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Pervasive multidecadal variations in productivity within the Peruvian Upwelling System over the last millennium

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ABSTRACT

There is no agreement on the pluri-decadal expression of El Niño–Southern Oscillation (ENSO) in the Pacific over the last millennium. Marine records from the Peruvian margin indicate humid conditions (El Niño-like mean conditions) over the Little Ice Age, while precipitation records from the eastern equatorial Pacific infer arid conditions (La Niña-like mean conditions) for the same period. We here studied diatom assemblages, nitrogen isotopes, and major and minor elements at the lamination level in three laminated trigger cores located between 11°S and 15°S on the Peruvian shelf within the oxygen minimum zone (OMZ) to reconstruct precipitation and ocean productivity at the multiannual to multidecadal timescales over the last millennium. We respected the sediment structure, thus providing the first records of the mean climatic conditions at the origin of the lamination deposition, which ones represent several years. Light laminations were deposited under productive and dry conditions, indicative of La Niña-like mean conditions in the system, while dark laminations were deposited under non-productive and humid conditions, representative of El Niño-like mean conditions. La Niña-like mean conditions were predominant during the Medieval Warm Period (MWP; 1000–600 years BP) and Current Warm Period (CWP; 150 years BP to present), while El Niño-like mean conditions prevailed over the Little Ice Age (LIA; 600–150 years BP). We provide evidence for persistent multidecadal variations in productivity over the last millennium, which were disconnected from the mean climate state. Multidecadal variability has been stronger over the last 450 years concomitantly to increased variability in the NAO index. Two intervals of strong multidecadal variability were also observed over the MWP, congruent to decreased solar irradiance and increased volcanic activity.

1. Introduction

The last millennium has been divided into several climatic periods, based on warmer global conditions over the Medieval Warm Period (MWP), colder temperatures over the Little Ice Age (LIA) and rising temperatures since the beginning of the Current Warm Period (CWP) (e.g. Jones et al., 1998; Mann et al., 1999). Most studies indicate a CWP beginning around AD 1800–1850 but there is no agreement on the exact temporal extent of the MWP and the LIA. Glacier extent and temperature reconstructions from historical sources place the limit between the MWP and the LIA around AD 1250–1270 (Grove, 1988; Lamb, 1985) while Greenland ice cores rather date the onset of the LIA around AD 1350 (Stuiver et al., 1995). Finally, North American records place the MWP between AD 1100 and AD 1375 and the LIA between AD 1450 and AD 1850 (Davis, 1994; Graumlich, 1993). The onset of the LIA has been extensively studied and is generally attributed to reduced solar activity (e.g. Mann et al., 2005; Swingedouw et al., 2011), although alternative hypotheses also suggest changes in the inflow of North Atlantic water into the Nordic Seas (Jungclaus et al., 2005). At lower latitudes, solar-driven temperature variations are thought to have induced changes in wind patterns and rainfall intensity. The northeastern trade winds would have been stronger during the LIA, leading to the southward migration of the Intertropical Convergence Zone (ITCZ) (Sachs et al., 2009) and aridity in the northern tropics, marked by droughts in southeast Asia (Zhang et al., 2008), east Africa (Wolff et al., 2011) and the Yucatán Peninsula (Hodell

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et al., 2005), as well as higher levels of precipitation in the southern tropics (Reuter et al., 2009).

These long-term hydrological changes have also been expressed in variations in El Niño–Southern Oscillation (ENSO). Existing records of ENSO provide contradictory information, however, both at the global and regional levels. Indeed, marine records from the Pacific Ocean indicate an LIA that was dominated either by arid conditions (La Niña-like mean state, Yan et al., 2011) or by humid conditions (El Niño-like mean state, Rein et al., 2004), while precipitation records from Ecuador evidence more frequent and stronger El Niño events over the MWP (Moy et al., 2002), despite decreased humidity in South America (Reuter et al., 2009). A possible explanation for the observed discrepancies could be that some records consider only El Niño events (Moy et al., 2002; Conroy et al., 2008) while other records also trace La Niña events (Cobb et al., 2003) and that the central Pacific is influenced both by the canonical El Niño (EP) and the El Niño Modoki (CP) (Ashok et al., 2007; Weng et al., 2007) while the eastern Pacific only records EP El Niño events (Dewitte et al., 2012). There, EP El Niño events (Kao and Yu, 2009) coincide with reduced upwelling intensity and decreased productivity off the coast of Peru (Pennington et al., 2006), as well as subsequent rises in Sea Surface Temperatures (SSTs) (Philander, 1990). The reduction in the upwelling of oxygen-depleted waters during EP El Niño events leads to an increase in the oxygen content of subsurface waters (Gutiérrez et al., 2008).

Published marine records from the Peru–Chile margin infer an MWP and a CWP dominated by La Niña-like mean conditions and an LIA dominated by El Niño-like mean conditions (e.g. Diaz-Ochoa et al., 2009; Salvatteci et al., 2014). These studies were based on discrete sampling, thus disregarding the sedimentary structures of the cores. Sediment from the oxygen minimum zones (OMZs) is finely laminated (Brodie and Kemp, 1994), enabling high-resolution records of variations in detrital and biogenic fluxes in relation to precipitation over the continent and upwelling intensity, respectively. We here study three trigger cores from the Peruvian OMZ at the lamination level in order to refine decadal to centennial variations in hydrology and productivity over the past millennium and propose possible forcing mechanisms.

2. Present-day characteristics of the study area

We here focus on the southern part (11–15°S) of the Peru–Ecuador margin, which extends from 1°N to 18°S along the west coast of South America (Fig. 1). In this region, trade winds blow northwestward and drive surface waters northward. This mechanism generates the Peru–Chile Coastal Current along the coast and the Peru–Chile Current further offshore (Fiedler and Talley, 2006). The Equatorial Undercurrent flows eastward under the surface waters; when it approaches South America, it is deflected southward, constituting the Peru–Chile Undercurrent. Similarly, the Southern Subsurface Countercurrent becomes the Peru–Chile Countercurrent when it starts flowing southward. The Peru–Chile Undercurrent sources the waters that are upwelled along the coast (Wyrtki, 1981; Toggweiler et al., 1991), which are characterized by low oxygen and high nutrient content. Oxygenation decreases when the currents circulate southward, which results in suboxic to anoxic subsurface waters south of 10°S (Fig. 1).

While subsurface oxygen concentrations decrease southward, contents in surface nutrients, in particular nitrates, increase northward. Productivity is more intense within the main upwelling region however (from 5 to 15°S and from the coast to 60 km offshore), where the nutrient-rich Peru–Chile Undercurrent is upwelled. The quantities of nutrients introduced into the Peruvian Upwelling System by the Peru–Chile Undercurrent are sufficient to sustain the highest production of chlorophyll-a and biomass in the world (Chavez and Barber, 1987; Chavez and Messié, 2009). The phytoplankton community is dominated by diatoms, especially the neritic bloom-forming *Chaetoceros* spp. (Cowles et al., 1977; Avaria and Muñoz, 1987).

Productivity varies throughout the year in response to seasonal variations in upwelling intensity combined with water mixing. The upwelling reaches its peak in austral winter (June, July, and August) (Messié et al., 2009), however biological production remains stable due to lower light availability caused by deeper mixing (Pennington et al., 2006). Concentrations in chlorophyll-a thus only reach their maximum in austral spring (Chavez et al., 1996; Echevin et al., 2008). However, these seasonal variations are low and high productivity levels are sustained throughout the year (Chavez, 1995), mainly because of the persistence of upwelling-favorable winds all year long (Strub et al., 1998). Interannual variations in phytoplankton productivity also occur, particularly under the influence of ENSO (Philander, 1990), which generates stronger variations than the ones observed at the seasonal timescale (Barber and Chavez, 1986). EP El Niño events lead to the persistence of warm surface waters offshore of Peru, despite the presence of winds favorable to upwelling (Strub et al., 1998). Upwelling still occurs but is restricted to a narrower area of the coast (Barber et al., 1996). The nutricline and thermocline are anomalously deep during EP El Niño events, causing the upwelling of warm, nutrient-poor waters. EP El Niño events lead to dramatic reductions in biological production and biomass as well as to changes in specific composition (Cowles et al., 1977) compared to normal conditions. In contrast, EP La Niña events are characterized by intensified upwelling conditions, favoring bloom-forming genera such as *Chaetoceros* spp. The Peruvian Andes receive seasonal precipitation, mainly in austral summer (January, February, and March), but the Peruvian coastal deserts remain dry except during EP El Niño events of sufficient magnitude (Ortlieb and Macharé, 1993; Wells, 1990). In contrast, La Niña events enhance the droughts that are characteristic of the region.

3. Methodology

The X-ray radiographies of the cores were carried out using an X-ray image-processing instrument (Migeon et al., 1999), and the elementary composition of the sediment was determined using the AVAATECH XRF core-scanner at the University of Bordeaux. Prior to analysis, the sediment surface of slabs carved from half-core sections was flattened and covered with Ultralene film to avoid desiccation during measurements, diminish surface roughness, and prevent contamination of the detector unit (Richter et al., 2006). XRF-measurements were conducted at two different tube voltages (10 and 30 keV) allowing for the determination of major elements associated with the biogenic (Silicon [Si]), organic (Bromine [Br]), and terrigenous fractions (e.g., Iron [Fe], Zirconium [Zr] and Titanium [Ti]). The analyses were performed at a high downcore resolution of 200 μm, thus enabling the capture of millimetric laminations based on their color (pictures), density (X-ray radiography), and elementary composition (XRF). These laminations were sampled individually, with respect to their shape in order to avoid the mixing of sediments of different age and composition.

For the diatom analysis, three slides were mounted per sample using the procedure described in Rathburn et al. (1997). Diatom identification was carried out using an Olympus BX-51 phase contrast microscope at a magnification of × 1000, following the counting rules described in Crosta and Koç (2007). A minimum of 300 valves were counted for each sample. Diatoms were identified at a species or species-group level, and the relative abundance of each species was determined as a fraction of the total quantity of diatom estimated in the sample. The identification of marine