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Hydroclimate variability of the South American Monsoon System during the last 1600 yr inferred from speleothem isotope records of the north-eastern Andes foothills in Peru

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Abstract

In this paper we explore a speleothem $\delta^{18}O$ record from Palestina Cave, North Eastern Peru, at a site on the eastern side of the Andes cordillera, upper Amazon Basin, interpreted as a proxy for South America Summer Monsoon (SASM) intensity. This record allows reconstructing SASM activity with ~ 5 yr time resolution over the last 1600 yr, spanning two major periods of climate variability: the Medieval Climate Anomaly (MCA; 900–1200 AD) and Little Ice Age (LIA 1400–1850 AD) recognized as periods of decrease and increase SASM activity respectively. Time series and wavelet analyses reveal decadal to multidecadal frequencies. Our results suggest that Atlantic Multidecadal Oscillation mode (AMO) plays an important role for SASM modulation on multidecadal scale ($\sim$65 yr), especially over dry periods such as observed during MCA. Frequencies of 8 and 25 yr simultaneously with multidecadal signal (65 yr) are found over the LIA. and suggest that those modes could be related to North Atlantic Oscillation (NAO) and Interdecadal Pacific Oscillation mode (IPO). Comparison with other South American Paleoprecipitation records shows that the Atlantic and Pacific decadal to multidecadal variability and their teleconnections play an important role in the intensity and the regional patterns of rainfall distribution during the last 1600 yr.

1 Introduction

South America paleoclimate reconstructions over the last millennium based on $\delta^{18}O$ proxy over different matrix such as speleothems, lake sediments and ice cores, have shown coherent patterns of changes which are globally synchronous during distinct events recognized as the Medieval Climate Anomaly (MCA; 900–1250 AD) and the Little Ice Age (LIA; 1400–1850 AD), respectively. These long climate events are manifested by changes in temperature over oceanic and continental areas that are also related to variations in hydroclimate conditions. Those changes were mainly recognized from historical and proxy records in Northern Hemisphere where warm/dry conditions

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were inferred from several proxies during MCA (ex. Graham et al., 2010 and references cited therein) and cold/wet conditions is evidenced by glacier advance through the LIA period (ex. Rabatel et al., 2008 and references cited therein).

Specifically for the South American Andes, earlier works at the 80 s, based on oxygen isotopic signal (δ^{18}O) from the Quelccaya glacier allowed the first climate reconstruction for the last 1500 yr. The LIA climate period was recognized in this record by more negative values of ice δ^{18}O originally interpreted as cold periods (Thompson et al., 1986). Other studies based on speleothems δ^{18}O record from eastern Andes suggest that rainfall during the LIA increases around 20 % compared to nowadays (Reuter et al., 2009). Moreover a recently published work based on authigenic calcite δ^{18}O deposited in annual laminated lacustrine sediments of a high altitude lake on east flank of Andes confirms the intensification of the South American Monsoon System (SASM) during the LIA period and diminished SASM activity at the MCA interval (Bird et al., 2011). The interpretations of δ^{18}O climatic signal in the Andean ice records are considered consistent with those proposed from the carbonate records from speleothems and lake records within SASM's domain (Vuille et al., 2012), because these records reflect primarily the isotopic composition monsoonal rainfall (Vuille and Werner, 2005; Vimeux et al., 2005). However, the climate response to these events in terms of summer precipitation could be spatially different over South America, for instance increased rainfall is observed over Andes and Southern Brazil during LIA (Oliveira et al., 2009; Vuille et al., 2012), while dryer climate is seeing in Northeastern Brazil (Novello et al., 2012). In addition relatively dry climate is documented during MCA not only over Andes but also in NE Brazil, but these conditions are not so distinctive from Southern Brazil speleothems.

Although the growing knowledge in paleoclimate reconstructions noticed for MCA; LIA, and Current Warm Period (CWP) events, the mechanism involved in changes of SASM mean state are still not plenty understood, even with the recent development of high resolution proxy records. Published works until today suggest that teleconnections between Pacific and Atlantic oceans and their variabilities affect SASM intensity and/or

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rainfall distribution over South America at different time scales (ex. Kanner et al., 2012; Novello et al., 2012). Those changes certainly play a significant role in response to changes in global forcing. In fact, there's considerable concern that the SASM dynamics will be significantly affected by increasing greenhouse gas concentrations in the 21st century (Seth et al., 2010). Hence there is an urgent need to better document and understand the causes of Monsoon variations in response to natural forcing during the most recent past period (Vuille et al., 2012). For instances, climate modeling studies and additional paleoclimate records of ocean and atmospheric conditions are needed to better define the relationships between SASM rainfall and ocean–atmosphere variability during the late Holocene.

Here we explore a new high resolution δ^{18}O record of the well dated speleothems PAL3 and PAL4 collected in Palestina Cave on the eastern side of the Andes Cordillera (North-East Peru) in a record comparison with other paleoclimate proxies along the Andes also related to the intensity of the SASM. The PAL3 and PAL4 records spam the last millennium with ~ 5 yr time resolution exploring the variability from the subdecadal to multidecadal time-scales. Time series and wavelet analyses are carried out in order to identify oceanic and atmospheric modes acting in the past SASM activity and their possible teleconnections. Additionally, possible mechanisms explaining temporal and spatial variability of SASM along the east-west δ^{18}O records (Brazil Northeast and Western Amazon) are discussed for the last 1600 yr.

2 Study area and modern climatology

The Palestina cave (Nueva Cajamarca, San Martín, Peru) was explored over 2380 m by the Bristol Exploration Club (BEC, UK) in 2003, and mapped by the French-Peru GSBM-ECA team in 2011. The cave is located in the Sub-Andean Northeast Peru (5.92° S; 77.35° W), upper Amazon basin in the eastern margin of the Andes Cordillera (870 m a.s.l.) in a Triassic-Jurassic Limestone-Dolomitic formation (INGEMET-Peru) (Fig. 1). The present day climate is tropical humid with annual precipitation around

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1570 mm showing a bimodal rainfall distribution, with peaks at November (beginning of SASM) and March (end of SASM), which correspond to around 63 % of the total annual rainfall. This semi-annual rainfall cycle also results from the zonal oscillation of the continental footprints of the ITCZ, associated with the semi-annual cycle of radiation and temperature (Marengo and Nobre, 2001; Espinoza et al., 2009).

On interannual timescales, changes in SASM intensity is partially related to SST anomalies in the Pacific Ocean associated principally to ENSO (Paegle and Mo, 2002; Garreaud et al., 2009; Grimm, 2010 and references cited therein). During the warm or positive phases of ENSO (El Niño), below average precipitation during the summer wet season is observed in northern South America, especially over the Northeast of the Amazon basin (Ronchail et al., 2002) and exceptionally in the western Amazon (Espinoza et al., 2011). Opposite conditions is observed during cold or negative phases (La Niña) where abundant rainfall and flooding occur in the north and northeast of the Amazon region (Ronchail et al., 2002; Espinoza et al., 2009, 2013). Those patterns are attributed to combination of Walker and Hadley circulation anomalies for each case (Ronchail et al., 2002; Garreaud et al., 2009; Marengo et al., 2012). The influence of the Atlantic SST's anomalies on the interannual variability of the SASM has not been extensively studied as the influence of Pacific SST anomalies. Warm SST anomalies in the tropical North Atlantic region have been associated with drought conditions over western (Ronchail et al., 2002; Marengo et al., 2008; Espinoza et al., 2011), and Southern Amazon Basin. For instance, the 2005 drought of Amazonia was not related to ENSO but to the tropical Atlantic variability (Espinoza et al., 2011; Marengo et al., 2008, 2012).

On decadal and longer time scales SASM activity is less understood because the limitations in instrumental data. The Pacific Decadal Oscillation (PDO) is considered important modulator for South America precipitation because its influence on ENSO state (Mantua et al., 1997; Garreaud et al., 2009). On the other hand, linkages to Atlantic Multidecadal Oscillation (AMO) with periodicities of ~ 64 yr as an important factor driving SASM variability, such as founded in proxy records over marine (Chiessi et al., 2009) and continental environments (Novello et al., 2012). However, there is still very limited information of the climate changes in Amazon region on these time-scales.

Oxygen isotopes ($\delta^{18}O$) in rainfall over South America, suggest that fractionation processes were principally related to *amount effect* (Reuter et al., 2009). Moreover, recent studies based on numerical models in precipitation representing isotopic variability through the eastern side of the Andes Cordillera (Kanner et al., 2012; Vuille et al., 2012) demonstrate that degree of moisture recycling and rainout upstream over the Amazon Basin associated with the intensity of the SASM as also a very significant controlling factor (Vuille and Werner, 2005; Kanner et al., 2013; Vuille et al., 2012). The rainfall in the study region is preferentially associated with summer precipitations related to SASM, although the winter precipitation related to residual equatorial rainfall is still significant.

3 Materials and methods

Two speleothems were collected in Palestina cave at sites near 600 and 700 m away from the entrance and ~ 80 m below the surface. Stalagmites PAL3 and PAL4 are a ~ 10 and ~ 17 cm tall respectively. Age models developed for the PAL-4 are constrained by 13 U-Th ages and PAL-3 by 6 U-Th ages, measured at the Minnesota Isotope Laboratory, University of Minnesota, using inductively coupled plasma-mass spectrometry (ICP-MS) technique (Cheng et al., 2013). The chemical procedures used to separate uranium and thorium for ^{230}Th dating are similar to those described by Edwards et al. (1987), where the most of dates present errors of (2σ) < 1 % representing a mean value of ~ 15 yr (Tables S1 and S2). The chronological model was developed by linearly interpolated ages in between dates.

Oxygen isotope analyses were obtained for 264 samples collected along the growth axis of PAL4 stalagmite, sampling interval of 0.3 mm, using a Sherline micro drill model 5400, coupled to an automated X-Y-Z Stage. This sampling approach provides a temporal resolution between 2 and 10 yr (~ 5 yr). Analyses of $\delta^{18}O$ were performed in

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a Delta Plus Advantage (Thermo Finningan) mass spectrometer, in the "*Laboratorio de Estudos Geodinâmicos e Ambientais"* at the University of Brasilia (UnB). For δ^{18}O, error analyses were 0.1 ‰. Records are reported as δ^{18}O ‰ relative to Vienna PDB Standard.

The oxygen isotope profile of PAL3 are based on 200 analysis using 100 µm sampling interval for the first 16 mm using a MicroMill–Micromachining System with high-speed precision drill stereomicroscope with CCD, mount for XYZ motion control, in order to obtain high resolution for the most recent period recorded in the speleothem. Between 16 and 39 mm, a 0.3 mm sampling interval was used, for comparison with δ^{18}O values of PAL-4 samples. This samples were also analyzed in the *Laboratório de estudos Geodinamicos e Ambientais* at the University of Brasilia (UnB) using a Kiel IV carbonate device coupled to a MAT 253 mass spectrometer (Thermo Finningan). This device allows to optimize the sample mass for analyses (≤ 20 µg of Carbonate) and analytical precision obtained are around ±0.06 ‰ for δ^{13}C ±0.09 ‰ for δ^{18}O.

Spectral analysis techniques were performed on annually interpolated PAL-4 and PAL3 δ^{18}O time series. Wavelets analysis (Torrence and Compo, 1998) is used to display the frequency variability of the δ^{18}O time series, while cross-wavelets analysis (Grinsted et al., 2004) is used to test the similarity and coherence in periodicities between our δ^{18}O records and other reconstructed indexes records on multi-decadal timescales.

4 Results and discussion

PAL3 and PAL4 calcite speleothems presents microcrystalline fabric and no apparent "hiatus". The twenty U-Th dates in PAL4 and PAL3 reveal that samples cover the period from 413 ± 10 to 1824 ± 16 AD and from 1096 ± 15 to 1925 ± 8 AD respectively. PAL4 show a mean growth rate around 0.056 mm yr^{-1} with variations between 0.03 and 0.08 mm yr^{-1} and PAL3 presents growth rate that lies around 0.049 mm yr^{-1} with variations between 0.035 and 0.07 mm yr^{-1} (Figs. S1 and S2). Sampling spacing of

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0.3 mm for PAL4 and 0.01 mm for PAL3 allows $\delta^{18}O$ reconstructing record with resolution between 2 and 8 yr (~ 5 yr) for both speleothems (Fig. 2).

Stable oxygen and carbon isotopes ratios ($\delta^{18}O$ and $\delta^{13}C$) are poorly correlated along the growth axis for both speleothems (PAL4 = 0.26 and PAL3 = 0.01, Fig. S3), which indicates that calcite deposition occurred close to equilibrium conditions with drip water (Hendy, 1971). Even though the speleothems have different sampling resolutions and age models, the two oxygen isotope records are nearly identical both in terms of the mean values and the magnitude of change through the overlapping ~ 900 yr interval, revealing variability at decadal to centennial timescales (Fig. 2). PAL4 stalagmite presents absolute values ranging between −7.66 and −5.73 ‰ with a mean value of −7.14 ‰. For PAL3 stalagmite, the mean value of $\delta^{18}O$ series lies around −7.08 ‰ showing maximum and minimum values between −6.67 and −7.44 ‰ respectively. Between 1395 AD and 1450 AD, it is observed an offset in the $\delta^{18}O$ of 50 yr among PAL3 and PAL4 stalagmite because the chronological control of PAL3 is less constrained than in the PAL4 record. Nevertheless, the range of absolute values in $\delta^{18}O$ for PAL3 and PAL4 are in agreement with other speleothem works for the same region (Van Breukelen, 2008; Reuter et al., 2009) confirming a common climate signal in the speleothem records.

The oxygen isotope ratios in PAL3 and PAL4 calcite are interpreted here as a function of SASM activity such as suggested by previous works in the eastern Andes (Bird et al., 2011; Vuille et al., 2012; Kanner et al., 2013). For PAL-4, enriched values in $\delta^{18}O$ (~ −6.8 ‰) reflect weak intensity in SASM from 410 to 570 AD followed by enhanced SASM activity from 580 to 720 AD confirmed by more depleted values in $\delta^{18}O$ (~ −7.46 ‰) (Fig. 2). From 720 to 820 AD an enrichment of $\delta^{18}O$ values (~ −6.6 ‰) in PAL4 signal is observed followed by a decrease of $\delta^{18}O$ values over the period dated between 820–920 AD (~ −7.46 ‰) showing similar fluctuations as before recorded. The Medieval Climate Anomaly spam the period between ~ 920 and 1200 AD showing most enriched $\delta^{18}O$ values documented in the record also reflecting diminished SASM activity. During the MCA a double peak structure is observed on decadal time scales

(~ 30 yr) centered at ~ 934 (~ −6.3 ‰) and ~ 1039 AD (~ −5.8 ‰) and correspond to the maximum $\delta^{18}O$ values in the whole record. Interestingly, they are also observed in the Pumacocha lake record (Fig. 3). The transition period from the MCA to LIA (~ 1200 to 1350 AD) shows mean value of −7.1 ‰ in $\delta^{18}O$ characterized by a persistent decadal variability. The LIA period is characterized by an substantial increase in SASM activity from ~ 1350 to 1830 AD defined by the lowest values of $\delta^{18}O$ in the record observed between 1400 and 1593 AD (−7.6 ‰) (Fig. 2).

Comparison between the Palestina cave isotope record with other high resolution proxies of SASM activity in the Andes, in particular with Pumacocha (Bird et al., 2011) (Fig. 3c), show striking relationship in time, magnitude and variability confirming that it reflects variations in the mean state of SASM. However, some differences are evident among records at the interval from 413 to 818 AD (not shown). We suggest that these differences are mostly related to accuracy in chronology, since ^{14}C AMS dating are less constrained through the older part of the Pumacocha record. In the same sense, Cascayunga speleothem record (Reuter et al., 2009) (Fig. 3b) located close to Palestina cave tracks similar variations in $\delta^{18}O$ trend during the last 900 yr record from CAS-D speleothem. Nevertheless, some discrepancies in timing and magnitude between these time series are seeing in the range of $\delta^{18}O$ values during the LIA event, supposed to differences in the chronological model, which is better constrained in the case of Palestina record. Quelccaya Ice core (Thompson et al., 1986) (Fig. 3a) also shows the same variations in the mean state of the SASM during the 1500 yr record, confirming the regional similitude in the $\delta^{18}O$ signal along the Andes, despite the timing uncertainties in definition of these events.

Comparison with other high resolution proxies of the SASM far from the Andes cordillera show also coherent fluctuations of $\delta^{18}O$ values (Fig. S4). Over southeastern tropical South America at Cristal cave in Brazil, it is also observed a more intense monsoon activity at the LIA period with some temporal lag in the onset of maximum precipitations (Taylor, 2010; Vuille et al., 2012). The most intense SASM is inferred from this proxy during seventeen century, about hundred years later than recorded in Palestina cave. These results confirm previous works revealing asynchronous LIA event over South America (Rabatel et al., 2008). In contrast, the SASM's activity during LIA in the SW part of Northeastern Brazil (Fig. 5) is defined by a deficit in monsoonal precipitation which is related to an increase in upper level subsidence to the east in response to enhanced monsoon over the Amazon region (Novello et al., 2012). On the other hand, similar weak monsoon inferred by higher values of δ^{18}O between Andean and NE Brazil records are observed during the MCA, however no anomalous values are seeing in Southern Brazil at the same period (Vuille et al., 2012). Thus, these results suggest important changes in SASM activity and spatial distribution over northern South America during LIA and MCA events.

Spectral analysis in the δ^{18}O time series of Palestina record indicates significant periodicities centered on 70, 44, 29, and 10 yr, within 95 % statistical confidence (Fig. S5). Additionally, wavelet analyses developed in the Palestina record confirm these results, indicating statistically significant superimposed periodicities (Fig. 4d). These observed periodicities are in concordance with other South America speleothems records. Time series of δ^{18}O in DV2 speleothem collected in Northeastern Brazil, which corresponds to a the northern boundary region of the SASM, shows similar cycles affecting summer precipitation such as 76, 65, 40, 22 and 15 yr (Novello et al., 2012). The statistically significant superimposed periodicities suggest a common large scale signature along the east–west domains of SASM over the continent probably related to similar climate mechanisms especially at multi-decadal timescales. However, these periods varies significantly from a relatively dry to wet periods. As illustrated in Fig. 4d, during the MCA relative low frequency variability is observed centered at ~ 70 and 48 yr. Over the transition period, after 1200 AD, periodicity of 48 yr is maintained, lower frequency signal diminishes and high variability of around 10 yr periodicity appears. At the LIA, highly significant periodicities of 8 to 16 and 32 yr persist throughout the event between 1600 and 1850 AD, together with the band periodicity from 60 to 80 yr (~ 70 yr).

Variations in the SASM activity through the last millennium have been linked to different mechanism related to the Pacific and Atlantic Ocean modes (ex. Moy et al.,

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2002; Conroy et al., 2008; Mann et al., 2009; Reuter et al., 2009; Bird et al., 2011; Novello et al., 2012; Vuille et al., 2012; Graham et al., 2010). Yet, a possible mechanism that could explain the significant changes in mean climate state during the last millennia such as observed at LIA and MCA events have to be tested according to the proxy record availability in South America. During MCA, proxy record available in South America have inferred expressions of Pacific Ocean mean states revealing Niña Like conditions (Cobb et al., 2003; Conroy et al., 2008; Mann et al., 2009; Graham et al., 2010) and Niño Like conditions (Moy et al., 2002; Thompson et al., 1996, 2013) in order to explain hydroclimate variations and teleconnections. Following modern patterns of rainfall variability over western Amazonia, we realize that dry conditions are exceptionally referred to El Niño episodes and strong rainfall events are related to La Niña events (Espinoza et al., 2011, 2012). For instance, if the ENSO phenomena was the main modulator of climate changes for the MCA, teleconnections patterns implies that we expect increase precipitation over Southeastern South America such as Palestina and Bahia Nordeste cave records (Novello et al., 2012), which is the contrary of what is observed in both regions.. Moreover, Cristal cave record do not experiment anomalous variations in δ^{18}O over the record suggesting that rainfall during MCA is not dominated by conditions in Pacific ocean. Western Amazonia is especially sensible to changes in tropical Atlantic SST's, which diminishes precipitation as positive anomalies are observed in the northern portion of it (Espinoza et al., 2011, 2012). Over the Atlantic ocean, there's evidence appointing that sea surface temperature anomalies (SSTA) in the North Atlantic sector during the MCA were unusually warm (Keigwin et al., 1996) showing similar patterns observed during positive AMO or NAO phases (Feng et al., 2008; Trouet et al., 2009). For SASM, there are indications that positive phase of AMO leads to reduce monsoon intensity at multidecadal timescales, linked to northward migration of ITCZ (Chiessi et al., 2009; Strikis et al., 2011; Bird et al., 2011; Novello et al., 2012). Periodicities observed in the Palestina cave series highlight a multidecadal influence over this time period in concordance with AMO signature of ~ 65 yr frequency as obtained in models and instrumental data (Knight et al., 2006) (Fig. 4d). In this sense, comparisons with reconstructed AMO index published by Mann et al. (2009); (Fig. 4a) present similar behavior to Palestina record (Fig. 4b) and evidence a persistent positive phase of the index at the MCA period, showing also the same structure of double peak with some lag in the time series. This observation suggests that for MCA hydroclimate variability can be explained by interactions of Pacific and Atlantic ocean modes, which impact rainfall distribution over South America. Moreover, modern teleconnections suggest that it would be preferentially related to North Atlantic variability (Espinoza et al., 2012, 2013; Ham et al., 2013).

Pumacocha Lake, Palestina record in the eastern Andes and DV-2 record over the Northeastern Brazil present the double peak structure over the MCA, expressed by enriched values in ^{18}O (Fig. 3). This feature, demonstrates a coherent variability in timing and structure in South America during MCA. In addition, intense humid events from Chaac stalagmite in Mexico are coincident with these peaks (Medina Elizalde, 2010), which is also evident based on peaks of Ti in Cariaco sediment record suggesting that ITCZ was displaced to northerly position (Haug et al., 2001). Diminishing moisture transported by SASM during austral summer and intense rainfall over the tropical Northern Hemisphere at boreal summer season could be reflected in our region by changing source and convective process driving precipitations with enriched signature of δ^{18}O explaining the magnitude of fractionation observed in the record for those double peaks.

As exposed, proxy records over South America for LIA period have revealed an increased SASM activity along the eastern Andes and Southeastern South America and opposite conditions in to the Nordeste region. Increased SASM activity over the LIA is synchronous with cold events in Northern Hemisphere (e.g. Gray et al., 2006; Mann et al., 2009). Those conditions trigger southward migration of the ITCZ (Haug et al., 2001; Reuter et al., 2009; Bird et al., 2011; Vuille et al., 2012; Novello et al., 2012) as evidenced by diminished Ti concentrations in Cariaco Basin during LIA (Haug et al., 2001) and a significant decrease in SST's over tropical north Atlantic (Black et al., 2007). Since ITCZ serve as the major moisture source fuelling SASM, a coherent intensification of this system is inferred from more negative δ^{18}O values in different matrixes in the Andean isotope records. Through eastern South America, Nordeste record shows opposite co-variation at LIA reflecting dry conditions, which cannot be associated with a forcing by ENSO once it is expected a in phase behavior between northern Peru and Brazil Nordeste (Fig. 5). In fact, this antiphasing behavior, as suggested by Novello et al. (2012), might reflect the intensification of the Bolivian High-Nordeste Low pressure system due to increased SASM rainfall and related convective heating over the south western portion of the Amazon region (Lenters and Cook, 1997). This mechanism, associated with increased upper level convergence, subsidence and a deficit in summer precipitation over northeastern Brazil during periods of enhanced SASM activity, has been invoked to explain the antiphasing between precipitation in Nordeste rainfall and most of tropical South America on orbital time scales (Cruz et al., 2009).

Intensifications of SAMS is also consistent with increased precipitation in the Eastern Pacific (Conroy et al., 2008) explained by a southward migration of the ITCZ (Newton et al., 2006; Sachs et al., 2009; Oppo et al., 2009). Moreover, definition of the Pacific state, based on zonal SST gradients (Fig. 4c), is not elucidated during LIA because low salinity are observed in both Western (Newton et al., 2006) and Eastern Pacific (Sifeddine et al., 2008; Gutierrez et al., 2009; Salvatecci et al., 2013) suggesting rainfall events that makes difficult to define a typical pattern of ENSO conditions. In addition, the intense SASM's described at sites located in northern Peru and southern Brazil during LIA cannot be explained by a dominant control of ENSO phenomena, because the climate response to ENSO is not expected to be so significant in Palestina cave region (Ronchail et al., 2002; Espinoza et al., 2011, 2012) or even opposite between these regions (Vera et al., 2006; Grimm and Zilli, 2009). It is likely that such enhancement of SASM over Amazon region could also promote anomalous monsoon rainfall in Southeast South America (SESA) because it favors the moisture transport by low level jet along its NW–SE trajectory. In the mean climatological fields, this feature is primarily associated to the moisture advection from ITCZ region to Amazon, which depends mostly on changes in the SST gradient between northern and southern Atlantic Ocean and also an intensification of NE trade winds (Vera et al., 2006; Marengo et al., 2012).

Wavelet Analyzes over DV2 and PAL4 record suggest that for LIA period, both parts of the continent are governed by different frequencies (Fig. 5). Over eastern Andes higher to lower frequencies of ∼ 8 ∼ 25 and ∼ 60 yr are superimposed through the end of the period in PAL4 (Fig. 5d). At this time, in Northeastern record, ∼ 64 yr is the most persistent frequency band found (Fig. 5b). These frequencies observed in δ^{18}O series might reflect different mechanisms governing precipitations in these regions at LIA time interval resolving hypothesis of Pacific–Atlantic Ocean interactions. The frequency of ∼ 9 yr cycle have been found in different rainfall and river flows records in SESA, and recognized as an independent signal other than ENSO, raising the possibility of a relationship with decadal variations in the North Atlantic Oscillation (Robertson and Mechoso, 1998). On the other hand, ∼ 15–25 yr frequency is one of the most energetic signal of the Pacific Decadal Oscillation wherein warm PDO (El Niño-like) periods tend to have anomalously wet subtropics but dry tropics and mid latitudes in both North and South America (Mantua et al., 2002). However, it is hard to disentangle the superimposed influences of the Pacific and Atlantic at different timescales, especially when both oceans trigger distinct modes and impacts differently the rainfall over the continental areas.

Reorganization in the adjustment between Hadley and Walker circulation over the tropics by ITCZ in its southmost mean position, might promote an increase in the activity of SASM associated with the low-level jet along the eastern flank of the Andes (Nogue's-Paegle and Mo, 1997). Based on modern climatologically data, it's worth noting that analyzed cases reveals increased activity in the LLJ when "Niño like" conditions are present (Marengo et al., 2004; Silva et al., 2009). For instance, Pacific Ocean conditions related to warm phase of PDO (similar to Niño like conditions) as suggested by frequencies obtained would resolves also dry patterns in Nordeste record and wet conditions in SESA. In this sense, we suggest that intensification in SASM activity over the Andes during LIA are more explained by variability related to Pacific Ocean and Walker circulation anomalies.

During the transition period between MCA to LIA shift in the climate system is observed accompanied by migration to negative phase of the AMO. This shift observed over marine records between 1300–1400 AD have been associated to weakening of the AMOC (Palastanga et al., 2011). A slowdown in the AMOC would trigger the enhanced migration of the ITCZ to the south during LIA (e.g. Haug et al., 2001; Medina Elizalde et al., 2010). Different hypothesis arise on the discussion of a possible dominant mechanism that could explain those climate variations. Decreasing solar activity and stronger volcanic activity are considered conceivable drivers of such climatic shifts (Trouet and Baker, 2009; Mignot et al., 2011; Gonzalez-Rouco et al., 2011), but internal variability of the atmosphere–ocean system is a plausible alternative hypothesis (Wunsch, 1999; Trouet et al., 2012). It has been proposed by Zhong et al. (2010) that the sea ice increase due to decadal paced volcanism might have been the trigger of a persistent AMOC weakening during LIA. These conditions were in part influenced by less solar irradiance (Maunder, Sporer solar minimums) and also by higher volcanic activity as described by increased sulfate aerosols in the atmosphere just before the beginning of LIA, such as described by Gao et al. (2008), which suggests that atmospheric states at the period of less irradiance was importantly influenced by previous conditions favoring the reorganization of the inter hemispherical SST gradient and Hadley-Walker circulation cells.

5 Conclusions

Palestina record reveals the details of changes in SASM activity over the last 1600 yr and confirms most of the major results from previous paleoclimate reconstructions in the eastern Andes. During the last millennium, SASM shows excursions from decrease to increase intensity which are synchronous with major global periods of climate changes recognized as MCA and LIA respectively.

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Statistical analyses in the $\delta^{18}O$ time series of Palestina record, allow recognizing cycles of variability through the last 1600 yr, indicating that multidecadal variability (~ 65 yr) is the most prominent mode in rainfall for the SASM. Based on our results we suggest that this multidecadal variability is mainly dominated by changes in the AMO phases, which involves inter-hemispherical SST gradients modulating the position of the Atlantic ITCZ and the moisture advection from Atlantic to the Amazon and adjacent regions. In this sense, this relation suggest that although ENSO is the main forcing for $\delta^{18}O$ variability over tropical South America on interannual time scales, that influence may be significantly modulated by Atlantic Ocean climate variability on longer time scales.

The east–west antiphased relationship of SASM along in the eastern Andes and Nordeste records, suggest that teleconnections observed on orbital timescales are also valid for centennial scale such the LIA event. Frequencies observed points out to decoupling mechanisms affecting precipitation at these two different areas during the MCA and LIA. Periodicities of 65 yr periodocities during MCA are founded in the records, suggesting that both parts of the continent were affected by the same mechanism that brings dry conditions. For the LIA period, interactions of different over imposed modes (8, 25, 65 yr periodicities) that brings more variability of the system explain increase SASM activity and its regional pattern. Moreover, based on modern teleconnections and periodicities, it's plausible that stronger influence arises from Pacific Ocean dynamics and its influence on Walker circulation. Additionally, during the transition period between MCA and LIA, decadal signal could falls in decadal influence of volcanic activity as observed in other records in concordance with our proxy. Additionally, more South continental records at high resolution and models outputs are needed to better understand the role of the Pacific and Atlantic Multidecadal climate variability and their interplay on the intensity and regional patterns of the SASM.

Supplementary material related to this article is available online at http://www.clim-past-discuss.net/10/533/2014/cpd-10-533-2014-supplement.pdf.

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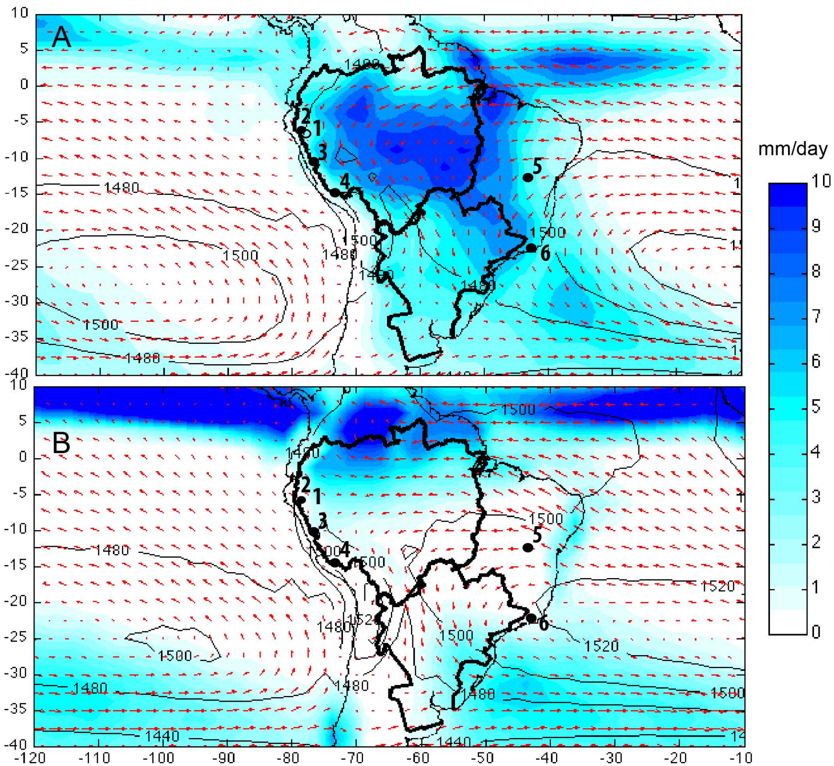

Fig. 1. Geopotential and total wind at 850 hPa from ERA-40 for the 1975–2002 period and Mean rainfall from CMAP data for the 1979–2002 period. **(A)** During DJF season. **(B)** During JJA season. Limit of the Amazon and the la Plata Basin are designed. Numbers in figure indicate locations of other proxies record in South America (1) Palestina Record (this study); (2) Cascayunga Cave record (Reuter et al., 2009); (3) Pumacocha Lake record (Bird et al., 2011); (4) Quelccaya Glacier (Thompson et al., 1986); (5) Bahia Cave record (Novello et al., 2012); (6) Cristal Cave Record (Taylor, 2010).

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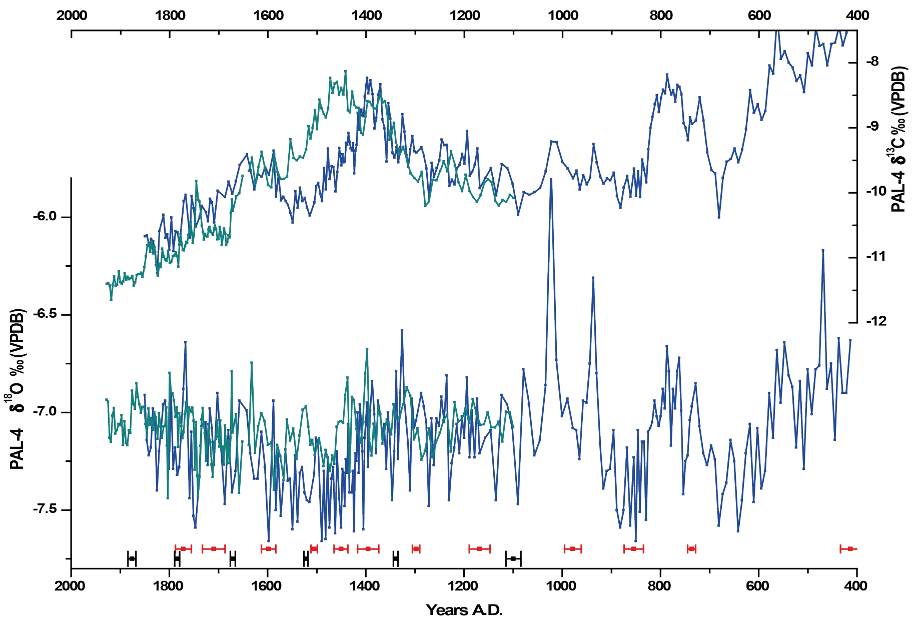

Fig. 2. Stable isotopes time series of $\delta^{13}C$ and $\delta^{18}O$ for PAL4 (blue line) and PAL3 (cyan line) respectively. U/Th dates and correspondent error bars are represented by red and black dots for Pal4 and Pal3 stalagmites respectively.

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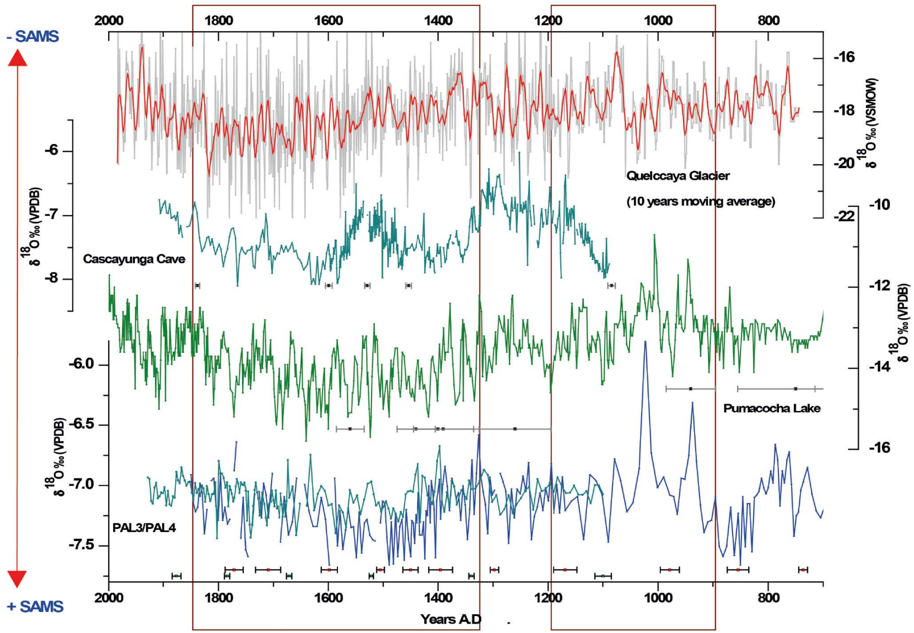

Fig. 3. Comparison between Palestina cave and other eastern Andes records with respectively chronological controls and error bars. From up to down: Quelccaya Glacier (Thompson et al., 1986), Cascayunga cave record (Reuter et al., 2009); Pumacocha lake record (Bird et al., 2011); Palestina Cave record (this study).

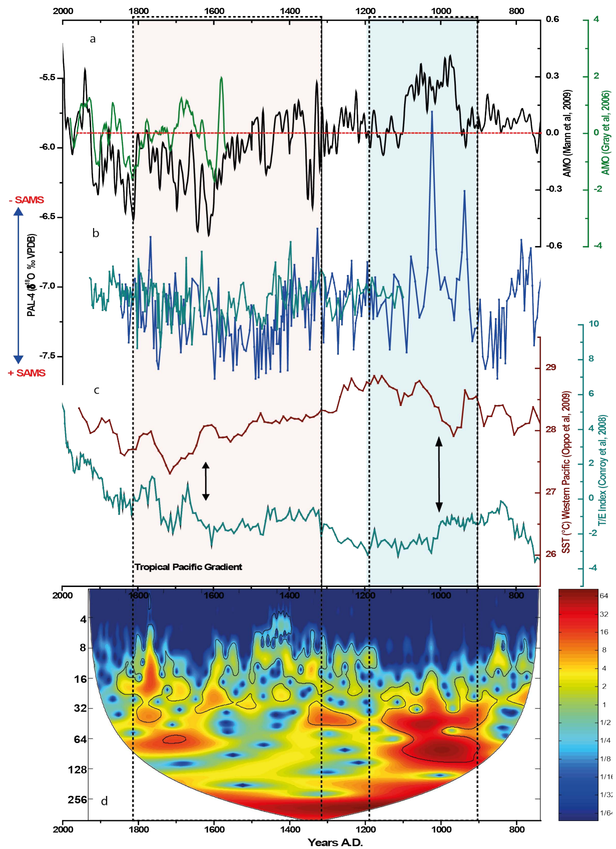

Fig. 4. (a) Reconstructed AMO series published by Mann et al. (2009); **(b)** Palestina δ^{18}O record, **(c)** Tropical Pacific Gradient composed by SST in Western Pacific (red line) (Oppo et al., 2009) and TE Index in Galapagos Island over the Eastern Pacific (green line) (Conroy et al., 2008); **(d)** Wavelet Analyses over the Palestina δ^{18}O record. The cyan and pink boxes with dotted lines represent the MCA and LIA respectively.

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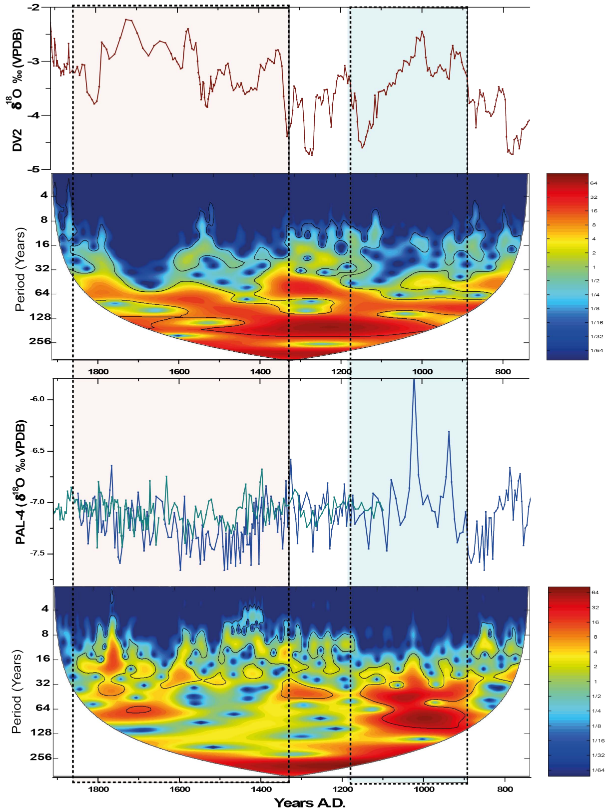

Fig. 5. (a) DV-2 δ^{18}O record (Novello et al., 2012), **(b)** Wavelet Analyses in DV-2 record; **(c)** Palestina δ^{18}O record; **(d)** Wavelet Analyses in Palestina Record. The cyan and pink boxes with dotted lines represent the MCA and LIA respectively.

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