ARTICLE IN PRESS

Continental Shelf Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Evaluation of surface Lagrangian transport barriers in the Gulf of Trieste

F. Enrile[a,*], G. Besio[a], A. Stocchino[a], M.G. Magaldi[b,c], C. Mantovani[b], S. Cosoli[d], R. Gerin[d], P.M. Poulain[d]

[a] DICCA, Dipartimento di Ingegneria Civile, Chimica e Ambientale, Università degli Studi di Genova, Via Montallegro 1, 16145 Genova, Italy
[b] ISMAR-CNR, S.S. di Lerici, Lerici, SP, Italy
[c] Johns Hopkins University, Earth and Planetary Sciences, Baltimore, MD, USA
[d] OGS, Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Trieste, Italy

ARTICLE INFO

Keywords:
Lagrangian Coherent Structures (LCS)
Gulf of Trieste
CODE drifters
FTLE and FSLE
Single-particle tracking

ABSTRACT

The present work aims to detect Lagrangian transport barriers in the Gulf of Trieste by means of Lyapunov-exponent approach and tensorlines of the Cauchy-Green tensor. Lagrangian Coherent Structures (LCSs) are calculated employing 2D surface velocity fields measured by the coastal radars of the TOSCA EU research project (Tracking Oil Spills & Coastal Awareness Network). Moreover, surface drifters were deployed during the project. Comparisons between Eulerian velocity of HF-radar fields and Lagrangian velocity of drifters are carried out alongside single-particle tracking reliability. In particular, the possible influence of the data gaps in the HF-radar fields have been carefully considered. LCSs have proven to be robust against the quality of the starting HF-radar fields, leading to helpful insights in drifter positions. Indeed, after 24-hour integration the observed position of the drifter is approximately 1.5 km far from the nearest LCS, while a standard approach based on single-particle computations leads to larger errors (up to 5–7 km). However, such result must be properly interpreted taking into account the elongated nature of LCSs. A comparison between two common diagnostic tools of Lagrangian barriers is performed: Finite-Time and Finite-Size Lyapunov Exponent fields are compared in order to assess whether the patterns detected by the two measures are comparable. Finally, a joint analysis between LCSs and single-particle tracking is carried out and the results suggest that it would be desirable to couple these two approaches in real applications.

1. Introduction

Knowledge of the fate of pollutants and biological quantities in coastal environments is of paramount importance owing to their impact on natural ecosystems. Several approaches have been proposed in order to tackle this challenging task. However, the most promising strategies shall be based on a Lagrangian point of view, being a natural framework for analyzing mixing processes. Among the available Lagrangian models and measures, Lagrangian Coherent Structures, hereinafter LCSs, are known to strongly control and govern the transport of mass in disparate complex fluid flows (Boffetta et al., 2001; Shadden et al., 2005). In fact, LCSs act as material lines/surfaces within a given flow field and, thus, mass transport is, in principle, inhibited through them and a possible spatial/temporal segregation of pollutants and nutrients might be generated and sustained for a given circulation pattern.

Their heuristic identification mainly relies on the application of Lyapunov-exponent-based diagnostic tools. In particular, heuristic LCSs are defined as the ridges, locus of maxima, in both Finite-Time and Finite-Size Lyapunov Exponent (FTLE and FSLE, respectively) scalar fields (Shadden et al., 2005). However, several restrictive conditions (Haller, 2011; Karrasch and Haller, 2013; Allshouse and Peacock, 2015b) are needed to actually detect transport barriers. Despite these restrictions, the application of FTLEs and FSLEs continues to soar, especially in geophysical applications. The success of this approach can be found in its relatively simple implementation and great efficacy in highlighting transport barrier candidates and detecting the directions along which transport is likely to develop (Lekien et al., 2005; Peng and Dabiri, 2009; Shadden et al., 2009; Huhn et al., 2012; Cencini and Vulpiani, 2013; Berta et al., 2014b; Hernández-Carrasco et al., 2014; St-Onge-Drouin et al., 2014; Allshouse and Peacock, 2015a; Garaboa-Paz et al., 2015). However, only a few examples of the simultaneous implementation of both temporal and spatial analysis can be found in the literature, often providing contrasting indications. Boffetta et al. (2001) show that FTLEs are limited to small-scale properties of dispersion, whereas FSLEs are the most efficient method for detecting large-scale cross-stream barriers. On the contrary, FTLEs have been shown to better

* Corresponding author.
E-mail address: francesco.enrile@hotmail.it (F. Enrile).

https://doi.org/10.1016/j.csr.2018.04.016
Received 16 June 2017; Received in revised form 10 April 2018; Accepted 27 April 2018

capture recirculation regions than FSLEs (Sadlo and Peikert, 2007). In a recent paper, Peikert et al. (2014) show that, if properly calibrated by similarity measures, both FTLEs and FSLEs may produce comparable results that can be interchangeably used for most purposes in flow visualizations. Further investigation, especially in the context of realistic geophysical flows, will thus provide valuable information on the mutual importance of the Lagrangian measures, namely FTLE and FSLE. Indeed, oceanic coastal circulations, as the ones considered in the present study, may represent a challenging task along this direction. In fact, the computation of the FTLEs and FSLEs fields requires an in-depth knowledge of the circulations velocity field.

This requirement is only partially fulfilled when either satellite altimeter data (Harrison and Glatzmaier, 2012), numerical models (Haza et al., 2007, 2008) or coastal observations (Haza et al., 2010; Berta et al., 2014b) are employed. As a matter of fact, temporal and spatial resolution of the latter datasets may not be adequate to resolve the range of scales typical of the high Reynolds number of oceanic or coastal circulations. In this case, observations in coastal areas have recently benefited by the use of high-frequency (HF) radars, the number of which is rapidly increasing owing to their better resolution with respect to other oceanographic observational systems and reliability of the measured velocities. HF-radars provide maps of surface velocity with ranges up to 100 km, horizontal resolution of the order 1.5–3 km, and temporal resolution of the order of 0.25–1 h (Gurgel et al., 1999; Harlan et al., 2010; Paduan and Washburn, 2013). HF-radar velocity measurements have been validated against Lagrangian drifter observations leading to averaged differences mostly within the range 3–5 cm/s, whereas larger deviations, e.g. around 20 cm/s, can be attributed to the unresolved spatial variability of velocity fields at subgrid scale (Ohlmann et al., 2007). Although the accuracy reached with HF-radars is more than satisfactory, still several issues exist regarding the radar coverage and its operability in particular conditions. In fact, the measurable coastal areas strongly depends on the coastline geometry and on the presence of fixed and/or temporary obstacles of different nature. Furthermore, insufficient signal-to-noise ratios can be registered within some radar cells owing to severe weather conditions (strong winds, rough seas with large waves) or external interference at the radar emission frequency. As a result, holes and gaps can appear in the HF radar velocity maps and the reliability of the transport estimates based on these measures can be questionable. This can be particularly true in small scale embayments or coastal gulfs where radar resolution plays a critical role as well as local processes.

So far, only a few applications of HF-radar datasets have been used for FSLE calculations in the Mediterranean Sea (Haza et al., 2010; Berta et al., 2014b), compared to the numerous applications in the Atlantic and Pacific oceans. Indeed, a direct comparison of FSLE ridges with drifter data in the Mediterranean Sea has been discussed only in Haza et al. (2010).

The present study tries to cover this gap of knowledge, at least in part, and aims to either address some methodological issues and provide quantitative estimations of the relevant Lagrangian parameters.

Regarding the LCS detection and application we aim to detect both heuristic LCSs, through FTLEs, FSLEs and LCSs, applying the geodesic theory of transport barriers (Haller and Beron-Vera, 2012). Besides, we intend to assess whether, starting from the same high Reynolds number turbulent fields, FTLE and FSLE techniques lead to similar heuristic LCSs and how accurately the latter compare with drifter observations in a Mediterranean small scale area. Moreover, we aim to test the robustness of these Lagrangian analysis when applied to HF-radar fields. In fact, quite often the HF-radar velocity fields show several spatial gaps, mostly owing to signal problems, and we intend to show that FTLE-FSLE-LCS based methods are less sensitive to these data gaps with respect to standard Lagrangian approaches, e.g. absolute dispersion. The importance of this aspect could easily be appreciated having in mind the possible application of risk monitoring and Search and Rescue (SaR) operations based on HF-radar information.

In this study, we focus on a small (~ 20 km × 20 km) Mediterranean gulf, namely the Gulf of Trieste, GoT in the following, located in the Northeastern Adriatic Sea. The GoT area was targeted by the EU-MED project TOSCA (Tracking Oil Spills and Coastal Awareness network, http://www.tosca-med.eu) to investigate and test science-based methodologies, best practices, and response plans in case of accidents at sea (Bellomo et al., 2015). A coastal monitoring network based on HF-radars has been established under the framework of TOSCA with a special emphasis on oil spill pollution and on SaR operations. Thus, the results of the present work have practical applications and can be useful to indicate how reliable Lagrangian transport estimates based on HF-radars velocity fields in case of accidents at sea are.

The paper is organized as follows: in Section 2 a description of the HF-radar network and drifters used during the TOSCA project is provided. Section 3 is dedicated to the definition of FSLEs and FTLEs and their comparison. Section 4 assesses the influence of HF-radar data gaps on the Eulerian and Lagrangian properties of the surface circulation. Section 5 is dedicated to the comparison of drifter trajectories and heuristic LCSs while Section 6 takes into account rigorous LCSs. Finally, the conclusions are drawn in Section 7.

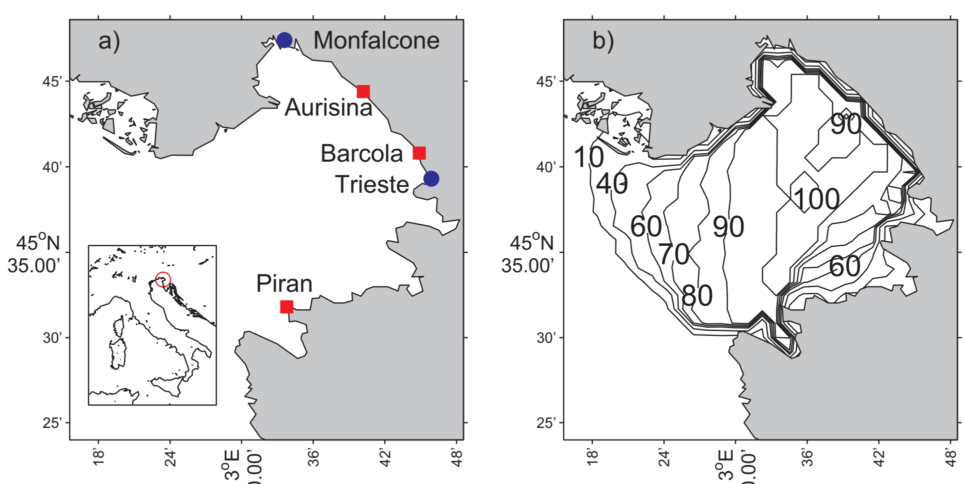

Fig. 1. Radar network locations in the Gulf of Trieste, red squares of Panel a), and percent coverage of the velocity field data derived from HF-radar measurements for April 23 to April 30, 2012, Panel b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).