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Atlantic Multidecadal Oscillation (AMO) forcing on the late Holocene Cauca paleolake dynamics, northern Andes of Colombia

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Abstract

The Atlantic Multidecadal Oscillation (AMO), is a major driving climate mechanism, in the eastern Caribbean Sea and the South Atlantic Ocean in relation to the dynamics of the South American Monsoon System (SAMS) for the late Holocene. Here we document the AMO signal in the San Nicolás-1 core of the Cauca paleolake (Santa Fé–Sopetrán Basin) in the northern Andes. Wavelet spectrum analysis of the gray scale of the San Nicolás-1 core provides evidence for a 70 yr AMO periodicity for the 3750 to 350 yr BP time interval, whose pattern is analogous to the one documented for the Cariaco Basin. This supports a possible correlation between enhanced precipitation and ENSO variability with a positive AMO phase during the 2000 to 1500 yr BP interval, and its forcing role on the Cauca ria lake deposits, which led to increased precipitation and to the transition from a *igapo* (black water) to a *varzea* (white water) environment ca. 3000 yr BP.

1 Introduction

The Atlantic Multidecadal Oscillation (AMO), whose frequency varies between ∼ 60 and 90 yr (e.g. Schlesinger and Ramankutty, 1994; Kerr, 2000; d'Orgeville and Peltier, 2007), is a basin-wide, sea surface temperature (SST) cycle that has been identified in a number of localities in the North Atlantic Ocean and the Caribbean Sea over the last 8 kyr interval (Knudsen et al., 2011). Changes in North Atlantic Ocean SST on these time scales are sufficiently large to imprint an AMO pattern on global mean "unforced" temperature variability (Crowley et al., 2014). Sedimentary evidences include the spectral analyses of the oxygen isotope (δ^{18}O) record of Lake Chichancanab (Guatemala) and the Ti% record of the Cariaco Basin (Venezuela) where 58–61 and 54–60–73 yr periodicities appear to be dominant from 6 to 1.5 kyr, and 6.5 to 0.9 kyr, respectively (Knudsen et al., 2011). These results are in accord with the suggestion of a southern migration of the intertropical convergence zone (ITCZ) after 3 kyr as evidenced in the Cariaco record (Haug et al., 2001). This ITCZ migration trend has also been documented in coastal terraces in the southwest Caribbean Sea (Martinez et al., 2010), and the Cauca paleolake in the northern Andean region (Garcia et al., 2011; Martinez et al., 2013). This region is influenced by the annual migration of the ITCZ, and El Niño – Southern Oscillation (ENSO), and the North Atlantic Oscillation (NAO) phenomena. Besides these, the northern Andes, which are more than 2000 m high, impose a significant barrier to the interaction between Atlantic and Pacific wind regimes, resulting in climate dynamics at decadal to centennial time scales that are still poorly understood. At decadal timescales, the 60 yr component of the Pacific Decadal Oscillation (PDO; e.g. Kayano and Andreoli, 2007), appears to be time-lag correlated with the AMO (Orgeville and Peltier, 2007). Evidence suggesting that the dynamics of the South American Monsoon (SAM) system is driven by the AMO cycle have been reported for the Amazon basin, and are found as far south as 30° S in the South Atlantic Ocean (e.g. Chiessi et al., 2009; Vuille et al., 2012). When AMO is in a positive (warm) phase, the ITCZ moves north leading to increased precipitation in western Europe and the Sahel and reduced precipitation in North America and northeastern Brazil. Conversely, when AMO is in a negative (cold) phase the ITCZ moves south and opposite precipitation conditions occur (e.g. Kayano and Capistrano, 2014; Garcia-Garcia and Ummenhofer, 2015).

Here we explore the San Nicolás sedimentary succession of the Cauca paleolake (6°30′ N; 75°50′ W), represented by the San Nicolás-1 core, as a unique high-resolution paleoenvironmental and paleoclimate record for the late Holocene. The sedimentary successions of the Cauca paleolake were recognized in three terrace levels, deposited during the late Holocene, that were formerly attributed to lacustrine sedimentation as the product of the episodic damming of the Cauca river by landslides in the Liborina region (Page and Mattson, 1981). In accompanying papers we: (1) document the palynofacies content of the San Nicolás succession in response to hydrological connectivity of the Cauca River with its tributaries and climate dynamics in northern South America (Garcia et al., 2011) and, (2) demonstrate that the formation of the terrace deposits was

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not due to landslides, but to sedimentation in a ria lake environment that changed from *igapo* (black water) to *varzea* (white water) conditions in the ∼ 3.5 to ∼ 1 kyr BP interval with sediment accumulation rates in excess of 600 cm kyr^{-1} (Martinez et al., 2013). The hydrological connectivity of the Cauca river with its tributaries, at seasonal to decadal time scales, resulted in a unique, high-resolution record of laminated sediments. In this previous contribution (Martinez et al., 2013), La Caimana, and the Sucre II field sections were presented, together with the San Nicolás-1 core. The latter record, which is unaffected by weathering processes common in the field sections, is documented herein in detail, together with the analysis of its time series. We demonstrate that in addition to the ENSO signal there is a strong multidecadal component, which matches the AMO frequency thus demonstrating its influence south of the Cariaco Basin, in the northern Andes, during the late Holocene.

1.1 Climatology and hydrology of the present Cauca Valley

Presently, climate in the Cauca Valley, as for most of the northern Andes, is dominated by a bimodal regime, i.e. two rainy seasons during March–May and September–November and two dry seasons during December–March and June–August (e.g. Poveda et al., 2006). This precipitation pattern results from the annual migration of the ITCZ. Conversely, the northern Andes act as a major barrier creating a very dynamic atmospheric system characterized by meso-scale convective cells and intense precipitation, mostly on the western and eastern flanks of the Western and Eastern Cordilleras, respectively.

In the eastern equatorial Pacific, the westerly low-level Choco jet, whose intensity is controlled by the sea surface temperature gradient between the cold tongue (south of the equator) and the Panama Basin, annually shifts with the ITCZ, and inter-annually with the ENSO phenomenon (Poveda and Mesa, 2000; Poveda et al., 2006, 2011). The Choco jet is forced by orographic lifting to deliver most of its moisture on the western flank of the Western Cordillera, thus producing a rain shadow or “dry island” effect on the inter-montane Cauca and Magdalena Valleys. However, through the Mistrato pass,

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located at 5° N on the Western Cordillera, some moisture reaches the Cauca Valley particularly between September and October when the ITCZ is in the north (Poveda and Mesa, 2000). This has an important effect on the hydrology of the middle Cauca Valley, and the Cauca paleolake, the subject of the present study.

Precipitation shows decadal to multi-decadal variability, which is smaller than yearly changes, and appears to be related to the PDO. However, this is a relation based on few climate stations with long time records (Garreaud et al., 2009).

Total annual precipitation in the Cauca Basin is 1887 mm, with 243 mm during the maximum month (Restrepo et al., 2005a). Furthermore, there is an inverse relationship between precipitation, induced by the positive phase of ENSO (El Niño), and water discharge and suspended sediment yield in the Cauca River, whose annual averages are 2373 m^3 s^{-1}, and 49.1 Mt a^{-1}, respectively (Restrepo et al., 2005a). The Cauca hydrographic basin, that is 59 615 km^2 large and extends from 2 to > 8° N (Restrepo et al., 2005b), is the recipient of precipitation from the ITCZ on its annual path (Fig. 1). This would make it difficult to reconstruct the ITCZ mean position in the past at a particular site in the middle Cauca Valley. Analogously, this also appears to be the case for the reconstruction of the ENSO phenomenon, whose influence is broad in northern South America, spreading from the Ecuadorian Andes to the Cauca Valley (e.g. Garreaud et al., 2009; Poveda et al., 2011).

Because the northern Andes act as a barrier to the South American Monsoon System (SAMS), it is expected that the North American Monsoon System (NAMS), has a major influence on the inter-montane Cauca and Magdalena valleys that drain to the Caribbean Sea. Both monsoon systems, however, are considered to be two extremes of the same climate cycle (Vera et al., 2006).

The Cauca Valley runs along the Cauca – Romeral Fault system that is a major structural suture between the Western Cordillera, of Cretaceous volcano-sedimentary oceanic origin, and the Central Cordillera, of Paleozoic – Mesozoic plutonic origin (e.g. Cediel et al., 2003). In the northern Cauca Valley the Cauca–Romeral Fault System is inverse, sinestral, and braided. This suggests that the Santa Fé–Sopetrán depression is a pull-apart basin, limited by the NW–SE Sopetrana, the NE–SW Cauca, and the N–S San Jerónimo Faults (Suter and Martínez, 2009; Suter et al., 2011). The Santa Fé–Sopetrán depression is partly filled with late Holocene fluvio-lacustrine sediments. The middle Cauca Valley is a steep and narrow valley, thus controlling the course of the Cauca River, which is entrained and mostly braided. Therefore, it has a high bed load, and is relatively unstable (cf. Schumm, 1981, 2005; Schumm et al., 2000).

2 Methods

The San Nicolás-1 core was retrieved, by rotary drilling, from the San Nicolás terrace, about 100 m south of La Caimana Creek (Fig. 1). Core sections, about 50 cm long, were transported to the laboratory where they were longitudinally cut and stored at 4 °C to prevent oxidation and degradation of organic matter. Following Nederbragt et al.'s (2004) recommendations, extreme care was taken during the acquisition of digital picture images of the core sections. After several trials with different source lights, digital pictures were taken with natural, indirect, light. Because of the limited length (50 cm) of each section, and the core retrieval technique used, some noise remained due to the combination of several variables, including light distribution, cracks, and core voids. These were digitally corrected using the image analysis software NIH ImageJ version 1.4, in order to obtain a composite section and a grey scale signal. The chronology of the San Nicolás-1 core is based on 14 radiocarbon (accelerator mass spectrometry, AMS^{14}C) analyses on bulk sediment samples, i.e. carbonaceous muds. Analyses were done at the Australian National University radiocarbon facility (Martinez et al., 2013). Calibrated age ranges were determined from the University of Oxford Radiocarbon Accelerator Unit calibration program (OxCal4.1). Therefore, in the present paper all ages indicated refer to calibrated years before present (cal yr BP).

3 Results

The sedimentary succession at the San Nicolás-1 core is 22.14 m thick (Figs. 2 and 3). It consists of laminated clays and silts, which are conspicuous all along the succession, whereas fine-grained sands are restricted to its top. Color varies from greenish dark grey (10BG4/1) to bluish grey (5B6/1) at the base, to dark red (2.5YR3/6) and yellowish brown (2.5Y3/6) moving upward in the section until 16.4 mbt (meters below the top) where the grey colors are less frequent and are replaced by yellowish light brown (2.5Y6/4), reddish brown (7.5YR4/3), grey (10YR5/1), and white (5Y8/1), among others (Fig. 2). This change in color reflects organic matter (OM) content and iron oxidation state (Martínez et al., 2013), which is reflected in the dark-light fluctuations of the grey-scale (Fig. 3).

Bioturbation along the San Nicolás succession are of animal origin at the bottom to plant origin at the top. In both cases, bioturbation is low and does not destroy lamination. As documented in the field sections and the San Nicolás-1 core, vertical burrows are < 0.8 cm in diameter, internally contain spreite structures and are conspicuous in the lower part of the succession, whereas horizontal burrows occur sporadically all through the succession. They were assigned to the *Scoyenia* and *Mermia* ichnofacies (Buatois and Mangano, 2009), respectively (Martinez et al., 2013).

3.1 Chronology of the San Nicolás succession

Except for the lowermost and the uppermost parts of the sections, where there are no chronologic controls due to the absence of enough OM for radiocarbon analysis, seven samples provided reliable data for building the age model by linear interpolation (Fig. 3). As previously explained, samples considered as the product of reworking of OM and outliers, were excluded from the age model (Martinez et al., 2013). This suggests that the succession ranges in age from ∼ 4000 to $<$ 500 cal yr BP and was deposited at an accumulation rate that exceeded ∼ 600 cm kyr^{-1} (Fig. 3).

3.2 Image and wavelet spectrum analyses

From the composite image (Fig. 2) a gray scale record was obtained for the San Nicolas core (Fig. 3). Then, this was separated into its components: red, green and blue. The red channel component was transformed to derive a time series signal (Fig. 4a). It was de-trended by subtracting the first reconstructed component, indicated by Singular Spectral Analysis to contain the trend, then filtered to remove frequencies larger than 5 yr^{-1}. Wavelet spectrum analysis of the 3750 to 350 yr PB time interval (Fig. 4b) was performed on the red scale data following Obrochta et al. (2012) method, using Matlab (Torrence and Compo, 1998). Significant, large variance (95 % confidence), 70 year peaks, appear at 3100, 2200, 1600 and 1000 yr BP; whereas, secondary peaks in the 8 to 32 yr band occur all over the 3750 to 350 yr PB time interval (Fig. 4b).

4 Discussion

Analogously to the Chichancanab Lake and the Cariaco Basin, we interpret the 70 yr periodicity as the AMO mode of climate variability. In particular, the reconstructed AMO pattern for the San Nicolás-1 core is very similar to the Cariaco Basin pattern for the 3750 to 350 yr BP time interval. Major differences might be due to age model uncertainties, and the potential bias introduced by the core retrieval technique used and the handling of core sections during drilling of the San Nicolás hole. Despite these possible sampling biases, which potentially mask and overprint the natural cycle, the hypothesis that AMO forcing controls the hydrological regime of the Cauca River basin, is supported as the evidence suggest that the dynamics of the SAM system is driven by the AMO cycle (e.g. Vuille et al., 2012). Assuming this is true, the AMO forcing might have controlled the discharge of the Cauca River and the episodic flooding of its tributaries, which resulted in ria lakes.

As documented for La Caimana Creek, there appears to be a conspicuous change in the hydrological regime of the Cauca River, from a *igapo* (black-water) to a *varzea* (white-water) regime ca. 3000 yr BP (Martinez et al., 2013). This is at 16.4 mbt when color change from grey to yellow-red (Fig. 2), and charcoal concentration abruptly drops in tandem with the steady increase in altered lignocellulose debris (Garcia et al., 2011; Martinez et al., 2013). All this indicates that precipitation significantly increased in response to the southern migration of the ITCZ, with its mean location probably lying over the upper reaches of the Cauca River, i.e. at about 2–3° N.

It has been hypothesized that the warm phase of the AMO results in a weaker ENSO variability (Dong et al., 2006) and/or, is related to the PDO (d'Orgeville and Peltier, 2007). Both, the Cariaco Basin and the Cauca paleolake records suggests otherwise, as ENSO variability appears to increase between 3800 and 2800 yr BP (Haug et al., 2001) when the AMO signal is not particularly significant as shown by Knudsen et al. (2011) and herein. By contrast, for the Galapagos Islands it has been suggested that precipitation and ENSO variability (more El Niño events) increased between 2000 and 1500 yr BP (Conroy et al., 2009), thus agreeing with a positive AMO signal in both, the Cariaco Basin and the Cauca paleolake.

The results we have obtained are very encouraging and underline the ria lake sedimentary successions as potential high-resolution records for paleoclimate research in the Neotropics. Nonetheless, we need to retrieve a new, more complete core with fewer section breaks, in order to test our AMO hypothesis obtained from the wavelet analysis of the San Nicolas-1 core. This will rule out any potential bias derived from coring artifacts.

5 Conclusions

Wavelet spectrum analysis of the gray scale of the San Nicolás-1 core provides evidence for: (a) a 70 yr AMO periodicity for the 3750 to 350 yr PB time interval, (b) a pattern analogous to the one documented for the Cariaco Basin, (c) a possible correlation between enhanced precipitation and ENSO variability with a positive AMO phase during the 2000 to 1500 yr BP interval, (d) a positive AMO forcing on the ria lake deposits, which led to the transition from a *igapo* (black water) to a *varzea* (white water) environment ca. 3000 yr BP.

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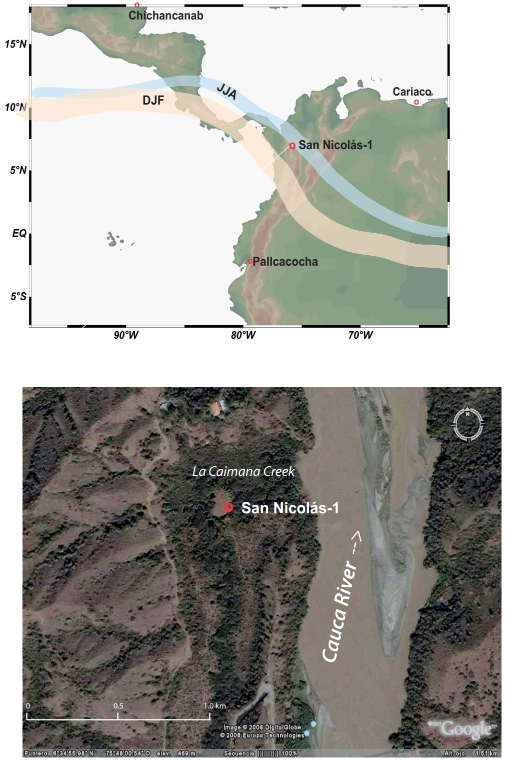

Figure 1. Location map. **(a)** The northern Andes and the mean positions of the intertropical convergence zone (ITCZ) during December–February (DJF) and June–August (JJA) and the location of other sites discussed in the text. **(b)** Satellite image with the location of the San Nicolás-1 well on the San Nicolás terrace.

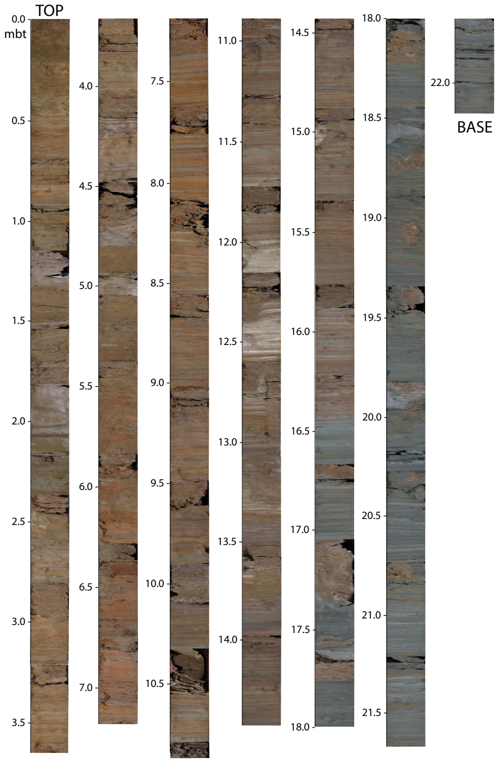

Figure 2. The San Nicolás-1 core. Composite photographic section. Note the change in color at 16.4 mbt, the laminated muds throughout the core, and some sand beds towards the top; mbt = meters below the top.

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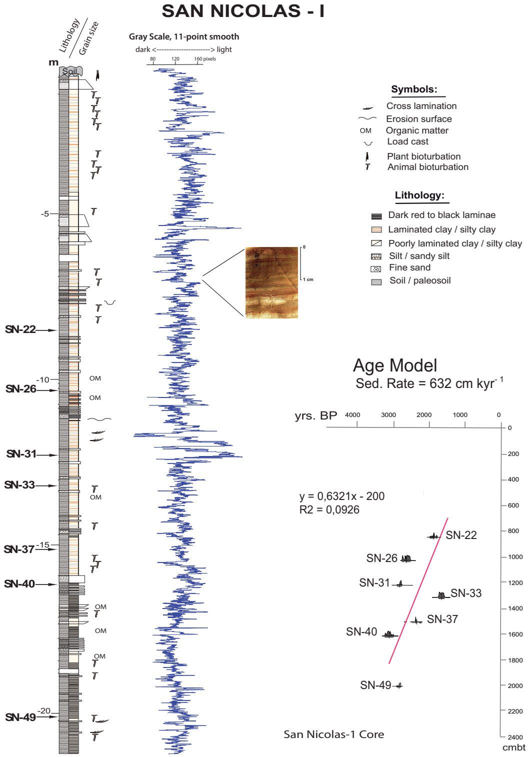

Figure 3. The San Nicolás-1 core. Stratigraphic column, gray scale, laminae (thin section insert), and age model (insert). SN = AMS^{14}C samples.

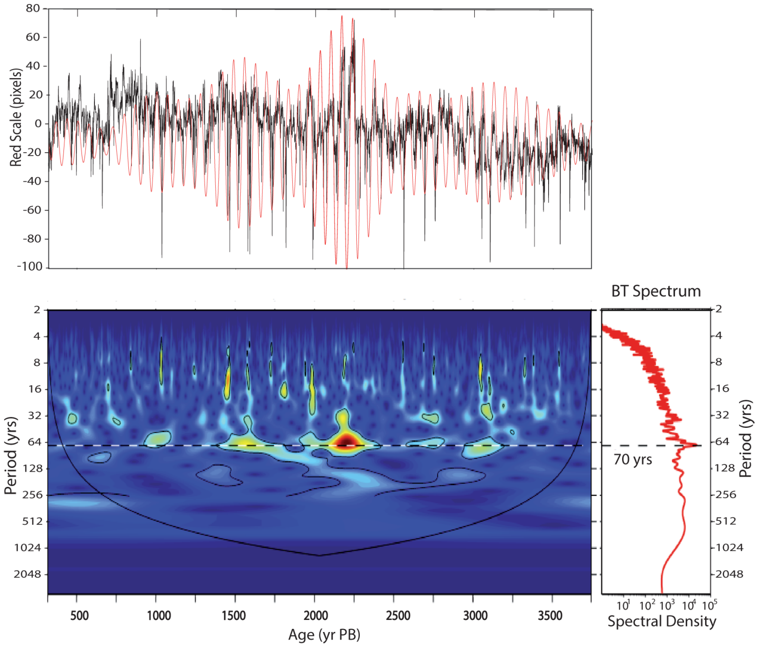

Figure 4. San Nicolas-1 record. **(a)** Fiver-year low-pass filtered, detrended (by subtracting the first principal component) red scale (black line) and the combined second and third reconstructed components (red line) time series, **(b)** Morlet wavelet power spectrum calculated using wavelet on the time series of red color intensity. Variance in the wavelet power spectrum is plotted as a function of both time and period. Yellow and red regions indicate higher degrees of variance, and the black line surrounds regions of large variance (95 % confidence intervals). Note the dominance of the 70 yr period, both in the wavelet power and the Blackman–Tukey (BT) spectra.