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Short communication

Late Holocene climate reorganisation and the North American Monsoon

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ABSTRACT

The North American Monsoon (NAM) provides the majority of rainfall for central and northern Mexico as well as parts of the south west USA. The controls over the strength of the NAM in a given year are complex, and include both Pacific and Atlantic systems. We present here an annually resolved proxy reconstruction of NAM rainfall variability over the last ~6 ka, from an inwash record from the Laguna de Juanacatlán, Mexico. This high resolution, exceptionally well dated record allows changes in the NAM through the latter half of the Holocene to be investigated in both time and space domains, improving our understanding of the controls on the system. Our analysis shows a shift in conditions between c. 4 and 3 ka BP, after which clear ENSO/PDO type forcing patterns are evident.

1. Introduction

The North American Monsoon (NAM) is a crucial precipitation source within its core region of Mexico and the south–west USA, providing up to 60% of annual precipitation (Metcalfe et al., 2015, Fig. 3b; Ropelewski et al., 2005), and is vital to sustaining agriculture, industry and biodiversity. Climate change projections for the NAM region suggest that both increased temperatures and reduced precipitation are likely in the coming century (Karmalkar et al., 2011). Better understanding of NAM variability and its controls are therefore essential (Englehart and Douglas, 2002). High temporal resolution proxy records (e.g. Stahle et al., 2012) are necessary to identify both the long term evolution of the NAM and its variability under different climate modes.

The NAM arises from the seasonal, insolation driven, northward migration of the Intertropical Convergence Zone (ITCZ) in the Northern Hemisphere (NH) summer, the development of a thermal low over the SW USA, and the development of a strong thermal contrast off the coast of Baja California (Barron et al., 2012). Its duration and intensity are affected by conditions in both the eastern tropical Pacific and the North Atlantic (Englehart and Douglas, 2002, 2010; Mendez and Magana, 2010). Investigations into the controlling role of the Pacific have focussed on the El Niño Southern Oscillation (ENSO) (Castro et al., 2001; Magaña et al., 2003) and the Pacific Decadal Oscillation (PDO), recognising that these are not entirely independent (Gutzler, 2004), as the PDO can be seen as an example of ENSO-type variability operating over different timescales (Castro et al., 2001; Wilson et al., 2010). In Mexico, NAM summer rainfall is reduced during El Niño events and positive phases of the Pacific Decadal Oscillation (PDO) (Castro et al., 2001; Magaña et al., 2003; Bhattacharya and Chiang, 2014) when the eastern tropical Pacific warms and the thermal gradient to the continental interior is reduced. During La Niña or negative PDO phases, summer NAM rainfall increases. NAM drivers associated with the North Atlantic, specifically the Atlantic Multidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) (Mendez and Magana, 2010), seem to have their greatest impact on the NAM in the summer season. Positive (warm) phases of the AMO give rise to wetter summers in central and southern Mexico and the

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wider Caribbean, as the ITCZ moves north, generating more Atlantic tropical cyclones (Knight et al., 2006; Mendez and Magana, 2010).

Understanding controls on NAM region precipitation is complicated by complex and variable connections between the two regions of NAM forcing i.e. Atlantic and Pacific Oceans (Englehart and Douglas, 2010; Stahle et al., 2012) and variability in, often localised, storm events (Curtis, 2008). It is also increasingly evident that NAM rainfall patterns are not spatially homogeneous and it has been suggested (Castro et al., 2001) that the NAM in Mexico should be treated separately from the NAM in the south–west USA, where winter rain is more significant and El Niño or positive PDO give rise to increased winter precipitation and overall wetter conditions.

Here we present an annually resolved proxy record of precipitation through the last 6000 years from the Laguna de Juanacatlán (Jalisco, Mexico) which is located close to the tropical core of the NAM (Englehart and Douglas, 2002). The record shows a marked shift in the dominant frequencies of variability between 4 and 3 cal ka BP. This change in the frequency domain coincides with a general shift in conditions through this time period to the pattern of precipitation seen today.

2. Site description

Laguna de Juanacatlán (20°37′N, 104°44′W; 2000 m.a.s.l.) is a lava-dammed lake with a maximum depth of 25–30 m, in the Sierra de Mascota close to the Pacific coast of Mexico. The basin (approximately 10 km^2) is orientated in a southeast to northwest direction, with the lake occupying about 0.5 km^2 at the northwest end (Metcalfe et al., 2010). The closest meteorological station is in Mascota (800 m lower and 12 km away) where annual average precipitation is 1026 mm/yr, of which 88% falls between June and October.

The sediments of Juanacatlán contain fine, mm scale laminations, with alternating organic, diatomaceous layers and pink clay from catchment in-wash. In addition a number of thick, cm scale, fining up layers consisting of sands and clays are present, which are interpreted as instantaneous turbidites.

Titanium (Ti) has been shown, via XRF scanning (see methods below), to mark the pink clay layers in the core and through comparison with observational, instrumental and historical records and other regional rainfall proxies through the last 2000 years, has been established as a proxy for run-off, which is derived principally from summer rainfall in this catchment (Metcalfe et al., 2010). The Ti profile from high resolution XRF scanning has been shown to follow sedimentary changes, recording higher values in the pink clay layers.

3. Methods and results

Two parallel, continuous cores (both ca. 9 m long) were taken from the deepest part of Laguna de Juanacatlán using a Kullenberg coring system, resulting, once disturbed sections of core had been avoided and instantaneous turbidites excluded from the record, in a 7.25 m continuous composite core sequence.

27 AMS radiocarbon age estimates from bulk organic matter were obtained from the core sequence, including two dates from sediment trap and core-top material to check for any reservoir effect (Fig. 1; Supplementary Table 1). Additional age control for the top of the core is supplied by clear peaks in ^{137}Cs (Metcalfe et al., 2010).

U-channels (2 cm wide) were taken from the cores and scanned using an ITRAX XRF scanner at 200 μm resolution (Croudace et al., 2006). An annually resolved Ti record was produced from the original 200 μm data set between 50 and 5821 years BP; each 200 μm data point was given an age from the age-depth model and

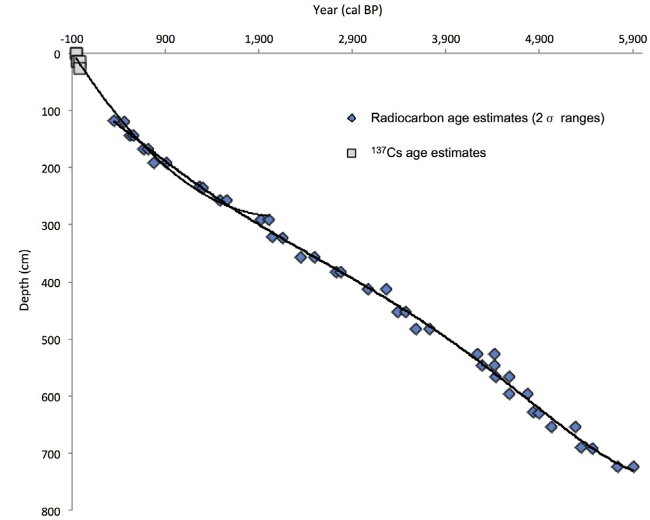

Fig. 1. Age-depth model for the Juanacatlán core sequence. The model is based on a 2nd order polynomial trend at the top of the core, until 262.21 cm, and then a 5th order polynomial model through the 2 σ age ranges as shown. The full list of radiocarbon dates from the Juanacatlán sequence can be found in Supplementary Table 1.

then rounded to the nearest year. Annual values were then calculated as the mean value for all the data points rounded to that given year.

The resulting record of rainfall variability (Fig. 2) shows variation at all time scales from inter-annual to millennial through the last 6000 years. Wavelet analysis of the Ti record identified variation at different frequencies (Fig. 2); significant (95% confidence interval) cycles appear at ~2000, ~565, ~105 and ~65 and ~22 years through large parts of the record (Fig. 3).

4. Discussion

The striking feature of the Juanacatlán Ti record is the change between 4 and 3 cal ka BP that marks a shift in the dominant frequencies of variability (Fig. 3). This period, particularly between 3.8 and 2.8 cal ka BP, is also a time during which overall precipitation apparently reduced (Fig. 2a), recording the lowest average Ti values for any individual 1000 year period in the record. Frequencies similar to the significant multi-centennial and millennial frequencies (~565 and ~2000 years) found in the Juanacatlán record, which both increase notably in strength after 3ka BP, have been

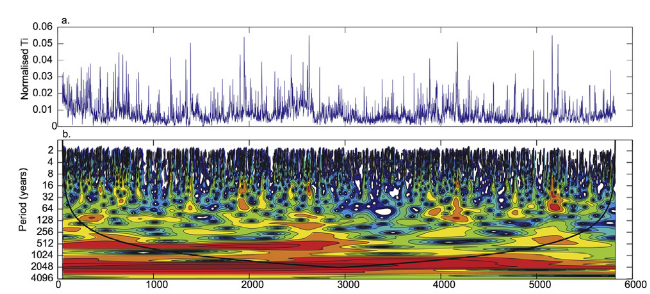

Fig. 2. The annual Juanacatlán Ti record (a), shown here as the Ti peak area normalised to the incoherent peak area (equivalent to Compton scattering) from the XRF (Supplementary Data) and a wavelet analysis of this data (b), using a Morlet wavelet in the Matlab code of Torrence and Campo (1998). The time periods when the dominant frequencies (red in this figure) are statistically significant are shown in Fig. 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)