Mixing, Lyapunov exponents, and biological activity in the Benguela and the Canary upwelling systems

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A comparative study of the horizontal mixing properties of the two eastern boundary Canary and Benguela upwelling systems is presented. It is based on Finite Size Lyapunov Exponents obtained from satellite-derived velocity fields. Each of the systems is subdivided into two regions attending to their mixing activity values, which coincide nicely with distinct biological activity. Surface horizontal stirring and mixing are inversely correlated with chlorophyll standing stocks. On the other hand, Ekman-transport induced upwelling exhibits a positive correlation with chlorophyll.

1 – The Benguela and Canary Upwelling Systems

- Benguela Upwelling System (BUS) and Canary Upwelling System (CUS): two of the four major eastern boundary Upwellings Systems.
- Nutrient rich upwelled cold waters close by the coastline enhancing primary production and then the whole ecosystem production.
- Widespread marine ressources harvesting and high implication in social, economic and human aspects → vulnerability.
- High spatial and temporal variability of these currents and their associated ecosystems.

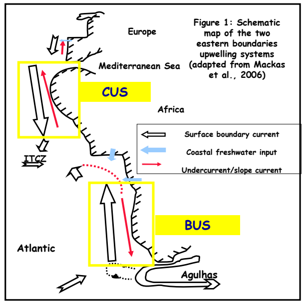


Figure 1: Schematic map of the two eastern boundaries upwelling systems (adapted from Mackas et al., 2006)

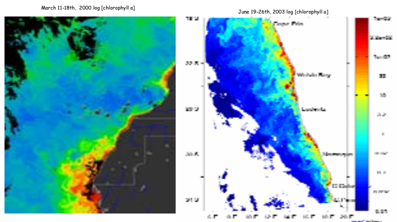


Figure 2 : Weekly SeaWiFS averages for the Benguela and Canary Upwelling Systems

Table 1: Main physical characteristics of the 2 upwelling systems (adapted from Mackas et al., 2006)

	Shelf width and orientation	Topographic features	Eddies, filaments	Ekman upwelling	Freshwater input/ buoyancy current	Coastal trapped waves	Wind stress
Canary	Mostly NS ; 75-200 km	Canary islands ; several large capes	+++ long filaments	Strong permanent upwelling	Very low	None	NE trade winds
Benguela	Mostly NS but zonal at S end ; 30-250 km	West pointing capes = upwelling centers ; Interaction with Agulhas at S end	++++ giant filaments	Strong permanent upwelling	None in S ; large at N end (Congo River)	Wind-driven T = 3-10 days	Strong spring summer north winds; earlier at N

2 – Data

* Montly SeaWiFS level 3 data (fig. 2), binned to a grid of approximately 9x9 km

* Surface velocity data (fig. 3) from a LEGOS/CTOH product (Sudre and Morrow, 2008). (u,v) computed at each grid point (¼°), from July 1999 until June 2006. This is a combination of:

- Geostrophic currents computed from a SSH field. To obtain this time variable Sea Surface Height (SSH), they combined Mapped Sea Level Anomaly (MSLA) with Mean Dynamic Topography (MDT) RIO05.
- Ekman currents at 15 m depth, from daily QuikSCAT wind stress fields.

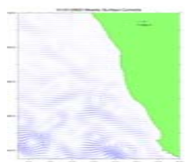
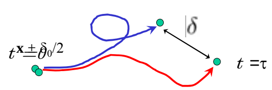


Figure 3: Surface velocity field of January the 1st 2003 over the Benguela region

3 – Finite-Size Lyapunov Exponents



$$\boxed{\lambda(\mathbf{x}, t, \delta_0, \delta_f) \equiv \frac{1}{\tau} \log \frac{\delta_f}{\delta_0}} \equiv FSLE \ (\text{days}^{-1})$$

The Finite Size Lyapunov Exponent (FSLE) (Aurell et al., 1997) is essentially the inverse of the time τ that it takes for two fluid particles initially separated a distance δ_0 to reach a separation δ_f. We set $\delta_0 = 0.025°$ and $\delta_f = 1°$.We can calculate FSLE by integrating the trajectories backward and forward-in-time. High values of FSLE locate strongly converging and diverging regions in the flow, respectively.

It is a Lagrangian tool that can be used to simultaneously characterize the mixing activity (highest where highest FSLE values) and the coherent structures that control transport at a given scale (d'Ovidio et al., 2004; d'Ovidio et al., 2008)

4 – Characterization of the horizontal mixing activity in the two Upwelling Systems

On fig. 4:

- Different mixing activity over each area.
- Typical FSLE values order of 0.01 to 0.25 days^{-1} corresponding to mixing times for mesoscale distances of 4-100 days.
- Low values of FSLEs in core of eddies (low dispersion rates), largest FLSEs in the outer part of eddies where streching is more important.

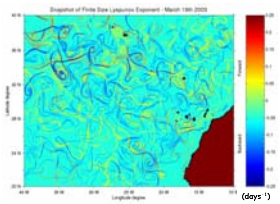


Figure 5: Snapshot of backward and forward FSLE over the CUS (March 19th 2003)

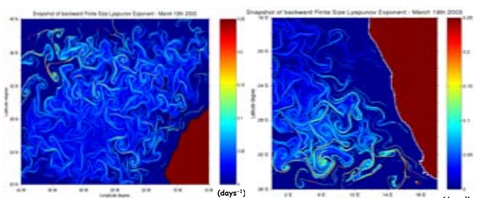


Figure 4: Snapshot of backward FSLE (March 19th 2003) over the CUS and BUS

On fig. 5:

- Regions with strong mixing appear organized in a tangle of stretching and compressing filaments (locating unstable and stable manifolds).
- Hyperbolic points are located at the intersections of the stable and unstable manifolds.

Geographical subdivision of each upwelling zone according to the temporal averages of FSLE (fig. 6)

- Computation areas are larger than analysis areas.
- BUS : the southern subsystem is more turbulent than the northern one, limited at 27°S (Lüderitz upwelling cell).
- CUS : the northern subsystem is more turbulent than the southern one, limited at 30°N (north of the Canarian archipelago).

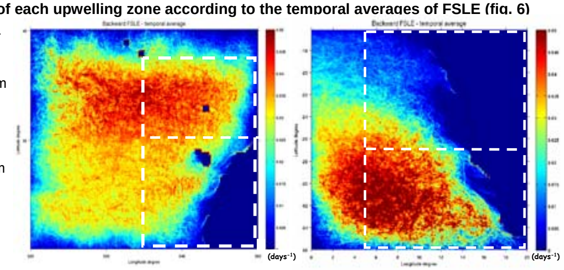
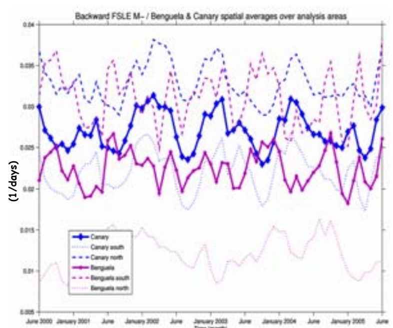


Figure 6: Temporal average of Backward FSLE over the whole period (June 2000 – June 2005) for CUS and BUS



Study of the mixing in each upwelling zone according to the spatial averages of FSLE (fig. 7)

- CUS is more turbulent than BUS.
- Strong inter-annual variability.
- The annual cycle is visible, especially in BUS.
- BUS: variability of the southern subsystem is high whereas the northern one is quite stable.
- CUS: high variability in phase of both subsystems.
- Coincidence between the low turbulence period and the period of upwelling relaxation.

Figure 7: Spatial average of Backward FSLE over the whole area for BUS and CUS

5 – FSLE and Chlorophyll

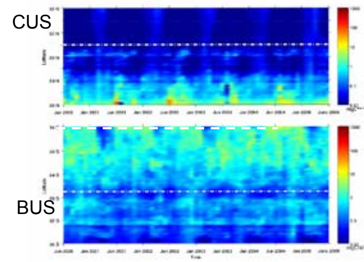
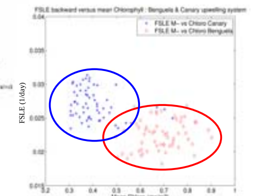


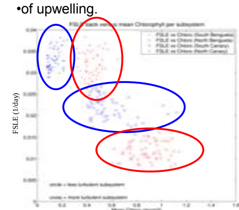
Figure 8: Hovmoller chlorophyll plot, integrated over the analysis area

- The subsystem limits from FSLE temporal averages are in good agreement with limits from chlorophyll Hovmoller.
- BUS: chlorophyll content is higher in the northern subsystem. In the CUS: chlorophyll content is higher in the southern one.

Figure 9: FSLE backward averages versus chlorophyll averages



- Clear characterization of each upwelling by a clear clustering.
- Good integrated index for comparative analysis of upwelling.



- LOW FSLE – HIGH CHLOROPHYLL. HIGH FSLE – LOW CHLOROPHYLL.
- Less turbulent systems are characterized by low FSLE & high chlorophyll (wide range).
- Most turbulent systems are characterized by high FSLE (wide range) & low chlorophyll.

Figure 10: FSLE backward averages versus chlorophyll averages per subsystem

6 – Ekman transport and Chlorophyll

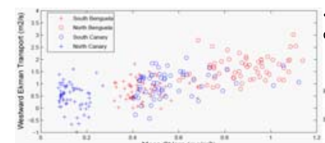
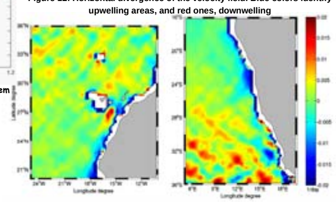


Figure 11: Ekman transport versus chlorophyll averages per subsystem

- There is a positive correlation between Ekman offshore transport and Chlorophyll

Figure 12: Horizontal divergence of the velocity field. Blue colors identify upwelling areas, and red ones, downwelling



- Vertical upwelling is correlated with high Chlorophyll, and also with low FSLE

7 – Summary

- Both upwelling systems are divided into 2 sub-systems, the northen and the southern ones. They have distinct mixing activity and chlorophyll signal.
- A new integrated index for a comparative study: FSLE vs Chlorophyll clusters.
- Negative correlation between FSLE and chlorophyll in upwelling areas
- Positive correlation Ekman transport with Chlorophyll
- Apparently, strong Ekman offshore pumping is associated with lower stirring activity, and with a larger amount of upwelling.

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