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Dispersion of passive tracers and finite-scale Lyapunov exponents in the Western Mediterranean Sea

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Abstract

A realistic 4-year dataset of the surface velocity field of the western Mediterranean Sea obtained with the Mediterranean Forecasting System and the GFDL-MOM model was used to obtain the finite-scale Lyapunov exponents (FSLE) and finite-size diffusion coefficients. Dispersive properties and Lagrangian parameters in four sub-basins are discussed, and a comparison is made between the FSLE and the Eulerian Okubo–Weiss parameter obtained for the same area with the same dataset. An additional comparison is made with the FSLE calculated from independent datasets obtained from 15 drifters launched in the Algerian basin during October of 1996.

Keywords: Diffusion; Finite-scale Lyapunov exponent; Surface circulation; Flow topology; Numerical simulations; Lagrangian drifters; Western Mediterranean Sea

1. Introduction

The study of horizontal transport and mixing in the ocean is of great interest in physical and biological oceanography because of the wide range of related phenomena, e.g., large-scale transport of water properties (Ganachaud and Wunsch, 2000, 2002), marine population dynamics (Bracco et al., 2000a; Martin, 2003), plankton patchiness (Fennel, 2001) or dispersion of pollutant spills. The most frequent approach to the study of tracer dispersion on the sea has been based on the Reynolds separation between the slowly variable mean flow and the turbulent movements acting on small scales. In the limit when the number of tracers tends to infinity, this approach leads to the well-known advection–diffusion equation, where the mean velocity appears in the advection term and the turbulent velocity has to be modelled. This is parameterized through the concept of eddy diffusivity, which allows one to write a Fickian diffusion term in which the characteristic coefficient is a function of space and time (Figueroa and Olson, 1994). However, studies on two-dimensional (2-D) and quasi-geostrophic turbulence have shown (Provenzale, 1999; Pasquero et al., 2001) that coherent structures as long-lived vortices induce non-Gaussian velocity probability density functions leading to an anomalous tracer dispersion not properly captured by this kind of simple model. In addition, very simple non-turbulent, time-dependant flows induce chaotic dynamics where both passive and active tracers evolve through complex

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particle trajectories (e.g. Ottino, 1990). The poor performance of eddy-like diffusion parameterization is, to a large extent, due to the fact that the diffusivity tensor is mathematically well defined only in the limit of infinite times and, therefore, gives a sensible result only if the characteristic length of the velocity field is much smaller than the size of the domain (Artale et al., 1997).

Another limitation for the applicability of classical methods for the characterisation of dispersion appears when the mean and turbulent parts of the flow are not well separated, as is the normal case in the velocity field of intermediate size seas. For this reason, increasing effort has been made in recent years to characterize the diffusion properties in some alternative way which can be used in these real situations. A promising approach is the finite-size Lyapunov exponent or finite-scale Lyapunov exponent (FSLE; Aurell et al., 1996; Boffetta et al., 2000) and the related finite-size diffusion coefficient (FSDC; Artale et al., 1997). Lagrangian approaches with the FSLE and the FSDC have been traditionally used only in the field of mathematical dynamical systems and are only beginning to be applied to geophysical flows (e.g. LaCasce and Bower, 2000; Joseph and Legras, 2002; Lacorata et al., 2004; d'Ovidio et al., 2004). The need to have high enough resolution, both in time and space, of the velocity field to compute such quantities has prevented the use of real-field data for such a purpose. At present things have notably changed because of intensive deployment of Lagrangian drifters through cooperative international programs and the improvement of high-resolution realistic numerical simulations of the ocean circulation (e.g. Garraffo et al., 2001; Mariano et al., 2002), and only rather recently has it been possible to use Lagrangian observations for computing FSLE (LaCasce and Bower, 2000; Lacorata et al., 2001; LaCasce and Ohlmann, 2003).

The FSLE technique has been used for two complementary goals: for characterizing dispersion processes and for detecting Lagrangian structures, such as transport barriers or vortex boundaries. Focusing mainly in the second use, Boffetta et al. (2001) compared the performance of Eulerian techniques, such as the Okubo–Weiss criterion and its generalisation proposed by Hua and Klein (1998), with the Lagrangian finite-time Lyapunov exponent and FSLE applied to a meandering jet. The FSLE was the only diagnostics able to give the correct description of the presence of large-scale barriers to the transport in the geometry studied.

In this study, the FSLE and FSDC are used to study dispersion and lateral mixing in the western Mediterranean Basin. The FSLEs are especially meaningful as a local diagnostic of transport when they are observed in an almost frozen-field time scale. However, the mean FSLE over periods of several years can be useful also as a bulk estimation of the long-term diffusivity in the sub-basin scale.

In the western Mediterranean Basin, fresh Atlantic waters entering through the Gibraltar strait spread over saltier Mediterranean water. The circulation of light waters is characterised in the westernmost part, the Alboran Sea, by two big anticyclones that fill the sub-basin. East of the Alboran Sea Atlantic waters propagate along the Algerian coast to the Channel of Sardinia, forming what is known as the Algerian Current (see Fig. 1). Further east, part of Atlantic waters flow through the Sicily Strait and enters the eastern Mediterranean Sea, while the rest of Atlantic waters circulates towards the Tyrrhenian Sea. In the northern part of the western Mediterranean Sea, the main feature is the presence of the Northern Current, which flows counterclockwise along the continental shelf (Millot, 1999). Such a current may become unstable, generating intense eddy activity, which enhances large-scale mixing in the surface layer in regions such as the Algerian Basin, as is evident in climatological atlases of water properties (Picco, 1990; Brasseur et al., 1996).

The complex geometry of the basin and its size make difficult the application of classical methods for the characterisation of dispersion. Some studies have already analysed FSLE and FSDC in the Mediterranean Sea and their implications for dispersion in the basin. Iudicone et al. (2002) have used this parameter to study the sensitivity of numerical tracer trajectories to uncertainties in the dataset using a simulated velocity field for the Mediterranean Sea and d'Ovidio et al. (2004) have used the same parameter to visualise and identify Lagrangian structures from a numerical model of the Mediterranean Sea forced by wind. Nevertheless, such studies have been based on numerical models in which the main goal was not to forecast the real daily behaviour of the Mediterranean Sea but to obtain the high numerical resolution needed to compute the quantities under study.

Data assimilation is essential in obtaining a realistic picture of the oceanic velocity field. In this work, we use a fairly realistic dataset of the surface velocity field over 4 years to obtain FSLE and