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Reconstructing El Niño-Southern Oscillation activity and ocean temperature seasonality from short-lived marine mollusk shells from Peru

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ABSTRACT

A critical need exists for quantitative reconstructions of long-term El Niño Southern Oscillation (ENSO) variability in the eastern tropical Pacific. Presented here is a method to quantitatively estimate past changes 1) in the seasonal amplitude of sea surface temperature (SST) in the Peruvian coastal upwelling system and 2) in the amplitude of ENSO-related interannual variability in the eastern tropical Pacific. The seasonal amplitude of SST (ΔT) along the length of the Peruvian coast is strongly correlated with the Niño1+2 index. We show that the frequency distribution of ΔT values provided by a modern sample of 13 *Mesodesma donacium* shells faithfully reflects modern ENSO variability at the regional scale, including the range of anomalies from La Niña to moderate El Niño events, but excludes extreme warm anomalies because of high shell mortality. We propose to use the frequency distribution of ENSO anomalies in paleoclimate studies for comparisons between shell records, coral records, and GCM simulations. Reconstruction uncertainties can be quantified using Monte Carlo simulations. The method presented here opens new perspectives for quantitative paleo-ENSO reconstructions in the Eastern Pacific since it may be applied with any mollusk species from Peru provided at least one annual cycle of SST is faithfully recorded by shell $\delta^{18}O$.

1. Introduction

Reconstructing a long-term record of El Niño Southern Oscillation (ENSO) is critical to identify the forcings that influence its activity and to estimate its sensitivity to global climate change. Past changes in ENSO variability not only involve changes of the event intensity and frequency, but also changes in the distribution of cold and warm events, and changes in the spatial pattern of sea surface temperature (SST) anomalies. This means that records of interannual SST are needed from across the tropical Pacific, from the warm pool to the cold tongue, to properly evaluate past ENSO modes.

So far, proxy records of the tropical Pacific SST with seasonal resolution have been obtained primarily from Sr/Ca and $\delta^{18}O$ analyses of coral (Cole and Fairbanks, 1990; Dunbar et al., 1994; McCulloch et al., 1996; Corrège et al., 2000; Tudhope et al., 2001; Evans et al., 2002; Cobb et al., 2003; Kilbourne et al., 2004; McGregor et al., 2010). Fossil corals faithfully record past interannual climate variability in the Pacific warm pool and in the central Pacific but they are very scarce in the eastern tropical Pacific. The most ancient coral analyzed in the eastern tropical Pacific was collected in the Galapagos Islands and reached 1587 A.D. (Dunbar et al., 1994).

On the eastern side of the Pacific, most paleoclimate studies dedicated to ENSO reconstruction for long intervals are based on rainfall proxies of the American continent (D'Arrigo and Jacoby, 1992; Stahle et al., 1998; Rodbell et al., 1999; Moy et al., 2002; Riedinger et al., 2002; D'Arrigo et al., 2005; Rein et al., 2005; Conroy et al., 2008). However, all these signals are communicated through atmospheric teleconnections that are likely to change over time. Changes in the rainfall regime may also be linked to changes in the intensity or in the seasonal movement of the intertropical convergence zone (ITCZ). In the tropical Andes, the Atlantic Ocean and the South American monsoon system also have a large influence on rainfall variability (Garreaud et al., 2009). Consequently, rainfall-related paleoclimate records provide valuable data for the study of continental rainfall variability but yield only indirect and often mixed information for past ENSO activity.

Marine indications for past changes in ENSO activity in the eastern tropical Pacific have been obtained from the variance of individual foraminifera $\delta^{18}O$ values in marine sediment samples (Koutavas et al., 2006; Leduc et al., 2009). Since marine cores have a centennial resolution and foraminifera live about a month, the variance of a foraminifera sample yields a mixed signal that involves temperature

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seasonality, temperature gradient in the mixed layer, ENSO-related interannual variability, and multidecadal variability.

Here we present a technique that responds to the critical need for quantitative estimates of the marine interannual variability in the eastern tropical Pacific. We show how short-lived marine mollusk shells, despite the brevity of their timespan, can be used as a paleoclimate archive for reconstructing the seasonal range of SST and ENSO variability in the tropical Pacific cold tongue, and how these data can be compared to coral records and model outputs. The technique shares similarities with the coral-based approach since it involves short high resolution windows at a monthly time scale, but also with the individual foraminifera technique since paleoclimate is estimated by the statistics of a random sample. The advantage of the mollusk-based technique compared to foraminifera is that it allows independent reconstruction of the seasonal cycle and more comprehensive characterization of ENSO variance.

It has been previously established that marine mollusk shell $\delta^{18}O$ may be a reliable SST proxy as long as water $\delta^{18}O$ can be reasonably constrained (Grossman and Ku, 1986; Hickson et al., 1999; Schöne et al., 2004). On the Peruvian coast, the monthly sea water $\delta^{18}O$ variations are very small (typically <0.1‰) because precipitation is virtually nonexistent and river discharge is minimal, so that mollusk species such as *Mesodesma donacium* faithfully record coastal SST variations at a monthly time scale over 1–3 year long windows (Carré et al., 2005). Although continuous records of at least several decades are generally preferred to study ENSO variability, we will examine here how a discontinuous sample of short-lived shells from Peru can also yield a reliable statistical estimate of ENSO variability.

We will examine the relationship between coastal SSTs in the Peruvian upwelling system and the Niño1+2 index to assess the spatial range of representativeness of coastal records. Uncertainties will also be quantitatively assessed using the MoCo program (Carré et al., 2012). Our approach, presented here with one species, is valid for any coastal mollusk species that faithfully records at least one annual SST cycle. Our study potentially opens new opportunities for direct and quantitative paleo-ENSO reconstructions in the eastern tropical Pacific, using anthropogenic or natural fossil shell accumulations in Peru.

2. Materials

M. donacium is an endemic intertidal bivalve species of Peruvian and Chilean sandy beaches that has been gathered for food since the first human occupation of the Peruvian coast (Sandweiss et al., 1989, 1998; Carré et al., 2009; Lavallée et al., 2011). In 1980, the northern limit of *M. donacium* was 10°S in Sechura Bay (Tarifeño, 1980). Its distribution today is restricted to south of ~15°S because of mass mortality induced by the extreme El Niño events of 1983 and 1998 (Riascos et al., 2009). This means that *M. donacium* shells cannot record extreme warm anomalies (9.5 °C in 1983 and 8.8 °C in 1998 in Puerto Chicama). After the 1983 event, populations recovered within a few years but the 1998 event had a much more prolonged impact since populations have not fully recovered so far, 15 years after the mortality event, perhaps because of competition or changes in the beaches slope and granulometry. Some periods following similar extreme events might therefore not exist in the fossil record but such potential gaps are not expected to produce any bias since there is no evidence that ENSO activity may be systematically stronger or weaker during the decade following an extreme event.

A sample of 13 *M. donacium* shells was collected in 2007 from modern shell mounds behind the long sand beach close to the Ica River mouth (14°52′19″S; 75°33′21″W) (Fig. 1). Based on fishermen testimonies and newspaper fragments found in shell mounds, we know that these shells were gathered by fishermen during the last decades of the 20th century, when these surf clams were a significant economical resource. These shells cannot be cross-dates. To minimize the probability of collecting shells from the same year, every shell was collected in a separate mound. This modern shell sample thus represents a random sample of 13 short-term windows which combined represent the environmental conditions during the last decades of the 20th century. In this, our modern sample would mimic shell samples from archeological middens and could therefore be used as a modern reference.

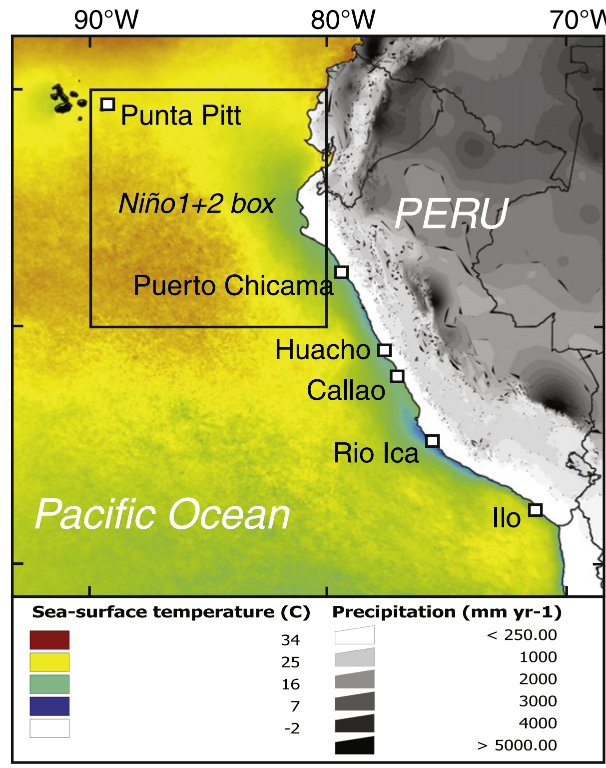

Fig. 1. Map of the study area with mean annual SST and annual precipitation on the continent. The Niño1+2 area and the sites mentioned in the text were indicated.

3. Methods

3.1. Microsampling and isotopic analyses

Radial shell sections were polished and serially microsampled in the outer layer using an automated microdrilling system (Micromill, Merchantek™) with a three-edged pyramidal dentist drill. Microsamples consisted in a ~0.15 mm deep and ~0.2 mm wide groove and were adjacent for a continuous sampling (Fig. 2). Based on shell growth lines, the length of the groove was adapted to the growth rate so the sample would integrate about a month.

The oxygen isotopic composition of powdered aragonite microsamples (~50 μg) was analyzed at the University of Washington Isolab using a Finnigan Delta Plus isotope ratio mass spectrometer coupled to a Kiel III carbonate device. Aragonite samples were digested in 100% phosphoric acid at 70 °C. The standard deviation for repeated measurements of the internal standard was better than 0.08‰. Raw $\delta^{18}O$ values were corrected as per Tobin et al. (2011) for temperature-induced isotopic drift observed in micromilled aragonite (−0.1‰/day at 70 °C). $\delta^{18}O$ values were reported with respect to the Vienna Pee Dee Belemnite (VPDB) scale using NBS19 ($\delta^{18}O = -2.2‰$) and NBS18 ($\delta^{18}O = -23.01‰$) (Coplen, 1996). Data points corresponding to seasonal extrema were re-sampled on the shell and re-analyzed. Values from replicate microsamples were then averaged. Isotopic values were not corrected for the difference of CO_2-acid fractionation factors between calcite and aragonite