XV Congreso Peruano de Geología. Resúmenes Extendidos.
Sociedad Geológica del Perú, Pub. Esp. N° 9 (2010), Cusco p. 8-12

COOLING AND INCREASED PRODUCTIVITY DOWNSTREAM THE MAIN UPWELLING CELL OFF PERU SINCE THE MID-TWENTIETH CENTURY

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Coastal upwelling ecosystems are hotspots of marine biological productivity in the global ocean. Particularly, the upwelling system off the Peruvian coast is unequalled in terms of fish productivity, yielding biomasses one order of magnitude higher than other coastal upwelling ecosystems (Chávez et al., 2008, Bakun & Weeks, 2008). Among the main factors that explain the outstanding productivity off the Peruvian coast, there are its latitudinal position near the Equator that allow a broader spatial scale of upwelling, and also its moderate wind regime (Chávez et al., 2008; Bakun & Weeks, 2008), which represents an optimal environmental window for pelagic fish recruitment (Cury & Roy, 1989). It has been postulated an enhancement of alongshore wind stress and coastal upwelling as a response to global warming, due to increasing thermal gradient between the dry coast and the adjacent ocean (Bakun, 1990). Some studies have suggested that this response is operating already in several regions, or has occurred in the past under global/regional warming periods (Vargas et al., 2007; McGregor et al., 2007). Therefore, there is great interest on what is and/or what would be the productivity response in the upwelling ecosystems in the near future (Bakun & Weeks, 2008; Demarcq et al., 2009).

Off Peru, instrumental opportunity records of wind velocities (ICOADS) indicate a positive trend of the regional alongshore wind stress since about 1940 to the end of the twentieth century (Jahncke et al., 2003), but the validity of this trend is challenged by other wind data sources (Goubanova et al., 2010). As systematic measurements of primary productivity are not available, and natural, low-frequency climatic variations are probably overimposed on the reported instrumental time-series, a longer time scope is needed to reveal the significance of the potential current changes in upwelling strength and productivity.

High-resolution sedimentary paleo-archives are an alternative to put into perspective the recent changes in the wind regime and the productivity response of the upwelling ecosystem. These laminated sediments are preserved in certain spots of the Peruvian coast (Gutiérrez et al., 2006). One of the main tools available to reconstruct past sea surface temperatures (SST) is the alkenone unsaturation index ($U^{K'}_{37}$) (Prahl & Wakeham, 1987). Alkenones are long-chain biomolecules produced by haptophyte microalgae. Even though there are potential biases in the estimation of SSTs due to alkenone production seasonality, advective particle transport, and alkenone preservation issues (Sachs et al., 2000; Conte et al., 2006; Rohtani et al., 2008), $U^{K'}_{37}$ is widely used as a proxy of ocean surface temperatures in sediment records (Goñi et al., 2001, Vargas et al., 2007, McGregor et al., 2007).

Our main goal here is to analyze the variation of near-surface sea temperatures and primary productivity during the past ~150 years, downstream the main upwelling cell of the Peruvian coast, as inferred from sedimentary proxy records and available instrumental information in the twentieth century.

METHODOLOGY

A Soutar-box core was collected from a laminated mud-lens (14º07'S, 76º30'S, 299 m depth), located on the upper continental margin off Pisco, central-southern Peru in May 2004. The Pisco area is located downstream of the San Juan upwelling cell, where the most intense winds along the Peruvian coast occur. Upwelling here remains active year-round but is stronger during winter/spring, as observed from the climatological SST and alongshore winds (Figure 1); in turn, primary productivity is higher during spring/summer, when surface waters are more stratified.

Mass accumulation rates were determined from downcore profiles of ^{241}Am, excess ^{210}Pb and radiocarbon dating (Gutiérrez et al., 2009). For alkenone analyses, lipids were solvent-extracted, separated on column chromatography (Bouloubassi et al. 2009), alkenones were analysed by GC-FID. Also high-resolution determinations of total organic carbon and total nitrogen were done using a Thermo Electron CNS elemental analyzer with corrections for carbonate content, which was estimated from carbonate minerals by Fourier Transformed Infrared Spectrometry (FTIR) (Bertaux et al., 1998).

SST was calculated from the $U^{K'}_{37}$ index (Prahl and Wakeham,1987) using the calibration: SST (°C)=($U^{K'}_{37}$ - 0.039)/0.034 (Prahl et al., 1988). The analytical precision was estimated to be ±0.3°C based on replicate analyses.

A climatology of chlorophyll-a was calculated for a grid around the study area that corresponds to about 1600 nm^2, as based on daily SeaWifs satellite data obtained at a spatial resolution of 10 x 10 km from September 1997 to December 2007. Historical (~1860 AD – 2005) alongshore wind stress and SST were extracted from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS) within 30 miles off Pisco (13 – 16°S), which are due to opportunity records onboard merchant ships. We also used monthly and seasonal time-series of surface wind from ECMWF – ERA 40 reanalysis (1958 – 2001), at approximately 100 x 100 km resolution. We used the Pathfinder High Resolution Sea Surface Temperature data set at 4km resolution (GHRSST-PP) (Vasquez-Cuervo et al., 2010) from 1985 to 2005 in order to estimate the SST summer average distribution off Peru. We also used this product to estimate quarterly time-series and seasonal climatologically maps off Pisco (14 – 15°S), at high resolution (<10km). Finally, monthly time-series of coastal SST measurements between 1950 and 2009 were obtained from IMARPE and the Peruvian Navy Hydrographic Survey (DHN) monitoring stations located in the central-southern coast [12°S, 15°S and 17°S].

RESULTS AND DISCUSSION

Reconstructed $U^{K'}_{37}$-SST ranged from 18.3 to 22.8 °C. A cubic polynomial model fit to the proxy temperature record can explain more than 50% of the variance (Figure 2a), showing a half-centennial cooling overimposed by multidecadal variability. Comparison between the model residuals and the ENSO chronology indicate a positive correspondence between the residuals and several warm ENSO events, but not with others, perhaps due to sediment sample resolution or to decreased overall production during El Niño. Three multidecadal periods can be distinguished in the proxy temperature record: i) from 1870 to 1910 AD, whereby there is a slight cooling trend; ii) from 1910 to 1945 AD, in which there is little temperature change; and iii) after 1950 AD, featured by a rapid cooling (-0.04 ± 0.01 °C y^{-1}).

Comparison of the $U^{K'}_{37}$-SST time series with ICOADS SST indicates a warming bias of the proxy record before 1950 (Figure 2b). In fact, it has been hypothesized that sediment-derived $U^{K'}_{37}$-SST tend to be higher than annual mean SSTs, due to seasonal effects (primary productivity and probably particle flux are higher in spring/summer) or due to microbial aerobic degradation of the more unsaturated alkenones (Conte et al., 2006; Rontani et al., 2008). However, after 1950 the cooling exhibited by the paleorecord is contrasted by warmer temperatures in the ICOADS record. This difference can be explained by the pronounced cross-shore SST gradient near the coast, and by the occurrence of cold, strong wind-driven episodes that are usually followed by navigation bans in the area, both leading to an under-representation of cold coastal temperatures in the ICOADS database.

On the other hand, the cooling trend is consistent with instrumental inshore SST time-series from central and southern Peru which also exhibit significant cooling since 1950 and particularly since ca. 1976. The cooling is mostly explained by spring temperatures (not shown), coinciding as well with increased alongshore wind intensity in this season, as evidenced by ECMWF-ERA 40 records (Figure 2c). A positive and significant trend of alkenone flux and TOC flux (not shown) indicates increased primary productivity for the same multidecadal period. Since spring is the annual period whereby primary productivity rises (Figure 1), the sediment alkenone record reflects the variability of the upwelling season. Considering that alkenones are produced in the surface mixed layer (Conte et al., 2006), then the $U^{K'}_{37}$-SST most likely reflects shoaling of the thermocline due to enhanced upwelling.

Finally, consistency between Southern Peru and Northern Chile coastal cooling trends (Garreaud & Falvey, 2008) supports a common forcing process, e.g. an intensification of the South Pacific High Pressure Cell, a possible regional scenario of global warming (Garreaud & Falvey, op.cit.). Recovery and analyses of coastal wind time-series at Pisco will clarify whether Bakun's (Bakun, 1990) mechanism is also involved in the observed trends.

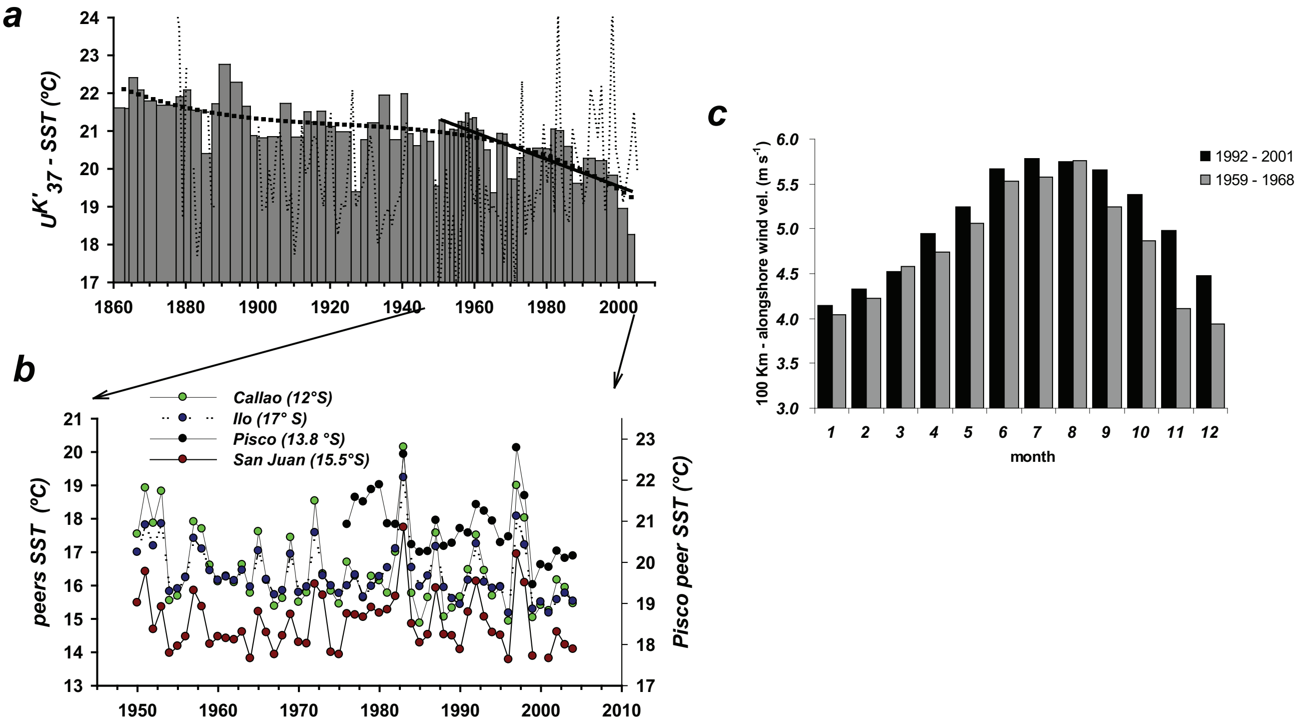

Figure 1. a) Location of boxcore B0406 (star), with bathymetric contour lines each 50 m down to 1500 m water depth; the dashed red box corresponds to the coastal area from which climatologies of Chl-a and SST were calculated; b) Average SST distribution off Peru (GHRSST-PP) during austral summer. The small black circle inside the square corresponds to the boxcore. White triangles indicate IMARPE peers along the central and southern coast; c) Climatology of Chl-a based on SeaWifs color data (1997 – 2006) and of the alongshore wind velocities (ECMWF – ERA40) inside the coastal core area depicted in 1a. The red line joins the monthly SST-means for the coastal area, based on a least squares fit between Pisco peer SST and GHRSST.

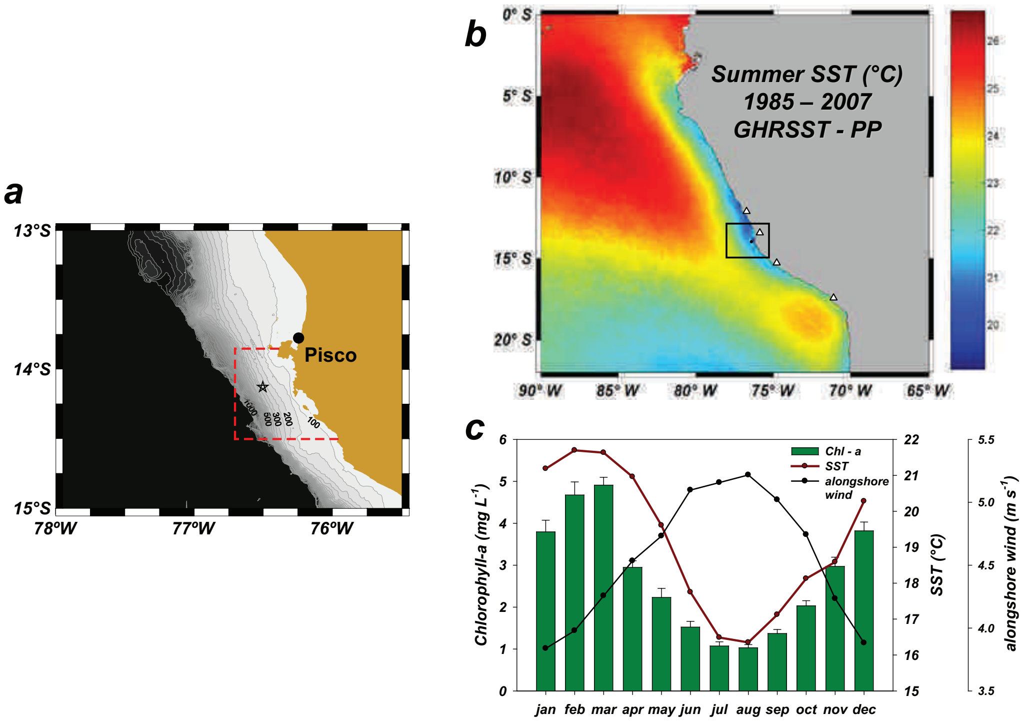

Figure 2. a) Time-series of boxcore B0406 UK'37-SST off Pisco. The dotted line is the cubic order polynomial fit to the entire series (R2=0.52). The solid line depicts the negative trend since 1950 AD (-0.04 ± 0.01 °C y-1, n = 30, p<0.01, R2 = 0.51); summer ICOADS SSTs are overimposed (dotted lines); b) Time series of annual means of the SST measured in the peers of central to southern Peru locations. Trends are negative (-0.02 to -0.04 °C y^{-1}; p<0.05) since 1950 for Callao and Ilo, and since 1976, for Pisco (no data before) and San Juan (p<0.1); c) Monthly alongshore wind velocities in 1959 -1968 and in 1992 – 2001 (ECMWF-ERA 40), 100 km offshore in the study region (13 – 16S°).

REFERENCES

Bakun A. 1990. Global climate change and intensification of coastal ocean upwelling. Science, 247, 198-201

Bakun A. & SJ. Weeks, 2008. The marine ecosystem off Peru: what are the secrets of its fishery productivity and what might its future hold?. Progress in Oceanography 79, 300-307

Bertaux, J., Frohlich, F., Ildefonse, Ph., 1998. Multicomponent analysis of FTIR spectra: quantification of amorphous silica and crystallized mineral phases in synthetic and natural sediments. Journal of Sedimentary Research 68 (3), 440–447.

Bouloubassi I., Nabais E., Pancost R.D., Lorre A., Taphanel M.-H. (2009) First biomarker evidence for methane oxidation at cold seeps in the South East Atlantic (REGAB pockmark). Deep-Sea Research II, 56, 2239-2247

Chavez F, Bertrand A, Guevara-Carrasco R, Soler P, Csirke J (2008) The northern Humboldt Current System: Brief history, present status and a view towards the future. Progress in Oceanography, 79, 95–105.

Conte, M.H., Sicre, M.-A., Rühlemann, C., Weber, J.C., Schulte, S., Schultz-Bull, D., Blanz, T., 2006. Global temperature calibration of the alkenone unsaturation index ($U^{K'}_{37}$) in surface waters and comparison with surface sediments. Geochemistry, Geophysics, Geosystems, 7, doi: 10.1029/2005GC001054.

Cury, P. & C. Roy. 1989. Optimal environmental window and pelagic fish recruitment success in upwelling areas. Can. J. Fish. Aquat. Sci., 46, 670-680.

Demarcq H. 2009. Trends in primary production, sea surface temperature and wind in upwelling systems (1998–2007). Progress in Oceanography doi:10.1016/j.pocean.2009.07.022

Garreaud R.D. & M. Falvey. 2008. The coastal winds off western subtropical South America in future climate scenarios. International Journal of Climatology . DOI: 10.1002/joc.1716.

Goñi, M., D. Hartz, R. C. Thunell & E. Tappa. 2001. Oceanographic considerations for the application of the alkenone-based paleotemperature $U^{K'}_{37}$ index in the Gulf of California. Geochimica et Cosmochimica Acta, 65(4), 545–557

Goubanova K., V. Echevin, B. Dewitte, F. Codron, K. Takahashi, P. Terray & M. Vrac. 2010. Statistical downscaling of sea-surface wind over the Peru-Chile upwelling region: diagnosing the impact of climate change from the IPSL-CM4 model. Climate Dynamics, DOI 10.1007/s00382-010-0824-0.

Gutiérrez, D; Sifeddine, A.; Reyss, J.L.; Vargas, G.; Velazco, F.; Salvatteci, R.; Ferreira, V.; Ortlieb, L.; Field, D.; Baumgartner, T.; Boussafir, M.; Boucher, H.; Valdés, J.; Marinovic, L.; Soler, P.; and P. Tapia, P. 2006. Anoxic sediments off Central Peru record interannual to multidecadal changes of climate and upwelling ecosystem during the last two centuries. Advances in Geosciences, 6, 119–125.

Gutiérrez, D., Sifeddine, A., Field, D., Ortlieb, L., Vargas, G., Chávez, F., Velazco, F., Ferreira, V., Tapia, P., Salvatteci, R., Boucher, H., Morales, M., Valdés, J., Reyss, J.-L., Campusano, A., Boussafir, M., Mandeng-Yogo, M., García, M. & Baumgartner, T. 2009. Rapid reorganization in ocean biogeochemistry off Peru towards the end of the Little Ice Age. Biogeosciences, 6, 835 - 848.

Jahncke J., D. M. Checkley Jr. & G. L. Hunt Jr .2004. Trends in carbon flux to seabirds in the Peruvian upwelling system: effects of wind and fisheries on population regulation. Fisheries Oceanography 13 (3), 208-223

McGregor, H. V., Dima, M., Fischer, H. W., and Mulitza, S. 2007. Rapid 20thcentury increase in coastal upwelling off Northwest Africa, Science, 315, 637–639

Prahl, F.G., and Wakeham, S.G., 1987, Calibration of unsaturation patterns in long-chain ketone compositions for paleotemperature assessment: Nature, 330, 367–369.

Prahl, F.G., Muehlhausen, L.A., and Zahnle, D.L., 1988, Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions: Geochimica et Cosmochimica Acta, 52, 2303–2310.

Rontani, J-F.; Harji, R.; Guasco, S.; Prahl, F.G.; Volkman, J.K.; Bhosle, N.B.; Bonin, P. 2008. Degradation of alkenones by aerobic heterotrophic bacteria: Selective or not ? Organic Geochemistry, 39(1), 34–51.

Sachs, J.P., R.R. Schneider, T.I. Eglinton, K.H. Freeman, G. Ganssen, J.F. McManus, D.W. Oppo. 2000. Alkenones as paleoceanographic proxies.Geochemistry, Geophysics, Geosystems, 1: 2000GC000059.

Vargas, G., Pantoja, S., Rutllant, J.A., Lange, C.B., Ortlieb, L., 2007. Enhancement of coastal upwelling and interdecadal ENSO-like variability in the Peru–Chile current since late 19th century. Geophysical Research Letters 34, L13607. doi:10.1029/2006GL028812.

Vazquez-Cuervo J, EM Armstrong, KS Casey, R. Evans,and K. Kilpatrick, 2010: Comparison between the Pathfinder Versions 5.0 and 4.1 Sea Surface Temperature Datasets: A Case Study for High Resolution, J. of Climate, 23,1047-1059.