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

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[1] 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.

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1. Introduction

[2] Eastern boundary upwelling zones constitute a major contribution to the world ocean productivity. 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 characterized, among other features, by a significant equatorward alongshore advection, physical forcings by local and large scale winds, a high sub- and mesoscale activity, seaward extension beyond the continental shelf of the boundary current and an intense biological activity via filament formation.

[3] 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 (similar studies in other upwelling systems can be consulted [e.g., see *Chase et al.*, 2007]).

[4] The basic inputs 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

suitable 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 e.g. *d'Ovidio et al.*, 2004, Figure 1] 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 work by *d'Ovidio et al.* [2004, also, Comparison between Eulerian diagnostics and finite-size Lyapunov exponents computed from altimetry in the Algerian basin, submitted to Deep Sea Research, 2008] and *Lehahn 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, despite the strong intrinsic dynamics of these tracers. In particular, it is discussed that FSLEs, because of the averaging effect produced by computing them by integrating over trajectories which extend in time and space, are rather robust against noise and uncertainties in the velocity data. Here we have checked this explicitly by considering a random perturbation of the velocity field at every spatial point at any time. The error obtained in our computations of averages of FSLEs ranges between 0.3% and 2.8% for multiplicative perturbations of the velocity field of 5% and 10%, respectively. 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. Inverses of FSLEs values give estimations of mixing times. We will use the FSLEs as an analyzer tool to highlight differences and similarities between the CUS and BUS. Finally, we quantify the amount of Ekman-transport induced upwelling and find a positive correlation with chlorophyll standing stocks. We discuss how vertical and horizontal processes may lead to the observed chlorophyll distributions.

2. Data

2.1. Computation and Analysis Areas

[5] 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 [*Mackas et al.*, 2006]. 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. The role of this

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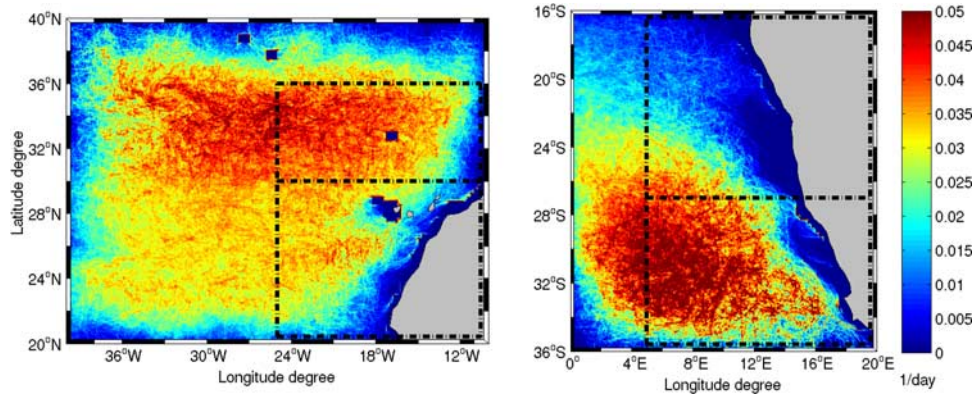


Figure 1. Time average over the period June 2000–June 2005 of the FSLEs (left) for the CUS and (right) for the BUS. The boxes denote the analysis areas of our study. The central horizontal line in each plot divides the two subsystems.

moving transitional area, at the border of the gyre, westward of the maximum extension of the chlorophyll filaments, must be considered. To investigate the island effect from the Canary Archipelago and to have, at the same time, a similar analysis area for CUS and BUS, we have adapted the areas from *Mackas et al.* [2006], by approximating them to the best fitting rectangle whose lateral sides are meridionally oriented. In Figure 1, the analysis areas are shown delimited by the dashed lines (25–10°W, 20–36°N for CUS and 5–20°E, 16–36°S for BUS). We used the full geographical areas shown in Figure 1 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 . In addition, several tests with different shapes and area selections (not shown) lead to similar results.

2.2. Velocity and Wind Stress Data

[6] The weekly global 1/4° resolution product of surface currents developed by *Sudre and Morrow* [2008] has been used. The surface currents are calculated from a combination of wind-driven Ekman currents, at 15 m depth, derived from Quikscat 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]. These weekly velocity data, which are then interpolated linearly to obtain a daily resolution, depend on the quality of their sources as the SSH fields and the scatterometer precision. However, they were validated by *Sudre and Morrow* [2008] with different types of in situ data such as Lagrangian buoys, ADCP, and current-meter float data. In both areas, zonal and meridional components show an average correlation with for e.g. Lagrangian buoy data, between 0.52 and 0.76. The Ekman transport U_E along the East-West direction was computed using the formula $U_E = T_y / (f\rho)$ where T_y is the meridional wind stress (obtained from the scatterometer Quikscat weekly wind estimates), ρ is the density of seawater and f is the Coriolis parameter.

2.3. Chlorophyll Data

[7] A 5 year long time series from June 2000 to June 2005 of ocean color data is 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. The bins correspond to grid cells on a global grid, with each cell approximately 9 by 9 km.

3. Results

3.1. Horizontal Mixing Properties

[8] In Figure 1 we draw the time average (covering the period June 2000 – June 2005) of the FSLE computed for the CUS and BUS. Following *d'Ovidio et al.* [2004] the prescribed length-scales in our analysis are $\delta_0 = 0.025^\circ$ and $\delta_f = 1^\circ$ so that we focus on the mesoscale horizontal features. Choosing a slightly different value of δ_f does not alter qualitatively our results (see caption of Figure 2). For both the CUS and BUS, two different subsystems, according to their mixing activity, can be defined: north and south of 30°N for the CUS, and north and south of 27°S (latitude of the intense Lüderitz upwelling cell) for the BUS. Comparing both 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.

[9] A further detailed comparison between the different subsystems follows by considering the averages of the FSLEs over the analysis areas. Results indicate similar values for the horizontal mixing times in the most active subsystems of both regions, ranging 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.

[10] *Waugh et al.* [2006] found a close relationship between the mean FSLE and the mean eddy kinetic energy (EKE) in the Tasman Sea. We have confirmed that a geographical subdivision similar to the one in Figure 1 is obtained from EKE. However, a clear relationship between these two quantities does not appear. Indeed, the Eulerian diagnostic EKE calculated for a given day only considers the corresponding snapshot of the velocity field and can not catch any temporal variability whereas the FSLE Lagrangian method does. Thus a robust relationship between EKE and FSLE is not expected when velocity fields are highly

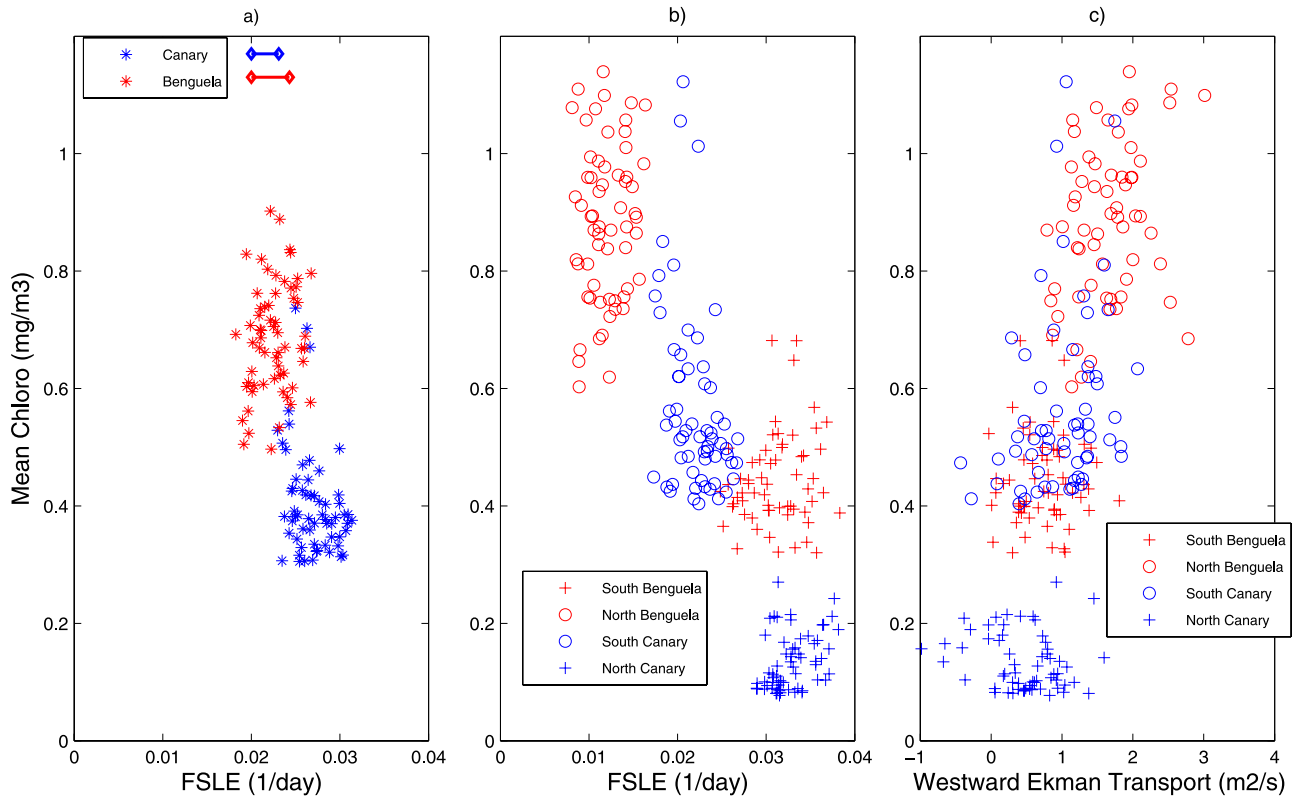


Figure 2. (a) Monthly-mean chlorophyll concentrations versus FSLE for the whole area: blue asterisks for CUS and red for BUS. Each horizontal bar represents the spatial averaged standard error of a FSLE mean for each domain, BUS (red) and CUS (blue). These errors were calculated at each grid point from temporal FSLE means over the 5 years time series. (b) Same for the different subregions as denoted in the legend. (c) Same as Figure 2b but for monthly-mean chlorophyll concentrations vs Ekman transport. The correlation coefficient for all the data in a) is $R^2 = -0.62$. This coefficient changes to -0.53 , and -0.66 , when changing δ_f to $\delta_f = 0.8^\circ$ and $\delta_f = 1.2^\circ$, respectively. If we consider the different subregions in b), the correlation coefficient is $R^2 = -0.83$. For $\delta_f = 0.8^\circ$ and $\delta_f = 1.2^\circ$, it becomes -0.80 and -0.85 , respectively.

variable. A detailed study of the relation between FSLE and Eulerian measurements is given by d’Ovidio et al. (submitted manuscript, 2008).

3.2. Biological Activity

[11] We study here the correlation of the FSLEs (horizontal mixing) with chlorophyll concentration data. Hovmöller plots of the surface chlorophyll distribution in both the BUS and CUS (not shown here) reveal the existence of two spatial zones with very distinct degree of chlorophyll in each upwelling system. The lines separating them (around 30°N for CUS and 27°S for BUS) coincide with those obtained from the FSLE analysis.

[12] If one plots spatial averages of chlorophyll concentration versus spatial averages of FSLE, over the entire analysis area (Figure 2a) and over each subsystem (Figure 2b), 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 is in the line of Gruber et al. [2007] findings of meso and sub-mesoscale processes associated to reduced 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].

[13] 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.

[14] 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). Figure 3 shows the average value of Δ over the period June 2000–June 2005 for the CUS and BUS. 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’s [2008] estimates of the northern system accounting for 80%, on average, of the total upwelled flux over the whole BUS.

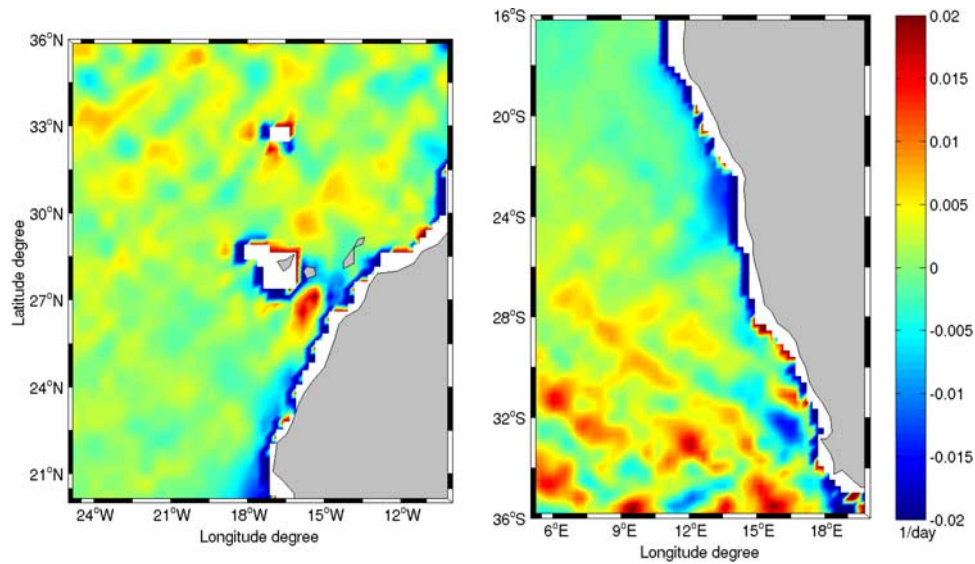


Figure 3. Temporal average value of the field $\Delta(x, y, t) \equiv \partial_z v_z = -(\partial_x v_x + \partial_y v_y)$ over the period June 2000–June 2005 for (left) CUS and (right) BUS. The blue color indicates upwelling areas whereas red signals downwelling ones.

Concerning the CUS (Figure 3, left) one can see a slight blue-color predominancy (enhanced upwelling) in the southern subregion.

[15] When we compute the Ekman transport we observe that 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. Figure 2c shows spatial averages of chlorophyll concentration vs averages of Ekman transport over each subsystem. Negative values of the average from June 2000 to June 2005 indicate an offshore transport to the east, whereas positive ones indicate a transport to the west. A positive correlation appears confirming the effect of Ekman-transport induced upwelling on biological productivity. This finding is not incompatible with the distinct clustering (Figures 2a and 2b) 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.

4. Summary and Conclusions

[16] The distribution of FSLEs 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. A clear subdivision within each system appeared according to the mixing activity, coinciding with distinct levels of chlorophyll richness.

[17] Previous studies have suggested that eddies tend to enhance biological productivity in the open ocean, particularly in low nutrient environments. Finding a negative correlation between horizontal mixing and chlorophyll

standing stocks suggests that this may not apply to upwelling regions. Comparing Figures 1 and 3 shows that areas characterized by high FSLE are correlated with intense vertical movements (downwellings as well as upwellings), whereas the areas with low FSLE are mainly dominated by upwards vertical velocities (upwellings). *Lehahn et al.* [2007] recently showed that vertical motions associated with eddies are more precisely located close to the lines of high FSLE. Regions of high FSLE averages indicate a high occurrence of intense eddies which modify the three dimensional mean flow. The nutrient Ekman pumping, dominant process in upwelling areas, weakened and the fueling of nutrients toward the surface decreased.

[18] Another possible explanation may rest upon the fact that upwelling from deeper waters and offshore Ekman transport of nutrients are important mechanisms for surface-waters enrichment. In the areas where the Ekman drift dominates over mesoscale activity, like in the northern BUS and southern CUS, a large dispersion of fluid particles, i.e., large values of FSLEs, does not occur. This would also indicate that the horizontal turbulent mixing of nutrients in surface waters is a second-order effect for biomass enhancement as compared to the vertical mechanisms.

[19] Other factors may of course influence the phytoplanktonic biomass. *Chase et al.* [2007] for instance showed in the upwelling system of the U. S. West Coast that there is a link between chlorophyll concentration and iron availability through river inputs and shelf deposition/re-suspension processes. In our two systems BUS and CUS exhibiting a larger shelf than that of the U.S. West coast, the very low river runoff can not deliver any major iron input to the inner shelf. Moreover, high dust deposition occurs leading to non-limiting iron concentration in both systems [*Jickells et al.*, 2005; *Mackas et al.*, 2006]. Consequently we did not consider these controls as primary factors in our analysis. Further work should investigate the robustness of the relationship found in our two systems when examining FSLEs versus production. 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.

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