Stretching fields and lines in the transport dynamics of the Western Mediterranean

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We summarize recent work on the location of Lagrangian structures in velocity fields obtained from realistic simulations and from satellite altimetry of the surface layers of the Mediterranean sea. Finite-size Lyapunov exponents are found to be useful quantities to characterize stretching and compressing structures, and their implications for mixing. Direct calculation of hyperbolic points and their stable and unstable manifolds identifies ocean structures, and allows the use of the tools of lobe dynamics to characterize fluid transport.

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Hyperbolic points and their manifolds organize the phase space of dynamical systems. In the Lagrangian description of fluid transport they determine transport routes and mixing properties [1]. Stretching fields are correlated with these structures and thus provide an heuristic method to approximate them. Calculations of the above mentioned objects has been performed in simplified model flows since some time ago. More recently, increased computer power and theoretical insight are allowing their identification in realistic and in observed fluid flows.

We have recently applied dynamical systems tools to the analysis of transport and mixing in surface velocity flows obtained from satellite altimetry and from numerical simulations of the Western Mediterranean. These are turbulent flows with a very complex spatial and temporal structure, but nevertheless useful information of oceanographic interest has been extracted. Section 1 describes calculations of Finite-size Lyapunov exponent distributions and Section 2 characterizes a frontal structure in terms of hyperbolic manifolds.

1 Finite-size Lyapunov exponents in the Algerian basin from satellite altimetry

Finite-size Lyapunov exponent (FSLE) fields characterize the local stretching experienced by fluid elements during their motion, as a function of their initial placement. They are qualitatively similar to finite-time Lyapunov exponents, but characterizing stretching up to a given size, instead of during a given time. In chaotic systems the regions of highest stretching are line-shaped, and heuristic arguments indicate that these lines approximate stable manifolds of hyperbolic points [2]. When calculated for the time-backwards evolution, the highest FSLE values locate strongly attracting lines which approximate the flow unstable manifolds. FSLE fields have been recently calculated in oceanographic contexts, giving insight into the transport properties and mixing intensity of ocean surface flows [3, 4]. Figure 1 shows the backwards FSLE distribution in the South-Western Mediterranean (particularly in the Algerian basin) in a particular day of the Spring of 1997. This has been calculated [5] from time and space interpolation of a sequence of surface velocity fields derived from satellite altimetry observations. 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 [3, 5]. Close agreement between the implications of these fields for tracer transport and actual satellite observations of surface temperature has been confirmed [5].

2 Manifold characterization of the North-Balearic front

FSLE fields provide a useful synoptic view of whole ocean regions. Locating and extracting the relevant lines in an objective way from such fields is however difficult and more direct calculations of hyperbolic points and stable and unstable manifolds is needed to quantify transport with the tools of lobe dynamics. A recent review of the available techniques is [6]. Figure 2 shows pieces of stable and unstable manifolds associated to hyperbolic points in the North-Western Mediterranean, as

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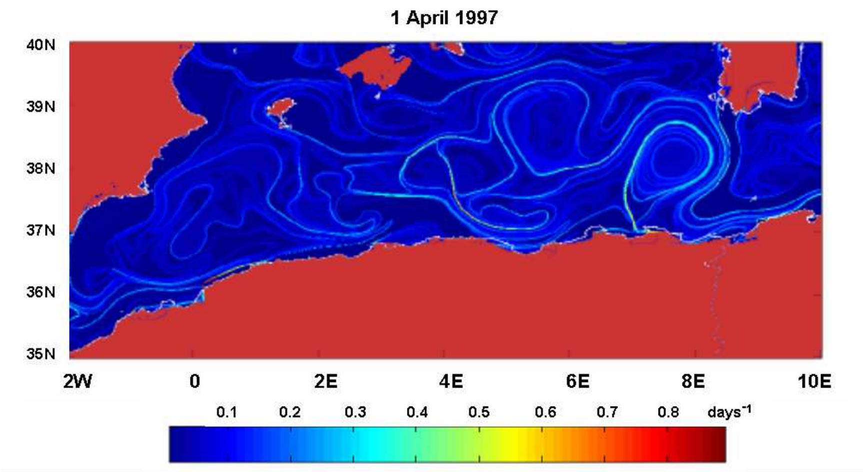

Fig. 1 Backwards FSLE distribution in the South-Western Mediterranean calculated from satellite altimetry [5]. Values are color coded and the largest ones arise along lines which approximate unstable manifolds of hyperbolic points.

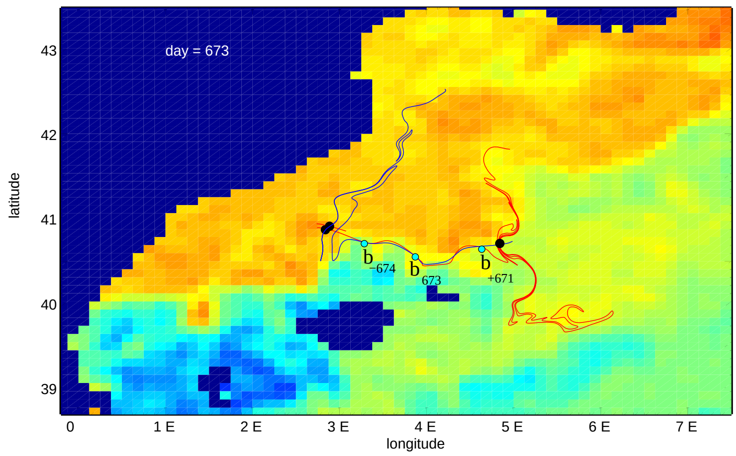

Fig. 2 Structures characterizing the North-Balearic front from computer simulated surface velocities. Blue line is the stable manifold of a eastern hyperbolic point (the black dot to the right) and the red one is the unstable manifold of a western one (one of the black dots to the left). The background colors display the surface salinity obtained from the same computer run.

calculated from a surface velocity field obtained from the DieCast ocean circulation model [7]. The horizontal structure, formed by intertwined pieces of unstable and stable manifolds, separates northern saltier waters (yellow-red colored) from southern fresher ones (blue colored). This is precisely the known location and behavior of the so-called North-Balearic front, the main transition region in the North-Western Mediterranean. Lobe dynamics calculations [7] identify the main transport routes, and help to understand the persistent observed gradients across the North-Balearic front as a consequence of the small area of the lobes which are able to cross the relevant manifolds.

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References

[1] S. Wiggins. *The dynamical systems approach to Lagrangian transport in oceanic flows*, Annu. Rev. Fluid Mech. **37**, 295 (2005).

[2] B. Joseph and B. Legras, *Relation between kinematic boundaries, stirring, and barriers for the Antartic Polar vortex*, J. Atm. Sci. **59**, 1198 (2002).

[3] F. d'Ovidio, V. Fernández, E. Hernández-García, and C. López, *Mixing structures in the Mediterranean sea from finite-size Lyapunov exponents*, Geophys. Res. Lett. **31**, L12203 (2004).

[4] Y. Lehahn, F. dOvidio, M. Lévy, E. Heyfetz,*Stirring of the Northeast Atlantic spring bloom: a Lagrangian analysis based on multi-satellite data*, J. Geophys. Res. **112**, C08005 (2007).

[5] F. d'Ovidio, J. Isern-Fontanet, C. López, E. Hernández-García and E. García-Ladona, *Comparison between Eulerian diagnostics and finite-size Lyapunov exponents computed from altimetry in the Algerian basin*, submitted (2007).

[6] A.M. Mancho, D. Small, and S. Wiggins, *A tutorial on dynamical systems concepts applied to Lagrangian transport in oceanic flows defined as finite time data sets: Theoretical and computational issues*, Phys. Rep. **437**, 55 (2006).

[7] A.M. Mancho, E. Hernández-García, D. Small and S. Wiggins *Lagrangian transport through an ocean front in the North-Western Mediterranean Sea*, J. Phys. Oceanogr., to appear (2007).

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