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Rapid reorganization in ocean biogeochemistry off Peru towards the end of the Little Ice Age

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Received: 21 August 2008 – Accepted: 29 August 2008 – Published: 29 September 2008

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Climate and ocean ecosystem variability has been well recognized during the twentieth century but it is unclear if modern ocean biogeochemistry is susceptible to the large, abrupt shifts that characterized the Late Quaternary. Time series from marine sediments off Peru show an abrupt centennial-scale biogeochemical regime shift in the early nineteenth century, of much greater magnitude and duration than present day multi-decadal variability. A rapid expansion of the subsurface nutrient-rich, oxygen-depleted waters resulted in higher biological productivity, including pelagic fish. The shift was likely driven by a northward migration of the Intertropical Convergence Zone and the South Pacific Subtropical High to their present day locations, coupled with a strengthening of Walker circulation, towards the end of the Little Ice Age. These findings reveal the potential for large reorganizations in tropical Pacific climate with immediate effects on ocean biogeochemical cycling and ecosystem structure.

1 Introduction

Paleoclimate evidence for large, rapid shifts in climate and biogeochemistry associated with Dansgaard-Oeschger events during the last glacial period indicate that the ocean-atmosphere climate system was susceptible to rapid changes in circulation and biogeochemical cycling (Schmittner et al., 2007). The Holocene appears more stable, however, large changes in tropical rainfall patterns at the Holocene thermal maximum (Haug et al., 2001), during the Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA) have been documented (Graham et al., 2007; Rein et al., 2004; Haug et al., 2001; Newton et al., 2006), and there are conflicting hypotheses concerning the role of the Walker circulation (Hendy et al., 2002; Koutavas and Lynch-Stieglitz, 2004).

Recent studies report climate and ecosystem “regime shifts” at multi-decadal time scales during the twentieth century (Mantua et al., 2004; Chavez et al., 2003). A regime shift can be considered as “a relatively brief time period in which key state variables

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of a system are transitioning between different quasi-stable attractors” (Mantua, 2004). Given ecosystem changes associated with current warming (Field et al., 2006), the potential for crossing attractor thresholds, or “tipping points”, and undergoing large regime shifts is of major interest, in particular for countries like Peru that are heavily dependent on marine resources.

The Eastern Tropical South Pacific (ETSP) is characterized by high productivity and depleted oxygen, particularly off Peru (Fig. 1), and is particularly sensitive to tropical climate variability (Barber and Chávez, 1983). This climate variability has been shown to propagate to the entire planet (D’Arrigo et al., 2005; Gergis and Fowler, 2006). Multiple proxies from laminated sediments collected from the upper Peruvian margin are used here to examine the coupling between biogeochemical cycles and centennial-scale climate modes during the past 700 years in the ETSP. High resolution sedimentary paleo-archives are preserved in certain topographic areas of the Peruvian margin within the oxygen minimum zone (OMZ) (Fig. 1; Reinhardt et al., 2003). The sediment cores retrieved from mud lenses off Callao (12° S, 184 m, Krissek et al., 1980) and off Pisco (14° S, 300 m, Gutiérrez et al., 2006) were analyzed and then compared to records from other regions.

2 Materials and methods

Based on previous sedimentological and geochemical information from exploratory surveys and literature, the Callao (~12° S) and Pisco (~14° S) areas were selected to perform box coring on board the R/V Olaya (IMARPE) in May 2004. Two Soutar-box cores were collected: one from the shelf off Callao (B0405-13, 12°00′ S, 72°42′ S, 184 m) and the other one from the upper slope off Pisco (B0405-06, 14°07′ S, 76°30′ S, 299 m) (Fig. 1). Subsampling for proxy determinations was performed following the stratigraphy (Gutiérrez et al., 2006; Morales et al., 2007).

The quantitative mineralogical composition, including lithic and biogenic-derived compounds, was obtained by Fourier Transformed Infrared Spectrometry (FTIR)

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(Bertaux et al., 1998). More detailed explanations on FTIR methodology are given in Sifeddine et al. (2008). Total organic carbon was determined from total carbon measurements with a Thermo Electron CNS elemental analyzer, corrected by the carbonate content. $\delta^{15}\text{N}$ was determined by mass spectrometry after acidification at the Department of Geosciences, University of Arizona (USA). Analyses of Molybdenum (Mo) and Cadmium (Cd) concentrations was carried out by ICP-MS and ICP-AES (Ultramass Varian) respectively, after hot plate acid digestion (combination of acid HF, HNO_3 , HClO_4), which was used to eliminate organic matter and to remove silicates (Cho et al., 1999).

Subsamples for foraminifera and fish scales were heated with hydrogen peroxide and sodium pyrophosphate to remove the organic matter and then were sieved through a $125\ \mu\text{m}$ mesh and $355\ \mu\text{m}$ mesh. The retained material in the $355\ \mu\text{m}$ mesh was sorted for fish remains (bones and scales) while foraminifera were counted and identified from the smaller size fraction with stereo-microscopy. Diatom valves and other siliceous remains were determined from splits that were acid cleaned with HCl 10% and H_2O_2 30% (Batterbee, 1989). Quantitative slides were made using $100\ \mu\text{L}$ of acid-clean residue of about 0.1 g of wet-sediment (equivalent of 0.02–0.03 g of dry-sediment) diluted on a 20-mL vial. A $22\times 22\ \text{mm}$ coverslip was permanently fixed over a $1''\times 3''$ glass slide with Zrax® ($R.I.=1.74$) to enhance diatom taxonomic features. Identifications were done with contrast-phase microscopy techniques.

Mass accumulation rates (MAR) for the past ~135 years were determined from downcore profiles of ^{241}Am and excess ^{210}Pb . Calibrated radiocarbon ages of the sedimentary organic matter, taking into consideration global and local reservoir effects, were used to estimate MAR in the lower sections of the cores. The final composite age models matched the ^{210}Pb -derived chronology with the age-mass curve based on the calibrated radiocarbon MAR (see supplementary information: <http://www.biogeosciences-discuss.net/5/3919/2008/bgd-5-3919-2008-supplement.pdf>).

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3 Results and discussion

3.1 Lithology and geochronology

The MAR varied by a factor of two, with the highest average values after ca. 1950 AD at both cores (Callao: $0.034 \pm 0.001 \text{ g cm}^{-2} \text{ y}^{-1}$; Pisco: $0.036 \pm 0.001 \text{ g cm}^{-2} \text{ y}^{-1}$) and lowest values before ca. 1820 AD (Callao: $0.017 \pm 0.001 \text{ g cm}^{-2} \text{ y}^{-1}$; Pisco: $0.022 \pm 0.001 \text{ g cm}^{-2} \text{ y}^{-1}$). The ages of the cores spanned the last 700 years approximately. Dating and sampling resolution resolve variability at sub-decadal to decadal time-scales (Fig. 2). Both cores show a shift in core lithologies at about 35-cm depth (Fig. 3a, j), as observed in dry bulk density and X-ray grey level, despite differences in location (300 km of distance) and depth within the OMZ. There is a striking similarity in the core lithologies and downcore patterns of lithic, geochemical and biogenic proxies between the two sites (Fig. 3), which indicates that regional- to large-scale processes largely determine the temporal variations. Terrigenous sedimentation dominates below 35 cm, whereas diatom/siliceous and organic matter are major constituents above that depth. The shift in core lithologies is dated near 1820 AD.

3.2 Centennial-scale regime change in multiple proxies

Terrigenous input to the Peruvian continental margin is mainly driven by precipitation and runoff-driven erosion of fine-grained material, followed by river discharge and dispersion by ocean currents (Scheiddeger and Krissek, 1982; Rein et al., 2007). A reduction in lithic fluxes near 1820 AD (Fig. 3b, k) suggests that the western flank of the Peruvian Andes changed rapidly from a wetter to a drier condition (Sifeddine et al., 2008).

The multiple geochemical and biogenic records developed in the study (Fig. 3) can be grouped into three classes of proxies of ocean biogeochemistry, according to their source and downcore behaviour. These proxies indicate a rapid change between centennial-scale biogeochemical regimes around 1820 AD, which differ in water col-

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umn oxygenation, sediment redox conditions, and productivity.

The first class consists of the $\delta^{15}\text{N}$ of organic matter and Cadmium (Cd) fluxes, which primarily reflect changes in water column oxygen and nutrient conditions. In oxygen-deficient waters nitrate is used as an electron donor for respiration during degradation of organic matter. Hence settling organic matter $\delta^{15}\text{N}$ will reflect enriched $\delta^{15}\text{N}$ nitrate taken up by phytoplankton from oxygen-depleted water masses (Altabet et al., 1999; De Pol et al., 2007). The $\delta^{15}\text{N}$ values from our records before ca. 1820 AD agree with background levels during the late Holocene until the LIA in the ETSP (Agnihotri et al., 2008). In the water column, Cd exhibits nutrient-like characteristics and its uptake by phytoplankton depends on surface water concentrations. Cadmium is delivered to sediments in association with organic matter and becomes fixed in reducing sediments (Tribovillard et al., 2006; Böning et al., 2004). Therefore, the step-like increase in baseline values of these two proxies near 1820 AD can be interpreted as a rapid change in source water properties towards lower oxygen and higher nutrient concentrations.

The second class reflects reduction-oxidation (redox) conditions in surface sediments:

1. foraminiferal preservation, as inferred by presence/absence of foraminifera,
2. percent of *Bolivina seminuda* in the benthic foraminiferal assemblage, and
3. Molybdenum (Mo) fluxes, as reported by Sifeddine et al. (2008).

Dissolution of calcitic foraminifera tests explains their absence (Morales et al., 2006) and occurs with lower alkalinity, a condition that is met at surface when sulphate reduction occurs deeper in the sediments (Froelich et al., 1988). Among the foraminiferal species present, *B. seminuda* is more dominant as conditions become more dysoxic (Resig, 1981), which occurs primarily in the post-shift period (Fig. 3). Finally, Mo, which displays a quasi-conservative behaviour in the water column, is scavenged when free sulphide and elemental sulphur species are present in pore waters, even in anoxic microniches, and in the water column (Tribovillard et al., 2006, 2008). On the Peruvian

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margin the highest Mo enrichment occurs in organic-rich sediments within the OMZ and on the shelf (Böning et al., 2004; McManus et al., 2006). The increase in foraminifera preservation and Mo fluxes at ca. 1820 AD (Fig. 2) are therefore consistent with a rapid upward expansion of the anoxic layer within the surface sediments.

5 While higher oxygenation in the water column characterized the LIA period prior to 1820 AD, sufficiently dysoxic conditions in the sediment-water interface still permitted the preservation of fine laminations in the deeper Pisco core, as flux varied between terrigenous and organic sources. The major shift primarily occurred in the large-scale depletion in oxygen that would have occurred throughout the Equatorial Subsurface
10 Waters (ESSW; Strub et al., 1998). The shift in $\delta^{15}\text{N}$ of our records is approximately 2 per mil. This abrupt shift is of the same order of magnitude as $\delta^{15}\text{N}$ changes observed in the eastern North Pacific and Arabian Sea during Dansgaard-Oeschger events (Schmittner et al., 2007), implying a major reorganization of circulation and biogeochemical cycling throughout the ETSP.

15 The third class of proxies reflect biological productivity and include Total Organic Carbon (TOC) flux, diatom concentrations and biogenic silica fluxes, and abundance of fish remains (scales, bones and vertebrae); the latter are proxies for variations in pelagic fish populations (Baumgartner et al., 1992). Changes in oxygen concentration may affect the preservation of the biological productivity proxies directly or indirectly.
20 Fish scales have more fissures and altered colorations in the centuries immediately preceding the shift, indicating that greater degradation may be partly responsible for the reduced number of fish scales. In this case, fish bones and vertebrae are more reliable indicators of variability in pelagic fish abundances as they are more resistant to degradation or dissolution than fish scales (DeVries, 1979). Persistently higher primary
25 productivity may not be apparent in the individual records of TOC and diatom fluxes after 1820 as there is a negative correlation between them ($r=-0.79^{**}$, $n=37$; and $r=-0.69^{**}$, $n=42$, for Callao and Pisco, respectively). However, greater alkalinity due to enhanced sulphate reduction near the sediment interface increases dissolution of diatom valves (Froelich et al., 1988). Thus, the combination of diatom remains and

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TOC indicate persistently higher primary productivity after 1820.

There are two different patterns in the biogeochemical proxies during and after the 1820 shift. The first one, typified by $\delta^{15}\text{N}$ and foraminifera preservation, shows a step-like change at ca. 1820 AD to persistent higher oxygen depletion and redox conditions.

The second pattern, typified by TOC and fish remain fluxes, shows a rapid increase after 1820 AD that persisted for a few decades, followed by a return towards pre-shift conditions from ca. 1845 to 1865 AD, and then persist at higher levels. Cd and Mo fluxes exhibit an intermediate behaviour, probably because their records reflect a combination of biological productivity and redox conditions. However, fluxes of diatom and biogenic silica are actually higher during the return to pre-shift conditions due to high abundances of *Skeletonema costatum*, which blooms during upwelling relaxation (Alvarez et al., 2005) and forms aggregates with increasing temperature (Thornton and Thake, 1998). Thus the transition patterns likely reflect a multi-decadal period whereby conditions were more stratified with fewer upwelling events, but oxygen and nutrient concentrations in the upwelling source waters were maintained at post-shift levels.

Several biogeochemical proxies ($\delta^{15}\text{N}$, Cd, Mo), fish scales, and fluxes of lithics also suggest a gradual change during the fourteenth to fifteenth century from a regime with lower oxygenation and higher productivity to the centennial regime prior to 1820 AD.

3.3 Climatic driver for the biogeochemical shift

Seasonal to interannual variability of water column structure, upwelling intensity and productivity in the ETSP are coupled to the strength of the Walker circulation, the expansion/contraction of the South Pacific Subtropical High (SPSH) and the position of the Intertropical Convergence Zone (ITCZ) (Strub et al., 1998). Generally, changes in Walker circulation, SPSH and ITCZ are correlated during El Niño (EN) events, whereby the coast of Peru is characterized by reduced productivity and an increase in subsurface oxygenation due to a weakening of the equatorial thermocline and Walker circulation (Morales et al., 1999). However, the expression of EN events along the Peru coast were less frequent and/or less intense during the LIA (d'Arrigo et al., 2005; Gergis and

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Fowler, 2006; Ortlieb, 2000) and therefore higher frequency of EN events is an unlikely explanation of the LIA conditions reported here.

We hypothesize that the centennial-scale shift in the Peruvian upwelling system was driven by a northward displacement of the ITCZ and the SPSH from their southward condition during the LIA to their modern positions, coupled with the enhancement of Walker circulation. Comparison of the $\delta^{15}\text{N}$ records off Peru with records of temperature and salinity from the Indo Pacific shows that a relatively abrupt change occurred in the Indo Pacific at the same time as the biogeochemical shift off Peru (Fig. 4). The large-scale oxygen depletion of ESSW and associated increase in productivity imply a basin-scale adjustment of the equatorial thermocline/ pycnocline tilt and greater equatorial upwelling (Pennington et al., 2006; Fiedler and Talley, 2006). Taken together, the records also imply enhanced southeast trades, expansion of the cold tongue, and a stronger zonal SST gradient across the Pacific.

Thus, the low productivity, less oxygen-depleted regime during the LIA was most probably maintained by a southward position of the ITCZ and reduced influence of the SPSH along the Peruvian margin, that also diminished equatorial upwelling and hence both the zonal and meridional SST gradients in the eastern tropical Pacific (Haug et al., 2001; Koutavas and Lynch-Stieglitz, 2004). A northward migration of the ITCZ, as inferred from the Cariaco basin (Fig. 4), might have caused a “tipping point” that shifted Walker circulation to its modern conditions.

There is considerable evidence for a southward displacement of the ITCZ during the LIA, attributed to the cooling of the northern hemisphere (Koutavas and Lynch-Stieglitz, 2004). The higher lithic fluxes to the Central/Southern Peruvian margin sediments during the LIA are in agreement with continental records that indicate enhanced humidity and monsoonal precipitation in the western Peruvian Andes (Jomelli et al., 2007; Unkel et al., 2007), when dry climatic conditions characterized the Cariaco Basin (Fig. 4; Haug et al., 2001). Lower salinity in Makassar Strait, a condition that prevailed during the LIA, occurs nowadays during austral summer, associated with higher precipitation and monsoonal winds but not during El Niño events (Gordon et al., 2003; Newton et

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al., 2006). Figure 5 illustrates how the inferred precipitation patterns during the LIA are consistent with a persistent austral summer-like southward migration of the ITCZ and the associated precipitation belt, rather than a strong zonal (El Niño-like) shift of precipitation eastward.

The southward position of the ITCZ was likely associated with a latitudinal contraction of the SPSH during the LIA, as lower paleotemperatures (U_{37}^K) off Concepcion (36° S) suggest an augmented latitudinal SST gradient across the southeast Pacific (Vargas et al., 2007). An enhanced latitudinal SST gradient and Hadley circulation also characterized the LIA in the subtropical South Pacific until around 1870 (Hendy et al., 2002). $\delta^{15}\text{N}$ records from northern Chile (Vargas et al., 2007) support low-latitude forcing of the 1820 AD shift, since the increase of $\delta^{15}\text{N}$ observed in Mejillones from 1820 to 1870 AD is delayed and gradual compared to the step-like change in the Peruvian margin records (Fig. 4). Slower changes at higher latitudes are consistent with a poleward expansion of oxygen-depletion, enhanced by a more persistent undercurrent, driven by a stronger SPSH and offshore Ekman transport (Strub et al., 1998). The variability in the Peru records from the transition in 1820 until 1870 AD and the observations at subtropical locations can be attributed to changes in the intensity of the SPSH. A continued strengthening of the SPSH along the Peruvian margin in the twentieth century may account for the trend towards greater TOC and redox conditions (Fig. 3).

3.4 Ecosystem responses to the biogeochemical shift

Diatom analysis suggests that both cool-upwelling and warmer-oceanic species were favoured after the 1820 AD shift rather than an alternation of different groups under different productivity regimes. While the abrupt increase in diatoms was dominated by the cool-water upwelling diatom assemblage, other groups increased as well (Fig. 6). In particular, oceanic diatoms off Pisco actually make up a greater portion of the total assemblage during several periods of the high productivity regime.

The response of pelagic fish species is similar, with the increase in productivity after 1820 AD being favourable for both cool-upwelling species as well as species that live in

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warmer-oceanic waters (Fig. 6). The records of fish remains from different locations in Fig. 6 reveal how different species have expanded and contracted both in abundance and population range.

The present day nucleus of the Peruvian anchovy or anchoveta, *Engraulis ringens*, is from 6° to 12° S and the Callao site lies within this range (Pauly and Tsukayama, 1987). Off Callao, all fish abundances inferred from scales, bones, and vertebrae, were dramatically lower prior to 1820 AD. During warm, less productive periods anchoveta migrate to the Pisco area (Mendo, 1991), which often retains a small upwelling plume even under EN events (Barber and Chávez, 1983). Fluxes of fish bones and vertebrae during the LIA were reduced from ca. 1450 to 1600 AD and also from 1700 to 1800 AD off Pisco. Further south, the Mejillones Bay (23° S) is within the distributional area of the present day Northern Chile anchoveta stock (Serra, 1983). Fish remains in Mejillones Bay sediments do not show the centennial shift around 1820 AD, though fish scales from anchoveta increased slightly around this date (Valdés et al., 2008). The combined records suggest that off central Peru pelagic fish populations were reduced during the LIA, and that the anchoveta nucleus moved southward.

Periods of low anchovy abundances are often associated with increases in sardine abundances over multidecadal timescales in various boundary currents during the 20th century (Schwartzlose et al., 1999; Chavez et al., 2003). Although sardine scales are much thicker and more resistant to degradation than anchoveta scales, no scales were found off Callao or Pisco during the low productivity regime, neither were any from larger offshore species such as jack mackerel (*Trachurus murphyi*) or horse mackerel (*Scomber japonicus peruanus*). At Mejillones Bay, scales of sardine and offshore species were present throughout the record with no signs of degradation, but as with bones and vertebrae, fluxes were not higher prior to 1820. The combined evidence from the three different sites indicates that sardines did not expand during the centennial-scale regime of low productivity.

Within the highly productive regime, a centennial-scale northward expansion of anchoveta is coupled with two multi-decadal periods of expansion of sardines (Fig. 6).

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The former period corresponds to low anchoveta scale fluxes and low fluxes of bones and vertebrae during the return to pre-shift conditions (1845–1865), which also shows that reduced fish debris here is not an artifact of degradation. The latter period corresponds to the decadal-scale “sardine regime” observed in the twentieth century (Chavez et al., 2003). Note that the flux of bones and vertebrae is diminished since the development of the fishery in the 1960s, likely ending up as fish meal rather than passing through the guts of predators and being transported to the sediments.

4 Concluding remarks

A large, rapid and persistent change in climate, ocean circulation and biogeochemical cycling occurred off Peru towards the end of the Little Ice Age, probably within a decade, around 1820 AD. The magnitude of the shift in biogeochemical cycling and particularly in the regional marine nitrogen cycling appears similar to the imprint of Dansgaard-Oeschger events in the Pacific and Indian Oceans. The abruptness of the regime shift reveals the potential for rapid reorganizations in the modern tropical Pacific climate and circulation, leading to centennial-scale changes in productivity and regional marine nitrogen loss.

While reduced Walker circulation is associated with warming across the globe during El Niño periods, the reduced Walker circulation during the LIA was probably maintained by a southern displacement of the ITCZ in association with global cooling. Furthermore, the current EN teleconnection that links precipitation anomalies in central Chile and Northwestern Peru was absent prior to ca. 1817 AD (Ortlieb, 2000, 2004), which is likely due to changes in tropical atmospheric circulation at this time. Thus ENSO teleconnections and the coupling of important processes (like the ITCZ and Walker circulation) may differ in the future under different climate scenarios.

The ecosystem response to the biogeochemical shift involved an overall increase of the major groups of diatom and pelagic fish, in contrast to observed multi-decadal alternations in pelagic fish observed during the twentieth century (Chavez et al., 2003).

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Without the centennial, climate-driven, increase in bottom-up productivity of the upwelling system the intensive anchoveta exploitation during the past decades would not have been possible. Given that looming climate changes may easily exceed variations observed in the twentieth century, major and non-linear regime shifts in the ecosystems that depart from twentieth century paradigms should be expected. Mechanistic understanding is needed to predict future scenarios and to develop adaptive policies.

Acknowledgements. We acknowledge support from the Instituto del Mar del Peru (IMARPE) PALEOMAP research program, the IRD PALÉOTROPIQUE research unit (UR 055), the PALEOPECES project (IMARPE-IRD), the IAI small grant project SGP 211-222 (P.I.D.G.), the Humboldt Current System program (ATI-IRD), the JEAI Mixpaleo project (IMARPE/INGEMMET), and the AIEA CRP El Niño (research contract No. 12789). Research contributions of D. F. came from the NSF International Research Fellowship Program (IRFP award OISE-0502387). We particularly acknowledge the crew of the RV J. O. Balandra and other scientific participants in the box-coring survey. We also acknowledge D. Kolber (MBARI) for her valuable help in the Figs. 1 and 4.

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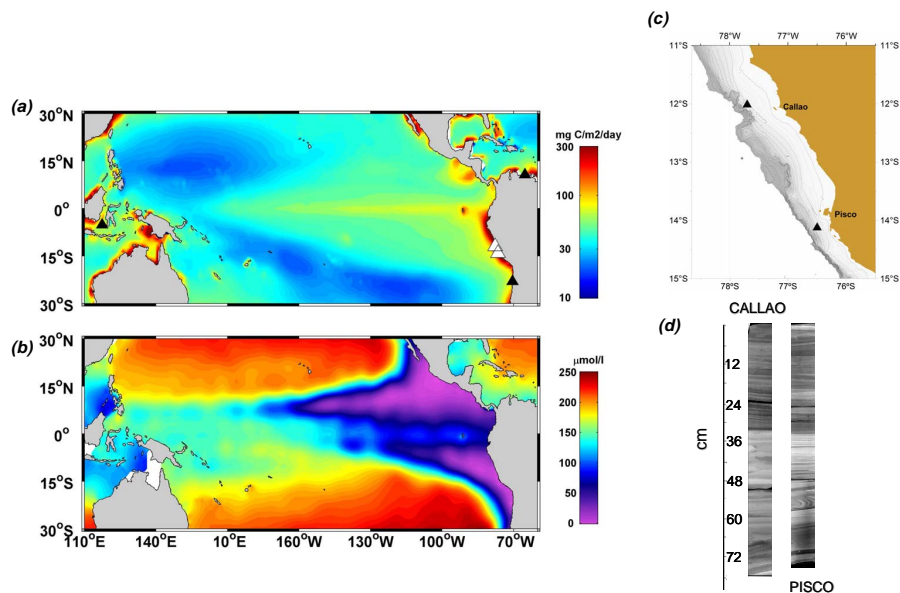


Fig. 1. **(a)** Map of average POC flux ($\text{g C m}^{-2} \text{y}^{-1}$) from the euphotic zone for 1999–2006 estimated from satellite measurements of chlorophyll and temperature in the Tropical Pacific (Laws et al., 2000). The highest present day export rates currently occur off the coast of Peru; **(b)** Present day climatological map of dissolved oxygen saturation at 150-m depth ($\mu\text{mol L}^{-1}$), from the World Ocean Data Center, showing the persistently low oxygen in the eastern tropical Pacific. The locations of the paleorecords used in this study are shown as white triangles; other paleorecord sites discussed in the text (Cariaco Basin, Caribbean Sea; Mejillones Bay, Northern Chile; and Makassar Strait, Indo Pacific) are shown as black triangles; **(c)** Zoom of the shelf off central Peru, showing the position of the boxcores off Callao and Pisco (black triangles). Bathymetric contour lines are shown for each 100-m depth (thick) and each 25-m depth (thin); **(d)** X-ray digital radiographies for both box cores.

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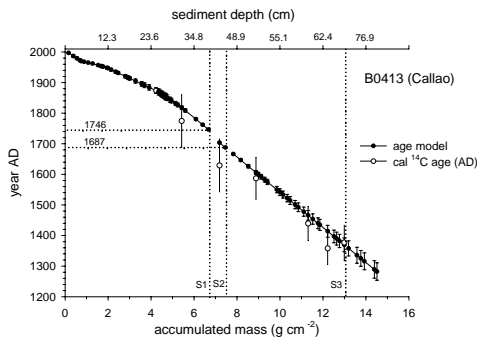
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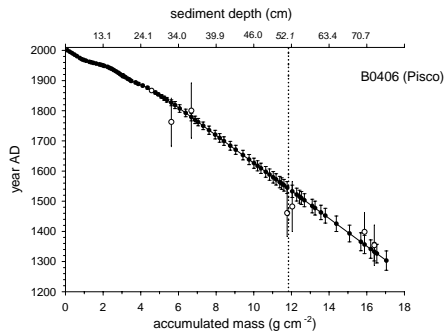
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(a)



(b)

Fig. 2. (a) Age model (accumulated mass versus age) for the Callao core. The predicted dates are compared with the calibrated radiocarbon ages, using the estimated local reservoir age (DR). The reference sediment depths are depicted in the top axis. Short-dashed lines indicate the slumps positions. The mid-section slumps (S1, S2) are interpreted as markers of the 1687 AD and 1746 AD earthquakes (Dorbath et al., 1990). (b) Age model (accumulated mass versus age) for the Pisco core. The predicted dates are compared with the calibrated radiocarbon ages, using the estimated DR. The slump at about 52 cm sediment depth is indicated with a short-dashed line. For more information, look at the supplementary information (<http://www.biogeosciences-discuss.net/5/3919/2008/bgd-5-3919-2008-supplement.pdf>).

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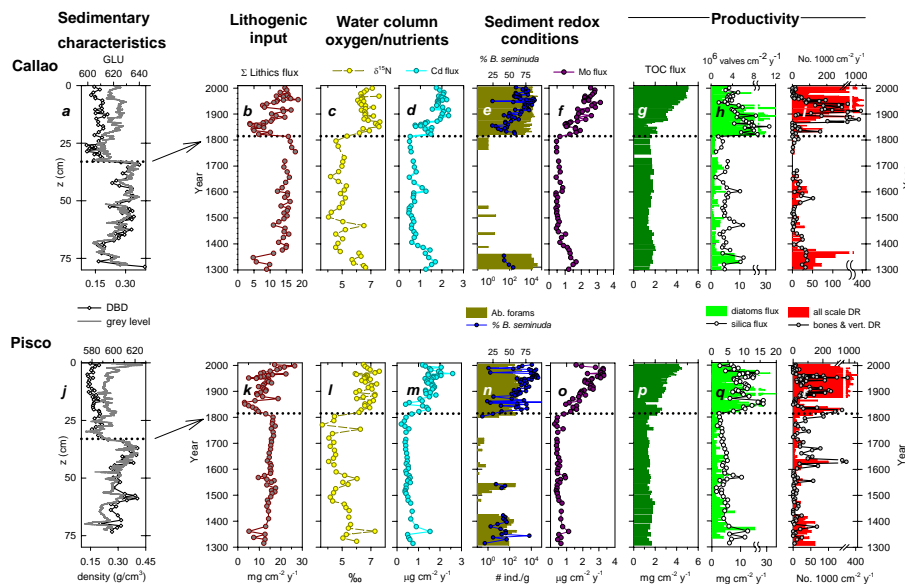


Fig. 3. Multiple proxies developed in the cores collected off Callao (a)–(i) and off Pisco (j)–(r). (a), (j) Dry bulk density (white circles; g cm^{-3}) and X-radiography gray level units (gray lines) are shown as a function of depth. All other proxies are shown as a function of time: (b), (k) Flux of the sum of lithic components (feldspar, quartz and clays; Sifeddine et al., 2008); (c), (l) $\delta^{15}\text{N}$ values of sedimentary organic matter (‰); (d), (m) flux of elemental Cadmium ($\mu\text{g cm}^{-2} \text{y}^{-1}$); (e), (n) bars: total foraminiferal abundance (Nr ind. g^{-1}), blue circles: percent of *Bolivina seminuda* in the benthic foraminiferal assemblage; (f), (o) flux of elemental Molybdenum ($\mu\text{g cm}^{-2} \text{y}^{-1}$) reported by Sifeddine et al. (2008); (g), (p) flux of total organic carbon ($\text{mg C cm}^{-2} \text{y}^{-1}$); (h), (q) bars: diatom accumulation rate (10^6 valves $\text{cm}^{-2} \text{y}^{-1}$), white circles: flux of biogenic silica ($\text{mg cm}^{-2} \text{y}^{-1}$); (i), (r) bars: fish scale deposition rates ($\text{No. 1000 cm}^{-2} \text{y}^{-1}$), gray circles: deposition rates of fish bones and vertebrae ($\text{No. 1000 cm}^{-2} \text{y}^{-1}$). A shift in DBD and grey level at 35-cm depth and its corresponding date (1820 AD) is indicated in each panel by dotted lines and connected with an arrow.

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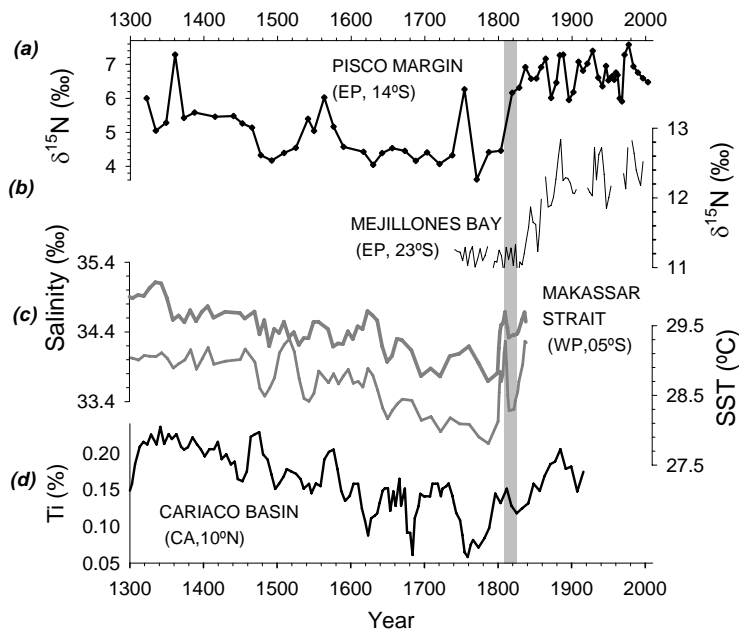


Fig. 4. Comparison of **(a)** $\delta^{15}\text{N}$ time-series in Pisco (this study) with paleo records developed in other regions: **(b)** $\delta^{15}\text{N}$ time-series in Mejillones Bay, which reflects alongshore winds intensity and influence of ESSW in coastal upwelling off northern Chile (Vargas et al., 2007), **(c)** Indo Pacific paleo-temperatures and paleo-salinities based on Mg:Ca and $\delta^{18}\text{O}/\delta^{16}\text{O}$ ratios of foraminiferal tests (Newton et al., 2006), **(d)** percent sedimentary Titanium concentration from the Cariaco Basin taken as an indicator of regional runoff and precipitation (Haug et al., 2001). The gray bar envelopes the shift period, within dating uncertainties.

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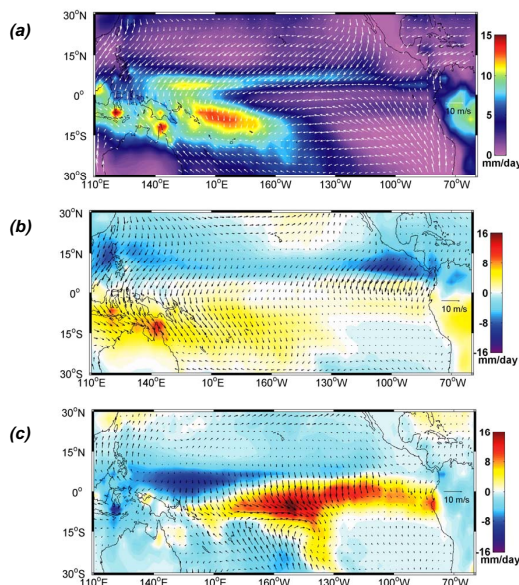


Fig. 5. Austral summer (JFM) versus 1997–1998 El Niño (JFM) precipitation (colors) and wind (arrows) patterns across the Tropical Pacific. Southward displacement of the ITCZ during present day austral summer (leaving dryer conditions in the Cariaco Basin) is coupled with weaker southerly trade winds in the Tropical South Eastern Pacific, as well as with wet conditions both in the Indo Pacific and in the Central Peruvian Andes. **(a)** Map of JFM climatology of wind (direction and velocity) and precipitation; **(b)** Map of JFM anomalies of wind (direction and velocity) and precipitation, relative to the annual cycle; **(c)** Map of anomalies of surface winds (direction and velocity) and precipitation patterns during the 1997–1998 EN (JFM). Winds are from the global monthly Blended Sea Winds available from NCDC (National Climate Data Center) Satellite Data Services. The spatial resolution is 0.25 by 0.25 degrees and extends from July 1987 to October 2007. Precipitation is from global monthly CMAP (CPC Merged Analysis of Precipitation) data from January 1979 to July 2007 (available from NOAA’s Earth System Research Laboratory). The spatial resolution is 2.5 degrees.

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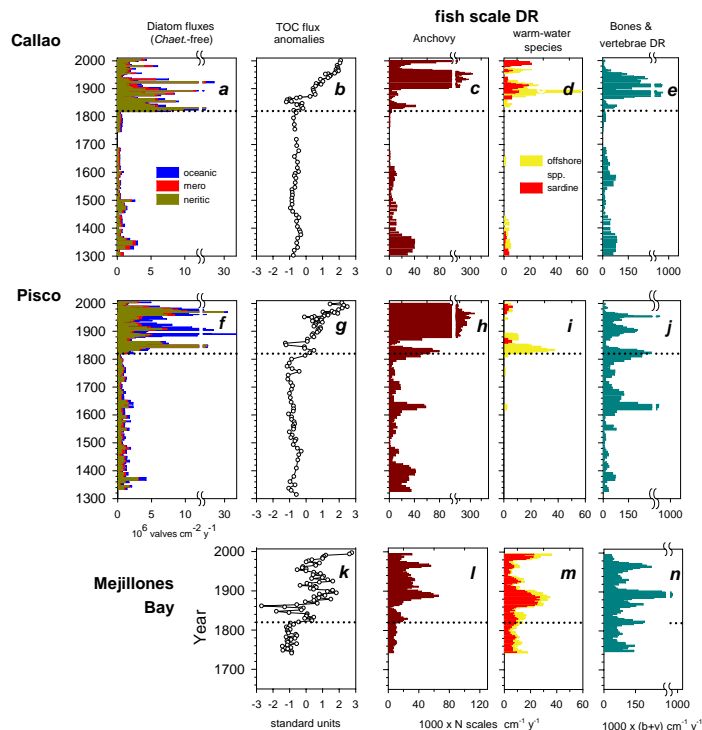


Fig. 6. Pelagic ecosystem proxies off Peru (Callao, (a)–(e); Pisco, (f)–(j) and in Mejillones Bay, Northern Chile (k)–(n). (a), (f) *Chaetoceros*-free diatom accumulation rates (DAR) shown as neritic, meroplanktic and oceanic groupings (10^6 valves $\text{cm}^{-2} \text{y}^{-1}$); (b), (g), (k) TOC flux anomalies, to permit comparisons of the variability between sites (standardized units); (c), (h), (l) 3-term averages of anchovy scale deposition rates ($\text{Nr} \times 1000 \text{ cm}^{-2} \text{y}^{-1}$); (d), (i), (m) 3-term averages of sardine scale deposition rates and offshore pelagic (jack mackerel+mackerel) scale deposition rates ($\text{Nr} \times 1000 \text{ cm}^{-2} \text{y}^{-1}$); (e), (j), (n) 3-term averages of deposition rates of bones and vertebrae ($\text{Nr} \times 1000 \text{ cm}^{-2} \text{y}^{-1}$).

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