A second and related major issue is that models of tropical South American climate have significant deficiencies (Li et al., 2006; Yin et al., 2014), limiting their ability to reliably simulate future and past climates.

Several recent papers review various aspects of the modern climate and hydrology of tropical South America (e.g., (Garreaud et al., 2009; Marengo et al., 2012b; Silva and Kousky, 2012)). Many of these concern the South American monsoon system (Zhou and Lau, 1998) and its variability on seasonal, inter-annual, and decadal timescales.

2.1. Atlantic, Inter-tropical convergence zone, and SASM variability at annual to decadal time scales

The dynamics of the Atlantic Ocean affect global climate, including the climate of tropical South America, via changes in the strength of the meridional overturning circulation and changes in sea-surface temperature (SST) and pressure fields, with their associated impacts on atmospheric and oceanic circulation. Prominent among these circulation features is the Inter-tropical convergence zone (ITCZ), which shifts in response to zonal SST gradients and is a major influence on the climate of both the northern and southern hemisphere tropics of South America.

The ITCZ and its embedded precipitation band migrate seasonally in the tropical Atlantic, reaching a maximum northern latitude ca. 10°N in August and a maximum southern latitude ca. 1°S in March (mean latitudes at longitude 30°W) (Nobre and Shukla, 1996). The direct influence of the ITCZ on the precipitation climatology of coastal northeastern South America is observed in the seasonal co-location of the ITCZ and the annual precipitation maximum from the northern Nordeste of Brazil (Hastenrath and Heller, 1977) to the north coast of Venezuela (Poveda et al., 2006). There has been an unfortunate tendency in the climate literature, and especially in the paleoclimate literature, to conflate the ITCZ with the SASM. This often is manifest in maps purporting to show deep penetration of the ITCZ into the South American continental southern subtropics. Cook (2009) clarifies the distinctions between these two systems. That said, it is plausible that ITCZ variability *indirectly* affects precipitation climatology and anomalies throughout the broader SASM region. For example, it has been posited previously that increased strength of the northeast trades increases moisture advection into the Amazon basin, thereby increasing the intensity of the SASM on both climate (Curtis and Hastenrath, 1999; Garcia and Kayano, 2014) and paleoclimate (Baker et al., 2009; Vuille et al., 2012) timescales.

On decadal timescales throughout the instrumental period, small, but persistent, SST anomalies develop in the northern and southern tropical Atlantic (Servain, 1991). These tropical Atlantic SST anomalies seem to be part of a recurrent pattern of zonally alternating SST anomalies that extends into higher northern and southern latitudes of the Atlantic, the so-called pan-Atlantic decadal oscillation (Xie and Carton, 2004; Xie and Tanimoto, 1998). The decadal tropical SST anomalies are only evident after averaging the far larger intra-annual variability and are not completely independent of El Niño-Southern Oscillation (ENSO) forcing (Enfield and Mayar, 1997). They may be, in part, maintained by regional wind-evaporation-SST feedback (Chang et al., 1997) and produce anomalous north-south shifts of the ITCZ, together with its embedded atmospheric circulations, toward the warmer hemisphere (Chiang and Koutavas, 2004). Significant variation of precipitation along the Nordeste coastal region of Brazil, throughout much of the Amazon basin, and in the Peruvian and Bolivian Andes is associated with these SST and circulation anomalies (Casimiro et al., 2012; Hastenrath and Greischar, 1993; Hastenrath et al., 2004; Nobre and Shukla, 1996; Zeng et al., 2008). For example, precipitation at Fortaleza, Brazil is tightly coupled with offshore SST anomalies (Fig. 2). When the tropical dipole index (Chang et al., 1997) is most negative, that is, when the tropical Atlantic is coldest in the north and warmest in the south, wet conditions prevail in the northern Nordeste of Brazil. As we discuss below, much larger

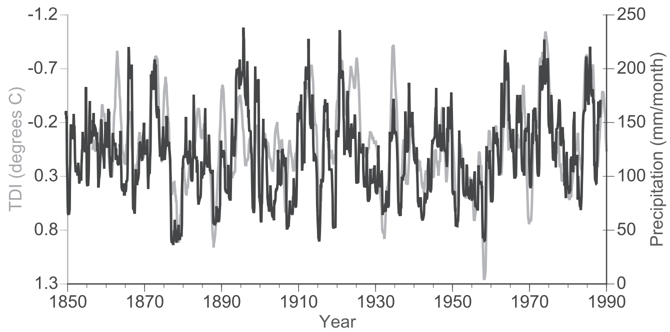

Fig. 2. Fortaleza, Brazil (3.7°S 38.5°W) precipitation and tropical Atlantic SST dipole index (TDI). The 13-month moving average of the tropical dipole index (TDI, Chang et al., 1997) defined as NTA SSTA over 40W–20W, 6N–20N minus the STA SSTA over 14W–4E, 14S–4S. This is plotted against the 13 month moving average of Fortaleza precipitation.

amplitude tropical Atlantic paleo-SST anomalies induced large paleo-precipitation anomalies across nearly the entire South American tropics at certain times in the past. Chu (1984) ascribed a 12.7–14.9 year periodicity in the precipitation time series from Nordeste Brazil to variation in tropical North Atlantic SST—cold SST values in the North Atlantic are related to wetter conditions in the Nordeste.

Surprisingly little has been written about decadal-scale variability of the SASM (Grimm and Saboia, 2015). This can be partially attributed to the aforementioned paucity of long instrumental climate records in tropical South America. Robertson and Mechoso (1998) identified significant decadal variability in the discharge of the Paraguay and Parana Rivers (rivers that arise in the core of the SASM region and that have instrumental records dating back to 1910), which they related to the North Atlantic Oscillation. Decadal-scale, negative SST anomalies over the tropical North Atlantic were associated with increased discharge of the Parana-Paraguay Rivers. Using principal component analysis, Zhou and Lau (2001) identified three significant modes of variability of South American summer precipitation (but only over the period 1979–1995), each associated with a distinctive time scale. Their second mode was decadal, with the strongest loadings forming a north-south precipitation dipole in eastern equatorial South America and the adjacent Atlantic. This mode was attributed to decadal variability of the tropical Atlantic meridional SST gradient and shifting locus of the Atlantic ITCZ, confirming the findings of Nobre and Shukla (1996). On the other hand, Garreaud et al. (2009) regressed annual precipitation in all of South America against the Pacific Decadal Oscillation (PDO) index. They found the strongest correlations in equatorial South America with a spatial pattern, not surprisingly, closely resembling that of the ENSO precipitation teleconnection. Yet, their method of analysis precludes the possibility of identifying the tropical Atlantic or ITCZ forcing that Zhou and Lau (2001) found in the same region.

It is in the longer *paleoclimate* record that the most robust decadal climate variation appears. For example, the $\delta^{18}O$ record from the Quelccaya ice core (Thompson and Mosley-Thompson, 1984), which has been annualized for at least 500 years, has highly significant and persistent decadal (12–14 years) variability that is correlated with the low-frequency variability of SST in the tropical North Atlantic (Melice and Roucou, 1998). Given that $\delta^{18}O$ is a reliable measure of SASM intensity or precipitation amount integrated over the upstream monsoonal domain (Baker et al., 2009; Vimeux et al., 2009; Vuille et al., 2012), the observed correlation associates cold SST values in the tropical North Atlantic with wet conditions in the Amazon and southern tropical Andes. Indeed, the Quelccaya record indicates that decadal variation was a hallmark of both Amazon/Andean precipitation and tropical North Atlantic SST for the past five centuries.

2.2. ENSO and inter-annual climate variability in tropical South America

Considerable attention has been paid to the role of ENSO in forcing inter-annual variations of temperature and precipitation in tropical South American climate and paleoclimate. However, Seager and Battisti (2007) discussed the "limitation of the ENSO blueprint" when offered as an explanation for the origin of abrupt (centennial to millennial) climate events of the late Pleistocene. Adopting their phrase, here we argue that the ENSO blueprint is also limited in explaining modern tropical South American climate variance even in the "ENSO band" (i.e. 2–8 yrs).

In their review of the modern climate of continental South America, Garreaud et al. (2009) correlated patterns of temperature and precipitation variation with three global-scale modes of climate variability: ENSO, the Pacific Decadal Oscillation (PDO), and the Antarctic Annular Mode (AAO). They presented a series of maps illustrating seasonal correlations between ENSO and surface temperature and precipitation for the period 1950–1999. These maps highlight the relatively warm and dry conditions during El Niño years that prevail over large swaths of tropical South America (and wet conditions over the La Plata basin) particularly during the austral summer (DJF) wet season, the peak season of ENSO forcing. Garreaud et al. (2009) concluded that ENSO variation was the dominant cause of continent-wide inter-annual variation of both temperature and precipitation and noted that the highest correlations are ~0.8; thus, ENSO explains about two thirds of the inter-annual variance of precipitation/temperature. However, while the correlation between the multivariate ENSO index (MEI) and surface air *temperature* throughout tropical South America is quite robust, particularly for the austral summer and fall seasons (Garreaud et al., 2009), the correlation with *precipitation* is considerably lower. For example, a recent detailed analysis of the instrumental record of the Peruvian Andes and Amazon (Casimiro et al., 2012) found that annual precipitation and the Southern Oscillation Index (SOI) were significantly correlated in only 4 of 56 stations, whereas temperature and SOI were significantly correlated in 27 of 47 stations. In fact, more than half of tropical South America (see Fig. 8 of Garreaud et al., 2009) exhibits no significant correlation of seasonal precipitation with MEI, and in more than three-quarters of tropical South America the correlations are below ~0.4, meaning that ENSO explains less than ~15% of the inter-annual variance of precipitation for most of the region. Yin et al. (2014) actually reported no statistically significant correlation over the period 1958–2009 between SASM precipitation and the Nino3.4 index. Thus, while ENSO variability is the most important source of inter-annual variability of precipitation in parts of tropical South America, it only explains a small amount of that variability over the vast majority of the region.

Garreaud et al. (2009) reiterate the point, originally made by Aceituno and Montecinos (Aceituno and Montecinos, 1993), that the correlation between ENSO and South American precipitation was not stationary in the twentieth century. We reinforce this conclusion by revising and updating Fig. 9 from Garreaud et al. (2009) with the addition of more recent precipitation data through 2005 for the Corrientes station, and we decrease the sliding window for computing correlation coefficients from 30 to 20 years. The latter revision allows better temporal resolution while keeping scatter acceptably low. The updated time series (Fig. 3a) indicates that periods exhibiting significant correlation between SOI and precipitation at Corrientes are actually quite limited: 35 years out of a total of 104 years. Moreover, in recent years the

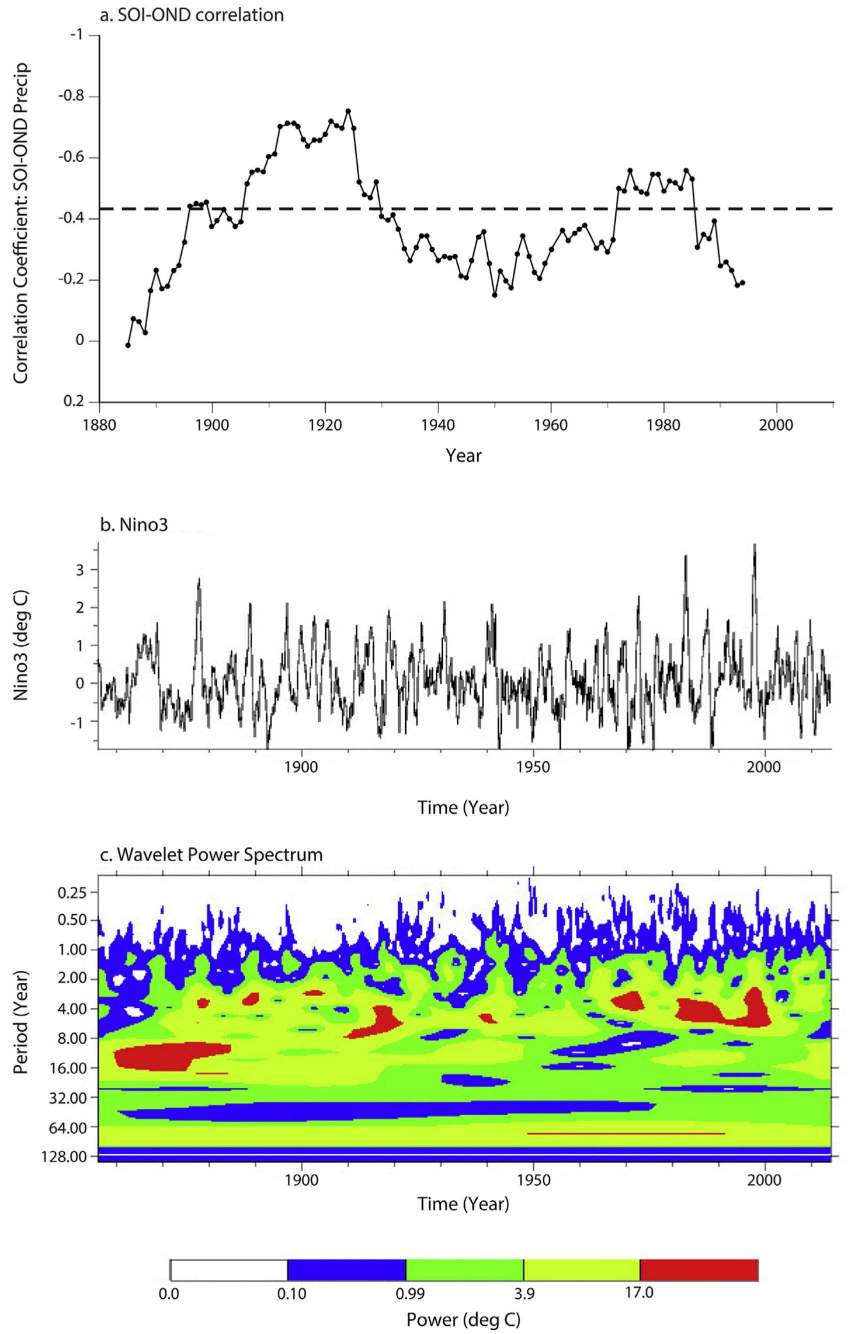

Fig. 3. (a) SOI index regressed against OND precipitation (complete through 2005 with two missing years) at Corrientes, Argentina. The horizontal line is the 95% confidence level. (b) Nino3 SST index through 2014; and (c) Wavelet power spectrum of the Nino3 index. The contour levels signify that 75%, 50%, 25%, and 5% of the wavelet power is respectively above each level (after Torrence and Compo, 1998).

correlation is not significant. One reason for the non-stationarity of this teleconnection is that the amplitude and locus of ENSO forcing itself was non-stationary over the same time period (Torrence and Webster, 1999). Thus, between 1925 and 1965, and again at the end of the twentieth century following the 1997/1998 strong El Nino event, ENSO variance was low (Fig. 3b, c), and the ENSO-Corrientes correlation was insignificant (Fig. 3a). Conversely, when ENSO variance was greatest in the 1920's and 1980's, the ENSO-Corrientes correlation was most significant. Similar non-stationary teleconnections presumably occurred throughout tropical South America, but a lack of long records precludes a more definitive analysis. A second reason for the non-stationarity of the ENSO teleconnection is that the geographic distribution of precipitation during any given El Niño or La Niña year varies greatly (Silva et al., 2007), and the El Niño teleconnection footprint is not simply the opposite of the La Niña one (Casimiro and Espinoza, 2014).

Both the short (seasonal) duration of a given event (El Niño or La Niña) and the spatial and temporal variability of the ENSO teleconnection mitigate the cumulative long-term effects of ENSO-forced inter-annual variability on hydrology, ecosystem viability, and the paleoclimatic record. While the largest El Niño events, such as those of 1982–1983 and 1997–1998 (Fig. 3b), organize precipitation and subsidence over large areas of tropical South America, their effects can be countered by a subsequent normal or wetter-than-normal year. Both the 1982/1983 and 1997/1998 El Niño events were indeed followed by such conditions, and neither of the years, as anomalous as they were, were part of a long-term (e.g. decadal) drought period in tropical South America. More typical “canonical” El Niño or La Niña events have more nuanced precipitation teleconnections and subtle long-term consequences.

Over the past decade (2005–2014), perhaps as a result of global climate change (Gloor et al., 2013), an extraordinary series of record droughts and floods has beset the Amazon region. Some occurred during non-ENSO years; none were commensurate with the relatively low amplitude of ENSO forcing during the decade. These hydrologic events began with the severe 2005 drought of the southwestern Amazon, coincident with a weak El Niño and ascribed instead to anomalously high SST in the tropical North Atlantic (Marengo et al., 2008; Zeng et al., 2008). The 2009 “flood of the century” was attributed to La Niña forcing (Chen et al., 2010), although the 2008/9 La Niña was weak. The epic 2010 drought coincided with a weak El Niño and was again ascribed to high SST in the tropical North Atlantic (Lewis et al., 2011; Marengo et al., 2011). The strongest ENSO event of the decade was the 2010/2011 La Niña, yet no significant precipitation anomaly was observed in the Amazon. On the other hand, historically heavy precipitation and devastating floods brought about severe damage and loss of life in the southern tropics (Rio de Janeiro). The 2012 floods of the Amazon exceeded those of 2009 and coincided with severe drought in the Nordeste (Marengo et al., 2013), yet the 2011/2012 La Niña was a weak event. Severe flooding in the southwestern Amazon in early 2014 and the worst drought in a century in São Paulo through 2014 and early 2015 coincided with largely neutral conditions in the Pacific. Thus, the emergent climate record of the past decade is one of highly anomalous historic floods and droughts over large swaths of tropical South America, yet these occurred during a period of relatively quiescent ENSO forcing.

In short, while ENSO is acknowledged as the most significant mode of global climate forcing on inter-annual timescales, it is not always the most important source of inter-annual variation of tropical South American precipitation. Its effects are non-stationary in space and time, and some of the largest hydrologic events in tropical South America occur without ENSO forcing. As a consequence, there is little in the instrumental record to suggest that changes in ENSO frequency or amplitude are likely to bring about significant long-term paleoclimatic or paleoecological change in this region. Furthermore, the paleoclimatic record suggests that past ENSO variance was not significantly greater than modern for at least the past 7 ka (see Section 3.1). In addition, the relatively constant zonal SST gradient across the Pacific Ocean for the past 12 Ma (Zhang et al., 2014) suggests the absence of any long-lasting “super ENSO” events, which have often been posited as an explanation for long-term (e.g., multi-decadal to millennial) drought or flood cycles. Together, these observations indicate the need to look elsewhere for explanations of climatically significant variation on paleoclimate time scales in the SASM region.

3. Paleoclimate

3.1. ENSO variation in the Holocene

The Laguna Pallcacocha sequence from Ecuador is an iconic record of paleoclimatology and for many years has been held as a standard for inferring ENSO variation of the late Quaternary. Fine clastic laminae in sediments from this lake were posited to record storm deposition associated with El Niño events over the last ~15 ka (Moy et al., 2002; Rodbell et al., 1999). The frequency of laminae increased from an average of 1 per 15 yr before 7 ka to 1 every 2–8.5 yr after 7 ka, a change interpreted as evidence for mid-Holocene establishment of the contemporary ENSO periodicity (Rodbell et al., 1999) in response to orbital forcing (Moy et al., 2002). Similar ENSO responses to changes in insolation also were observed in climate simulations (Clement et al., 2002). Two lacustrine records from the Galapagos (Conroy et al., 2008; Riedinger et al., 2002), as well as marine records from the tropical Pacific (Koutavas et al., 2006; Rein et al., 2005), also were interpreted as records of ENSO variability but do not show an increase in event frequency until after 4.5 ka. While event frequency in the Pallcacocha record increased into the late Holocene, it declined in the last millennium (Rodbell et al., 1999). Various other proxy records spanning the last millennium differ substantively from Pallcacocha and each other regarding inferred patterns of ENSO variation (Conroy et al., 2009; Dunbar et al., 1994; Moy et al., 2002; Rein et al., 2004; Sachs et al., 2009). Thus, there is no clear coherence among regional records regarding the timing of the hypothesized onset of stronger ENSO variability or about the character of the last millennium.

Based on a series of highly resolved coral stable-isotopic records from the central tropical Pacific that span the last 7 ka, Cobb et al. (2013) concluded that ENSO activity was variable over the mid to late Holocene, but underwent no significant secular trend in variance. Likewise, isotopic records in speleothems and lacustrine carbonates from the tropical Andes of Peru do not show precipitation patterns consistent with the hypothesis of intensified ENSO variance in the late-Holocene (Kanner et al., 2013). In fact, the AR5 IPCC assessment concluded “with high confidence” that past ENSO variance was little different from modern for at least the past 7 ka (Masson-Delmotte et al., 2013), bringing coral and speleothem proxy evidence into agreement with the majority of current-generation climate models. In short, the ENSO blueprint as an explanation of large amplitude/low frequency climate changes of the past, abrupt or otherwise, is not well supported in the SASM monsoon region.

3.2. Orbital variation

3.2.1. The South American summer monsoon

A prominent role for insolation in affecting the intensity of tropical monsoons has long been recognized (Prell and Kutzbach, 1987), with precession pacing insolation variation at tropical latitudes and eccentricity modulating its amplitude (Berger, 1978). In tropical South America, insolation variation can move the mean latitude of the Atlantic ITCZ and its component parts (meso-scale convective systems, trade winds, equatorial surface ocean currents). Insolation variation also impacts the intensity of the SASM and its component parts (continental heat low, the South American low-level jet, the Bolivian high, the South Atlantic Convergence Zone).

Paleoclimate records from multiple sites show the influence of precession on past precipitation variation in the SASM domain (Fig. 4). Speleothem records from the western Peruvian Amazon (Cheng et al., 2013; van Breukelen et al., 2008), Ecuador (Mosblech et al., 2012), the Peruvian Andes (Kanner et al., 2013, 2012), and southeastern Brazil near the exit region of the SASM (Cruz et al., 2005; Wang et al., 2006) indicate that climate was moderately wet at the Last Glacial Maximum (LGM, ~25–20 ka), near the summer (DJF) insolation maximum, and dry in the early to mid-Holocene shortly after the insolation minimum. Ice-core stable oxygen or hydrogen isotopic records from Peru (Thompson et al., 1995) and Bolivia (Ramirez et al., 2003; Thompson et al., 1998) show a similar pattern, with lower values of $\delta^{18}O$ or $\delta^{2}H$ at the LGM and higher mid-Holocene values, which respectively indicate intensification and subsequent reduction in the intensity of the SASM. In the Peruvian (Bird et al., 2011; Ekdahl et al., 2008; Hillyer et al., 2009;

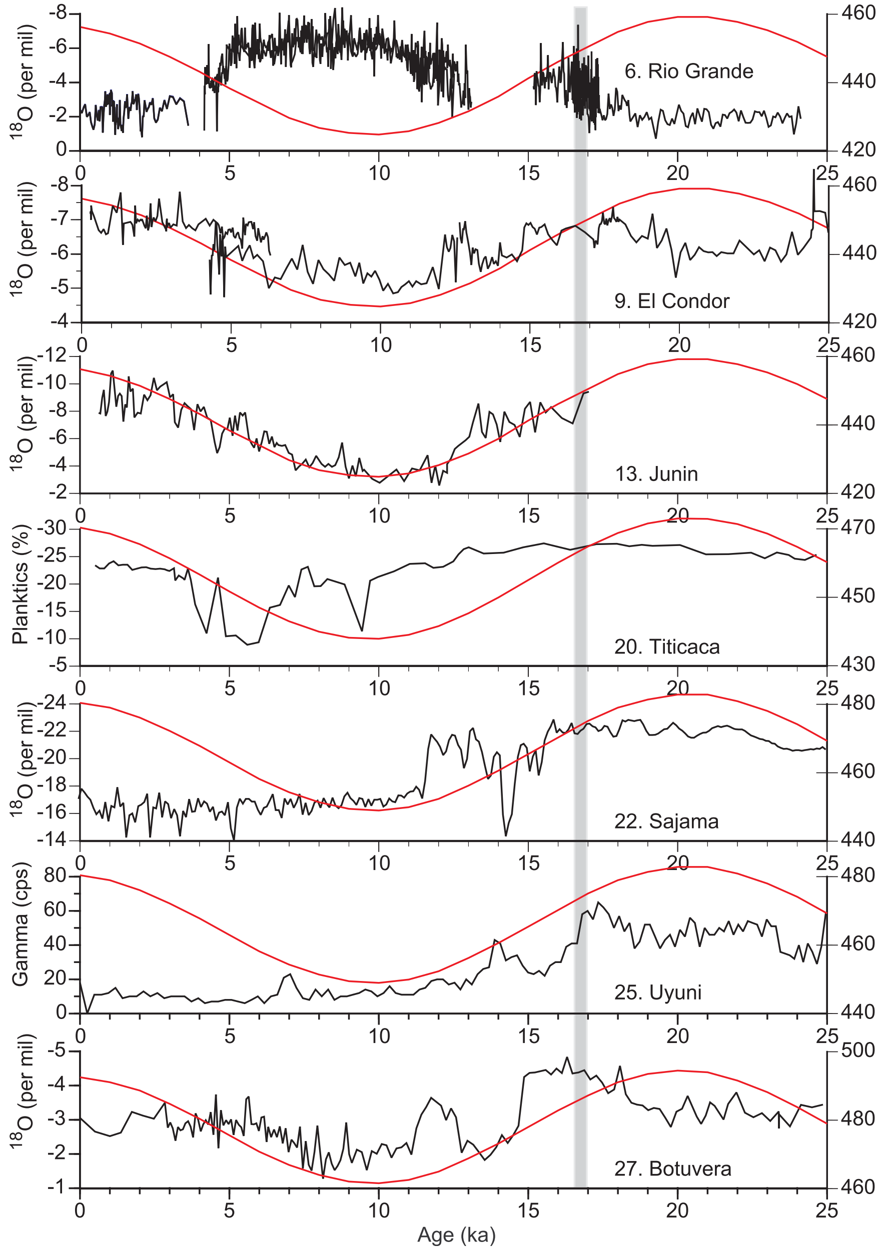

Fig. 4. Selected paleoclimate records that span the last 25 ka in relationship to wet season (January) insolation (watts/m^2) at the latitude of each site. Sites are arrayed north (5°S) to south (27°S). Numbers given for each site indicate the location as shown on Fig. 1. The % planktic curve for Lake Titicaca represents the proportion of deep-water (planktic) diatoms relative to shallow-water (benthic) diatoms. The gamma curve for Salar de Uyuni is a measure of the natural γ radiation in the Salar drill hole, which is a proxy for effective moisture (see Baker et al., 2001a for more details). Other sites show measurements of $\delta^{18}O$ in glacial ice (Sajama) or in lacustrine (Junin) or speleothem (Rio Grande, El Condor, Botuvera) calcite. The gray bar represents the timing of Heinrich 1, when all sites show wet conditions.

Seltzer et al., 2000) and Bolivian (Baker et al., 2001a, 2001b) Andes, lake levels were high and waters were fresh during the LGM and shallower and more saline in the early to mid-Holocene. Thus, a variety of proxies in a variety of archives show the direct response of the SASM to precession variation during the last 25 ka. Water-balance calculations for the western Amazon and Andes suggest that mid-Holocene precipitation was reduced 15–30% relative to modern (Baker et al., 2009; van Breukelen et al., 2008).

In contrast, in the eastern parts of the Southern Hemisphere tropics, including the Nordeste (Cruz et al., 2009) and the eastern Amazon (Cheng et al., 2013), precipitation was anti-phased with regions to the west and with southeastern Brazil, with a dry LGM and a wet mid-Holocene. This east-west precipitation dipole has been attributed to enhanced uplift and convection in the western Amazon and Andes in response to wet season insolation maxima and associated subsidence and drying to the east (Cruz et al., 2009), with opposite conditions during insolation minima (Cheng et al., 2013).

Large changes in moisture availability (P–E) also occurred on ~100 ka (eccentricity) cycles, synchronous with global glacial cycles. This is most clearly observed in drill cores from Lake Titicaca (Fig. 5) that record advances of glaciers in the Eastern Cordillera of the Andes and positive water balance in the lake coincident with global glacial stages, whereas glacial retreat and major lake-level decline was coincident with global interglacial periods (Fritz et al., 2007). In contrast, the tropical Andes north of the equator

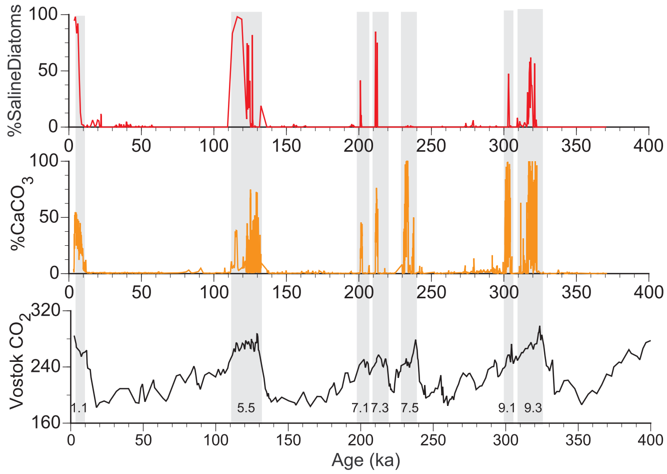

Fig. 5. The 400 ka paleoclimate record from Lake Titicaca showing the increased salinity during major interglacial stages (shaded).

were cold and dry, with low lake levels, during glacial stages and wet and warm in the interglacial stages (Torres et al., 2013). The global glacial stages apparently were also the wettest periods in the western Amazon (Cheng et al., 2013). In their speleothem record, Cheng et al. (2013) found that the highest $\delta^{18}O$ values of the last 250 ka occurred during the mid-Holocene (Fig. 6), implying that this was the interval of lowest precipitation over that period. In the Lake Titicaca drill core records, based on the abundance of saline diatom taxa and calcium carbonate (Fig. 5), earlier interglacial periods were more saline than the Holocene and based on unconformities observed in seismic reflection data (D'Agostino et al., 2002), lake levels were far lower during Marine Isotope Stage 5 than during the mid Holocene. These low lake levels and highly elevated salinities are a result of negative water balance for a sustained period, requiring a combination of low precipitation and high evaporation, conditions that dropped lake-level below its outlet and caused the gradual build-up of dissolved solids (Cross et al., 2000; Fritz et al., 2007). The greater extremes of salinity and lake level of MIS5 relative to the mid Holocene could reflect more extreme aridity, but more likely reflects longer-lasting aridity in the former period relative to the latter.

In low-latitude areas of South America, the influence of precessional variation on SASM intensity was apparently reduced during times of extensive Northern Hemisphere glaciation (Fig. 6). Thus, millennial variability (see Section 3.3) is more prominent than precessional insolation forcing during MIS3 in the western Amazon (Cheng et al., 2013; Kanner et al., 2012; Mosblech et al., 2012), whereas the orbital signature remains strong throughout the last glacial cycle in the sub-tropical latitudes of southeastern Brazil (Cruz et al., 2005; Wang et al., 2007).

3.2.2. *Temperature variation*

Relatively few reconstructions of Quaternary temperature exist for tropical South America. Some records from the Andes or the adjoining lowlands are derived from the advance and retreat of temperature-sensitive plants and alpine glaciers. However, given the competing influences of precipitation and temperature on both plant growth and glacial mass balance, it is difficult to disentangle their relative influences with confidence. In the Eastern Cordillera of Bolivia, Kull et al. (2008) used a glacier-climate model that incorporated multiple climate variables and estimated a LGM cooling of 6 °C (relative to pre-industrial modern temperatures), a value which is similar to recent estimates of cooling based on TEX86 measurements in Lake Titicaca (Fornace et al., 2011). LGM temperatures based on Andean glacier equilibrium line measurements range from 2 to 12 °C below modern at individual locations (Mark et al., 2005; Mark and Helmens, 2005). Estimates of LGM cooling derived from pollen vary between 1 and 9 °C, although most fall in the middle of that range. Multiple sites document the downslope migration of Andean forest taxa during the global glacial stages in response to the locally cooler temperatures, and quantitative reconstructions derived from transfer functions or biome modeling suggest a cooling of ~5 °C in both the northern (Marchant et al., 2002) and southern tropical Andes (Bush et al., 2004b). Temperature reconstructions from the Atlantic forests in southeastern Brazil (Behling and Negrelle, 2001) also suggest a ~5 °C cooler LGM based on the expansion of grasses and cold-adapted plants, as do the noble gas paleotemperature estimates in the Brazilian Nordeste (Stute et al., 1995). Thus, the majority of records suggest moderate cooling, perhaps of 5 °C, of the South American tropics and sub-tropics during the global glacial stages. Episodes of glacial advance documented in the Western and Eastern Cordillera of Bolivia and Peru during parts of the mid-Holocene suggest the possibility that although mid-Holocene climate was dry in these regions, at times it may have been somewhat cooler than today (Rodbell, 1992; Smith et al., 2009).

3.3. *Millennial variability in the tropical Atlantic and in paleoclimate records of tropical South America*

Although tropical Atlantic variability is only one influence on tropical South America's climate in the instrumental period, there is considerable evidence in paleoclimate records for Atlantic dominance in forcing large, persistent, and abrupt climate changes in tropical South America during portions of the late Quaternary. Climate model simulations also provide support for both the sensitivity of tropical South American precipitation to North Atlantic SSTs and the linkage between North Atlantic cold events, northern tropical Atlantic cold SSTs, and tropical South American precipitation (e.g. (Broccoli et al., 2006; Harris et al., 2008; Nace et al., 2014; Zeng et al., 2008)).

Large precipitation increases (decreases) synchronous with North Atlantic cold events were first observed in the southern (northern) tropics of South America in paleoceanographic records from the Brazilian Nordeste (Arz et al., 1998) and the Cariaco Basin (Peterson et al., 2000) and on the continents in lacustrine sediment records from the Andes of Peru and Bolivia (Baker et al., 2001a, 2001b; Fritz et al., 2010). Since those early observations, paleoclimate change in concert with North Atlantic cold events has been observed in multiple records throughout the South American tropics (Fig. 6), including southern Brazil (Cruz et al., 2006, 2005; Wang et al., 2006; Wang et al., 2007), northeastern Brazil (Cruz et al., 2009; Nace et al., 2014; Wang et al., 2004), the Peruvian Andes (Fritz et al., 2010; Kanner et al., 2012), western Amazonia (Cheng et al., 2013; Mosblech et al., 2012), and central Amazonia (Cheng et al., 2013).

Northern tropical Atlantic SST apparently cooled in concert with high-latitude North Atlantic SST during all of the Pleistocene and Holocene North Atlantic cold events, including stadial cold periods, Heinrich events, the Younger Dryas, and Holocene Bond events. Whereas detrended (for global warming) annual SST anomalies in the northern tropical Atlantic have never exceeded 1 K between 1980 and 2015 (Reynolds and Smith OISST Version 2, averaged over the region 10°N to 20°N latitude and 79°W to 20°W longitude), the amplitudes of SST anomalies associated with the North Atlantic cold events in the past were much larger. For example, during typical stadial events of the last few glacial cycles, average SSTs in the mid-latitude eastern North Atlantic decreased by ~6–8 °C (Martrat et al., 2007). During the Younger Dryas, SSTs in the eastern

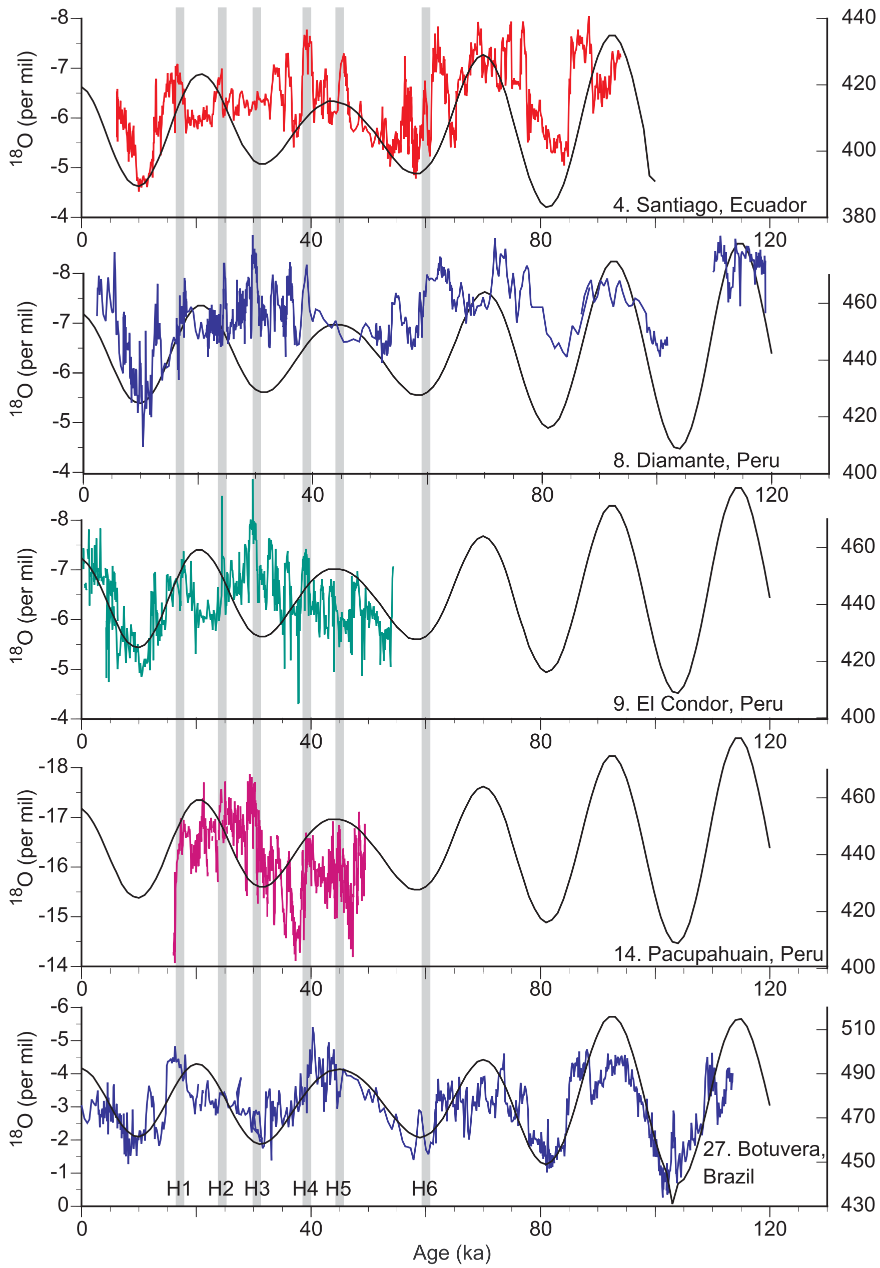

Fig. 6. Selected speleothem records that span the last 125 ka in relationship to wet season (January) insolation (watts/m^2) at the latitude of each site. Sites are arrayed north (3°S) to south (27°S). Numbers given for each site indicate the location as shown on Fig. 1. The gray bars represent the timing of Heinrich Events (H1–H6).

Caribbean averaged ~3 °C lower than the preceding Bolling–Allerod or the early Holocene (Lea et al., 2003). It stands to reason that the climate anomaly amplitudes associated with these dramatic tropical Atlantic SST anomalies were equally dramatic.

4. Special topics

4.1. A refined interpretation of tropical South American speleothem records

A problematic aspect of most publications on speleothem isotopic records is that two well-known and large-magnitude isotopic signals have generally not been adequately accounted for in interpretation of these records. One is the influence of temperature on carbonate-water isotopic fractionation. The other is the variation of seawater $\delta^{18}O$ due to glacial-age sequestration in continental ice sheets of ^{16}O-enriched water. With regard to the first factor, it is often argued that the temperature influence on fractionation is small relative to the total magnitude of the signal. The second factor, which *has* to affect tropical source waters whether they are marine or recycled, is also ignored, perhaps for the same reason. Yet the combined influence of both effects is often the same magnitude as the total variation due to all other processes and should not be ignored. Here, we present an example of an original and corrected isotopic record and the considerable difference in paleoclimate interpretation implied by these corrections.

Cheng et al. (2013) collected and analyzed stalagmites from two caves located on the eastern flank of the eastern cordillera of the Andes. We utilize their carefully dated isotopic record from five speleothems collected from Cueva del Diamante at ca. 6°S and 960 m.a.s.l, which together span most of the past 250,000 years and provide one of the most complete and well-dated archives of South

American paleoclimate (Fig. 6). However, neither the temperature effect on fractionation nor the changing isotopic composition of Atlantic Ocean source water were included in the original interpretation of these records.

To constrain the mean annual air temperature at Cueva del Diamante during the LGM, we use the estimate based on noble gas ratios in groundwater (Stute et al., 1995) of ca. 5 °C cooling during the LGM relative to the late Holocene, consistent with other regional estimates (see 3.2.2). Assuming the same cooling at Cueva del Diamante, speleothem carbonate would have had a temperature-induced increase (relative to modern cave air temperatures) during the LGM of ~1.25‰ (Friedman and O'Neil, 1977). The global increase of $\delta^{18}O$ in seawater during the LGM was ca. 1‰ (Schrag et al., 2002), and all other considerations aside, this would have led to a 1‰ increase in the $\delta^{18}O$ of water vapor, precipitation, groundwater, and speleothem carbonate. Thus, an amount of 2.25‰ should be subtracted from the $\delta^{18}O$ value of LGM speleothem calcite to account for both effects. For other time periods, we subtract the benthic $\delta^{18}O$ time series of Lisiecki and Raymo (2005), scaled by multiplying 2.25/1.79 (the difference between modern and LGM $\delta^{18}O$ of Lisiecki and Raymo, 2005), from interpolated values of the Cheng et al. (2013) time series (blue curve of Fig. 7) to produce the "corrected" time series (red curve of Fig. 7). The largest corrections (to more negative values) are needed during glacial maxima and the smallest corrections during interglacials (when temperature and $\delta^{18}O$ of seawater were near present-day values).

The corrected time series requires a substantial change in interpretation of the record, particularly for MIS6. Assuming (admittedly, a bit simplistically) that $\delta^{18}O$ of precipitation can be interpreted as a proxy for precipitation amount or intensity of the SASM, it is clear that all glacial stages were far wetter than interglacials—just how much wetter will remain speculation until we get quantitative precipitation reconstructions from either models or paleoclimate data. Interglacial stages 7e, 7c, 7a, 5e, 5c, 5a, and the Holocene all appear to be dramatically drier than the intervening glacial stages. At Paraiso Cave in the eastern Amazon (X. Wang, personal communication; Cheng et al., 2013), the only speleothem record from the central Amazon, the same 2.25‰ correction applied to the mean value of $\delta^{18}O$ during the LGM completely changes the climate interpretation: the LGM $\delta^{18}O$ becomes exactly equal to the late Holocene value, in contrast to the original interpretation that the LGM was "severely dry" (Cheng et al., 2013). Applying a similar 2.25‰ correction to the speleothem record from Rio Grande do Norte in the Brazilian Nordeste (Cruz et al., 2009) (Fig. 4), it becomes evident that the late Holocene was the driest period of the last 26,000 years (there is no record of the Bolling–Allerod period), and the LGM, while drier than the early Holocene, was significantly wetter than the late Holocene.

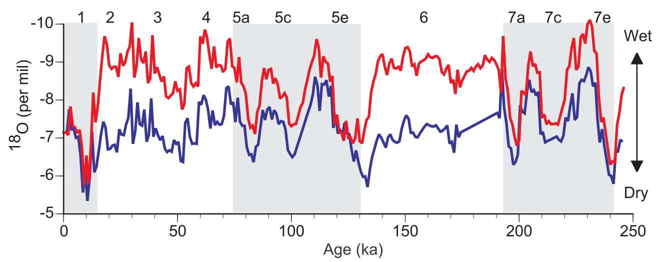

Fig. 7. Uncorrected isotopic trends at Botuverá Cave (blue line) and isotopic trends corrected for the influence of temperature on carbonate-water isotopic fractionation and the variation of ocean water $\delta^{18}O$ due to glacial-age sequestration of ^{16}O-enriched ice (red line). See text for details. Interglacial periods are shaded in gray and marine isotopic stages are labeled.

In tropical South America, the two adjustments act in the same direction and tend to increase the true amplitude of the paleohydrologic signal (but by different amounts in glacial and interglacial stages). These corrections have even graver implications for the interpretation of tropical Northern Hemisphere speleothem records (e.g. Chinese speleothems), where the combined adjustments tend to decrease or even eliminate the "true" signal amplitude.

4.2. *The chronology of lake-level variation on the Bolivian Altiplano*

The Altiplano of Peru and Bolivia is a high-elevation internally drained plateau that occurs between the eastern and western cordilleras of the tropical Andes (Fig. 1). In the relatively wet northern Altiplano lies the large, deep, freshwater Lake Titicaca, which, during prolonged wet periods of historical and instrumental observation, overflows southward via the Rio Desaguadero to the shallow Lago Poopo. In the drier central Altiplano are large salt flats, the Salar de Coipasa and Salar de Uyuni, which are underlain by lacustrine strata from past climate intervals that were wetter than today. During extremely wet periods of the late Quaternary, overflow from Lake Titicaca into Lago Poopo and subsequently into Coipasa and Uyuni Salars created a hydrologic connection between the northern and central Altiplano.

Paleoshorelines and lacustrine deposits that form "bathtub ring" deposits surrounding the Salar de Uyuni (modern surface level of 3653 masl), Salar de Coipasa (3656 masl), Lago Poopo (3686 masl), and (much less obviously) Lake Titicaca (3812 masl) basins have been the focus of scientific investigation for over a century (Agassiz, 1875; Ballivan et al., 1978; Bills et al., 1994; Blard et al., 2011; Bowman, 1914; Forbes, 1861; Minchin, 1882; Placzek et al., 2006; Pompecki, 1905; Rondeau, 1990; Servant and Fontes, 1978; Sylvestre et al., 1999). In the northern Altiplano, lacustrine deposits that represent periods of expansion of Lake Titicaca have been designated as Mataro (3950 masl), Cabana (3900 masl), and Ballivian (3860 masl) (Hoffstetter et al., 1971; Newell, 1949; Pompecki, 1905). The ages of these paleolakes, in some cases even their existence (Clapperton, 1993), are uncertain. Fossils (Hoffstetter et al., 1971; Pompecki, 1905) and K–Ar dating of an underlying ash (Lavenu et al., 1984) suggest that they date from the early to mid-Pleistocene. In the central Altiplano late-Pleistocene paleoshoreline deposits were described as: (1) an older unit named Minchin (<3730 masl) (Steinmann et al., 1904), which was later sub-divided into three lacustrine phases separated by dry intervals (Wirrmann and Mourguiart, 1995); (2) a younger unit named Tauca (<3760 masl) (Bills et al., 1994; Wirrmann and Mourguiart, 1995); and (3) an upper short-lived lake deposit named Coipasa (<3700 masl) (Sylvestre et al., 1999). More recent investigations (Placzek et al., 2006) introduced new nomenclature designating the lacustrine units that had been attributed to Lake Minchin as Ouki (<3740 masl, 120–98 ka), Salinas (<3670 masl, 95–80 ka), and Inca Huasi (<3670 masl, 47 ka), with ages based on U–Th measurements on the tufas. A younger, supposedly short-lived unit named Sajsi (<3670 masl, 24–20.5 ka) was also recognized.

Well more than a kilometer of sediment underlies most of the modern Salar de Uyuni. The upper sequences of these sediments have been recovered from two scientific boreholes. First, in 1986, Risacher and collaborators (reported in Fornari et al., 2001) recovered the upper 121 m of interbedded muds and salts. In 1999 Baker and collaborators (reported in Baker et al., 2001a; Fritz et al., 2004) returned to nearly the same location and recovered a similar sequence in the upper 121 m, but extended their drilling to a total depth of 220.6 m below the salar surface. In both drill holes, recovery was nearly complete. The uppermost lacustrine units in both drill cores were dated with radiocarbon (Baker et al., 2001a;

Fornari et al., 2001). U–Th isochron dating was undertaken on salt units that bracketed the lacustrine muds, thus dating was extended beyond the range of radiocarbon (Fritz et al., 2004).

In the 1999 drill hole, we also undertook continuous downhole logging of natural gamma radiation to a total depth of 188.7 m below the surface, where the logging tool encountered obstruction. The logging data (the complete record is presented in Fritz et al., 2004) provide a high-fidelity and continuous record of interbedded salt units (very low gamma values) and mud units (high gamma values). The salt beds generally represent dry periods and the lacustrine mud beds represent wet periods. Lake level was qualitatively determined in the lacustrine mud intervals based upon diatom assemblages and stable oxygen isotopic ratios (Fritz et al., 2004). The recovery of continuous logging records and nearly continuous drill core records from the center of the Salar de Uyuni is significant, because it is here that sediment accumulation has been most continuous and the mud intervals best record the timing of lacustrine intervals on the Altiplano. By contrast, while lake highstand deposits surrounding the Salar are a valuable record of minimum water depth at a given time, they obviously cannot capture the continuous record of lacustrine deposition.

General consensus exists among multiple studies (Baker et al., 2001a; Bills et al., 1994; Blard et al., 2011; Fornari et al., 2001; Fritz et al., 2004; Placzek et al., 2006; Sylvestre et al., 1999) regarding the ages and relative depths of the Altiplano paleolakes of the last 24 ka. From ~24 to 15 ka and again during the Younger Dryas (~13–11 ka), paleolakes occupied the Salar de Uyuni – these are intervals when Lake Titicaca was deep, fresh, and overflowing to the south (Baker et al., 2001b; Fritz et al., 2007). The shoreline elevations (<15 m above the basin) and diatom assemblages suggest that the 24–15 ka paleolake was likely shallow until near its demise, when it reached its greatest depth (~140 m in the Salar de Uyuni, Bills et al., 1994), apparently coincident with the Heinrich 1 cold event of the North Atlantic (Fig. 4). Glacial advance in the Bolivian Altiplano coincides with this large Paleolake Tauca (Blard et al., 2014; Clayton and Clapperton, 1997; Smith et al., 2009). The paleolake desiccated in the Bolling–Allerod interstadial and refilled during the Younger Dryas, when it attained a water depth ca. 45 m.

The correlation of the drill core sequence with the shoreline chronology of high lake stands during periods prior to 25 ka has been the subject of recent controversy. The drill core chronology of Baker and Fritz (Baker et al., 2001a; Fritz et al., 2004) relies on both radiocarbon measurements on lacustrine mud units and U–Th ages of interbedded salt units. In the periods of overlap (<42 ka), the two dating methods are concordant. Yet Placzek and colleagues (Placzek et al., 2013) summarily rejected all drill core radiocarbon ages >25 ka (Baker et al., 2001a; Fornari et al., 2001) and all drill core U-series ages on salts (Fritz et al., 2004). Placzek et al. (2013) instead establish their own chronology for the pre-25 ka drill core sediments based on a single Ar–Ar date on an interbedded tuffaceous sandstone of 191 ka (Fornari et al., 2001); our U-series chronology dates this level to ~59 ka (Fritz et al., 2004). The 191 ka age would require a dramatic change of sedimentation rate, whereas our U-series ages yields a relatively constant sedimentation rate through time, comporting with a nearly linear extrapolation of the radiocarbon age–depth model. We know from our own previous experience that Ar–Ar dating of young, late-Quaternary deposits on the Altiplano is often problematic. Commonly Ar–Ar ages are significantly older than ages of the bounding strata as determined by other dating methods (Fritz et al., 2004, 2007), possibly because of the length of time that biotite crystals spent in the magma chamber prior to eruption or the length of time that volcanic sediments resided on the landscape prior to re-deposition in the basin. We also consider it highly unlikely that the drill core radiocarbon dates are in error by the tens of thousands of years required to accept the revised chronology proposed by Placzek and colleagues (Placzek et al., 2013), especially given the concordance between radiocarbon and U-series dates in the regions of overlap. The original chronology of the drill core sequence (Fritz et al., 2004) and associated climatic inferences are in accord with other regional paleoclimatic records (Cheng et al., 2013; Fritz et al., 2007; Kanner et al., 2012).

A far more parsimonious core-tufa correlation that we put forth here (Fig. 8) leaves unchanged the Fritz et al. (2004) chronology, yet is also consistent with the Placzek highstand dates (2006; 2013), as well as with earlier U-series isochron analyses of shoreline tufas in the basins (Rondeau, 1990). The combined drill core and paleoshoreline data suggest the existence of a long-lived shallow lake (L4) in the Salar de Uyuni basin between ~46 and 36 ka and a long-lived shallow and salty lake (L5 unit) dated between ~60 and 55 ka. These inferred wetter periods are concordant with inferences of wet conditions in the Lake Titicaca basin during MIS3 (Fritz et al., 2010, 2007), the timing of paleolakes in the Rio Desaguadero valley (Rigsby et al., 2005), and cool intervals of glacial advance in the central Altiplano (Blard et al., 2014). The relatively long-lived lacustrine phases were preceded in the Salar de Uyuni basin by multiple, very short-duration perennial shallow to very shallow lake phases between 65 and 125 ka. The inferences of lake depth and salinity are based on diatom species composition (Fritz et al., 2004). The inference of short duration is based upon the thickness of the sediment layer and an assumption of a typical sedimentation rate ca. 1 mm a^{-1}. Although Placzek et al. (2006, 2013) suggested the existence of a deep lake in the Salar de Uyuni basin between 120 and 98 ka (their so-called Ouki phase), all of their dated shorelines in this interval (Fig. 8a) actually come from the Lago Poopo basin, ~70 km to the north of Salar de Uyuni and previously separated from Salar de Uyuni by a hydrologic sill that prevented overflow from paleo-Lago Poopo downstream to the Salars of Coipasa and Uyuni. Prior to the breaching of this sill, which we believe took place between 80 and 60 Ka (Fritz et al., 2012; Nunnery, 2012), overflow from Lake Titicaca and regional drainage from the central Altiplano would have filled the Poopo basin, sometimes to considerable depth, but would not have flowed farther south. Thus, these older highstand data from Placzek et al. (2013) are not representative of fluctuations in the Salar de Uyuni basin (Fritz et al., 2004; Nunnery, 2012; Servant and Fontes, 1978). Moreover, if an Ouki paleolake persisted in the Salar de Uyuni basin for 22,000 years as suggested by Placzek et al. (2013) then it should be represented by an accumulation of approximately 20 m of mud at the average accumulation rate of sediments in paleolake Tauca and glacial-age Lake Titicaca (Fritz et al., 2007)—no such bed exists in the entire drill core record. As a result, the chronology presented by Placzek et al. (2013) for the pre-LGM history of the Salar de Uyuni basin should be rejected given the unified and parsimonious integration of the drill core and shoreline data based on Fritz et al. (2004), a history consistent with other regional paleoclimatic sites.

4.3. *A climate-forcing model of South American summer monsoonal precipitation*

To provide insight into both the nature and the causes of past variability of the SASM, we have created a very simple model of the low-frequency, time-variant climate forcing of tropical South America that we test by comparison of the model output with oxygen isotopic values of speleothem calcite as a measure of past precipitation amount. The model is based on the assumption that low-frequency variation of SASM precipitation is largely forced by a combination of two extrinsic factors: regional summer insolation and the north-south hemispheric Atlantic SST gradient (see Section 2.1). Here we describe the development of the model and compare

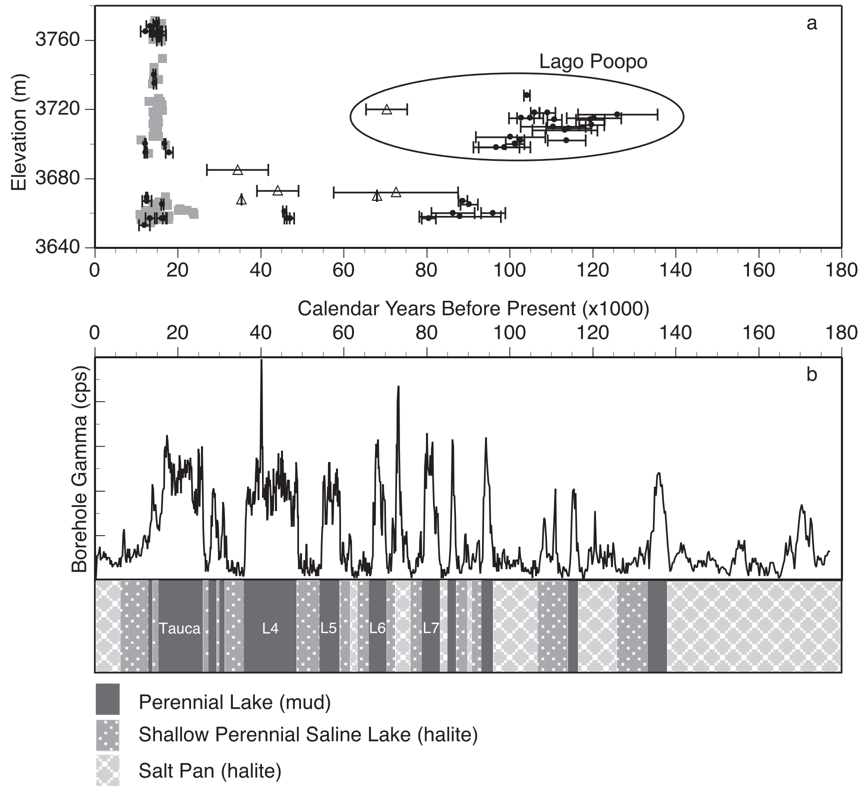

Fig. 8. (a) Paleoshoreline chronology of the Salar de Uyuni, Salar de Coipasa, and Lago Poopo basins — black circles are the U-series ages and the gray squares are the calibrated radiocarbon ages of Placzek et al. (2006). Also shown (open triangles) are the U-series ages of Rondeau (1990). Circled samples are from the Lago Poopo basin; other sites are in the Salar de Uyuni or Salar de Coipasa basins. Note that all of the ages>100 ka are from the northeastern portion of the Lago Poopo basin. (b) The natural gamma log of the Salar de Uyuni drill core site using the Fritz et al. (2004) age model, along with the generalized lithology of the drill core based on sedimentary structures (see Fritz et al., 2004 for additional information). The uppermost lake phases are labeled according to the scheme of Fornari et al. (2001).

predictions of this model with a previously published oxygen isotopic record of speleothems from Botuverá cave in southern Brazil (Cruz et al., 2005).

4.3.1. Model construction

To reconstruct the hypothesized paleoclimatic forcing, we utilize past top-of-the-atmosphere insolation values (Berger and Loutre, 1991) and north-south hemispheric surface temperatures inferred from ice core stable isotopic records from Greenland and the Atlantic sector of Antarctica. We use mid-summer January insolation at 15°S, a mid-tropical latitude that approximately coincides with the latitude of maximum integrated summer heating. Ice core oxygen isotopic time series are utilized as proxy records of northern and southern high-latitude Atlantic surface air temperatures in lieu of SST reconstructions, because the former are made at far higher resolution than any SST reconstructions spanning the time period of interest.

The Antarctic oxygen isotopic data are from EPICA Dome (EPICA, 2006) using the EDML1 chronology (Ruth et al., 2007). The Greenland oxygen isotopic data are from NGRIP (North Greenland Ice Core Project Members, 2004) using the GICC05 time scale (Andersen et al., 2006; Rasmussen et al., 2006; Svensson et al., 2008; Vinther et al., 2006; Wolff et al., 2010). Andersen et al. (2006) conservatively estimated a relative error in their age model for NGRIP of 4% (2σ). The dating uncertainty for EDML1 is likely to be greater than 100 yr at the LGM, greater than 1500 yr at 40 ka, greater than 3000 yr at 100 ka, and greater than 6000 yr at 130 ka (Parrenin et al., 2007; Ruth et al., 2007).

The values in the climate forcing data sets (stable isotope ratios in ice cores and insolation) were interpolated at 100-year time intervals. The series mean of the insolation values was subtracted from each individual value at each centennial interval, and the calculated difference was divided by the standard deviation of the series to normalize the insolation data. The isotopic values from the ice cores were treated similarly. The north-south "temperature" gradient was produced by subtracting isotopic values of the EDML record from the isotopic value of the NGRIP record. The expected phase relationship of north-south forcing (Baker et al., 2009; Nobre and Shukla, 1996; Vellinga and Wood, 2002; Vuille et al., 2012; Wang et al., 2006) is that colder northern climates and warmer southern climates (lower north-south temperature gradients) produce wetter conditions over the monsoonal region of South America and more negative values of $\delta^{18}O$ in the speleothems (see Section 2.1). Lacking detailed quantitative understanding of the combined magnitude of forcing due to both insolation and the north-south temperature gradient, we simply sum the equally weighted factors.

4.3.2. Model predictions

The combined paleoclimatic forcing is compared to the Botuverá target data set of Cruz and co-workers (Fig. 9). We corrected the original Botuverá record for the influence of temperature on carbonate-water isotopic fractionation and for variation of ocean water $\delta^{18}O$, as described above (Section 4.1). The age model for the Cruz et al. record is constrained by 49 U–Th dates with a reported mean relative error of 2.9% (2σ). Their 688 isotopic measurements span approximately 114 ka, averaging 165 years between samples.

Dating error (2σ) in ice core and speleothem records (at 50 ka) of ~1450 yr, ~2500 yr, and ~2000 yr can be respectively inferred for the Botuverá (Cruz et al., 2005), the NGRIP (Andersen et al., 2006),

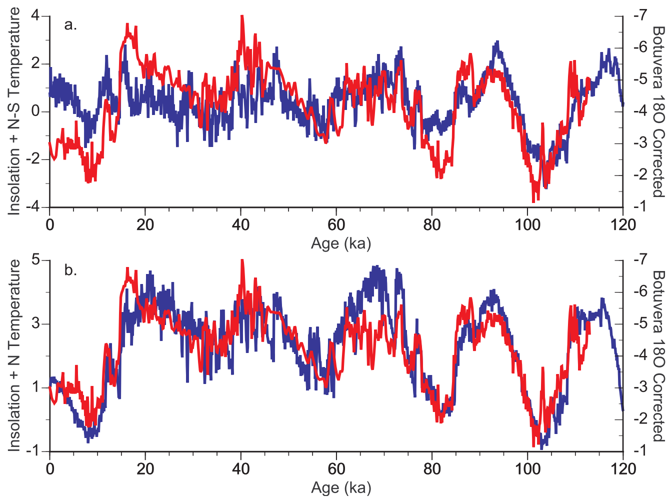

Fig. 9. A climate-forcing model (blue line) generated from a combination of mid-summer (January) insolation at 15°S and Atlantic SSTs (derived from ice core stable isotopic records from Greenland and the Atlantic sector of Antarctica) compared with the history of the SASM from the oxygen isotopic record of speleothems from Botuverá cave in southern Brazil (Cruz et al., 2005): (a) comparison of the isotope record with a model that utilizes the north–south hemispheric SST gradient; (b) comparison of the isotopic record with a model that uses only north SSTs. See Section 4.3 for further details.

and the EDML (Ruth et al., 2007) records. Given this error, the proposed climate forcing explains the variation of the stable oxygen isotopic records of the Botuverá speleothems to a remarkable extent (Fig. 9a). This supports the hypothesis that large-amplitude changes in past amounts of SASM precipitation in this region are largely explained by two climate forcing factors of approximately equal strength, one regional (insolation) and one nearly global (north-south Atlantic temperature gradient). In fact, the correlation between the forcing and target data sets appears to qualitatively improve when insolation and only northern temperature forcing are summed (Fig. 9b). This is likely so, because temperature variance is much greater in the North Atlantic sector, thus northern temperatures are the primary control on the north–south gradient.

To some extent, these results are not surprising. When Cruz et al. (2005) first published the Botuverá speleothem isotopic record, they discussed the correlation between past monsoonal activity and precession-paced summer insolation forcing of the SASM, a relationship that had been demonstrated previously in other records from sub-tropical South America (e.g. Baker et al., 2001b; Martin et al., 1997) and in other monsoon regions (e.g. Kutzbach, 1981; Yuan et al., 2004). Subsequent oxygen-isotopic analyses of Botuverá speleothems (Wang et al., 2006, 2007) demonstrated an inverse correlation between the residual higher-frequency (multi-centennial) variations in $\delta^{18}O$ from Botuverá and speleothem records from eastern China, positing a mutual control through variations in the Atlantic meridional overturning circulation (AMOC).

The novel aspect of what we show here is that a simple combined climate forcing, determined from paleoclimatic records (ice cores and insolation), is quantifiable from an equally weighted linear combination (sum) of summer insolation forcing and North Atlantic temperature forcing. Most importantly, this climate forcing "model" is an accurate predictor of past monsoon precipitation at high temporal resolution over the past ~100 ka (and likely beyond).

4.4. Biogeography and biodiversity

In 1969, Jurgen Haffer published his seminal paper on the Amazon refugia hypothesis, which set in motion decades of research examining the nature of climate variation during the Quaternary and its impacts on tropical biota. Haffer (1969) proposed that during dry intervals of the Quaternary, rainforest contracted into small isolated areas (refugia), where water availability was higher, separated by vast open areas of savanna, which promoted isolation and biotic differentiation and hence enhanced speciation in Amazon forests birds. In a later publication Haffer (1974) specifically proposed that the dry periods were correlative with Northern Hemisphere glacial periods.

A large number of pollen records from tropical South America depict patterns of late-Quaternary vegetation change through time (reviewed in Mayle et al., 2009), but most are from the Andes or margins of the Amazon forest, and the majority of records span less than 50 ka. Fluctuations in the distribution of rainforest, seasonal dry forest, savanna, and grassland are evident in ecotonal areas (Hermanowski et al., 2012; Mayle et al., 2009), but knowledge of the composition of the vast central basin of the Amazon during the Quaternary is still very limited. Hill of Six Lakes, an inselberg in lowland Brazil, contains the only long pollen record located well within the limits of the contemporary Amazon forest. The pollen record was purported to show the continuous presence of closed tropical rainforest taxa throughout the 40 ka record (Bush et al., 2004a; Colinveaux et al., 1996), however there is a clear unconformity that precludes such a conclusion for the critical LGM interval (Bush et al., 2004a; D'Apolito et al., 2013). Sediments deposited prior to the Holocene show the expansion of *Podocarpus* and other cool-adapted taxa, possibly indicating the downslope migration of high-elevation taxa during glacial times. The migration of taxa along elevation gradients is a common pattern in records from the Andean slopes and adjoining areas (Bush et al., 2004b; Groot et al., 2011) and produced new mixtures of taxa that likely affected multiple aspects of ecosystem structure and function, as well as evolutionary processes.

The anti-phasing of precipitation variation north and south of the equator and between the eastern and western Amazon on orbital time scales (Section 3.2), coupled with large increases in precipitation during the Heinrich events throughout the Southern Hemisphere tropics (see Section 3.3), produced spatial patterns of moisture availability very different from those envisioned by Haffer (1969). This variable patterning of climate likely created different spatial domains of favorable versus unfavorable habitat at different temporal scales. For example, Cheng and colleagues (Cheng et al., 2013) speculated that forest expansion during moderately wet glacial intervals connected the western Amazon forests and the southern Atlantic forests via a western forest corridor, whereas establishment of an eastern corridor of continuous forest may have occurred only during Heinrich events.

Clearly, the magnitude of precipitation change at orbital and millennial scales was large, as exemplified in paleohydrological records and modeling studies (e.g. Cruz et al., 2009; Fritz et al., 2007), with the potential to affect growth rates, viability, and dispersal of diverse plant and animal populations. Yet whether biomes, communities, or species in different regions of tropical South America – such as in the eastern Amazon, where precipitation is lower and soils are less fertile than in the west (ter Steege et al., 2006) – were differentially affected by precipitation variation is unclear. It is also possible that small scale wet and dry regions (as observed in the instrumental record, Killeen et al., 2007), created by the interaction of precipitation, topography, and winds may have persisted through intervals of variable regional climate, affording stable conditions favorable to the development of fine-scale biodiversity "hotspots". In any case, to a large extent, the impact of Quaternary climate variation on the biodiversity, structure, and function of tropical biomes remains poorly explored.

5. Conclusions and implications

In the past two decades there has been a large increase in the quantity and quality of paleoclimate records from tropical South America. Lacustrine sediment records and speleothem isotopic records are foremost among these, with each type of archive claiming some advantages in dating accuracy, temporal resolution, fidelity of proxy, or length of record. As more records appear, the regional map is becoming filled, however, one persistent and crucial gap that remains largely unfilled is the core Amazon region itself.

The emergence of these many records has led to a greatly improved understanding of the spatio-temporal variation of climate, more so precipitation than temperature and other variables. As outlined here, climate variation can be recognized at (1) eccentricity-paced, glacial-interglacial timescales, when global glaciation coincided with regional glaciation and generally high lake stands (Lake Titicaca) in the tropical Andes; (2) precession-paced timescales when summer season top-of-the-atmosphere insolation changes coincide with changes in the intensity of the South American summer monsoon at sites far south of the equator (Botuverá), yet Northern Hemisphere glacial boundary conditions seem countervailing at sites located near the equator. East–west antiphasing of precipitation in the deep tropics is a newly identified pattern (Cruz et al., 2009). (3) Centennial-millennial precipitation pluvial events occur in phase with North Atlantic cold climate events of MIS3 and have the same sign throughout the southern tropics. Decadal climate events on the Altiplano seem to have the same Atlantic teleconnection.

As these patterns of past climate emerge, they bring into focus the challenge of understanding the climate mechanisms that underlie the observed patterns. The only likely method to achieve this goal is climate modeling, yet climate models have been shown to be quite unreliable in tropical South America. It remains to be seen if it will be possible to use models to understand the magnitude of past climate variation, the mechanisms underlying the North Atlantic-South American teleconnection, the linkage between variation of the ITCZ and the SASM, and the role of the North Brazil Current and trans-equatorial heat flux in variations in AMOC and the North Atlantic heat budget. Isotope-enabled GCM's in particular have potential to improve our quantitative understanding of proxy records from speleothems and lake sediments.

Essentially no climate records from tropical South America extend back prior to 0.5 million yr, thus, our knowledge of early Quaternary and pre-Quaternary climates is virtually non-existent. We need to recover such records in order to improve our understanding of the influences on tropical South American climate of Andean uplift, the widening Atlantic, cooling Cenozoic climate, and changing atmospheric greenhouse gas concentrations. These climates are significant, because the majority of modern tropical species arose in this earlier period. Furthermore, these warmer climates may provide some of the best inferential evidence for understanding the survival of these taxa in human-modified climates and landscapes of the near future (Magrin et al., 2014).

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