International symposium on Eastern Boundary Upwelling Ecosystems

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From the 2nd to 6th June 2008, an international symposium on Eastern Boundary Upwelling Ecosystems (EBUEs) was held in Las Palmas de Gran Canaria, Spain. EBUEs are some of the most productive marine ecosystems of the world; the four main EBUEs, the Canary, California, Humboldt and Benguela Currents provide over a fifth of the marine fish global catch, significantly contributing to securing livelihood strategies and food in many countries. EBUEs are narrow strips of the ocean (10 to 300 km wide but extending latitudinally in excess of 1,000 km), located on the western margin of the continents (eastern parts of the oceans), on each side of the equator. In these regions, intense trade winds combined with the earth’s rotation generate coastal upwelling, bringing cold, nutrient-rich waters from the deep ocean to the surface. The arrival of this water to the sunlight-exposed surface layer fuels production and supports a complex and highly dynamic food web. It also contributes very significantly to gas exchanges between the ocean and the atmosphere, particularly CO₂.

The dependency of EBUEs on environmental drivers makes them particularly relevant to anthropogenic climate change research. How climate change will affect EBUEs is crucial, not just in terms of the biochemical balance of the planet, but also in terms of the social and economic consequences of potential changes in global fish production. This symposium was an international effort to present the state-of-the-art in our understanding of EBUEs, with particular emphasis on both integrating our knowledge from climate processes all the way to fisheries dynamics, and comparing the dynamics of EBUEs across the world. The ultimate goal was to identify climate change impacts on EBUEs and pave the way for adequate adaptations to these.

Geographical coverage and challenges. The symposium covered the four major eastern boundary upwelling ecosystems: the Canary and Benguela Current ecosystems in the Atlantic Ocean and the California and Humboldt Current ecosystems in the Pacific Ocean (Fig. 1). The countries bordering these ecosystems are Spain (from its NW corner to the Canary Islands), Portugal, Morocco, Mauritania, Senegal and Gambia for the Canary ecosystem; Angola, Namibia and South Africa for the Benguela ecosystem; USA and Mexico for the California ecosystem and finally Peru and Chile for the Humboldt ecosystem. The coastal zones of these countries host the most productive marine areas but this productivity is highly variable from year to year and from decade to decade due to strong forcing factors like El Niño events, decadal climate oscillations and fisheries exploitation. Collaboration and cooperation between countries and ecosystems is needed to face new challenges represented by climate change, generalised overexploitation of marine resources, economic globalisation and food security.

Scientific focus. In the past, a number of international symposia and conferences have focused on one or more eastern boundary upwelling ecosystems, but none of these explicitly covered the four main EBUEs and considered all aspects of their dynamics, structure and functioning. These aspects include climate and ocean dynamics, climate change, physics of the ocean and atmosphere, biogeochemistry, ecosystem production, ecology, food web structure and dynamics, trophic interactions, fisheries assessment and management. Furthermore, the comparative emphasis of this symposium allowed a better understanding of the key processes responsible for the productivity and dynamics of the four main EBUEs.

Partnership. The symposium was supported and organised by the European network of excellence EUR-OCEANS, the French Institute of Research for Development (IRD), the Global Ocean Ecosystem Dynamics (GLOBEC) programme and the University of Las Palmas, Gran Canaria (ULPGC). Additional sponsorship was provided by IMBER (Integrated Marine Biogeochemistry and Ecosystem Research project), SOLAS (Surface Ocean Lower Atmosphere Study), BENEFIT (Benguela, Environment, Fisheries, Interactions, Training programme), GTZ (German Society for Technical Cooperation), SCOR (Scientific Committee on Oceanic Research) and various Spanish national and regional authorities. These grants allowed us to sponsor 26 scientists and students, mostly from developing countries, and to partially support 20 keynote speakers. In total the programme included 144 oral presentations and 170 posters were on display.

Audience. More than 350 people, coming from almost 40 countries from the five continents, attended the event.
**Research highlights**

Numerous presentations demonstrated the benefit of using regional physical models with high spatial resolution, embedded in basin scale models. This was particularly the case to show the specificity of EBUEs and their export of nutrients, organic matter and plankton toward offshore regions. The role of mesoscale features, such as eddies, filaments and fronts, was underlined by the use of such models, and the ability of these models to reproduce mesoscale features was demonstrated through satellite tracking of drift buoys. Results from a new generation of autonomous observing devices (gliders), helped characterise the whole water column, both physically and chemically, providing new information on the functioning of EBUEs and their links with the open ocean. Concurrent biological information also contributed to the validation of physical models, through model coupling, allowing a realistic reproduction of the fate of fish early stages after long distance transport. This is, for instance, the case of the transport of larvae of several pelagic species from the North African coast to the Canary Islands, where they support fish stocks that are exploited away from their spawning grounds.

The increase in the accuracy of remotely sensed sea surface temperature since the mid-1980s allowed comparisons of warming trends between EBUEs. The warming is not uniform between the four major EBUEs: the Canary Current ecosystem warmed up by around 1.5°C over the last 22 years, while the other three main EBUEs warmed by less than 0.5°C (Fig. 2). The cause(s) of this warming and its link with trends in wind intensity and direction (which vary according to the data sources) are still debated. The consequences of this warming are diverse and variable according to the ecosystem. A recent finding is that the abrupt inshore-offshore gradient of the wind, which generates a wind-stress curl, plays a more important role than the coastal wind on the plankton and sardine production off central California (Fig. 3).

Although satellite estimates of phytoplankton abundance in the upper part of the ocean are available only from 1997, it appears that there is a decrease in the mean productivity of the global ocean during the last decade. Nonetheless, EBUEs display an opposite trend, in particular in their coastal areas (Fig. 4), which is favourable for pelagic fish species (anchovy and/or sardine). However, off the coasts of Mauritania and Senegal we observe a falling trend in productivity. Further north, in NW Spain, where the production of mussels (shellfish farming) in the deep bays (rias) is very important (15% of the world production), the decrease in intensity of winds and/or changes in direction have reduced the water renewal rate. This triggers an increase in the frequency of red tides, resulting in bans on mussel sales, with heavy economic repercussions.

![Figure 2. Comparison of the spatial SST trends observed between 1985 and 2006 a) from the enhanced ICOADS data set and b) the AVHRR pathfinder v5 SST product.](image1)

![Figure 3a. Low rates of nutrient supply provided by offshore curl-driven upwelling lead to the production of small size classes of plankton which favour sardine, whereas high rates supply inshore favour anchovy.](image2)

![Figure 3b. Sardine production in central California is correlated strongly with curl-driven upwelling, not coastal upwelling.](image3)
The operational importance of biogeochemical cycling in upwelling areas with regards to global ocean production was underlined. Many of the critical biogeochemical conditions are hyper-sensitive to change, so that a small change e.g. in oxygen depletion (resulting from either natural or anthropogenic causes) can lead to major changes in biogeochemical pathways and ultimately to orders-of-magnitude changes in the fisheries yield of these systems. Besides, the role of upwelling ecosystems in the carbon and nitrogen cycle is essential.

From a biological point of view, EBUEs represent carbon sinks. This is due to the high CO$_2$ fixation by phytoplankton, which exceeds community respiration in the long term. Nevertheless, in spite of the high productivity, which may be up to two orders of magnitude higher than in other coastal or open ocean regions, EBUEs frequently behave as sources of CO$_2$, since cold upwelled water, with high gas solubility, releases CO$_2$ when warming at the surface. There is a concern that production increase in certain coastal zones (such as California) may trigger further ocean acidification.

The production of nitrogen dioxide and methane (another greenhouse gas) has been recently considered significant in EBUEs. Nano- and pico-plankton play an important role in the formation of these gases. For instance, bacteria can contribute up to 30% of the carbon dioxide and 50% of the carbon monoxide gas emissions. However, other sources of CO$_2$ emissions remain to be discovered in order to explain the strong concentrations observed in these last years worldwide.

The zooplankton also strongly reacts to these climatic fluctuations (especially in higher latitudes), although differently according to ecosystems and without showing any global synchrony. The trend component in zooplankton biomass is positive in the Benguela, but negative in the Humboldt and California Current systems. Furthermore, there is evidence of strong poleward displacement of zoogeographic boundaries in time intervals when temperature and stratification anomalies are positive. Zooplankton faunistic assemblages largely depend upon the source of the upwelled waters, which affect their average lipid

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Figure 4. Spatial trends of the chlorophyll biomass observed between 1998 and 2007 from SeaWiFS data for the four EBUS: a) California Current, b) Canaries, c) Humboldt and d) Benguela. The 400m isobath is shown in red. Figure courtesy of H. Demarcq, IRD, France.
composition, which in turn influences fish growth. Recent hydro-acoustic developments have enabled us to separate echoes from fish and zooplankton using standard ecosounder systems (two frequencies only), which should allow a better understanding of the mesoscale spatio-temporal dynamics of the trophic interactions between fish and plankton.

The warming of the oceans is leading to increases in stratification. This has important consequences in upwelling regions because the oxygen content decreases with increasing biological production, promoting suboxic or anoxic environments (Fig. 5). This affects not only the vertical distribution of marine organisms, but also the functioning and structure of the whole food web. In Namibia, for example, the decrease of trade winds, combined with overexploitation, has brought deep changes, including decreasing dissolved oxygen concentrations at depth and increasing methane and hydrogen sulphide emissions. Sardines have practically disappeared from this ecosystem and it is argued that the new conditions favour gobies and jellyfish.

Long-term global warming often aggravates climatic variations that apply to shorter time scales (decades, years or months), likely to cause, for example, a decrease in abundance of African penguins, or slower individual growth, as in the case of the sea lions. In several upwelling ecosystems the species available habitat has been restrained to surface layers due to the growth and ascent of the oxygen minimum zone. This is particularly true in the case off Namibia, Peru and Chile. In extreme cases, the lack of oxygen has forced hundreds of tons of spiny lobsters to come out of the water off South Africa, where they die from dehydration (Photograph 1). This is not a new phenomenon but its frequency seems to have become more accentuated recently.

Biological processes in nearshore marine and estuarine ecosystems can be deeply modified by variation in upwelling processes that occur over a wide range of temporal and spatial scales. Unlike in open waters, the biophysical interaction in the coastal environment has a strong spatially-explicit component due to the persistent topographic features of the coastline. Consequently, research in these areas presented at the symposium focused on the spatial variation in upwelling intensity, on ways to understand and quantify this variation in the physical environment along the coast, and on the consequences for biological systems. Three main pathways of physical-biological coupling were explored in the different presentations: a) spatio-temporal variation in upwelling intensity and nutrient delivery to shore, including its consequences for the dynamics of harmful algal blooms and benthic macroalgae, b) upwelling-driven variation in the supply of organic matter for benthic filter feeders and grazers, and c) the effects of upwelling on larval transport and patterns of recruitment along the shore.
Large changes in the foraging behaviour of certain species are caused by climate change associated with anthropological effects. For example it was observed that in South Africa pelicans attack other bird species' chicks, such as Cape gannets (Photograph 2). This behaviour has recently intensified due to an artificially increased pelican population. This population expansion may be caused by the availability of agricultural offal to the pelicans, which otherwise were dependent on limited natural sources of food. In a similar way, cannibalism tends to increase in certain species where grown-up fishes (hake, sardine and anchovy) feed on the eggs and juveniles of their own. Finally, although adult sea birds feeding off fishing boats discards survive without any trouble, this food is not appropriate or not of good enough quality for their chicks, causing strong mortality amongst the later.

Another important phenomena, already observed in terrestrial ecosystems, are phenological changes. The changes in the temperature seasonal cycle can provoke a delay of a month or two in the appearance of zooplankton, as observed in California. In other ecosystems, such as the southern Benguela, predators are confronted with unseasonal migrations of their prey. For the last ten years, a progressive shift of the centre of gravity of anchovy and sardine populations from west to east has been observed. Some of their natural predators, such as the Cape gannet and the African penguin, which live and reproduce in particular islands, experienced the disappearance of their prey from their foraging ground, causing reproduction failures. In the 1980s, after the long-term sardine stock collapse in Namibia, these same gannets were able to relocate their colonies to South Africa. It is uncertain whether they will continue migrating if their prey persist in moving east and whether they will find new available islands on which to settle.

Upwelling systems, by virtue of being relatively well understood in terms of their structure and function, and being comprised

![Figure 6. Coupling the OSMOSE IBM size-based model with the ROMS N2P2Z2D2 biogeochemical model. Figure courtesy of M. Travers, IRD, France.](image-url)
of relatively few species compared to both temperate and tropical ecosystems, are particularly good candidates for end-to-end food web studies. These are defined as studies that aim to integrate across species and functional groups from biogeochemical processes and primary producers through to top predators. There is an increasing number of physical numerical models, which are now coupled to biological compartments that go from plankton to top predators, including fishers.

In addition to individual-based models (IBM) of early life history, two different ecosystem modelling approaches were used to represent marine food webs at the symposium: size-based trophic models (e.g. OSMOSE - Object-oriented Simulator of Marine ecOSYSems Exploitation; Fig. 6) and mass-balance models (e.g. Ecopath with Ecosim, EwE). These models are becoming realistic enough to improve our understanding of upwelling ecosystems, particularly on the interactions between exploitation and climate change. We note in particular that upwelling ecosystems are less resilient to these changes when they are intensively exploited. Because they are situated in the centre of the trophic pyramid, pelagic fish often play a central role in regulating the functioning of upwelling ecosystems.

This symposium has confirmed that pelagic fish are more carnivorous (zooplanktivorous) than herbivorous (phytoplanktivorous), which, combined with the evidence that a number of small-sized zooplankton in their diet, shows that in general their food supplies depend on a wider range of organisms than suspected before. Nevertheless, these fishes are very dependent on the upwelling intensity, as much for their food as for the fate of their eggs and larvae, which could be transported offshore with lethal consequences, which is counteracted through retention adaptive strategies, to limit losses.

There is emerging evidence that many of the EBUEs appear to be changing, with either spreading of hypoxic/anoxic areas or appearance of novel hypoxia/anoxia, and that these changes are consistent with possible impacts of climate change. Paleontological studies based on scale depositions in anoxic marine sediments have allowed us to observe biological changes over long time scales. Off Peru, for example, we note that anchovy abundance during the last century was exceptional and that the observed organic carbon increase during the same period is twice as intense as during the last two millennia. This allows us to interpret present observations in a new and more complete context.

One of the issues raised at the symposium was the need and wish to ensure that ecosystem management takes account of the biological health of stocks and ecosystems, social dynamics of fleet and fishers, as well as other socio-economic considerations (e.g. employment). Vessel Monitoring Systems (VMS) were presented as potential new tools, not just for management (e.g. to monitor effort, study interactions between fleets, monitor protected areas) but to study interactions between resources, fisheries and top-predators (Fig. 7).

In conclusion, the symposium confirmed that EBUEs play an essential role in the functioning of the oceans, both at the regional scale (from the coast up to a few hundred miles outside the continental shelf) and globally. EBUEs are characterised by dramatic and sudden changes affecting their dynamics at all temporal and spatial scales, from their climate forcing all the way to the extreme of the trophic chain (top predators and fishers).

The symposium showed many scientific advances in different fields of marine science and the willingness of the scientific community to make progress toward integrated research. But as usual, as the scientific advancements improve our knowledge, new questions appear, such as whether the importance of wind-stress curl off central California can be generalised to other ecosystems, or whether the links between wind, temperature and phytoplankton production are similar in the four ecosystems. Similarly, the role of iron rich continental dusts deposits on the productivity of the oceans remains an open question. Despite these unknowns, this symposium represented a big step forward in cementing a multi-disciplinary scientific community focused on the dynamics of upwelling ecosystems, able to exchange ideas and share experiences on how to study and manage these particular and important ecosystems.

The proceedings of this conference will be published in the journal Progress in Oceanography, with an expected publication date of 2009. For more information, visit the symposium webpage, http://www.upwelling-symposium.org.

Reference
Members of the Secretariat during a moment of leisure: Javier Arístegui, Georgina Rouhana, Pierre-François Baisnée, Mariló Güemes, Jessica Heard, Susana Barroso and Santiago Hernández-León (chair).

Working on the balcony of the conference centre.

Question time for session PL2 chaired by Manuel Barange (left).

Javier Arístegui (centre right) meeting other participants.

Symposium participants networking over coffee.
Santiago Hernández-León (chair of the local organising committee) being interviewed for TV.

Participants listening to presentations in a packed hall.

Coffee break by the sea.

Postersession.

Local students at the coffee break.