Comparative study of mixing and biological activity of the Benguela and Canary upwelling systems

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We present a comparative study of the horizontal mixing properties, from satellite derived data of the surface velocity field, of the two eastern boundary Canary and Benguela upwelling systems, based on a Finite Size Lyapunov Exponents analysis. Each area can be subdivided into two subsystems attending to their mixing activity values. These coincide nicely with distinct biological signatures. When investigating links with chlorophyll as a proxy for biological activity in these two upwelling systems, results show that surface horizontal stirring and mixing vary inversely with chlorophyll standing stocks. Ekman-transport induced upwelling exhibits a positive correlation with chlorophyll. These two findings are complementary since spatial structure in plankton distributions results from both dynamics of the $3D$ turbulent medium and of the marine ecosystem.

Introduction

Eastern boundary upwelling zones constitute the largest contribution to the world ocean productivity, up to 17% of the global fish catch [*Pauly and Christensen* 1995, @], thus playing a key biological and socio-economical role. They include the Canary and Benguela upwelling systems (hereafter CUS and BUS, respectively), located along the African coast symmetrically with respect to the Equator. Both areas are particularly characterized, among other features, by a strong alongshore advection, physical forcing by local and large scale winds, seaward extension beyond the continental shelf of the boundary current and an active biological activity via filaments formation. The intensity of the sub- and mesoscale activity is rather high and it is a major challenge to study the complex chlorophyll spatial distribution in connection with the physical mechanisms.

The aim of this work is to make a comparative study of these two upwelling systems, focussing on their mesoscale activity and the interaction between marine surface hydrodynamics and biological processes. The basic input to our analysis are satellite data of the marine surface, including velocity field and chlorophyll concentration. We quantify horizontal transport processes by the well-known technique of the Finite Size Lyapunov Exponents (FSLE) [*Aurell et al*, 1997, @], which is specially suited to study the stretching and contraction properties of transport in geophysical data [*d'Ovidio et al*, 2004, @]. The calculation of the FSLE goes through computing the time, τ, at which two fluid parcels initially separated at a distance δ_0, reach a final separation δ_f. At position $\mathbf{x}$ and time t the FSLE is given by $\lambda(\mathbf{x}, t, \delta_0, \delta_f) = \frac{1}{\tau} \log \frac{\delta_f}{\delta_0}$. In a typical snapshot of the FSLE (see Fig.1 in *d'Ovidio et al*, 2004 [@]) the maximum values organize in lines which are a

good approximation for the areas of maximal convergence, if they are calculated for the backwards-in-time dynamics, which is the one performed all along this work. In *d'Ovidio et al,* 2004 [@] and *d'Ovidio et al,* 2007 [@] the adequacy of the FSLE to characterize horizontal mixing and transport structures in the upper ocean has been demonstrated, as well as its usefulness when correlating with distributions of tracers such as temperature or chlorophyll. In addition, spatial averages of FSLEs can define a measure of mixing in a given spatial area, the larger this average the larger the mixing activity. We will use the FSLEs as an analyzer tool to highlight differences and similarities, both at the hydrodynamic and biological levels, between the CUS and BUS.

Data

Computation and analysis areas:

Our study focuses on the transitional area of exchange processes between the shelf and offshore in the open ocean. Among these processes, sub- and mesoscale structures such as filaments contribute to the offshore export of organic matter produced in the very coastal upwelling. These filaments in the fluctuating boundary between the upwelling and the edge of the oligotrophic subtropical gyres play a key role in the modulation of the carbon balance by seeding the inner ocean.

We thus defined our analysis areas depending on the maximum westward extension of the chlorophyll filaments and then made the approximation to the closest proper rectangle fitting the best. In Fig. 1 the analysis areas are shown delimited by the dashed lines. The full geographical areas ($40 - 10°W$, $20 - 40°N$ for CUS, and $0 - 20°E$, $16 - 36°S$ for BUS) are those we used to make our numerical computations. Note that the computation areas

are larger than the analysis ones, considering the fact that particles may leave the area before reaching the fixed final distance δ_f.

Velocity data:

Weekly global 1/4° resolution product of surface currents developed by *Sudre and Morrow*, 2007 [@] have been used. The surface currents are calculated from a combination of wind-driven Ekman currents, at 15 m depth, derived from Quickscat wind estimates, and geostrophic currents computed from time variable Sea Surface Heights. These SSH were calculated from mapped altimetric sea level anomalies combined with a mean dynamic topography from *Rio et al,* 2005 [@].

Chlorophyll data:

A 5 year long time series from June 2000 to June 2005 of ocean color data are used. Phytoplankton pigment concentrations are obtained from monthly SeaWiFS (Sea-viewing Wide Field-of-view Sensor) products of level 3 binned data, generated by the NASA Goddard Earth Science (GES)/ Distributed Active Archive Center (DAAC) with reprocessing 5.1 (version July 2005, http://oceancolor.gsfc.nasa.gov /REPROCESS-ING/SeaWiFS/R5.1/). The bins correspond to grid cells on a global grid, with each cell approximately 9 by 9 km.

Results

Horizontal mixing properties

In Fig. 1 we draw the time average (covering the period June 2000- June 2005) of the FSLE computed for the CUS (left) and BUS (right). Following *d'Ovidio et al,* 2004 [@]

the prescribed length-scales in our analysis are $\delta_0 = 0.25°$ and $\delta_f = 1°$ so that we focus on

the mesoscale horizontal features. For both the CUS and BUS, two different subsystems,

according to their mixing activity, can be defined: north and south of the $30°N$ for the

CUS, and north and south of $27°S$ (latitude of the intense Lüderitz upwelling cell) for

the BUS. Comparing both upwelling zones, the most clear distinction is that while in the

BUS the subdivision in two areas of activity is rather evident, in the CUS this is not so

sharp. Note also that the imaginary division line passes north of the Canary archipelago.

A further detailed comparison between the different subsystems can be found in Fig. 2,

where we plot the time evolution of the spatial averages of the FSLEs over the analysis

areas, for both regions. The difference of horizontal mixing activity is clear between the

subsystems in any of the regions. As already mentioned, this difference is more pronounced

in the BUS than in the CUS. In the former, the ratio of the average FSLE between more

mixing to less mixing subareas is 2, while in the latter this is of the order of 1.5. Comparing

both upwelling zones, one can note that in the most active subsystems the values of the

FSLEs are similar: within the range $(0.025, 0.038)$ day^{-1}, i.e., horizontal mixing times

from 26 to 40 days. On the contrary, the least active subsystem in the Canary has much

larger values for the FSLEs than the least active one in the BUS. While in the CUS the

mixing times are in the range $37 - 56$ days, in the BUS this is $53 - 90$ days.

In the time evolution of the mean FSLE for the whole areas the seasonal variability

reflects the fact that in winter the sea surface exhibits a more turbulent behavior. In the

southern subsystem of the BUS, the upwelling relaxation period (March through May) is

marked with minimum turbulence values. The northern and southern subsystems in the

CUS seem to vary in phase whereas this does not hold for the BUS. A strong interannual variability of the mixing is clearly remarkable, showing the high temporal variability of this physical forcing in both areas.

The same geographical subdivision is observed by computing the mean eddy kinetic energy (EKE) (not shown). Areas of more mixing are characterized by a larger EKE. This may be linked with the very energetic warm water currents as the Agulhas and Azores currents located south and north of BUS and CUS, respectively.

Next we proceed to investigate the correlation between horizontal mixing with the biological activity in our study regions.

Biological activity

We study here the correlation of the FSLEs with chlorophyll concentration data. First we perform Hovmöller plots of the surface chlorophyll distribution in both the BUS and CUS (Fig. 3). These plots are done by averaging the chlorophyll concentration along lines of constant latitude within the analysis areas. Then one draws, versus time, the variation with latitude of these longitudinal means. The dashed-dotted lines on the Hovmöller chlorophyll concentration (Fig. 3) are those obtained from the FSLE analysis (around $30°N$ for CUS and $27°S$ for BUS). Note that here also they separate spatial zones with very distinct degree of chlorophyll richness.

If one plots spatial averages of FSLE versus spatial averages of chlorophyll concentration, over the entire analysis area (Fig. 4a) and over each subsystem (Fig. 4b), for each month from June 2000 to June 2005, a negative correlation between FSLEs and chlorophyll concentration emerges. For both areas, the subsystems with more mixing activity are

the ones poorer in chlorophyll. This opposite effect is in the line of *Gruber et al,* 2007 [@] findings of meso and sub-mesoscale processes tending to reduce biological activity in coastal upwelling systems. We note that theoretical studies in idealized settings, in which nutrients reach plankton only by lateral stirring, display also negative correlation between mixing and biomass (although mixing and productivity may be positively correlated) [*Tél et al,* 2005, @; *Birch et al,* 2007, @].

Upwelling areas are definitely affected by water vertical movements and velocities which are not captured by the surface analysis provided by FSLEs. Thus, the vertical part of the physical forcing will be taken in consideration in the following. Moreover, we examine the influence of Ekman transport which brings nutrients from the coast and can also play a very relevant role in the chlorophyll signature.

First we evaluate the horizontal divergence of the surface velocity field: $\Delta(x, y, t) \equiv \partial_z v_z = -(\partial_x v_x + \partial_y v_y)$. Negative (positive) values of Δ indicate upwelling (downwelling) areas because it signals surface spatial points where fluid parcels diverge (converge). Fig. 5 shows the average value of Δ over the period June 2000- June 2005 for the CUS (left) and BUS (right). The blue color of the Δ field in the coastal areas indicates the presence of upwelling processes there. Note that in the coastal zones of the Benguela, the well known upwelling cells Cape Frio, Walvis Bay and Lüderitz in the northern subsystem appear clearly, being more intense than the southern cells, in agreement with *Monteiro* 2007 [@] estimates of the northern system accounting for 80%, on average, of the total upwelled flux over the whole BUS. Concerning the CUS (Fig. 5 left) one can see a slight blue-color predominancy (enhanced upwelling) in the southern subregion.

To complete the analysis we have calculated the Ekman transport, U_E, along the E-W direction (not shown here), by using the formula $U_E = T_y/(f\rho)$, where T_y is the meridional wind stress, ρ is the volumic mass of seawater, and f is the Coriolis parameter. The northern region of the BUS, richer in chlorophyll, is characterized by a higher offshore transport. In the CUS, both sub-areas have high values for the offshore transport very close to the coast, with similar values in the southern and northern subregions. Further from the coast, the highest westward transport in the southern CUS area coincides again with the highest chlorophyll content. Fig. 4c) shows averages of Ekman transport vs spatial averages of chlorophyll concentration, over each subsystem. Negative values of the average from June 2000 to June 2005 indicate an offshore transport to the west, whereas positive ones indicate a transport to the east. A positive correlation appears confirming the effect of Ekman-transport induced upwelling on biological productivity. This finding is not incompatible with the distinct clustering (Fig. 4a,b) since horizontal currents are strongly related to the vertical circulation. Creation of sub- and mesoscale surface chlorophyll structures results from the full $3D$ turbulent motion of the ocean.

Summary and conclusions

The distribution of FLSEs computed over a 5 year period with state of the art velocity fields derived from multiple sensors (altimeter, scatterometer) allowed us to compute horizontal stirring rates in the surface ocean of two major eastern boundary upwelling systems of the Atlantic ocean: the Canary and Benguela systems. Previous studies have suggested that eddies tend to enhance biological productivity in the open ocean, particularly in low nutrient environments. We demonstrate here that meso and sub-mesoscale processes in

upwelling coastal systems tend to produce a reduction of chlorophyll standing stocks. Further work should investigate the robustness of this relationship when examining FSLEs versus production. Of course vertical processes and the intrinsic biological dynamics do play a role. Still much needs to be done to fully understand how plankton distributions are controlled by the interplay between their turbulent medium and the non-linear processes of their ecology. However FSLEs lead to a clear clustering of subsystems suggesting that one may use these simple Lagrangian diagnostics as integrated and comparative indices for characterizing horizontal dynamical features in all eastern boundary upwellings.

Acknowledgements

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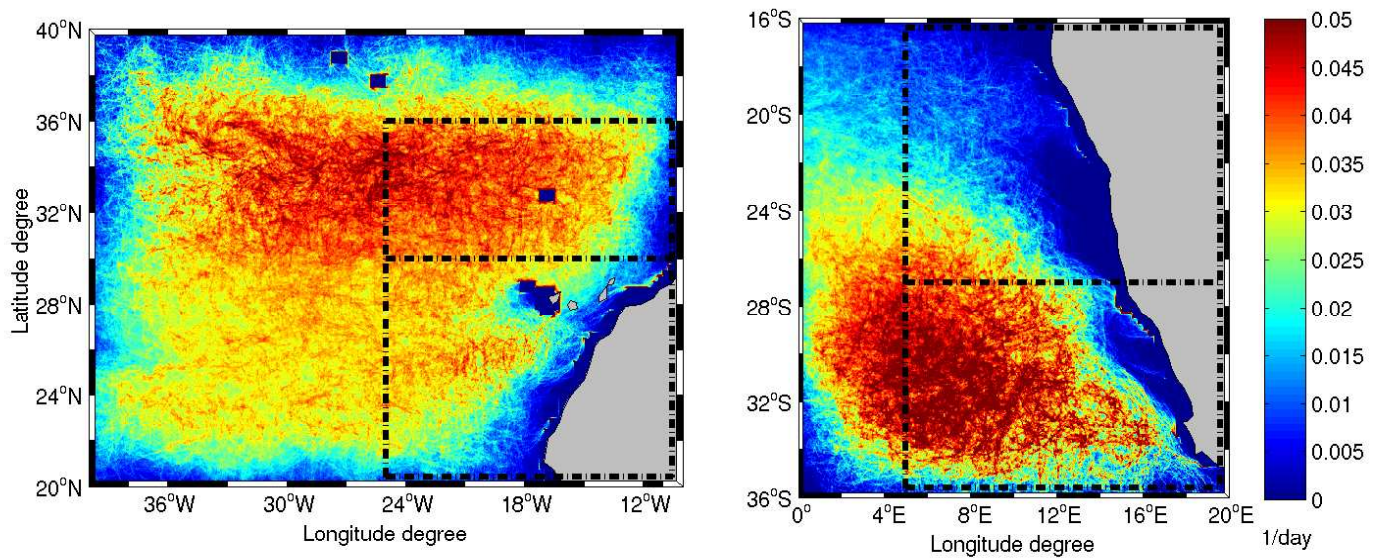Van Meurs, P., and P.P. Niiler, Temporal variability of the large-scale geostrophic surface velocity in the northeast Pacific, *J. Phys. Ocean.*, 27:2288-2297, 1997.

Figure 1. Time average over the period June 2000- June 2005 of the FSLEs. Left is for the CUS and right for the BUS. The boxes denote the analysis areas of our study. The central horizontal line in each plot divides the two subregions.
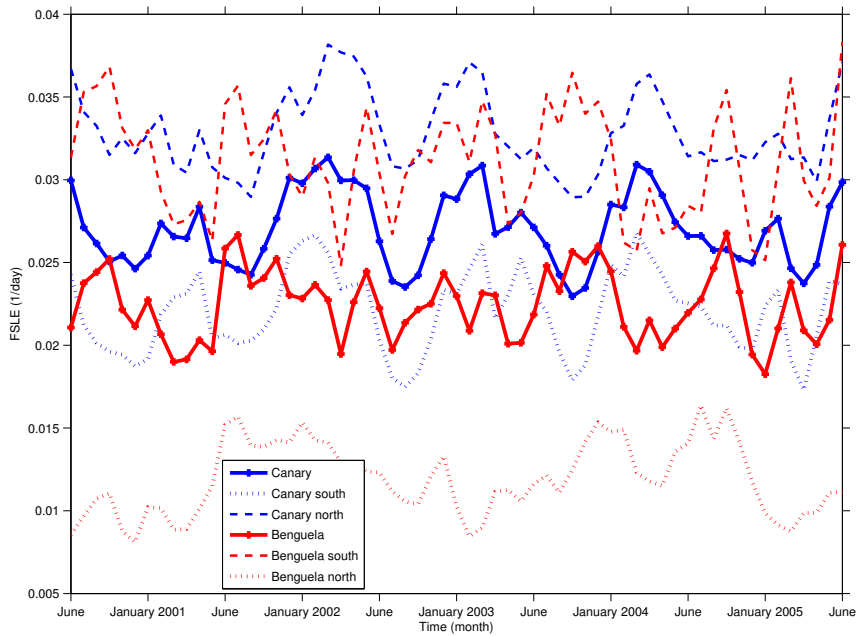
Figure 2. Spatial average vs time of the FSLEs. We plot the spatial averages over the different analysis areas: north (blue-dashed line) and south (blue-dotted line) Canary, and the average over the whole Canary analysis area (blue-solid line). The same for the Benguela but with red color.
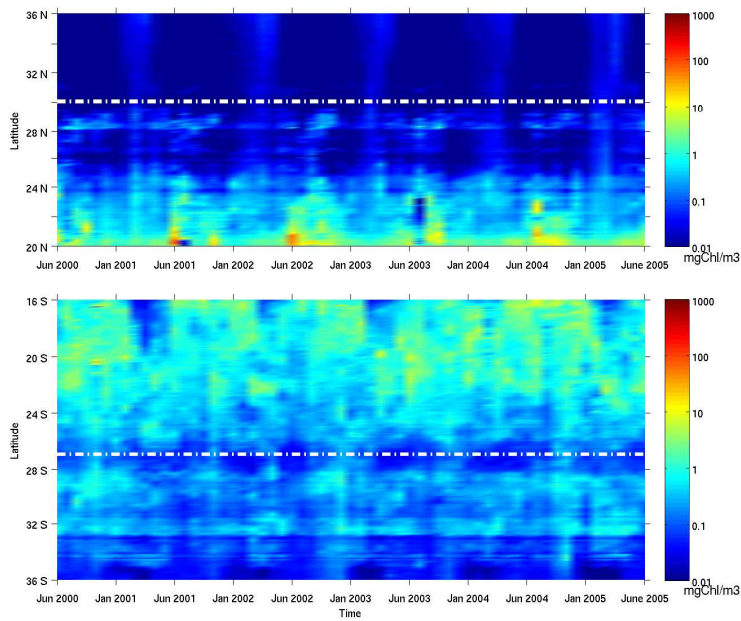
Figure 3.   Hovmöller plots of the chlorophyll a concentration. For CUS (upper plot) is averaged over $25-10°W$ and for BUS (bottom) over $5-20°E$. White-horizontal lines delimit geographical subdivision.
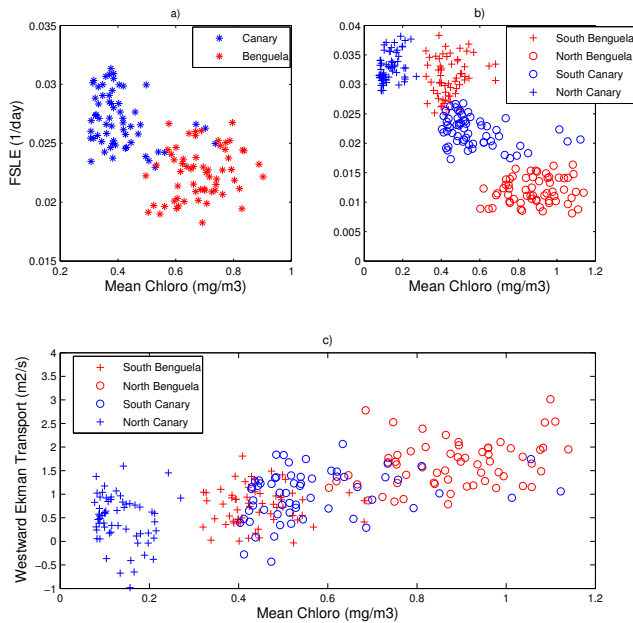
Figure 4.   a) FSLE vs monthly-mean chlorophyll concentrations (from June 2000 to June 2005) for the whole area: blue asterisks for CUS and red for BUS. b) Same for the different subregions as denoted in the legend. c): Same as for b) but with Ekman transport vs monthly-mean chlorophyll concentrations.
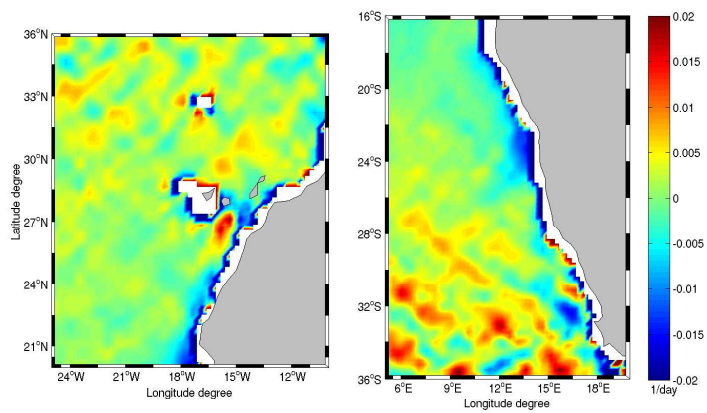
Figure 5. Temporal average value of the field Δ (June 2000- June 2005). CUS (left) and BUS (right). The blue color indicates upwelling areas whereas red signal downwelling ones.