

Biological Impact of Ocean Transport: A Finite-Size Lyapunov Characterization ^{*}

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Abstract: The Lagrangian description of fluid transport has been largely enriched with the introduction of stretching quantifiers such as the different types of Lyapunov exponents. Here we will focus on the finite-size Lyapunov exponent case, as applied to horizontal ocean flows estimated from satellite altimetry. The influence on biological organisms of the structures revealed by the Lyapunov analysis will be illustrated with examples from the bottom and from the top of marine ecosystems: the distribution of phytoplankton in ocean upwelling areas, and the trajectories of frigatebirds in the West Indian Ocean, which fly on top of the ridges of Lyapunov structures. The convenience of moving from a two-dimensional to a fully three-dimensional description is highlighted.

Keywords: Lagrangian transport, Lyapunov exponents, Lagrangian Coherent Structures, ocean altimetry, ocean upwelling, chlorophyll distribution, phytoplankton, frigatebirds.

1. INTRODUCTION

Mixing and transport properties of the sea surface are being widely studied from the Lagrangian viewpoint (Buffoni et al., 1997; Griffa, 1996; Mancho et al., 2006). Lagrangian diagnostics exploit the spatio-temporal variability of the velocity field by following fluid particle trajectories, in contrast with Eulerian diagnostics, which analyze only frozen snapshots of data.

The most used of these Lagrangian quantities are the different types of local Lyapunov exponents, which measure the relative dispersion of transported particles (Artale et al., 1997; Aurell et al., 1997; Boffetta et al., 2001; Haller and Poje, 1998; Haller, 2000). They give information on dispersion processes but also detect and visualize Lagrangian Coherent Structures (LCSs) in the flow such as vortices, barriers to transport, or fronts (Haller and Yuan, 2000; Lapeyre, 2002; Joseph and Legras, 2002; Koh and Legras, 2002; d'Ovidio et al., 2004; Beron-Vera et al., 2008; d'Ovidio et al., 2009).

It is known that filaments, eddies, and other mesoscale and submesoscale structures present in oceanic flows impact marine ecosystem dynamics in a variety of ways (Bakun, 1996; Rossi et al., 2008, 2009; Tew Kai et al., 2009). Thus, the ability of Lagrangian indicators to trace these

structures and track them from the point of view of the organisms moving with the currents makes Lyapunov-like quantities a powerful tool to analyze the impact of ocean motions on marine ecosystems. In the following we briefly introduce finite-size Lyapunov exponents and describe in terms of them the surface stirring at several ocean locations, noting the impact of the structures found both at the base of the trophic chain (phytoplankton distributions) as on top predators (frigatebirds).

2. CHARACTERIZING SURFACE OCEAN FLOW WITH LYAPUNOV EXPONENTS

2.1 Velocity data from the ocean surface

We have used the weekly global $1/4^\circ$ resolution product of surface currents developed by Sudre and Morrow (2008). 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 satellite altimetry sea level anomalies combined with a mean dynamic topography from Rio and Hernández (2004).

2.2 Finite-size Lyapunov exponents

We quantify horizontal transport by Finite Size Lyapunov Exponents (FSLEs) (Aurell et al., 1997), which are spe-

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cially 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 particles initially separated by a distance δ_0 reach a final separation distance δ_f , following their trajectories in a 2D velocity field. At position x and time t the FSLE is given by: $\lambda(x, t, \delta_0, \delta_f) = \frac{1}{\tau} \log \frac{\delta_f}{\delta_0}$. We are in fact considering the four neighbors of each gridpoint and we selected the orientation of maximum separation rate (fastest neighbor to reach the final separation distance). The equations of motion that describe the horizontal evolution of particle trajectories are computed in longitudinal and latitudinal spherical coordinates. Numerical integration is performed by using a standard fourth-order Runge-Kutta scheme with an integration time step of $dt = 1$ day. Spatiotemporal interpolation of the velocity data is achieved by bilinear interpolation.

An alternative to FSLE is the Finite-Time Lyapunov exponent (Haller, 2001; Beron-Vera et al., 2008) but we expect that similar results would be obtained by this last technique for the present spatial and temporal scales. This is so because we use a value of δ_0 smaller than the typical structures in the velocity field, so that FSLE is close to the value of the local Lyapunov exponent and thus of the FTLE at large times (Aurell et al., 1997; Artale et al., 1997).

In most of the applications we follow the trajectories for 300 days, so that if τ gets larger than 300 days, we define $\lambda = 0$. FSLEs depend critically on the choice of two length scales: the initial separation δ_0 and the final one δ_f . d’Ovidio et al. (2004) argued that δ_0 has to be close to the intergrid spacing among the points x on which FSLEs will be computed, which is $\delta_0 = 0.025^\circ$. On the other hand, since we are interested in mesoscale structures, δ_f is chosen equal to 1° , implying a separation distance of about 110 km close to the equator. In this respect, the FSLEs represent the inverse time scale for mixing up fluid parcels between the small-scale grid and the characteristic scales of eddies in these areas. Choosing slightly different values for δ_f does not alter qualitatively our results, the main pattern and averages remaining the same.

The time integration of the particle trajectories can be performed in two different ways: forward or backward in time. In chaotic systems the regions of highest stretching are line-shaped, and heuristic arguments indicate that these lines, in the forward-in-time integration case, approximate stable manifolds of hyperbolic points (Joseph and Legras, 2002; Boffetta et al., 2001; Koh and Legras, 2002; d’Ovidio et al., 2004). When calculated for the time-backwards evolution, the highest FSLE values locate strongly attracting lines which approximate the flow unstable manifolds. As a consequence, these ridges, i.e. lines of maximum separation or convergence rates, move with the flow as if they were material lines and thus delineate fluid domains with quite distinct origin and characteristics. Backward FSLEs’ lines have a clear interpretation as fronts of passive scalars driven by the flow (d’Ovidio et al., 2009). These lines strongly modulate the fluid motion since when reaching maximum values, they act as transport barriers for particle trajectories thus constituting a powerful tool for predicting

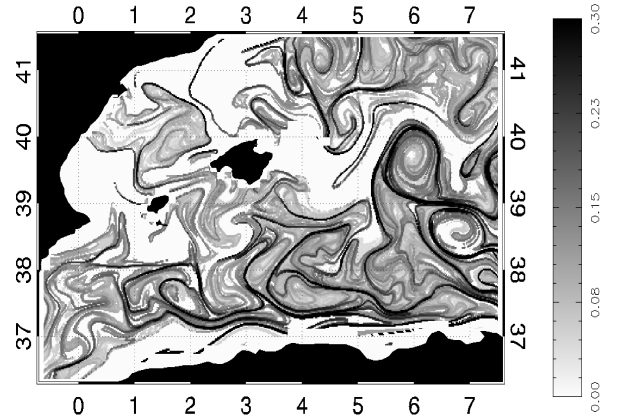


Fig. 1. Backwards FSLE distribution in the Western Mediterranean (21 June 2010) calculated from satellite altimetry. Values are coded in grey levels, from 0 to 0.30 day^{-1} , and the largest ones arise along lines which approximate unstable manifolds of hyperbolic points.

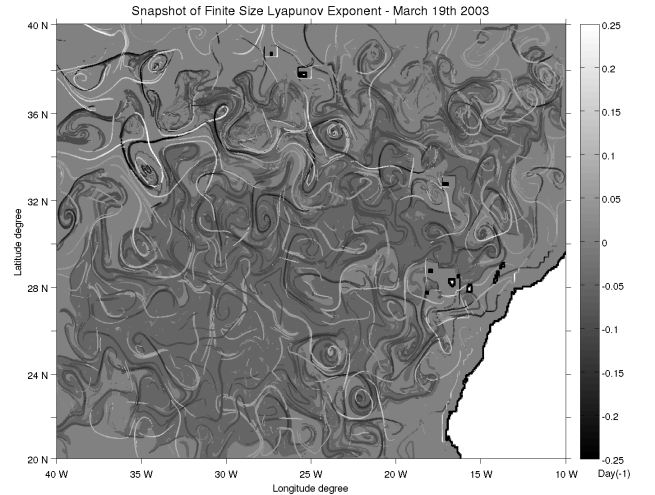


Fig. 2. FSLE fields in the Canary Islands area. Values of the forward FSLE are coded in gray levels with positive values, and backward with negative ones. The intersections of the strongest lines locate intense hyperbolic points.

fronts generated by passive advection, eddy boundaries, material filaments, etc. which greatly influence biological organisms living in the sea.

Figure 1 shows the backwards FSLE distribution in the Western Mediterranean in a particular day of June 2010. A variety of eddy- and front-like mesoscale structures is observed. The strongest lines act as material separations between water masses, their motion characterizes the routes of transport, and mixing measures can be obtained from them (d’Ovidio et al., 2004, 2009). Close agreement between the implications of these fields for tracer transport and actual satellite observations of surface temperature has been confirmed d’Ovidio et al. (2009).

On the other hand, Fig. 2 shows forward (positive values in the grey-level code) and backward (negative values in the

grey-level code) FSLEs in the Atlantic Ocean close to the Canary Islands. Eddies and filaments are seen again, but now we can also identify the strongest hyperbolic points as the intersections of the lines of large Lyapunov values in the forward and backward integrations. The hyperbolic points are the fundamental entities in more *lobe-dynamics*-oriented approaches to Lagrangian transport (Mancho et al., 2006, 2008).

3. BIOLOGICAL IMPACT OF SURFACE STIRRING

3.1 FSLE and chlorophyll distributions

Phytoplanktonic organisms of different types and sizes populate the upper layers of all the world oceans. Their distributions can be conveniently monitored from space by satellite radiometers observing the ocean color at the frequency bands of the phytoplankton pigment *chlorophyll-a*.

We have analyzed (Rossi et al., 2008, 2009) a five-year long time series (from June 2000 to June 2005) of chlorophyll-*a* concentrations from the SeaWiFS satellite sensor, with a resolution of approximately 9 by 9 kilometers. Our focus was the study of the Eastern Boundary Upwelling Systems (EBUS), which are the most biologically productive regions of the world. They include the Canary and the Benguela upwelling systems in the Atlantic Ocean and the Peru/Chile and California upwelling systems in the Pacific Ocean. Under the action of wind from quasi-stationary high pressure cells over the subtropical ocean basins, a surface uprising of deep cold water rich in nutrients occurs over continental shelves almost all year long. This process explains the high primary production in these regions which constitutes the base of a highly dynamical and rich food chain.

These EBUS develop diverse structures such as intense fronts, coastal plumes in retention areas, offshore filaments and eddies which interplay with the complex spatial distribution of phytoplankton. We have investigated this link between turbulence and chlorophyll concentration (as a proxy for biological activity) and Fig. 3 summarizes one of the main results (Rossi et al., 2008, 2009): there is a clear negative correlation between horizontal stirring activity, as quantified by the FSLE values, and chlorophyll concentration, so that the strongest horizontal turbulence, smaller the chlorophyll amount. The interpretation is that intense stirring disperses the high input of nutrients which the EBUS are receiving from depth, so that larger amounts of nutrients remain in the more quiescent areas. This behavior contrasts with the one expected in poor areas with small input of nutrients, in which localized eddies and turbulent active spots enhance productivity (Oschlies and Garçon, 1998).

3.2 Frigatebirds fly on top of Lyapunov ridges

Since planktonic organisms are transported in a nearly passive way by ocean currents, the influence of turbulence and stirring on phytoplankton, as exemplified in the previous subsection, is not surprising and in fact it has been a subject of research since long time ago. Less understood is the way in which this influence at the base of the food chain scales up thorough plankton consumption and consequent

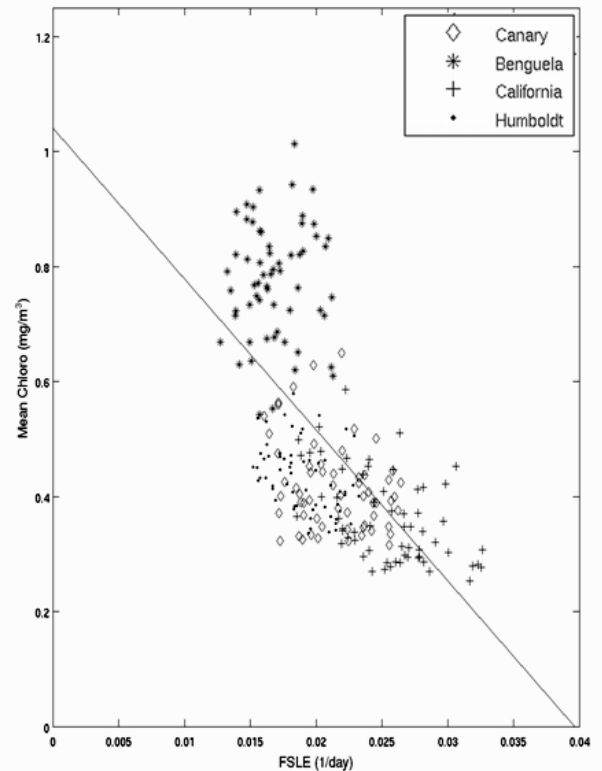


Fig. 3. Chlorophyll-*a* versus backward FSLEs, averaged over the areas of each of the four upwelling systems. Each symbol corresponds to the average data for one of the months between June 2000 and June 2005. The line is a linear fitting.

predation towards higher trophic levels until arriving to the higher predators.

We have analyzed (Tew Kai et al., 2009) 50 trajectories of eight frigatebirds in the Mozambique channel (i.e. the area of the West Indian Ocean between Madagascar Island and the African coast, obtained over a 2-month observation period (August and September 2003). These birds occupy, together with tuna, dolphins and other marine animals, the top-predator position of their ecosystem, consuming small flying fishes and squids which come at the sea surface. They fly hundreds or thousands of kilometers from their nest colony (Europa Island in the middle of the channel) in a few days and spend their entire foraging trips in flight. The birds were equipped with miniature transmitters and altimeters which allowed tracking of their flying trajectories. Simultaneous altimetric satellite data in the region were used to calculate FSLE maps during the study period. The outcome, exemplified in Fig. 4, was quite surprising: statistical analysis, and sometimes even direct observation of the images, indicates that most of the time frigatebirds fly on top of the structures identified by the Lyapunov analysis (the LCSs), so that they should be using these physical structures for navigation and fishing. These Lyapunov structures, with convoluted filamental shapes, appear then as the analogous to the *ecological corridors* of terrestrial ecology. After comparing



Fig. 4. Composite image showing the study area (rectangle) in the Mozambique channel, a frigatebird, and a picture of a frigatebird trajectory (small circles and triangles) on top of a map of FSLE values (in grey shades). The bird's trajectory traces the Lagrangian Coherent Structures revealed by the FSLE map.

bird positions during long and short trips and different parts of these trips, we have proposed (Tew Kai et al., 2009) several hypotheses to understand how frigatebirds can follow these LCSs. The birds might use visual and/or olfactory cues and/or atmospheric current changes over the structures to move along these biologic corridors.

4. TOWARDS THREE-DIMENSIONAL LAGRANGIAN COHERENT STRUCTURES

Complete understanding of the relationship between physical circulation, as quantified by the Lyapunov methods described above, and biological dynamics clearly will need of a fully three-dimensional description of the flow. This is so because vertical motions in ocean are responsible for most of the transport of nutrients from deep waters towards the surface, and thus they will be responsible for enrichment processes at least as much as, and probably more than, horizontal motions. The Lyapunov techniques discussed above can be readily generalized to three-dimensional flows. An example of backwards FSLE distribution is shown in Fig. 5 which is computed from a three-dimensional numerical simulation of a turbulent channel flow (Reynolds number 3110). Lagrangian Coherent Structures appear as sheets instead of lines. Similar analysis may be performed from velocity fields obtained from ocean numerical models, but obtaining from actual ocean observations three-dimensional data sets of enough resolution remains an important challenge.

5. CONCLUSION

We have shown that the technique of the FSLEs is a powerful tool to characterize both the horizontal stirring in the ocean surface and its impact on biological organisms.

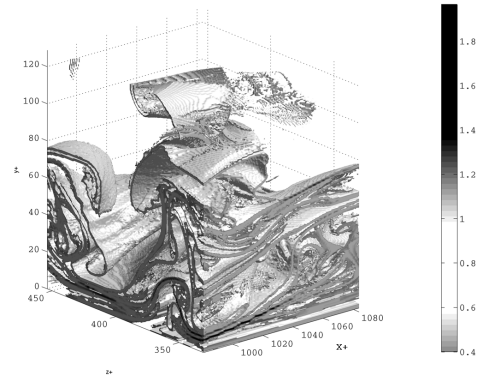


Fig. 5. Backwards FSLE distribution from a three-dimensional numerical computation of a turbulent channel flow (Reynolds number 3110). Mean flow direction is in the direction labeled as $X+$, and a wall is at the bottom. Lagrangian Coherent Structures appear as sheets instead of lines.

By means of two examples we have seen that whole ecosystems, from primary plankton producers to higher predators, respond to the presence of physical structures in the ocean turbulence by means of mechanisms which we could now begin to elucidate. Moving from the analysis of surface flows towards a three-dimensional description will improve our understanding of the processes involved.

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