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Short Paper

Geoarchaeological evidence for multidecadal natural climatic variability and ancient Peruvian fisheries

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Abstract

Understanding the influence of natural climatic variability on modern fisheries is complicated by over a century of industrial fishing. Archaeological data provide unique opportunities for assessing precolonial and preindustrial fisheries. Records show that anchoveta-vs sardine-dominated fisheries correlate with 20th-century climate change in the Pacific Basin and are linked to multidecadal climatic variability. The "anchovy regime" is characterized by cooler conditions and lower frequency El Niño/Southern Oscillation (ENSO) events, while the "sardine regime" is associated with warmer conditions and higher frequency ENSO. Fish remains excavated at Lo Demás, an Inca-period (ca. A.D. 1480–1540) fishing site at 13°25′S on the Peruvian coast, document a shift from an anchoveta-to a sardine-dominated fishery at about A.D. 1500. This shift correlates with records for increasing ENSO frequency at the same time. Middle and late Holocene sites have archaeofish assemblages that also suggest regime changes. Here we show that changes in fish regimes can result from natural variability and we support the potential role of archaeological assemblages in tracking multidecadal climate change in the Pacific Basin throughout the Holocene (0–11,500 cal yr B.P.).

Keywords: Climate change; Geoarchaeology; Fish; El Niño; Peru

Introduction

The Peruvian coastal upwelling ecosystem is one of the most productive regions of the world's oceans, supporting the world's largest single-species fishery (anchoveta; Bakun, 1996). It is also a critical area for reconstructing the long-term behavior of El Niño/Southern Oscillation (ENSO) and multidecadal climate change in the Pacific Basin. Therefore, this region plays an important role in understanding the impact of climatic variability on marine living resources. Following studies of 20th-century Pacific fisheries and climate (Chavez et al., 2003), we demonstrate the utility of archaeological data to extend the record of such interaction earlier in the Holocene and show that fish regime change occurred even in the absence of a large-scale industrial fishery.

Peruvian anchovetas, sardines, and present-day climate

Variability in physical forcing in the equatorial Pacific and coastal Peru is dominated by the ENSO phenomenon at periods of 2 to 7 years (Philander, 1999). During El Niño, reduced nutrient flux dramatically reduces productivity and disrupts the food web across the equatorial and coastal environments of the eastern tropical Pacific (Barber and Chavez, 1983; Chavez et al., 1999). One of the most dramatic biological effects during ENSO is the significant

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reduction in the catch of Peruvian anchoveta (*Engraulis ringens*) (Fig. 1a). The anchoveta feeds mainly on diatoms and lives only 3 years. The anchoveta stock is very sensitive to environmental conditions. The strong covariation of thermal anomalies and anchoveta catch reflects a causal relationship that depends on changes in the basin-scale thermal and nutrient dynamics during ENSO. The gradient separating nutrient-rich subsurface waters from nutrient-depleted surface waters is referred to as the nutricline. In the eastern equatorial Pacific and on the coast of Peru, the nutricline correlates well with the thermocline. During El Niño events, decreased trade winds in the central equatorial Pacific cause a basin-wide thermal anomaly. This is accompanied by depression of the thermocline and nutricline below the depth at which source water is entrained into the upwelling circulation along the coast of Peru (Barber and Chavez, 1986). The deepening thermocline and nutricline result in increased sea surface temperature, decreased nutrient supply to the surface, and reduced productivity during El Niño events. Using the 1982–1983 El Niño as an example, the dramatic decrease in primary production of phytoplankton decreased growth, survival, and reproductive success of the anchoveta. Growth and survival were affected because adult anchoveta feed directly on phytoplankton so that larval survival and reproduction depend upon its abundance. Consequently, reproductive success was reduced during the

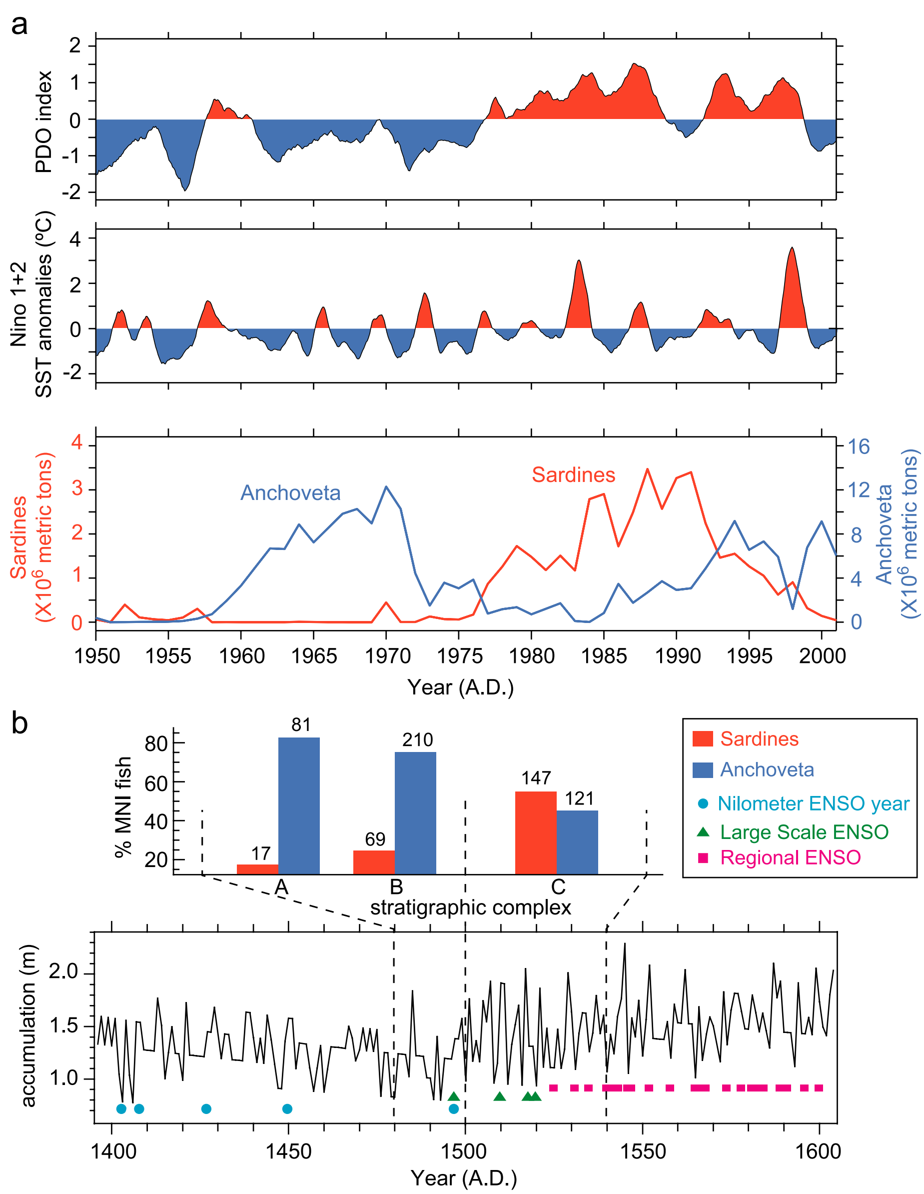

Fig. 1. Climate and fisheries data. (a) A.D. 1950–2000. Top: The Pacific Decadal Oscillation (PDO), derived from principal component analysis of North Pacific sea surface temperature (SST) (Mantua and Hare, 2002), has been smoothed with a 2-year running mean. Middle: SST anomaly along the coast of Peru (Nino 1+2) smoothed with a 1-year running mean. Bottom: Time series of annual anchoveta and sardine landings from Peru. (b) A.D. 1400–1600. Top: Minimum number of individuals (MNI) by stratigraphic complex, Sector I, Lo Demás, Peru (Sandweiss, 1992). Bottom: Quelccaya ice accumulation record (Thompson, 1992) and ENSO history (Quinn, 1992).

1982–1983 El Niño (Barber and Chavez, 1986). These combined larval and adult processes reduced the anchoveta catch to record low levels in 1983.

The South American sardine (*Sardinops sagax*) is also a pelagic fish found in large schools off the coast of South America. It feeds on copepods and phytoplankton and can live up to 25 years. Because of this long life span, the sardine stock is less sensitive to ENSO than is the anchoveta stock, although the distribution may shift southward as southern water becomes warmer. For example, during the 1982–1983 El Niño, sardines decreased to almost zero in the Ecuadorian catch, decreased slightly in the Peruvian catch, and increased in the Chilean catch, showing a southward shift in distribution. Analyses of stomach contents in 1983 showed that 47% were phytoplankton and 40% were zooplankton, suggesting that phytoplankton biomass is a good indicator of sardine location. During ENSO, adult sardines can feed in areas with high plankton concentrations. Some of these areas are near shore, where sardines can be caught easily during ENSO warm events (Barber and Chavez, 1986). Therefore, when water temperatures off the Peruvian coast change from cool to warm in response to ENSO, we should expect anchovetas to become less common and sardines to increase, defining two alternating, temperature–sensitive fish "regimes". This is exactly what Chavez et al. (2003) noted comparing the 20th-century climate record with fisheries data.

The Pacific Ocean also exhibits variations at decadal time scales (10 to 30 years), and these changes directly impact marine ecosystems and pelagic fisheries. Air and ocean temperatures, ocean productivity, and fish landings show synchronous variations on multidecadal time scales (Chavez et al., 2003), but there are no well-articulated hypotheses that link physical and chemical variations with biological responses. Peruvian anchoveta and South American sardine catch data from Peru show a fluctuation at periods similar to those of the Pacific Decadal Oscillation (PDO) (Fig. 1a). In the mid-1970s, the Pacific changed from a cool equatorial and eastern boundary current regime favorable to anchovetas to a warm equatorial and eastern boundary current regime favorable to sardines (Chavez et al., 2003). The early 1950s through the early 1970s represent an "anchovy regime." In the mid-1970s there was a return to a "sardine regime" that prevailed into the 1990s. Throughout the 20th century, anchoveta stocks were high when sardine stocks were low, and vice versa, reflecting the PDO phase. In fact, the notorious collapse of anchoveta stocks in the late 1970s and early 1980s that has been blamed on overfishing could very well be due in part to a 50-year cycle in stock abundance closely correlated with the periodicity of climate change in the Pacific Basin (Chavez et al., 2003). Recent evidence suggests that another PDO change occurred around 1998 with a return to cooler, 1960s-like conditions (Mantua and Hare, 2002), with sardine catches declining from 4 million metric tons in the 1980s to 40,000 metric tons in 2001.

Archaeological fish remains and regime change

The archaeological site of Lo Demás in the Chincha Valley, Peru (Fig. 2), was excavated in 1983–1984 to study the economic organization of fishing in an Inca coastal colony (Sandweiss, 1992). Deposits were well stratified. In Sector I, where the common fishermen lived, the many strata fell into three well-defined complexes (B, C, and D from bottom to top; A was ephemeral). Six ^{14}C dates on charcoal generally fit the stratigraphy and the assigned age of the deposits in this sector, but radiocarbon dating provides less precise dates than do historic records and artifacts (Fig. 3). The Inca conquered Chincha ca. A.D. 1479 and Spaniards conquered the Inca in A.D. 1532. The first monastery was established in the Chincha Valley in A.D. 1542. Inca and Inca-related material from the base of Complex B indicate a maximum age of ca. A.D. 1480 for Sector I. A minimum age of ca. A.D. 1540 is suggested by the absence of European materials except for one piece of a foreign plant (Bermuda grass, *Cynodon dactylon*) and a piece of possible cowhide. Both are from the top of Complex D and may be intrusive from the surface.

Fish remains from Lo Demás were identified by G. Mariano Astocondor, then of the Javier Prado Natural History Museum in Lima (Sandweiss, 1992). Sardines (*S. sagax*) and anchoveta (*E. ringens*) accounted for 67.5% of number of identified specimens and 91.2% of MNI (mini-

Fig. 2. Locations of sites mentioned in the text.

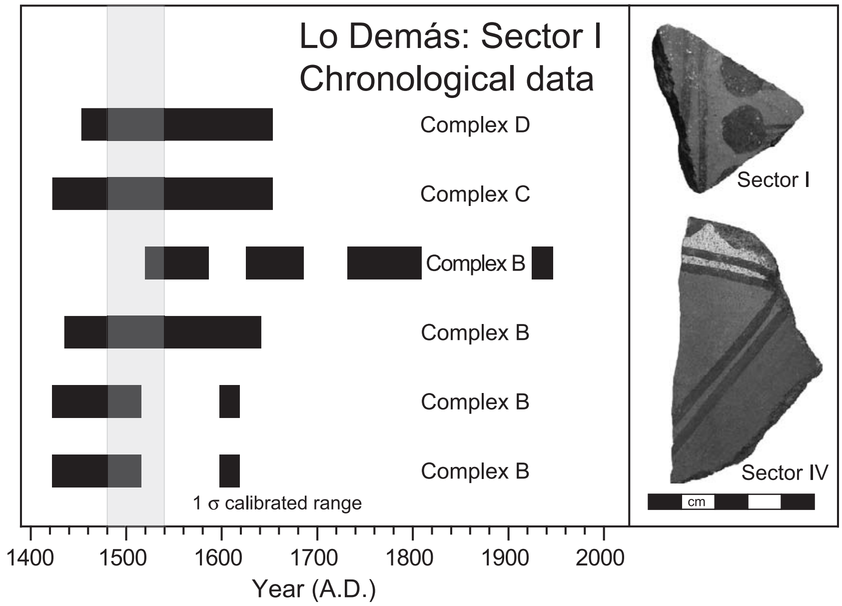

Fig. 3. Chronological data from Lo Demás. Radiocarbon dates were calibrated using Calib 4.3 (http://depts.washington.edu/qil/calib/calib.html). The vertical gray bar marks the historic age range of the site. Top potsherd: Inca design from Sector I, basal Complex B. Bottom potsherd: Inca design from Sector IV.

mum number of individuals; conservatively aggregated by Complex) for the Sector I sample. Anchoveta dominated the lower two complexes (B, C), while sardines were more abundant in the upper complex (D) (Fig. 1b).

The presence of anchovetas and sardines in significant quantities in all three complexes suggests that availability rather than preference accounts for the shift between Complexes C and D. This implies that the archaeological deposits at Lo Demás record a shift from a cool anchovy regime to a warmer sardine regime between A.D. 1480 and A.D. 1540. Though originally interpreted as the result of technological factors (Sandweiss, 1992), comparison to the Chavez et al. (2003) study and to two interannual records linked to ENSO support the inference that a fish regime and concomitant climate change occurred ca. A.D. 1500.

Fig. 1b shows annual accumulation of ice between A.D. 1400 and A.D. 1600 in a core from the Quelccaya Ice Cap in southern Peru (Thompson, 1992). A decrease in annual accumulation at Quelccaya correlates with the warm phase of ENSO (Thompson et al., 1984). In comparing the characteristics of this record just prior to and after A.D. 1500, both accumulation rates and the frequency of interannual fluctuations are lower in the earlier part of the record. We interpret this shift as evidence for increased warming associated with increased ENSO frequency. Quinn (1992) compiled historical records and proxies for ENSO events since A.D. 622. To compare to the Quelccaya accumulation record and the Lo Demás fauna, we used Quinn's datasets for Nile discharge from A.D. 1400 to 1497 ("Nilometer" record), the composite large-scale ENSO record from A.D. 1497 to 1525, and the regional Peruvian El Niño record for A.D. 1525–1600 (Fig. 1b). Following Quinn's strength rating, we show only events rated Moderate to Very Strong (or 3–5 for the Nilometer record). These data agree with the Quelccaya and Lo Demás records that indicate an increase in ENSO frequency after A.D. 1500. However, our archaeofish record is not sufficiently long to signal transitions before or after the occupation of Lo Demás, so we cannot comment on possible variability in the length of the fish regime cycle.

The published literature on Peruvian coastal archaeology does not include other well-dated, stratigraphically resolved cases of fish regime change. Nevertheless, such records are potentially recoverable. Aggregate samples from sites of varying age indicate that anchovetas and sardines are present prior to the 16th century A.D. and that different regimes prevailed at these sites. At the site of Paloma (ca. 8600–5400 cal yr B.P.; Benfer, 1984) at 12°30′ S, anchovetas were much more abundant than sardines (MNI of 77:11 anchoveta:sardine), both in the site assemblage as a whole and in each of the four levels distinguished in the excavation (Reitz, 2003). At El Paraíso (ca. 4200–3250 cal yr B.P.; Quilter, 1985) at 11°55′S, anchoveta were the most common fish, and sardines were present, but quantitative data are not published (Quilter et al., 1991). We have argued previously that the Peruvian coast south of 10° S was cool and El Niño absent between 9000 and 5800 cal yr B.P. (Sandweiss et al., 1996, 2001; Sandweiss, 2003), conditions that would support anchoveta dominance under the fish regime scenario proposed by Chavez et al. (2003) and discussed above.

At Pampa de las Llamas/Moxeke (ca. 4100–3250 cal yr B.P.; Pozorski and Pozorski, 1986; E.J. Reitz, 1999, unpublished) at 9°30′S, anchovetas dominate the assemblage (MNI of 229:26 anchoveta:sardine in the fine-screened column sample). For the period 5800 to 3000 cal yr B.P., we have demonstrated that El Niño was present but occurred at low frequency and that the coast north of 10° S supported molluscan species adapted to cooler average water conditions than prevail at present (Sandweiss et al., 2001; Sandweiss, 2003). Such conditions are consistent with anchoveta dominance under the fish regime scenario. Despite these intriguing correlations, however, further research at these sites is necessary to determine whether the archaeofish assemblages represent long-term, general conditions, as suggested, or whether they are time-averaged composites of changing fish regimes.

For sites north of 10° S and dating before 5800 cal yr B.P., application of fish regimes to paleoclimatic interpretation is problematic. Other members of the anchoveta family (Engraulidae) frequent shallow, warm, inshore waters and it is these taxa that might have been common rather than *E. ringens* in this earlier period, when northern coastal Peruvian waters were warmer than present (Sandweiss et al., 1996, 2001). This problem is not likely to affect southern sites or northern sites occupied after 5800 cal yr B.P., when northern waters cooled to their present temperatures. Additional research at early northern sites is necessary to determine whether they include Engraulidae with different habitat preferences.

Discussion and conclusion

The mechanism responsible for the decadal variability in anchoveta and sardine stocks is poorly understood because it is difficult to perform oceanographic sampling at the time and space scales necessary to elucidate the connections between large-scale physical processes and the smaller scale biological responses. Nevertheless, the archaeological data presented here show that there are long-term changes between anchoveta and sardines along the coast of Peru that cannot be explained by industrial-scale fisheries alone. The climatic processes responsible for the switch between the anchovy regime and sardine regime may be similar to the ENSO effects on these two fish stocks off the coast of Peru. The variability along the Peruvian coast should be associated with basin-wide Pacific and global climatic forcing.

Chavez et al. (2003) point to the need for longer temporal records of subtle climate change in the Pacific Basin. Our study demonstrates that the archaeological record can provide insight into such changes in fish abundances through time, thus contributing to a perspective on multidecadal climate change in the region during the Holocene.

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