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Notes

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ABSTRACT

Analysis of mollusks from archaeological sites on the north and central coasts of Peru indicates that between ca. 5800 and 3200–2800 cal yr B.P., El Niño events were less frequent than today, with modern, rapid recurrence intervals achieved only after that time. For several millennia prior to 5.8 ka, El Niño events had been absent or very different from today. The phenomena called El Niño have had severe consequences for the modern and colonial (historically recorded) inhabitants of Peru, and El Niño events also influenced prehistoric cultural development: the onset of El Niño events at 5.8 ka correlates temporally with the beginning of monumental temple construction on the Peruvian coast, and the increase in El Niño frequency after 3.2–2.8 ka correlates with the abandonment of monumental temples in the same region.

Keywords: archaeology, El Niño, global change, Holocene, paleoclimate, Peru.

INTRODUCTION

Long-term proxy records for El Niño–Southern Oscillation (ENSO) events indicate variable recurrence intervals and intensities. Those proxies that resolve interannual variability of ENSO events, however, are limited to the past ~1500 yr, rely on distant teleconnections, and/or date to the late Pleistocene (e.g., Cole et al., 1992; Eltahir and Wang, 1999; Rittenour et al., 2000; Thompson et al., 1992). ENSO history for other periods, including the early and middle Holocene, relies on lower resolution records such as faunal remains from archaeological sites (Sandweiss et al., 1996), pollen and charcoal records (McGlone et al., 1992; Shulmeister and Lees, 1995), and floating short-term chronologies with annual resolution (Gagan et al., 1997; Hughen et al., 1999; Tudhope et al., 2001). We have previously used archaeological remains to support other, independent lines of evidence (Sandweiss et al., 1996, 1997) that ENSO events were absent or significantly different between 8.8 and 5.8 ka. (All dates reported in this paper were calibrated by using Calib 3.0 [Stuiver and Reimer, 1993].) Here we show how midden remains from Peru for the succeeding millennia suggest an increase in ENSO frequency between ca. 3.2 and 2.8 ka. This shift correlates with climate records throughout the Pacific basin, indicating that fully modern conditions were not achieved until about that time. These changes had apparent cultural consequences: the onset of El Niño phenomena at 5.8 ka is temporally correlated with the beginning of monumental construction on the Peruvian coast, whereas the increase in El Niño frequency after 3.2–2.8 ka is correlated with the abandonment of monumental temples in the same region after nearly three millennia of uninterrupted development and growth.

The Pacific coast of southern Ecuador and northern Peru (Fig. 1) is a core region of ENSO activity, and paleoclimate records there should reflect ENSO history. Because the area lacks corals and coastal pollen catchments, few such records are available. However, Peruvian coastal middens contain abundant marine mollusk valves that are proxy indicators for nearshore oceanic conditions. Mollusks found in sites dating before 5.8 ka and located north of lat 10°S are members of tropical taxa now found only north of 4°S, and thus indicate very different conditions prior to that date (Sandweiss et al., 1996). After 5.8 ka, the warm-adapted species were replaced by the temperate molluscan assemblage characteristic of present-day southern Peru and northern Chile. By 2.8 ka, the most warm-temperature-sensitive of these species (*Choromytilus chorus, Mesodesma donacium*) had disappeared

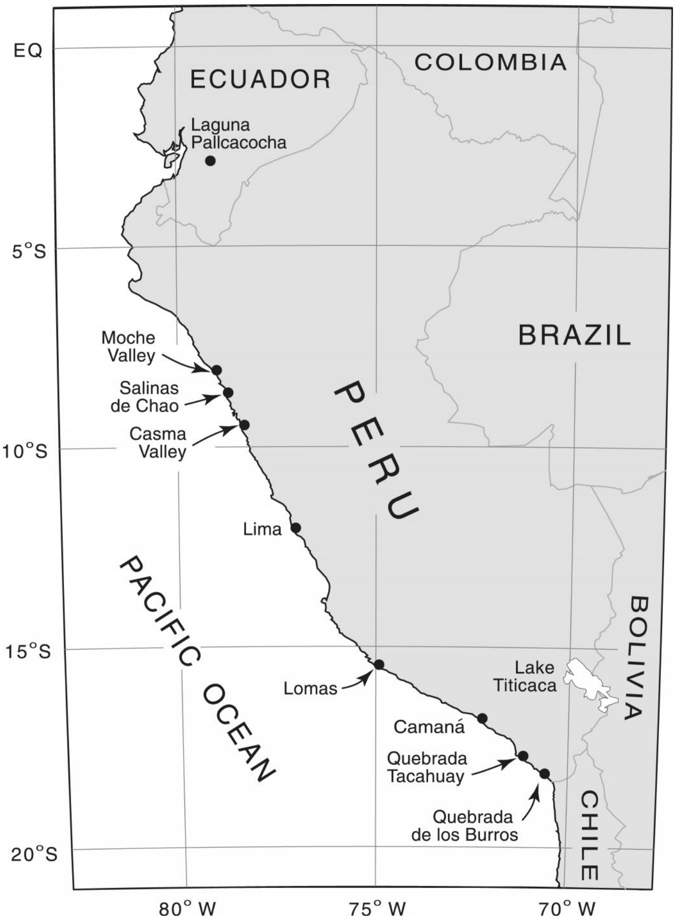

Figure 1. Map of Peru and adjacent regions, showing places discussed in text.

from middens north of 9°S and over the following centuries were largely replaced by the more eurytopic surf clam *Donax obesulus. D. obesulus* is much smaller than either *M. donacium* or *C. chorus,* which are among the most economically utilized mollusks of western South America. Modern behavior of *C. chorus* and *M. donacium* suggests that they would be present in northern Peru only under conditions of diminished frequency of strong El Niño events.

PERUVIAN MOLLUSKS AS ENVIRONMENTAL INDICATORS

Experimental results show that Chilean *C. chorus* die at an increasing rate as a function of rising temperature: the LT-50 (the temperature at which 50% of individuals die within a 24 h span) of this species is 28 °C (Urban, 1994). With a duration of 12–18 months and temperatures in excess of 28 °C on the Peruvian north coast, strong El Niños like the 1982–1983 and 1997–1998 events are capable of causing local extinction of *C. chorus.* Although LT-50s for *M. donacium* have not been determined, distributional data for the past 17 yr indicate that this species is also highly sensitive to the warm sea-surface temperatures (SSTs) brought by ENSO events. Prior to the 1982–1983 ENSO event, *M. donacium* was commercially available as far north as Lima at 12°S. Along the Peruvian littoral in 1982–1983, this species ''died in almost its entirety in waters of less than 4 m depth'' (Arntz and Valdivia, 1985, p. 92), close to the inferred depth limit of Initial Period (4.1–2.8 ka) extraction methods (Sandweiss, 1982). After that ENSO event, the range of *M. donacium* was restricted to south of Lomas, Peru, at 15°30′S. By the onset of the 1997–1998 ENSO, *M. donacium* had not regained its former range, and this event pushed it even further south. In 1999, *M. donacium* at Camaná (16°50′S) had not recovered fully, and the Peruvian fisheries ministry declared a ban on harvesting that species (Peruvian Ministry of Fisheries Resolución Ministerial 099-99-PE).

In contrast to the high mortality and slow recuperation of *M. donacium* and *C. chorus* populations during El Niño, *D. obesulus* recovers very rapidly (Arntz and Valdivia, 1985). The modern range of this species extends to the tropical waters of Ecuador at 1°S (Alamo and Valdivieso, 1987), indicating a broad range of temperature tolerance that probably explains the ability of Peruvian *D. obesulus* populations to survive strong ENSO events.

ARCHAEOLOGICAL DATA AND ANALYSIS

M. donacium and *C. chorus* are absent from Peruvian archaeological sites north of 10°S and dating prior to 5.8 ka. From 5.8 to ca. 3.2–2.8 ka, they are common constituents of archaeological middens from about 7°S southward along the Peruvian coast. By 2.8 ka, these two species had disappeared almost entirely from Peruvian sites between about 7° and 9°S and were replaced largely by *D. obesulus.* Table 1 shows this sequence of molluscan assemblages from archaeological sites in three north Peruvian coastal valleys. Identified molluscan assemblages from other north coast valleys followed the same trend, but complete temporal sequences from these valleys are not yet available. *M. donacium* and *C. chorus* remained minimally present in the Casma Valley past 2.8 ka, probably because of the transitional position of this valley, at the southern extreme of the area most affected by frequent El Niños (Table 1). Casma is close to the historical northern limit of *M. donacium* and *C. chorus,* and these species are not reported north of Casma in recent time.

Given the differential sensitivity of *M. donacium* and *C. chorus* to temperature and the period required for these species to recolonize coastal zones where high ENSO SSTs cause mass mortality, the rapid disappearance of these species from northern Peruvian archaeological sites probably reflects an increase in the frequency of strong El Niño events to within the modern range of variability. In the Casma Valley, where *C. chorus* and *M. donacium* became rare after 2.8 ka (Table 1) (Pozorski and Pozorski, 1987), the ENSO flood record of Wells (1990, p. 1136) indicates that ''there has been an increase in flooding during the past 3.2 ka.'' Although Wells suggested that these data do not indicate an increase in frequency of strong ENSO events, the molluscan assemblages and other evidence support shorter ENSO recurrence intervals as the cause for the more frequent flooding.

OTHER CLIMATE RECORDS OF INCREASED ENSO AFTER 3.2 KA

Various records suggest that modern climate conditions in the Pacific basin were not obtained until at or shortly after 3.2 ka. A marine paleoclimate record (32°45′S) from Chile reflects ''more frequent and more intense El Niño events'' for the past 3000 yr (Marchant et al., 1999, p. 115), and terrestrial data from 27–33°S indicate that ''climate . . . has become more variable since 5000 yr B.P., especially since 3000 yr B.P.'' (Veit, 1996, p. 107). Water levels in Lake Titicaca (Peru-Bolivia) rose rapidly ca. 3.5 ka and approached modern levels ca. 2.9 ka (Abbott et al., 1997). Lake levels in northern Chile also show a similar trend (Grosjean and Núñez, 1994; Valera-Garcés et al., 1996; cf. Betancourt et al., 2000). On the far south coast of Peru, ENSO-related flood records from Quebrada Tacahuay (17°48′S) (Keefer et al., 1998) and Quebrada de los Burros (18°1′S) (Fontugne et al., 1999) show a hiatus from slightly before 8.8 ka to shortly after 5.8 ka, corresponding to our hiatus in ENSO activity (Sandweiss et al., 1996). The Quebrada Tacahuay record ends with a flood event at 5.29 ka; the

TABLE 1. PRESENCE OR ABSENCE OF *MESODESMA DONACIUM, CHOROMYTILUS CHORUS,* AND *DONAX OBESULUS* FROM LATE MIDDLE HOLOCENE (5.8–3.2 KA) AND LATE HOLOCENE (3.2–0.5 KA) SITES, FROM THREE NORTH PERUVIAN VALLEYS

Valley	Site	S Lat.	Age	*M. donacium*	*C. chorus*	*D. obesulus*	Source
Moche	Padre Abán	8°10′	LP	0.1	31.5	2.1	Pozorski, 1979
Moche	Alto Salaverry	8°10′	LP	0.1	17.9	0.9	Pozorski, 1979
Moche	Gramalote	8°10′	IP*	0	7.1	0	Pozorski, 1979
Moche	Caballo Muerto	8°10′	IP*	0	21.9	0.2	Pozorski, 1979
Moche	Cerro Arena	8°10′	EIP	0	0.6	0.6	Pozorski, 1979
Moche	Moche huacas	8°10′	EIP	0	0	2.7	Pozorski, 1979
Moche	Galindo	8°10′	MH	0.2	0	0.2	Pozorski, 1979
Moche	Chan Chan	8°10′	LIP	0	0.3	10.4	Pozorski, 1979
Moche	Cerro La Virgen	8°10′	LIP	0	1	25	Pozorski, 1979
Moche	Choroval	8°10′	LIP	0	0	19.6	Pozorski, 1979
Salinas de Chao	Los Morteros	8°45′	LP	P	P	P	Cárdenas, 1979, 1995; Sandweiss et al., 1983
Salinas de Chao	Salinas de Chao	8°45′	LP	28.3–52.5	46.0–5.9	0.8–4.3	Alva, 1986
Salinas de Chao	Site C	8°45′	IP	Ø	Ø	P	Cárdenas, 1979; Sandweiss et al., 1983
Casma	Tortugas	9°30′	LP	++	–	–	Pozorski and Pozorski, 1987
Casma	Huaynuná	9°30′	LP	+	++	–	Pozorski and Pozorski, 1987
Casma	Las Haldas-Preceramic	9°30′	LP	++	++	Ø	Pozorski and Pozorski, 1987
Casma	Las Haldas-Initial Period	9°30′	IP	++	++	Ø	Pozorski and Pozorski, 1987
Casma	Pampa las Llamas	9°30′	IP	+	+	–	Pozorski and Pozorski, 1987
Casma	Las Haldas-Early Horizon	9°30′	EH	Ø	Ø	Ø	Pozorski and Pozorski, 1987
Casma	Pampa Rosario	9°30′	EH	Ø	+	–	Pozorski and Pozorski, 1987
Casma	San Diego	9°30′	EH	+	–	++/+	Pozorski and Pozorski, 1987

Note: For each valley, sites are in chronological order. LP = Late Preceramic (5.8–4.1 ka); IP = Initial Period (4.1–2.8 ka); EH = Early Horizon (2.8–2.15 ka); EIP = Early Intermediate Period (2.15–1.3 ka); MH = Middle Horizon (1.3–0.9 ka); LIP = Late Intermediate Period (0.9–0.5 ka). For Moche Valley sites, numbers indicate estimated percentage of meat diet; for Salinas de Chao sites, P = present, Ø = absent, numbers indicate percentage fragments-percentage whole valves identified for each species; for Casma Valley sites, ++ = abundant, + = moderately abundant, —= present but not abundant, Ø = not listed.
*These sites span a range from 3.7 to 2.6 ka.

Quebrada de los Burros record has an event at approximately the same time, but modern conditions were not achieved until 3.38 ka.

Rodbell et al.'s (1999) Laguna Pallcacocha lake record from highland Ecuador at 2°46′S shows an increase in rainfall events, suggested to be ENSO derived, beginning at 7.0 ka, with modern recurrence intervals achieved after 5.0 ka. Although offset by 1200 yr from our record and others, this sequence follows the general trend we identify here. ENSO might have been more effective in terms of regional precipitation in this near-equatorial setting, although lake records from the equatorial Galapagos Islands show the same trend in ENSO frequency, with a chronology more closely paralleling our own (Colinvaux, 1972; Riedinger et al., 1998). Charcoal-particle stratigraphy from the Sierra Nevada of California also indicates an intensification of El Niño in the late Holocene (Anderson and Smith, 1997). In the western Pacific, pollen and charcoal records from New Zealand and Australia show strong ENSO influence only after 5.8 ka and full development of ENSO after 3.2 ka (McGlone et al., 1992; Shulmeister and Lees, 1995). A change in ENSO frequency between ca. 3.2 and 2.8 ka would be consistent with the majority of records of Pacific basin climate change reviewed above.

Results from modeling experiments are consistent with these changes in ENSO behavior over the middle to late Holocene. Clement et al. (2000) used an idealized model of the tropical Pacific coupled ocean-atmosphere system to demonstrate that orbitally driven changes in the seasonal cycle led to a steady increase in large El Niño events over the Holocene, with a peak in the intensity and frequency of these events during the period 3–1 ka. This latter period coincides with an orbital configuration in which incoming solar radiation was slightly enhanced relative to the present at the end of the fall (with perihelion occurring in October–November), which increases the amplitude and frequency of large warm events in the model. Further modeling work is necessary to examine the influence of orbital forcing in ENSO behavior, but together, the model results and majority of records of Pacific basin climate change reviewed here provide a consistent and compelling picture of the behavior of ENSO in the late Holocene and its potential impacts on coastal societies.

CULTURAL CONSEQUENCES

Technology, history, cultural practices, religion, perception, and individual and group idiosyncrasies can all affect the way a society and its members respond to change. However, radical environmental change requires some response from the people who experience it. The changes in ENSO detailed herein are such a case. During the Late Preceramic Period and Initial Period, ca. 5.8–2.8 ka, a series of increasingly large temples was built on the Peruvian coast between the Lambayeque Valley (6°40′S) and the Lurín Valley (12 °15′S) ~800 km to the south. Sites such as Caballo Muerto, Pampa de las Llamas-Moxeke, Aspero, El Paraíso, Garagay, Mina Perdida, and others were impressive for their size, complexity and, often, their elaborate public art. The earliest of these sites was constructed shortly after the onset of El Niño at 5.8 ka. By ca. 2.9–2.8 ka, however, these temples and the political-religious system they supported had collapsed (Burger, 1981, 1992). In the Lurín Valley, where several Initial Period sites have been studied intensively (Burger and Gordon, 1998; Burger and Salazar-Burger, 1991), the one center that lasted longest (until 2.8 ka) was the only one with evidence for El Niño mitigation by temple leaders: at Manchay Bajo, a major labor investment was made to construct a wall between the temple and the mouths of two ravines that can carry mudslide debris during El Niño rainfall events. The 1999 excavations at Manchay Bajo revealed that following flooding from an ENSO event, this monumental wall (or dam) was reinforced and enlarged; an accelerator mass spectrometry radiocarbon measurement dates this modification to 3.339–3.079 ka (2 σ range, sample AA34632).

Climatic perturbations that occur less than once a generation have different consequences than those that occur several times a decade. We have identified a shift from absent to infrequent to frequent El Niño perturbations on the Peruvian coast. The close temporal correlation between these changes in ENSO frequency and the construction and abandonment of monumental temples in this region suggests that climate and culture are here linked in a complex causal network. The Andean region is a dynamic one in terms of climate and environment, and other processes (some linked with changes in ENSO frequency) may also have influenced mid-Holocene cultural development in this area. Further work is necessary to model and test these relationships in detail; in general, the stresses and opportunities presented by the different climate regimes outlined herein must have played a role in the social changes recorded in the rise and fall of early Peruvian temples.

SUMMARY

In this paper we demonstrate the potential of archaeological materials to contribute to Holocene paleoclimate studies in a region that lacks long interannual archives older than ca. 1.5 ka. Our reconstruction of past ENSO frequencies allows new interpretations of archaeological indicators of cultural change; resolves problems in interpreting prior data sets such as Wells's (1990) Casma flood record; provides new details concerning the onset of fully modern climate conditions in the Pacific basin identified by previous studies; and gives climate modelers trying to understand ENSO another paleobenchmark against which to test their models.

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