Eddy-driven dispersion processes in the Canary Current upwelling system: comparison with the California system

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Introduction

The Canary Current System is one of the four major upwelling regions of the world. It is poorly studied compared to the other eastern boundary current systems (California, Humboldt, Benguela) even though it sustains large fisheries resources and constitutes a major economical component for the neighbouring African countries: Morocco, Mauritania, and Senegal. The basic coastal upwelling process is well understood: equatorward trade winds along West Africa lead to an offshore transport of surface water and subsequent upwelling of cold, nutrient rich waters in the coastal area. The mesoscale synoptic structure observed in the Coastal Transition Zone (CTZ) is a combination of upwelling fronts, offshore squirts and filaments, and eddies, many of which occur as dipoles. These features are part of a highly non-linear dynamical system associated to the basic upwelling process and their impact on the transport and distribution of coastal properties is still a matter of research (Marchesiello *et al*., 2003). More importantly, the mesoscale and sub-mesoscale activity of the CTZ is expected to be a major contributor to the processes controlling the downscaling of global climate changes to the scale of the regional upwelling systems.

Upwelling ecosystems are characterized by high primary production due to sustained nutrient input by the vertical circulation. Upwelling zones also provide a very dispersive environment where nutrients, phytoplankton, zooplankton and meroplankton can be quickly swept from the coastal area. Usually, sardines and anchovies, essential components of the ecosystem and the local fisheries, tend to avoid the upwelling zones for spawning (Roy *et al.*, 1992), although examples of the opposite can be found off southern Morocco and Senegal. Spawning success may be related to the physical environment through a balance between various processes of enrichment, retention/dispersion and concentration (Bakun, 1998). It is one of the objectives of this study to understand the mechanisms that govern spawning of small pelagic fish and the variability in time and space of these mechanisms.

Modeling Approach

The Regional Oceanic Modeling System (ROMS; Shchepetkin and McWilliams, 2003) was developed to simulate both coastal and oceanic regions and their interactions. ROMS solves the primitive equations in an Earth-centered rotating environment, based on the Boussinesq approximation and hydrostatic vertical momentum balance. The model grid, forcing, initial and boundary conditions are built using the ROMSTOOLS package (Penven, 2003).

Our strategy for managing the large range of scales from regional down to the local scales is a multi-level approach based on the AGRIF package developed by Blayo and Debreu (1999). This is an online (synchronous) nesting procedure which allows a rapid setup of a series of embedded domains with increasing resolution. To encompass the whole Canary Current System, we have designed a parent grid extending from 5°N to 38°N and from 30°W to 5°W (Fig. 1, see p.4) at a resolution of 25km horizontally with 32 vertical levels. Child grids have also been designed, in particular a zoom off Southern Morocco at 7km resolution which will be used to examine mesoscale physical processes. The resolution here is still coarse with regards to convergence experiments performed in Marchesiello *et al.* (2003) and further refinement of the model will be considered.

Our modeling approach is of incremental complexity. It starts by addressing the mean circulation, seasonal cycle and mesoscale physics in the Canary Current System, leaving aside the inter-annual variability. The model is forced by COADS ocean surface monthly climatology (Da Silva *et al*., 1994) for the heat, fresh water fluxes and momentum fluxes. The three lateral open boundaries (Marchesiello *et al.*, 2001) are forced using a climatology derived from Levitus *et al.*, (1994). A parameterization of the Mediterranean outflow is realized by nudging temperature and salinity for depths deeper than 750m to their monthly Levitus means with a time scale of 50 days. In climatological runs, the model is integrated until a statistical equilibrium is obtained (spin-up of 2 years), then integration is continued for several seasonal cycles to study the dynamical equilibrium of the system. A first validation of the seasonal cycle was realized by comparing model output with climatologies from satellite and in-situ data and global models. It shows the skills of the model to reproduce the regional circulation and the seasonal cycle of coastal upwelling in agreement with other studies, (Nykjaer and Van Camp, 1994; Mittelstaedt, 1983).

Eddy-driven Dispersion of Coastal Properties

In a previous study of the California Current System (Marchesiello *et al*., 2003), we intentionally posed our calculations without synoptic and interannual forcing. The success of the simulations, in approximately matching the observations, suggested that the mesoscale variability of an upwelling system is intrinsic, hence chaotic with limited predictability, while the large-scale structure is substantially a deterministic response to the low-frequency, large-scale atmospheric forcing (whether local or remote) and transmitted through the regional boundaries.

We are following a similar approach for the Canary Current System. Figure 2 (see p.4) shows maps of sea surface height (SSH) variability from the model and from Topex/ERS (gridded by AVISO) for both the Southern Morocco region of the Canary system and the central upwelling region of the California system. Both regions are similar in size and feature comparable upwelling-favourable winds over the year cycle. A comparison of the observed and modeled broad patterns shows that there is a good match in both regions due to realistic model representation of the unstable jet, eddies, offshore squirts and associated filaments (Fig. 1, see p.4). However, the comparison of SSH variability between the two regions reveals a striking quantitative difference where the variability in the California System is more than twice the amount shown for the central Canary system. Since both regions are forced with equal intensity, the reason for such a difference is found in the stratification background.

Mesoscale variability in upwelling systems is produced mainly through baroclinic instability of the coastal upwelling jet (Marchesiello *et al.*, 2003). In terms of energy, the wind drives available potential energy in the coastal area which is transformed into eddy kinetic energy during the baroclinic instability process. The amount of energy conversion varies with the available potential energy, or equivalently with vertical shears of the coastal jet which is largely dependent on stratification (the reduced gravity number **g'** representing the variation of density between surface and subsurface layers, gives a good index of velocity shear in the two-layer upwelling problem). Values of **g'** in the California Current System are more than twice as large as the values in the Canary Current System. The reasons lie in the salinity structure provided by the large-scale circulation. In the North Pacific, a low-salinity signal of subarctic water can penetrate the upwelling system and travel far south while saline equatorial water is transported northward in the subsurface layer. This results in a negative vertical salinity gradient which is unique among large upwelling systems (Huyer *et al.*, 2004). In the North Atlantic, there is a barrier to the subarctic water which cannot affect the subtropical region while equatorial waters have a limited expression due to the intrusion of fresh Antarctic intermediate waters. The resulting difference in vertical gradients of salinity between the two systems leads to a large difference in available potential energy and eventually in mesoscale activity as suggested by our model results.

Analysis of the heat budget in the California Current System permitted a quantification of the impact of mesoscale activity on cross-shore distribution of coastal properties. It showed that the offshore eddy heat fluxes provide the principal balance against near-shore cooling by mean Ekman transport and upwelling. This result can be explained by considering the eddy flux working as eddy diffusion. This eddy diffusion mixes cold near-shore water, originating from upwelling of subsurface water with warm offshore water. This eddy diffusion can be expected to also affect nutrients and plankton concentrations by eroding coastal high values in regions where mesoscale activity is important. Our model results therefore suggest that the Canary Current System has a much less dispersive environment that the California Current System.

Interannual Variability

Interannual variability can be introduced in the model as remote forcing through the lateral boundaries and as local forcing through surface fluxes, particularly wind stress. The former type of forcing requires use of global or basin-scale model outputs while the latter is done using atmospheric models or satellite scatterometer data. Weekly ERS 1-2 wind stress fields (Bentamy, 1996) has been used here to estimate the part of interannual variability which is forced locally in the system. The product gridded at a spatial resolution of 1 degree is interpolated on the 25km model grid (the zoom is not applied here and the mesoscale activity is relatively weak) for the period August 1991 to January 2001. Time-integration starts from an equilibrium solution of the climatological run.

We are presenting only preliminary results from comparisons of the model SST with Pathfinder observations (Vazquez *et al.*, 1998). The inter-annual signal is extracted by subtracting the mean seasonal cycle from the observed or computed SST and then applying a 6 months running average in order to filter intra-seasonal variability. The correlation coefficient between time series of observed and computed SST anomalies is high all along the coast (Fig. 3, see p.4). Both signals clearly follow the North Atlantic Oscillation index for the period 1991-2001. These high correlation values decrease offshore in the coastal transition zone because intrinsic variability which is unpredictable in nature becomes dominant. This is consistent with results obtained in other upwelling regions (Blanke *et al.*, 2002). Interestingly, the coastal high correlation values have a more limited offshore extent in regions of stronger eddy activity such as the lee of the Canary Islands and the Cape Blanc area (Barton *et al.*, 1998). Note that beside the unpredictable nature of the mesoscale response to interannual forcing, the differences between model and data can also be attributed here to the use of coarse resolution which leads to under-resolving the cross-shore exchanges induced by eddies and filaments. A better resolution in the future of the eddy activity should allow a more realistic downscaling of the interannual forcing in the coastal transition zone.

Discussion: Downscaling and Spawning Success

Sinclair *et al.* (1985), analysing El Niño impacts on larval success in decades of CalCOFI data, suggested that despite lower enrichment of coastal waters, El Niño provides a period of low dispersal of fish eggs and larvae for certain species which is favorable to later recruitment. What seemed puzzling to Sinclair *et al.* was the absence of correlation between local wind intensity and El Niño signal in the CCS (consistent with the generally accepted notion that upwelling intensity decreases in the CCS during El Niño essentially because the thermocline deepens, not because the upwelling-favourable winds are reduced). Our results on mesoscale patterns provide an interesting solution to this problem and a clear example on how downscaling may operate in upwelling regions: a deepening of the thermocline leads to reduced upwelling of dense subsurface water hence reduced available energy for mesoscale dispersion. This is consistent with anecdotal evidence from satellite observations that upwelling filaments have a more limited extent during El Niño events. This idea is yet only speculative and a clear demonstration has to be made, but it may provide a pathway to explore the non-linear response of spawning strategies to regime changes and the different strategies adopted in different systems.

If sardines spawn on the innershelf of southern Morocco in the heart of the upwelling regime, it may be because of a less dispersal environment as suggested above. However it may also be due to the presence of a large, shallow innershelf which can provide protection from the dispersive upwelling regime (Roy, 1998). All of these physical mechanisms have to be considered in a fully integrated approach.

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Figures for Marchesiello *et al.* p.5-7

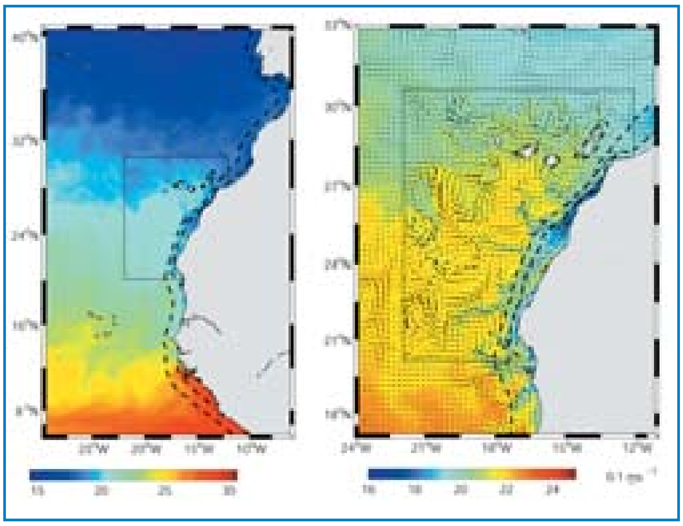

Figure 1. (Marchesiello, p.5-7) Left panel: sea surface temperature in the Canary Current System model; the whole regional domain at 25km resolution is shown with an embedded subdomain at 7km resolution in southern Morocco. Right panel: surface temperature and currents in the southern Morocco region

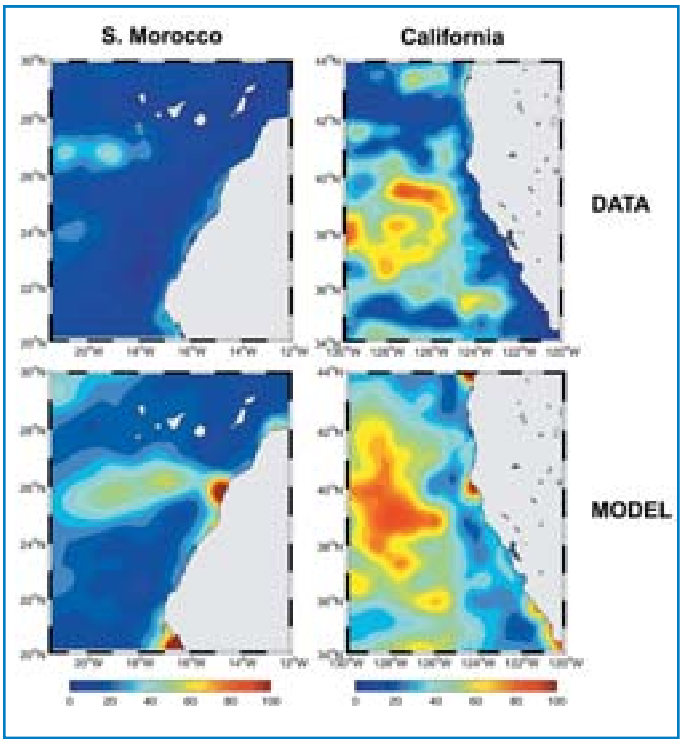

Figure 2. (Marchesiello, p.5-7) Variance of sea level anomalies from the climatological simulation (top panels) and Topex/ERS altimeter data (bottom panels) for the upwelling regions off southern Morocco (left) and California (right). Note that the high coastal values present in the altimeter data can be attributed to synoptic and interannual forcing which is absent in these simulations.

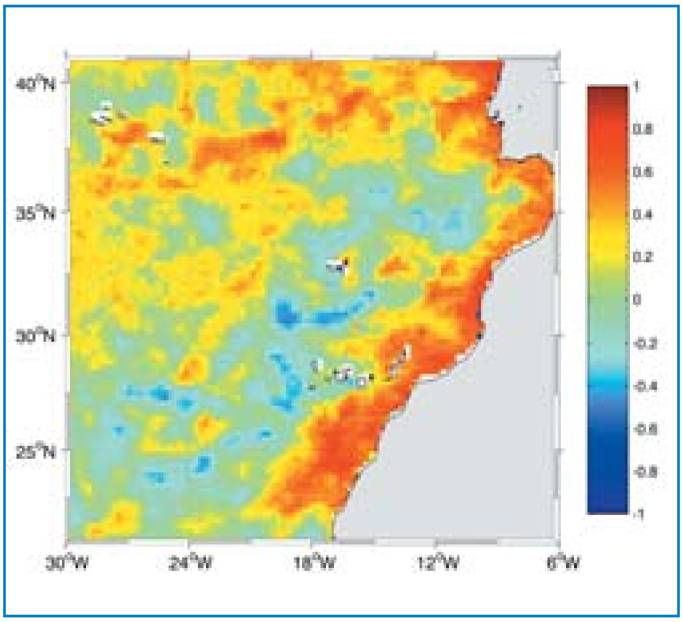

Figure 3. (Marchesiello, p.5-7) Correlation coefficient between time series of observed and modeled SST anomalies for the 25km resolution regional model. It shows high coastal correlation values and relative loss of correlation offshore where eddy dynamics are dominant.

Figure for Robinson p.8

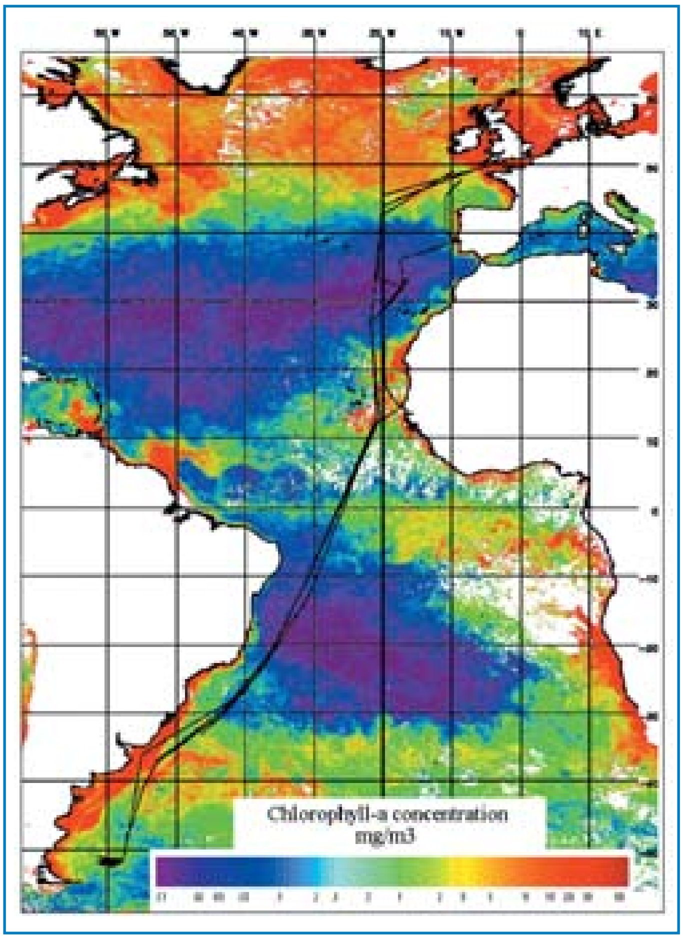

Figure 1. (Robinson, p.8) AMT cruise tracks

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