Rapid 20th-century increase in coastal upwelling off northwest Africa revealed by high-resolution marine sediment cores

Helen V. McGregor[1,2] and Stefan Mulitza[3,4]

[1]Institute for Environmental Research, ANSTO, Lucas Heights, Australia; mcgregor@uni-bremen.de; [2]School of Earth and Environmental Sciences, University of Wollongong, Australia; [3]DFG Research Center Ocean Margins, University of Bremen, Germany; [4]MARUM Center for Marine Environmental Sciences, University of Bremen, Germany

The climate of the last two millennia has emerged as a crucial baseline period for assessing the present global warming trend. Reconstructions of climate during this period require high resolution (decadal or better) proxies such as ice cores, corals, tree rings and varved lake sediments. Marine sediment-core records, essential for providing information on past oceanic behavior, are generally not considered to be able to provide comparable detail.

Recent programs, however, such as the EU Patterns of Climate Variability in the North Atlantic (PACLIVA) Project (Jansen, 2007), have focused on producing climate records from marine sediment cores of decadal or better resolution. Here, we present two marine sediment core records of alkenone-derived sea surface temperature (SST) that span the last 2500 years, overlap temporally with instrumental data sets for most of the 20th century, and have an exceptional sampling resolution of between 2 and 25 years per sample (McGregor et al., 2007), comparable with other high-resolution proxies. The two cores (gravity core GeoB6008-1 and multi-core GeoB6008-2) were recovered from Cape Ghir off the coast of Morocco (30°50.7'N, 10°05.9'W; 355 m water depth), a location characterized by coastal upwelling, typical for the northwest African margin. The sediment core records allow an unprecedented view of 20th century and late-Holocene coastal upwelling history.

Coastal upwelling, such as that off northwest Africa, occurs along the eastern margins of major ocean basins and develops when predominantly alongshore winds force offshore Ekman transport of surface waters, leading to the rise (or upwelling) of cooler, nutrient-rich water (Tomczak and Godfrey, 2005). Coastal upwelling is of large economic importance and accounts for ~20% of the global fish catch, yet constitutes <1% of the world's oceans by area (Pauly and Christensen, 1995). Coastal upwelling is also of major importance to marine productivity and strongly influences atmosphere-ocean CO_2 exchange, carbon recycling and export to the open ocean. The understanding of potential global warming–related changes in the intensity of coastal upwelling has become increasingly important because of the likelihood of dramatic ecosystem and socioeconomic impacts (IPCC, 2001; Bakun and Weeks, 2004; Goes et al., 2005; Harley et al., 2006). Although there is some evidence that the vigor of coastal upwelling, at least at the decadal scale, has progressively increased as a result of anthropogenic greenhouse gas emissions (Bakun, 1990; Anderson et al., 2002; Goes et al., 2005), most evidence is based only on short instrumental records. Longer temporal records, such as those provided by marine sediment cores, are needed to assess whether upwelling truly has intensified. Thus, using the well-established alkenone unsaturation index ($U_{37}^{K'}$) as a SST proxy, we reconstructed SST and upwelling at Cape Ghir (McGregor et al., 2007).

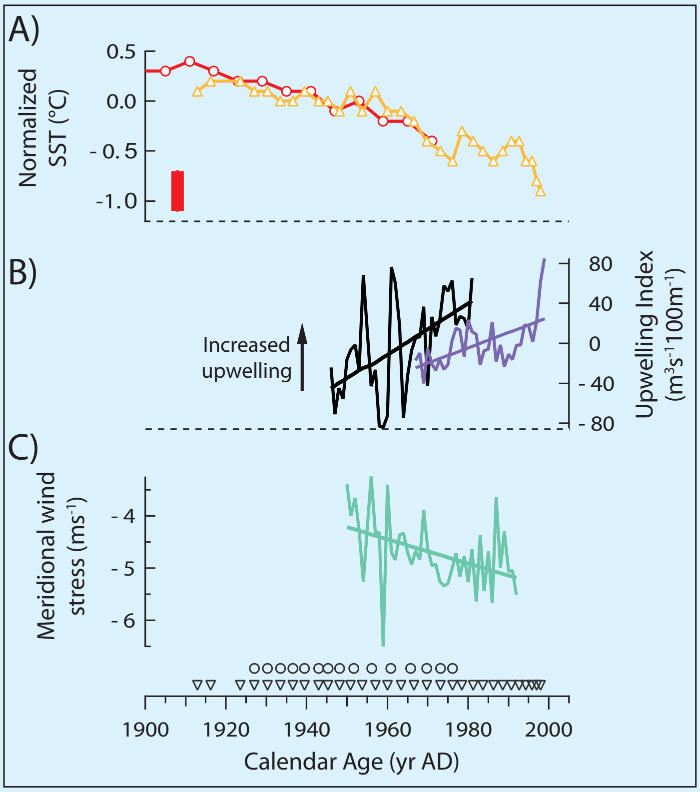

*Figure 1: **A**) Normalized alkenone SST records from cores GeoB6008-1 (**red**) and GeoB6008-2 (**orange**) for the 20th-century (vertical red bar indicates error on estimates) (McGregor et al., 2007); as compared with **B**) the Bakun upwelling index for NW Africa (**black** line) (Bakun, 1990), an upwelling index calculated for Cape Ghir (**purple** line) (www.pfel.noaa.gov, Schwing et al., 1996), and **C**) meridional wind speed data for 31°N, 11°W from 1950–1992 AD (Comprehensive Ocean-Atmosphere Data Set Release 1; Slutz et al., 1985). Alkenone SST records are normalized to the mean for the overlapping period between them (1912-1971 AD) to allow for a ~0.5°C offset. ^{210}Pb dates for GeoB6008-1 (**black circles**) and GeoB6008-2 (**black triangles**) are shown at the base of the graph. Both upwelling indices are presented at annual resolution and as the deviation from the mean of each record. More negative meridional wind speed values indicate more southerly (equatorward), upwelling-favorable winds.Figure from McGregor et al., 2007.*

Alkenone SST records of coastal upwelling

The two alkenone SST reconstructions from Cape Ghir show a steady cooling trend of ~1.2°C for the 20th century, indicating an increase in upwelling intensity (Fig. 1). In addition, the patterns of variability during the ~60-year period where the two cores overlap (1912-1971 AD) are notably similar, which attests to the consistency of the age model (Fig. 1, Fig. 2A) in this part of the core and of the SST signal in each record. The trend to cooler SSTs and increased upwelling through the 20th century is consistent with pronounced upwelling intensification for the latter part of the 20th century, inferred from two calculated upwelling indices for the Canary Current region (Bakun, 1990; Schwing et al., 1996), and with increased upwelling-favorable meridional wind-speed observations for Cape Ghir (Slutz et al., 1985) (Fig. 1).

When looking at the SST anomaly reconstruction for the past 2500 years (core GeoB6008-1; Fig. 2B), the final 100 years of the record clearly show the strongest decrease in SST (corresponding to an increase in upwelling), which is larger and more rapid than any other change in the record. The alkenone SST record of this core also shows pronounced millennial-scale variability during the past 2500 years (Fig. 2B). The reconstructed millennial mode for GeoB6008-1, identified through singular spectrum analysis, highlights this variability and shows local SST extremes that correspond to inferred periods of warming and cooling in the northern hemisphere, the most recent of which being the Medieval Warm Period (MWP) and Little Ice Age (LIA) (Osborn and Briffa, 2006) (Fig. 2B).

20th-century intensification of coastal upwelling

SST records for the 20th century suggests an influence of global warming on the temperature evolution and upwelling intensity at site GeoB6008. The rapid 20th-century cooling at Cape Ghir also coincides with the rise in atmospheric CO_2 (Fig. 2C). This reflects the influence of CO_2 on the land-sea thermal contrast in NW Africa and, in turn, on the alongshore winds driving the upwelling. According to the mechanism proposed by Bakun (1990), increased atmospheric CO_2 concentration could lead to warmer surface air temperatures (SATs) over land relative to those over the ocean, particularly at night time when radiative cooling is suppressed by the blocking of outgoing longwave radiation by CO_2. The increased SAT deepens the thermal low-pressure cell over land, while a higher-pressure center develops over the slower-warming ocean waters. The winds blow clockwise around the high and anticlockwise around the continental low. The coast represents the boundary separating the two centers. Therefore, along the coast, the wind is oriented alongshore and southward (equatorward), which thus drives the upwelling and negative SST anomalies.

Coastal upwelling during the past two millennia

The Cape Ghir SST anomaly record—which includes the rapid temperature changes of the past century and the millennial-scale variability—co-varies with Northern Hemisphere Temperature Anomaly (NHTA) reconstructions (Jones et al., 1999; Mann and Jones, 2003; Moberg et al., 2005), though with the opposite sign; a reverse "hockey stick" pattern (Fig. 2B, 2C). The antiphased behavior is an unexpected result, given the large regional variability captured from different locations by the proxy records used in the NHTA reconstructions as compared to the variability of alkenone SST record, which is a point-recorded time series. The link, however, between NHTA reconstructions and upwelling could come through the land-sea thermal contrast proposed above. The millennial-scale, hemispheric temperature variations could manifest as a greater change in land SAT as compared to SATs over the ocean, which may affect land-sea pressure gradients, alongshore winds, and therefore upwelling.

Conclusions

The sensitivity of upwelling to increases in CO_2 during the 20th century, in addition to our paleo-results of a distinct upwelling response to hemispheric-scale warming and cooling, strongly implies that upwelling may continue to intensify with future increased levels of atmospheric CO_2 and global warming. Upwelling regions, including Cape Ghir, show extremely high levels of biological activity, yet the ecosystem response to upwelling in these regions is dependant on a complex balance of temperature, ocean and circulation, and fishing pressure (Harley et al., 2006). Given the importance of these marine ecosystems, our dependence on these highly valuable

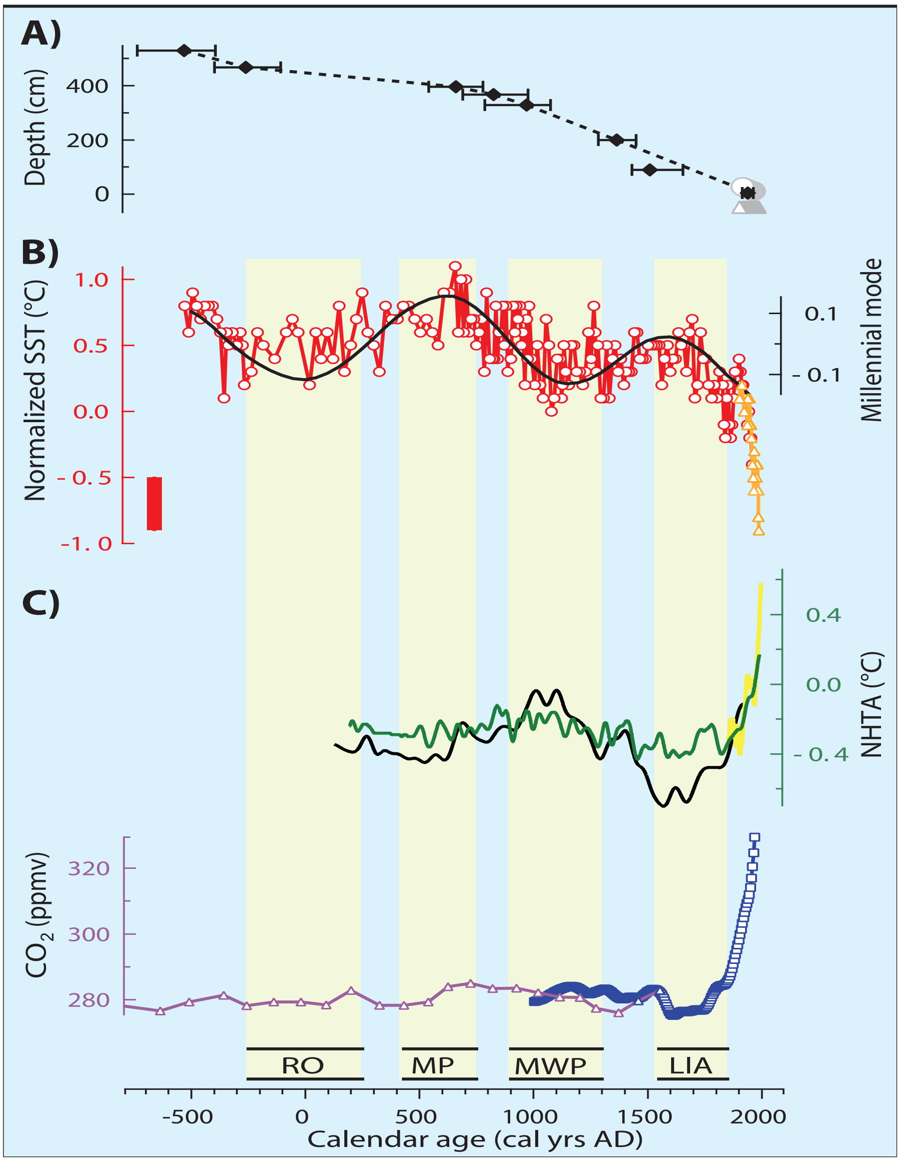

*Figure 2: Age/depth relationship, and normalized alkenone SST for the full length of cores GeoB6008-1 and GeoB6008-2, compared with Northern Hemisphere Temperature Anomalies (NHTA) reconstructions and ice-core CO_2 records. Periods highlighted at the base of the figure represent the Little Ice Age (LIA), Medieval Warm Period (MWP), Migration Pessimism (MP), and the Roman Optimum (RO); **A**) Age model for GeoB6008-1 based on the calibrated AMS ^{14}C ages (**diamonds**; ages are reported as calibrated radiocarbon years AD and error bars represent the 2σ-calibrated age range), ^{210}Pb dates (**gray circles**), and the age model for GeoB6008-2 based on ^{210}Pb dates only (**gray triangles**). ^{210}Pb dates for both cores are shown in more detail in Figure 1. **B**) Normalized alkenone SST from GeoB6008-1 (**red circles**) and GeoB6008-2 (**orange triangles**), and the reconstructed millennial mode from the gravity core GeoB6008-1 alkenone SST record (**solid black line**). Vertical red bar indicates the error on alkenone SST estimates; **C**) Three NHTA reconstructions: the instrumental record (10-point smoothing; **yellow line**) (Jones et al., 1999), ~2000-yr reconstruction based predominantly on terrestrial proxies (**green line**) (Mann and Jones, 2003), and ~2000-yr reconstruction with the use of high- and low-resolution proxy data (**black line**) (Moberg et al., 2005); and from Law Dome (**blue squares**) (Etheridge et al., 1996) and Taylor Dome (**purple triangles**) (Indermühle et al., 1999) atmospheric CO_2 records. Figure from McGregor et al., 2007.*

fisheries, and the potential role of upwelling in the drawdown of atmospheric CO_2, further understanding of climate feedbacks in upwelling regions and the ecological and socioeconomic repercussions is imperative.

This study also demonstrates that marine sediment cores do provide levels of information comparable to more traditional high-resolution proxies. Future studies focused on decadal-resolution marine sediment cores have the very real potential to contribute invaluable data on ocean and climate processes.

Note

The data are archived at the Publishing Network for Geoscientific and Environmental Data public digital library (www.pangaea.de/).

References

Anderson, D.M., Overpeck, J.T. and Gupta, A.K., 2002: Increase in the Asian Southwest Monsoon during the past four centuries, *Science*, **297**: 596-599.

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

Goes, J.I., Thoppil, P.G., do R Gomes, H. and Fasullo, J.T., 2005: Warming of the Eurasian Landmass is making the Arabian Sea more productive, *Science*, **308**: 545-547.

Harley, C.D., Hughes, A.R., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L. and Williams, S.L., 2006: The impacts of climate change in coastal marine systems, *Ecology Letters*, **9**: 228-241, doi:10.1111/j.1461-0248.2005.00871.x.

McGregor, H.V., Dima, M., Fischer, H.W. and Mulitza, S., 2007: Rapid 20th-Century increase in coastal upwelling off northwest Africa, *Science*, **315**: 637-639, doi: 10.1126/science.1134839.

For full references please consult:
www.pages-igbp.org/products/newsletter/ref2007_2.html

UK IGBP - Paleo and modern perspectives on global change: A personal summary

London, UK, 27 June 2007

Sandy Harrison

School of Geographical Sciences, Bristol University, UK; Sandy.Harrison@bristol.ac.uk

The need to understand the mechanisms and processes of climate and environmental change is a fundamental scientific challenge with profound practical implications. The components of the Earth System respond to perturbations on very different timescales: the atmosphere reacts in hours to years, natural ecosystems over years to centuries, the ocean over centuries to millenia, and the cryosphere over millennia and longer. Thus, it is important to examine climate and environmental changes in the perspective offered by the geological record of the past million years or so, as well as in the recent or historical period, in order to assess (and potentially improve) our ability to quantify anthropogenic effects.

Questions that arise from the paleorecord are modeling foci in several of the IGBP core projects. Explaining the tightly controlled upper and lower limits on atmospheric trace gas concentrations through glacial-interglacial cycles as shown by the ice core record is a focus in IGAC, iLEAPS and SOLAS. Understanding how ecosystem structure and function are affected by changes in atmospheric composition, biogeochemical cycles and climate is a focus in GLP and IMBER. However, paleodata gathering and analysis activities (necessary to compare with modeling results) fall within the domain of PAGES. This structure, combined with the generally limited communication between modelers and observationalists and between scientists working on modern and paleo timescales, may limit progress towards an integrated understanding of global change.

It was with these concerns in mind that the UK IGBP Committee organized a one-day meeting at the Royal Society in June this year to explore commonalities between modern and paleo-perspectives on global change. Speakers from each of the core projects, and members of the PAGES community, were invited to address the common themes of: biodiversity, ecosystem structure and functioning; the regulation of ocean productivity; ocean fertilization and the biological pump; fluxes to the coastal ocean—changing land-surface conditions and human interactions; and natural regulation of atmospheric oxidizing capacity.

One theme that emerged is the scarcity of high-quality data on key processes. In the ocean, for example, there are large uncertainties in estimates of primary production and vanishingly few measurements of respiration outside the Atlantic. Estimates of iron solubility in the ocean range over several orders of magnitude; different measures of export production sometimes yield opposite signals of change between glacial and interglacial states. On land, assessments of contemporary rates of biodiversity loss are heavily biased by sampling of charismatic species, while natural migration rates are poorly constrained. There are few experiments quantifying CO_2 fertilization outside the temperate forest zone; there is very limited understanding of the differential resilience of plants, insects and mammals to environmental change. However, the lack of data to address key questions may sometimes be more apparent than real: a major limitation is the availability of data in appropriate formats and centralized facilities. Networking and synthesis activities sponsored by PAGES and the Paleoclimate Modeling Intercomparison Project (PMIP) have shown that there are many hundreds more individual paleo records than are generally known to the paleo-modeling community. Similarly, GLOPNET (Wright et al., 2004) and the IGBP Fast-Track Initiative on Plant Functional Classification are demonstrating that there is an untapped wealth of measurements that could be used to analyze plant and ecosystem processes when brought together in a global database.

A second emerging theme was that multiple data sources can offer valuable complementary perspectives but that this synergy is often not exploited. The existence of multiple paleo proxies for a given process or variable has often been interpreted as increased "uncertainty" in paleoclimate reconstructions, largely because of the focus on statistical rather than process-based interpretation of the records. Paleo-observations can challenge our understanding of modern processes in surprising ways: the record of past changes in vegetation patterns, for example, indicates that migration rates can be fast, and that plant species have been extremely resilient in the face of large and rapid climate changes such as occurred in the North Atlantic region during the deglaciation. Sedimentary records from estuarine environments indicate much