Continental Shelf Research 77 (2014) 14–23

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Surface transport in the Northeastern Adriatic Sea from FSLE analysis of HF radar measurements

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ARTICLE INFO

Article history:
Received 18 February 2013
Received in revised form
9 November 2013
Accepted 22 January 2014
Available online 28 January 2014

Keywords:
Adriatic Sea
Trieste Gulf
Radar
Surface transport
FSLE
LCS

ABSTRACT

This study focuses on the surface transport in the Northeastern Adriatic Sea and the related hydrodynamic connectivity with the Gulf of Trieste (GoT) under calm or typical wind conditions: Bora (from the NE) and Sirocco (from the SE). The surface transport in the area has been investigated by evaluating the Finite-Size Lyapunov Exponents (FSLE) on the current field measured by the High Frequency (HF) coastal radar network. FSLE allow us to estimate Lagrangian Coherent Structures (LCSs), which provide information on the transport patterns associated with the flow and identify regions characterized by different dynamics. This work includes the development and set-up of the FSLE algorithm applied for the first time to the specific Adriatic area considered. The FSLE analysis during calm wind reveals an attractive LCS crossing the GoT entrance, marking the convergence between the Northern Adriatic and the outflowing gulf waters. During Bora episodes this attractive LCS is displaced westward with respect to the calm wind case, indicating that Bora drives an extended coherent outflow from the GoT. On the other hand, Sirocco wind piles up the water along the northern end of the basin. In this area an attractive LCS is found, extending mainly in the SW–NE direction. The sirocco-induced inflow of Adriatic waters in the GoT is mainly driven along its northern (Italian) side, as evidenced by the orientation of the LCS. Under Sirocco condition, as in the Bora case, there is no barrier in front of the gulf. No relevant LCSs are observed in the southern radar coverage area except for Bora cases, when a repulsive LCS develops in front of the Istrian coast separating water masses to the North and the South of it.

1. Introduction

The Adriatic Sea is a basin of the Eastern Mediterranean Sea enclosed between the Italian and the Balkan peninsula, and it separates respectively the Apennine mountains from the Dinaric Alps (Fig. 1). It extends in the NW–SE direction and communicates with the Ionian Sea through the Otranto Strait, located at its southern end. The mean surface circulation of the Adriatic Sea is characterized by a northwestward flow along the Balkan coast, known as the Eastern Adriatic Current (EAC), and a southeastward flow along the Italian coast, called the Western Adriatic Current (WAC) (Artegiani et al., 1997b; Zore, 1956). The EAC–WAC system results in a basin-wide cyclonic circulation in which three cyclonic gyres are embedded at the southern, middle and northern part of the Adriatic Sea, respectively (Artegiani et al., 1997a; Malanotte-Rizzoli and Bergamasco, 1983). Observations of water mass properties and currents evidence that the Northern Adriatic circulation is strongly influenced by the winds over the Adriatic area (Poulain et al., 2001). Due to its geographical orientation with respect to the surrounding orography (Apennines and Dinaric Alps) it is particularly affected by Bora and Sirocco winds (Orlić et al., 1994).

The Bora is a northeasterly cold and dry katabatic wind, with the most severe manifestations occurring typically during winter (Yoshino, 1976). The Sirocco blows from S–SE and by crossing the Mediterranean Sea it gets warm and humid. Unlike the Bora, which is characterized by a gusty nature, it keeps more homogeneous spatial characteristics over the Adriatic Sea (Ferrarese et al., 2008).

In the Northern Adriatic area, the Bora drives several dynamical processes both at the surface and in the deeper layers. These include the dense water formation in the northern and central part, the latter compensated by strong upwelling along the eastern margin (Lazar et al., 2007; Orlić and Gačić, 1992), and the intensification of the WAC (Ursella et al., 2006). The most prominent Bora-induced feature is a double gyre circulation (Zore-Armanda and Gačić, 1987) developing

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http://dx.doi.org/10.1016/j.csr.2014.01.016

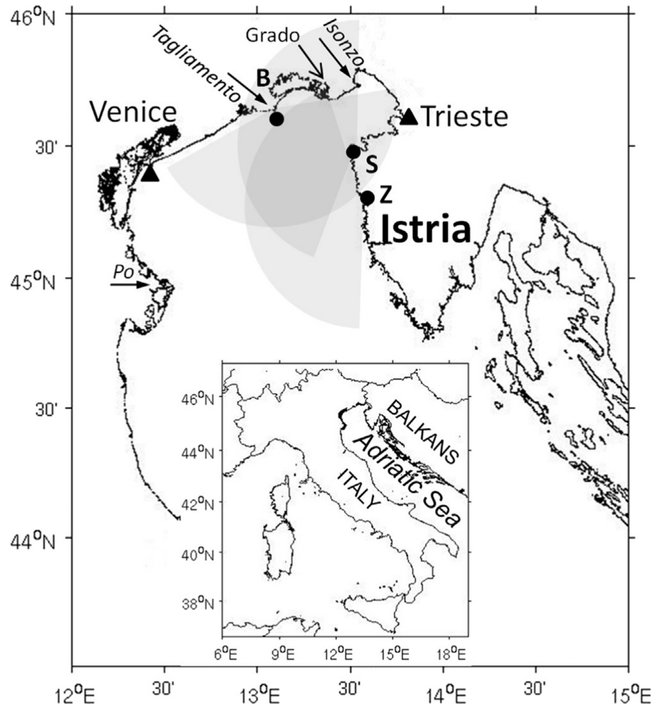

Fig. 1. The data set coverage over the Northern Adriatic area with the radar stations (dots) in Bibione (B), Savudrija (S) and Rt Zub (Z). The meteo-mareographic stations in Trieste and Venice (triangles). The main river estuarines: Po, Tagliamento and Isonzo. The Gulf of Trieste is the sea area landlocked within Savudrija-Grado ideal baseline.

as a consequence of the funneling of Bora to the North and the South of Istria (these paths are called "Bora corridors") (Lazić and Tošić, 1998). This pattern has been identified both by drifter trajectories (Poulain, 2001) and by model simulations (Kuzmić et al., 2007; Jeffries and Lee, 2007). On the other hand, Sirocco enhances the EAC (Ursella et al., 2006) by piling up sea water along the Northern Adriatic coasts. Occasionally, it can reverse the WAC along the Italian coastline, inducing a north-westward current particularly intense in the Northern part of the basin (Ferrarese et al., 2008; Kovačević et al., 2004). As a consequence, a sea level rise is often observed in the region during Sirocco episodes (Orlić et al., 1994).

This study focuses on the northeastern area, which corresponds to the shallow area of the basin and thus it is extremely sensitive to wind forcing and riverine inputs (Po, Tagliamento, Isonzo; Fig. 1). For these reasons, surface currents in this part of the Adriatic Sea have been continuously monitored by a coastal radar network in the framework of the NASCUM (North Adriatic Surface CUrrent Mapping) project. The surface currents in this area were analyzed by Mihanović et al. (2011) through the SOM (Self-Organizing Map) technique to identify the typical patterns developing for different wind conditions, with particular emphasis on those associated with the prevailing wind regimes of Bora and Sirocco. The detected current patterns were indeed characterized by the expected circulation response, but, at the same time, they also evidenced new sub-mesoscale features never reported in previous studies.

The present study will focus on the eastern part of the Northern Adriatic, aiming in particular at investigating the surface transport and the related hydrodynamic connectivity associated with the surface circulation between the Gulf of Trieste (GoT) and the Northern Adriatic Sea under the typical wind conditions. The GoT is defined as the region of the Adriatic Sea North-East of the ideal line connecting Savudrija and Grado (Fig. 1). According to Malačič and Petelin (2001) and Bogunović and Malačič (2009) the circulation in the GoT is driven by the EAC intrusion at an intermediate depth along the southern side of the gulf. This induces GoT waters to follow the gulf coastline with a cyclonic pattern and then to exit along the Italian margin. At the same time, a transversal outflow current develops at the surface crossing the GoT entrance from SE to NW (Malačič and Petelin, 2009).

The surface transport in the area will be investigated through the Finite-Size Lyapunov Exponent (FSLE) technique. This method allows us to identify Lagrangian Coherent Structures (LCSs) on the basis of the relative dispersion between initially close particles. LCSs provide information on the transport patterns associated with the flow and they allow us to identify regions characterized by different dynamics (Ottino, 1989; d'Ovidio et al., 2004). They indicate the directions along which water masses are advected by the flow; and, at the same time, the converging and diverging regions of the flow, since water masses are squeezed along attractive LCSs and stretched across repulsive ones. Finally, LCSs also represent transport barriers since they cannot be crossed by the advected water masses. The FSLE method can be regarded as a complementary approach with respect to other Eulerian analysis usually applied to identify eddy's core and to characterize mixing based on velocity field snapshots (such as vortex identification from eddy kinetic energy or Okubo–Weiss parameter). In fact FSLE maps depend on the spatio-temporal evolution of the velocity field and of its transport properties, and not only on the velocity configuration at a given scale and time (García-Olivares et al., 2007; d'Ovidio et al., 2009). Since FSLE maps are computed through the integration of particle trajectories, they identify dynamical structures that organize the transport in a velocity field, with details below its original resolution and without any assumption on small scale dispersion features (Hernández-Carrasco et al., 2011). This is possible because the integration of trajectories from an Eulerian velocity map to the next ones allows us to extract the information contained in the flow field temporal dependence that on the other hand is lost when looking at each velocity map independently. Indeed, the trajectories of the synthetic particles advected in the surface current fields capture the smaller scale dynamics resulting from the variability of the mesoscale field.

In the Adriatic Sea, the FSLE method has been first used by Haza et al. (2007) to identify LCSs from NCOM (Navy Coastal Ocean Model) currents. Being based on a numerical model output, the comparison between the drifter trajectories and the identified LCSs corroborated the potential of integrating predictive coastal models with the FSLE method. A subsequent work by Haza et al. (2008) investigated the relative dispersion for the whole Adriatic Sea based on the NCOM model currents. The study showed that tracer dispersion is mainly controlled by large-scale circulation rather than by local regimes. This is in agreement with other studies based on open ocean LCSs derived from satellite velocity fields (Lehahn et al., 2007; d'Ovidio et al., 2009). Nonetheless, a recent study by Nencioli et al. (2011) has shown that smaller scale processes, not resolved by large scale model or satellite data, are fundamental for studying transport patterns in coastal areas.

In terms of small scale processes, HF radars have a clear advantage over large scale models and satellite surveying, in that velocities measured by the HF radar include processes over a broader range of spatial and temporal scales (from the submesoscale to larger scale circulation). For this reason, radar velocities are particularly suited for the analysis of coastal LCSs. This has been confirmed by the study performed in the Ligurian Sea by Haza et al. (2010), in which LCSs identified from VHF WERA radar current fields (Gurgel et al., 1999) were compared with the trajectories of drifter clusters. Although the LCS theory assumes 2D non-divergent flows, it was found that the motion of the surface drifters followed the VHF radar derived transport barriers, in spite of the presence of significant vertical velocities.

The present work represents the first development of an analogous FSLE technique applied to HF radar currents in the Adriatic Sea. This study aims at determining transport patterns in the Northeastern Adriatic Sea during Bora and Sirocco events. This goal will be achieved by analyzing the high-resolution current measurements from the NASCUM radar network with the FSLE technique. This work will also focus on several methodological aspects concerning the application of the FSLEs technique to radar datasets. This is particularly important since radar velocity fields are highly variable and cover smaller domains compared to satellite and numerical model fields used in previous studies. The sensitivity of the technique to different configurations of the FSLE parameters will be discussed.

The paper is organized as follows: in Section 2 the datasets and the developed FSLE algorithm are described. Section 3 shows the results of the sensitivity analysis for different FSLE parameter settings and describes the LCSs maps obtained for different wind regimes. Finally, the discussion of results and the conclusions are presented in Section 4.

2. Data and methods

2.1. Wind episodes identification

The FSLE analysis on sea surface currents is applied during periods characterized by strong, long-lasting events of Bora and Sirocco. In order to identify the most relevant wind episodes over the radar area, several datasets have been used, i.e. measured wind and sea level (SL) from different meteo-mareographic stations along the Northern Italian coast (Fig. 1). The wind data in Trieste, come from the meteo-oceanographic buoy, MAMBO-1, managed by OGS (*Istituto Nazionale di Oceanografia e di Geofisica Sperimentale*[1]). The wind time series in Venice are recorded at the Acqua Alta platform by ISMAR-CNR (*Istituto di Scienze Marine – Consiglio Nazionale delle Ricerche*[2]). While the SL time series are provided by ISPRA (*Istituto Superiore per la Ricerca e la Protezione Ambientale*[3]).

The hourly wind data have been low-pass filtered (33 h LP) to remove diurnal-period oscillations, associated with the sea-breeze regime (Cosoli et al., 2012). The same filter has been applied to the hourly SL series to remove tidal harmonics and Adriatic seiches.

Bora events have been detected from the filtered wind time-series of the Trieste station (Fig. 2, upper panels). The episodes of Bora are defined when at least 75% of the wind vectors, over a window of 3 days minimum, blow from the first quadrant (i.e. between North and East, Ursella et al., 2006), with speed greater than 5 m/s.

The Sirocco events have been identified from the filtered wind data of the Venice station (Fig. 2, central panels). The episodes of strong Sirocco are defined when at least 75% of the wind vectors, over a window of 3 days minimum, blow from S–SE, with speed at least equal to 5 m/s. Moreover, the effects of the Sirocco occurrence have been identified from the tide-gauge measurements in the Venice station (Fig. 2, bottom panel). In fact, the Sirocco piles up sea water along the northernmost border of the Adriatic Sea, leading to the SL rise along the northern Adriatic coast (Orlić et al., 1994). A further contribution to the SL rise may also be given by the large low atmospheric pressure structure with weak horizontal pressure gradients, which however drives Sirocco itself (Poulain and Raicich, 2001).

Calm wind periods have also been investigated as a term of comparison. These are defined as periods of at least 7 days with wind intensity lower than 3 m/s.

[1] http://www.ogs.trieste.it/.
[2] http://www.ismar.cnr.it/.
[3] http://www.mareografico.it/.

The wind episodes are selected in the period limited to the widest available radar coverage (February 2008 to August 2008, see Cosoli et al., 2012). Such conditions allow for better performances of the FSLE method, since particles can be advected in a wider domain.

For each wind regime the most significant events have been selected in order to evidence possible recurrent features in the detected LCSs. The identified wind events are summarized as follows (see Fig. 2): the episodes of Bora of the 4–8 March 2008 and of Sirocco of the 14–18 May 2008 are the strongest wind manifestations for the entire period considered. These wind episodes were also identified by Mihanović et al. (2011) for describing the sea surface current patterns during typical wind episodes. An additional episode of weak Bora (12–15 June 2008) is shown for comparison with the strong Bora case. The longest calm wind period is found between 17 and 29 February 2008.

The different temporal length of these episodes does not affect the analysis since the particles, launched for the evaluation of the FSLE, are initialized in the period of interest, but their evolution is not forced to stop at the limits of this period. However, they can leave the velocity field according to the transport properties of the currents themselves.

The occurrence of these wind episodes has been further confirmed by high-resolution modeled wind fields coming from ALADIN/HR (*Aire Limitée Adaptation dynamique Développement InterNational*), run by the Croatian Meteorological and Hydrological Service.[4] ALADIN/HR wind maps are available with 2 km spatial resolution and 3 h temporal resolution (not shown).

2.2. HF surface currents

The installed NASCUM network was composed of 3 CODAR (Coastal Ocean Dynamics Application Radar) Sea Sonde HF radar stations (dots in Fig. 1), active from August 2007 to August 2008. Two stations were located along the Istrian coast (in Rt Zub and Savudrija) and the third one, included since December 2007, on the Italian coast (in Bibione – Punta Tagliamento). The radars were set up in the 25 MHz frequency at 100 kHz bandwidth, allowing a range up to 50 km offshore with 1.5 km radial resolution and 5° angular resolution. Surface currents are mapped over a regular grid of about 30 km $\times$ 20 km (maximum coverage) with 2 km spatial resolution and 1 h temporal resolution. The current field covers the eastern and shallowest part of the Northern Adriatic with bottom depth from 20 m to 40 m, right in between the northern Bora "corridors" and directly affected by the Tagliamento river output (Fig. 1).

The HF current dataset[5] comes from the processing of the raw radial measurements performed by Cosoli et al. (2012). For more information about the treatment, the reader is referred to Chapman and Graber (1997) and Kovačević et al. (2004). The current signal includes also the tidal component. Episodically, current fields show some missing values at few points of the grid close to the baseline Bibione-Savudrija. This is due to the constraints in the intersecting beam geometry, required to minimize the effects of the site-to-site baseline instabilities. Therefore, a linear interpolation has been applied in order to complete the gap in the grid nodes to avoid the problem of truncated trajectories due to missing velocity values.

2.3. FSLE application

The FSLEs are evaluated by measuring the time needed for a particle pair to separate from an initial distance δ_i to a final distance δ_f. Thus, the analysis developed for this study includes

[4] http://meteo.hr/index_en.php/.
[5] http://poseidon.ogs.trieste.it/jungo/NASCUM/index_en.html.

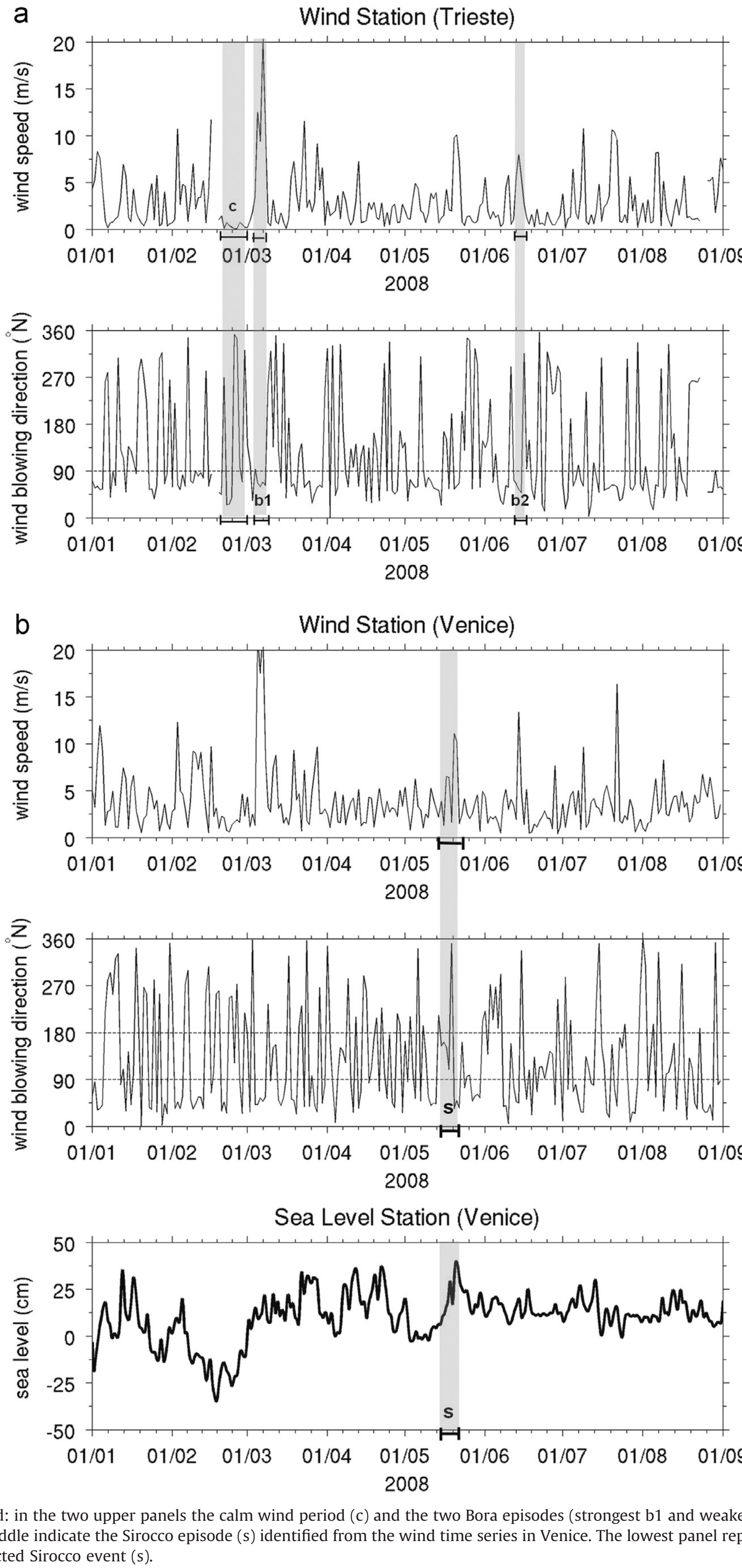

Fig. 2. The wind periods selected: in the two upper panels the calm wind period (c) and the two Bora episodes (strongest b1 and weaker b2) from the wind time series in Trieste. The two panels in the middle indicate the Sirocco episode (s) identified from the wind time series in Venice. The lowest panel represents the sea level time series in the Venice station with the selected Sirocco event (s).

two stages: first, the computation of the synthetic trajectories; second, the code which evaluates the FSLE and maps the final result. Particles trajectories are calculated by discretizing the advection equation and applying the 4th order explicit Runge–Kutta method with a 4 point bilinear interpolation (Hernández-Carrasco et al., 2011). The values of δ_i and δ_f influence the identification of the LCSs in the flow field, and depend on the characteristics of the flow field itself, on the length scale of the structures of interest and on the size of the domain. The initial distance affects the visibility of the details (the smaller δ_i, the more details), as the resolution of the grid where the FLSEs are computed is chosen to be equal to the initial distance between particles (d'Ovidio et al., 2004; Lehahn et al., 2007). This ensures that all the space in the velocity field is sampled once and just once. On the other hand, the final distance influences the detection of the structures (with larger δ_f, only the most stable and intense structures emerge).

Once these parameters are chosen, the FSLEs are computed by launching an ensemble of synthetic particles over the FSLE grid and following the evolution of their relative distance. For each node of the FSLE grid, five particles are initialized with a central particle located over the grid node and the other four placed around it at a distance δ_i along the latitudinal and longitudinal directions. This choice allows us to account for the different intensity of dispersion along different directions (Boffetta et al., 2001) in order to retain the fastest diverging couples. FSLEs are computed every 3 h using both forward and backward integration in time, which allow us to identify both the strongest repulsive and attractive LCSs during different wind regimes. Values of the FSLE λ are calculated at each node according to the definition (Sandulescu et al., 2007):

- forward integration:

$$\lambda^+ = \frac{1}{\tau} \ln \frac{\delta_f}{\delta_i};$$

- backward integration:

$$\lambda^- = -\frac{1}{\tau} \ln \frac{\delta_f}{\delta_i};$$

where τ is the time needed to separate two particles of the ensemble from δ_i up to δ_f. The faster the divergence is, the smaller the τ is, and the larger (in absolute value) the λ is. It is important to remark that divergence in backward integration actually identifies regions of convergence of the flow. If one of the particles of an ensemble leaves the velocity field before δ_f is reached, then λ is not defined. Maximum values of the λ^+ and λ^- fields identify repulsive and attractive LCSs, respectively. The maps in this paper present tangles of attractive and repulsive LCSs obtained by superposing both forward and backward integration FSLE fields (Molcard et al., 2006).

3. Results

3.1. FSLE method set-up

The application of the FSLE algorithm to the radar current field requires to set up the parameters defining initial and final separation distance between particles, δ_i and δ_f respectively. Since there are no previous studies on FSLE analysis in the Northeastern Adriatic Sea, an overview on the sensitivity analysis performed on the δ_i and δ_f parameters for this particular case study is presented.

In general, a suitable combination of the two parameters must be chosen. This should take into account that although δ_i can be fixed arbitrarily small, there is an intrinsic limit on the details of the resulting structures which is associated with the surface shear information captured in the current field itself. Furthermore, if δ_f is chosen larger than the separation distance achievable by the particles advected within the finite spatial domain of HF radar velocities, no structures will be detected from the flow field.

Given the characteristics of the dataset and the focus of the present work, we aim at identifying the transport structures associated with small-scale (i.e. mesoscale) processes. The horizontal scale of mesoscale processes is represented by the internal Rossby radius of deformation, which is about 3–5 km in the Middle and Northern Adriatic (Masina and Pinardi, 1994). However, eddies can have even smaller size during winter when waters are completely mixed and the first baroclinic Rossby radius of deformation almost vanishes (Bergamasco et al., 1996). Recent numerical findings from a climatic circulation model of the northern Adriatic Sea confirm values around 3 km in spring (Malačič et al., 2012).

In order to find a choice of parameters able to identify appropriately both weak and strong LCSs during any of the wind regimes considered, several tests for all the wind cases have been performed (not shown). The following results are representative of calm wind, but are purposefully shown in order to evidence how the characteristics of the FSLE field, and thus of the identified LCSs, change depending on the chosen parameter values.

As a first trial, according to the value of the Rossby radius, δ_f is fixed to 3 km and several FSLE maps obtained for different δ_i are compared (Fig. 3). Starting from an initial distance between particles equal to the resolution of the radar velocity field (2 km) and successively reducing the parameter δ_i, the detected LCSs keep their configuration while their features become sharper. This property of FSLE-based LCSs has been first recognized by Hernández-Carrasco et al. (2011), who identified it as fractal behavior. At the same time, it is important to remark that by reducing δ_i the number of particles used in the analysis, and thus its computational requirements, increases. Considering the radar field resolution and the scales of interest, δ_i=0.4 km represents a good compromise between the FSLE map resolution and the computational efficiency to resolve structures within the range of few kilometers. Once the value of δ_i is set, an analysis on the sensitivity of the detected LCSs for different values of δ_f is also performed. Since mesoscale ranges within less than 3 km up to about 5 km, different values of δ_f were tested from 1 km to 5 km (Fig. 4). Usually just a limited group of particle couples is able to reach the relative final distance chosen, depending on the spatial extension of the current field and on the surface shear caught by radar measurement. Moreover the greater the final distance is, the longer will be the time required for each couple to separate up to this value. Therefore for small δ_f a lot of couples separate in very short time and the structures in the FSLE map are very broad and almost indistinguishable from one another, since they are detected also for very weak transport structures. On the other hand for large δ_f fewer particles separate up to this value and the resulting structures are formed by only few points of the map. These are associated with the stronger, more persistent structures, which therefore are more relevant for characterizing the transport properties of the flow. This is true especially in strong wind cases (not shown) when currents are so strong and coherent in space that for δ_f=3 km all the particles leave the radar field before having reached the fixed final distance, so that the transport structures cannot be identified at all. In conclusion, the final distance which allows the identification of transport structures for any wind condition under study is δ_f=1.6 km.

3.2. LCS patterns during wind episodes

To investigate the changes in the LCS patterns with different wind conditions, several episodes for each wind regime have been analyzed and the most representative cases are presented

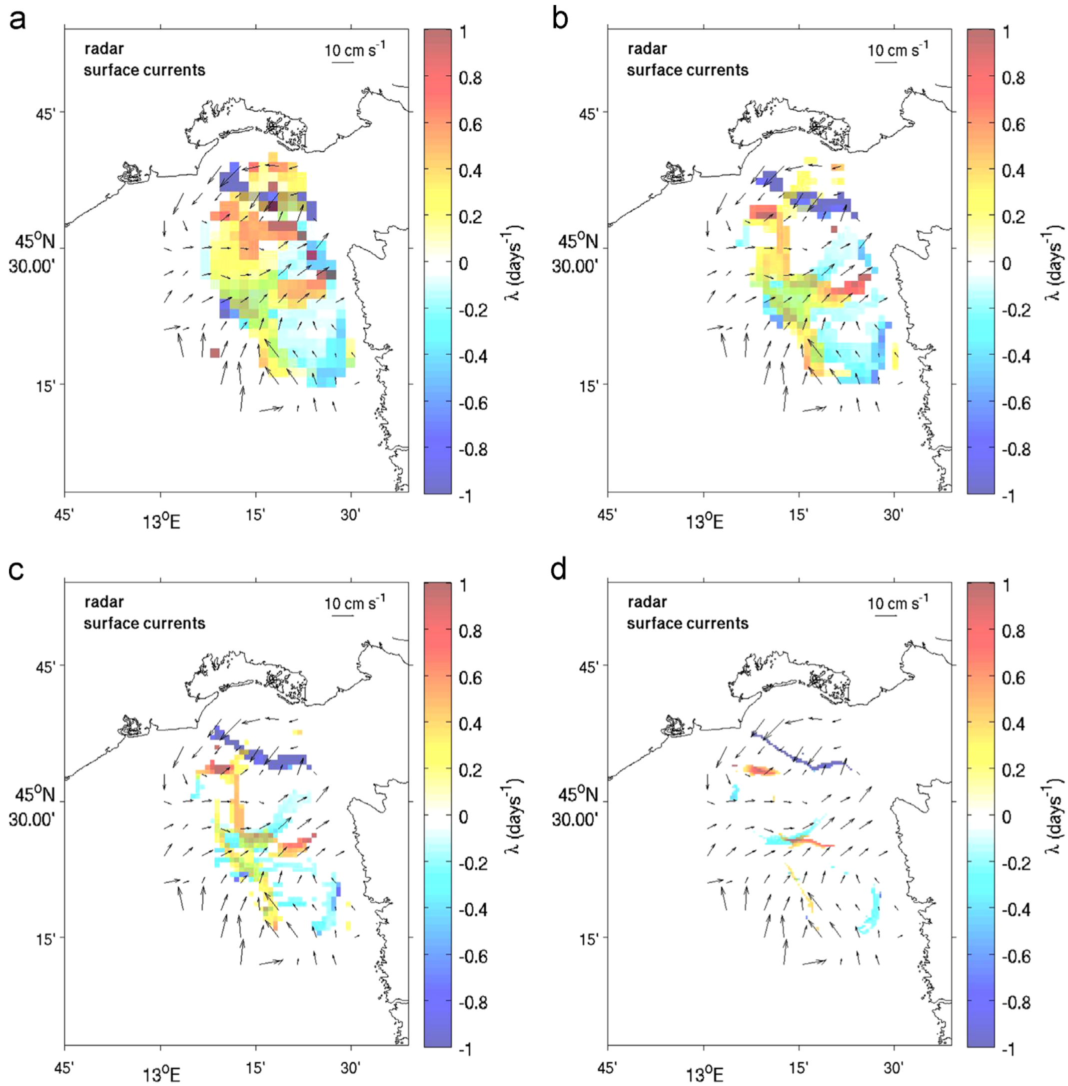

Fig. 3. FSLE (days^{-1}) trial maps for different δ_i: (a) 2 km, (b) 1.4 km, (c) 1 km and (d) 0.4 km. The parameter δ_f is set to 3 km. Black arrows indicate the surface current configurations at the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.

in Figs. 5–7. These maps show the FSLE field for a time centered within a given wind episode, to ensure that the dynamical conditions just before and after this period do not affect the trajectories evolution at the sea surface. In the figures, repulsive LCSs (FSLE maxima/separating trajectories) are in red, whereas attractive LCSs (FSLE minima/converging trajectories) are in blue.

For the calm wind case in February the spatial configuration of the transport structures is quite broad and detailed (Fig. 5). Several attractive and repulsive LCSs are identified and they cross each other within the radar velocity field. These transport structures evolve with a longer time scale (up to 3–4 days), independently from the high temporal variability characterizing the velocity field (due to tidal oscillations in the diurnal and semidiurnal frequency bands and near-inertial oscillations, as observed by Cosoli et al., 2012). This is a typical feature of LCSs since they result from the integration of trajectories over time scales much longer than the ones characterizing the variability of the velocity field.

An attractive LCS is present in front of the Italian coast throughout the entire calm wind period. The structure marks the convergence between GoT and Northern Adriatic waters. Its eastern half is oriented South-East to North-West, as mean advection goes from the Istrian coast toward the river mouth of the Tagliamento. There, it forms a right angle with the Italian coastline direction, because the jet along the Italian coast is deviated by the fresh water output from the Tagliamento river. Cosoli et al. (2012) observed an analogous deviation of the surface currents in front of the Tagliamento estuary.

A repulsive structure occupies the central part of the current field and crosses the attractive structure facing the entrance of the GoT and other weaker attractive structures in the field. The attractive structure to the south-east of the radar field is associated with an anticyclonic vortex in front of the Istrian coast. The current field presents several patterns with length scale larger than the internal Rossby radius of deformation identified by Masina and Pinardi (1994). The mesoscale length and variability also depend on stratification conditions and can be several times smaller/bigger than the internal radius of deformation (about 5 km), as observed also by Bergamasco et al. (1996). For this reason, in order to compare this case to the other wind episodes, the analysis will focus on the pattern that can be considered recurrent, that is the strongest attractive filament at the entrance of GoT, related to the water exchange between the North Adriatic and the gulf itself (process already observed in the seasonal mesoscale study by Malačič and Petelin, 2009).

The FSLE analysis in the Bora case focuses on the March episode (Fig. 6(a)). Before and after the Bora event, wind conditions are

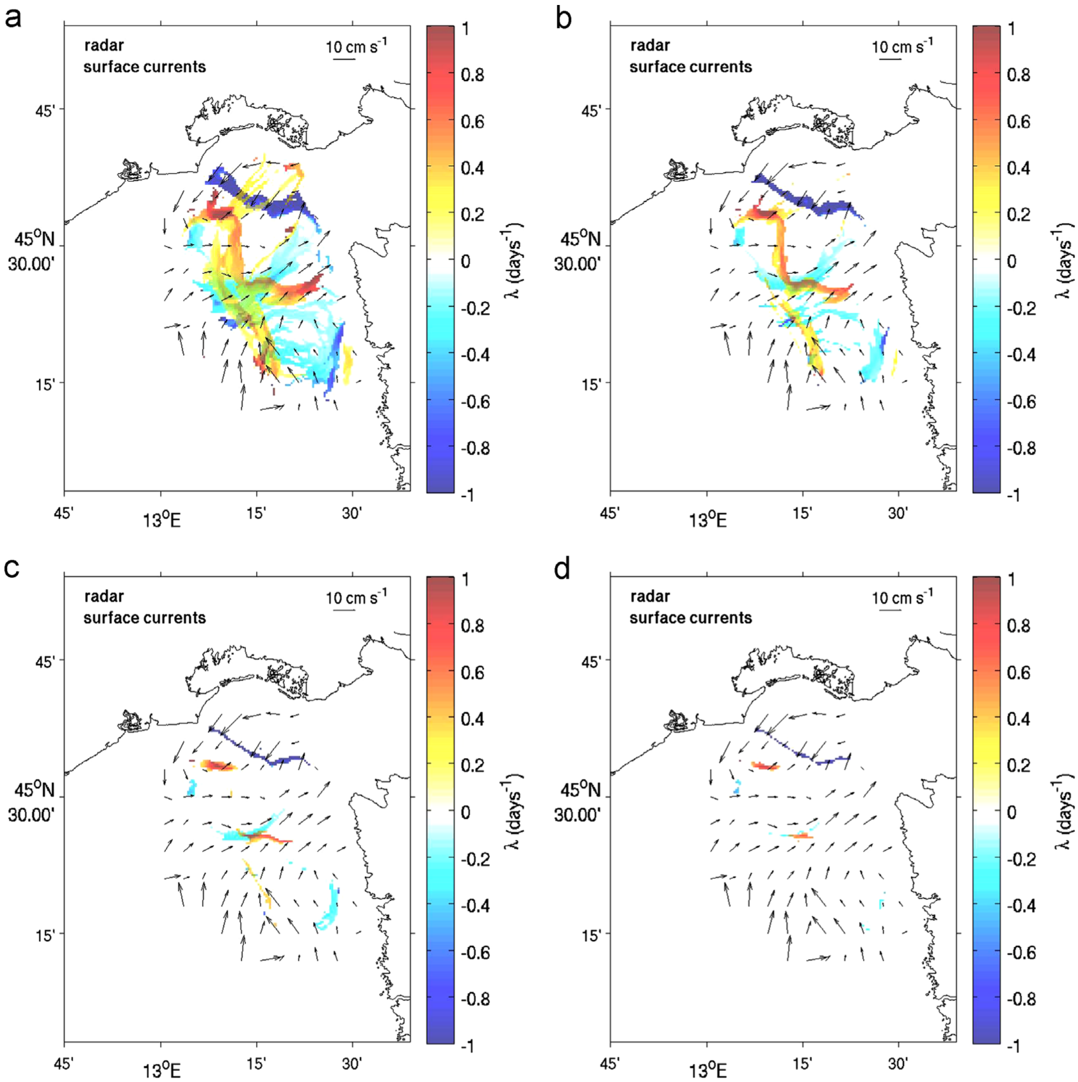

Fig. 4. FSLE (days^{-1}) trial maps for different δ_f: (a) 1 km, (b) 1.6 km, (c) 3 km and (d) 5 km. The parameter δ_i is set to 0.4 km. Black arrows indicate the surface current configurations at the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.

predominantly calm and the spatial organization of LCSs is similar to the calm case of February just described. The response of the surface current to Bora wind is almost instantaneous, showing the development of intense westward/south-westward currents throughout the radar domain. This is in agreement with the observations from Cosoli et al. (2012), Malačič et al. (2012), Mihanović et al. (2011). Along the Istrian coastline, these currents are weaker than the ones further north. The resulting meridional current shear reflects the wind pattern over this part of the Adriatic basin: Bora is stronger along the northern "corridor", and weaker to the south where it is screened by coastal orography. This north–south current shear introduces cyclonic vorticity extending far off from the Istrian coast, as already observed by Cosoli et al. (2012).

The evolution of the LCSs during Bora cases is characterized by a sequence of recurrent patterns: at the beginning of the Bora episode the attractive LCS typical of calm wind conditions (Fig. 5) is still present in the northernmost part of the radar domain in front of the Italian coastline. The structure remains stable until the Bora has fully developed (not shown), but it is not present anymore as soon as the westward current pattern extends over the whole Northeastern Adriatic (Fig. 6(a)).

The disappearance of this attractive transport structure during Bora episodes, and its reappearance as soon as Bora ceases, indicates that the LCS does not vanish but it is just displaced westward outside the radar domain by the presence of the intense, homogeneous Bora-driven currents. This can be evidenced through the analysis of an episode of weak Bora, such as the one identified in June 2008 (Fig. 6(b)). The initial evolution of the transport structures is analogous to the strongest Bora case already analyzed. In fact, at the beginning of the Bora episode an attractive LCS is present to the north of the radar domain. However, during such event, the Bora-driven westward currents are less homogeneous over the basin, so that the region of convergence is still present in front of the Italian coast.

The development of a repulsive LCS in front of the Istrian coast is another common feature of both strong and weak Bora episodes. However, during the weaker events, this LCS is less intense but more extended than the one developing during the strong ones.

The FSLE analysis in the case of Sirocco forcing focuses on the event in May 2008 (Fig. 7). Regardless of the currents configuration before a Sirocco event, as soon as Sirocco starts to blow it induces an homogeneous north–northeastward current. After the Sirocco has reached a steady state, this uniform current, developed throughout all the radar field, induces the piling up of surface waters in the northern part of the basin. A part of this water mass converges where the attractive LCS is found, stretched from SW to NE, and enters the GoT mostly along the northern (Italian)

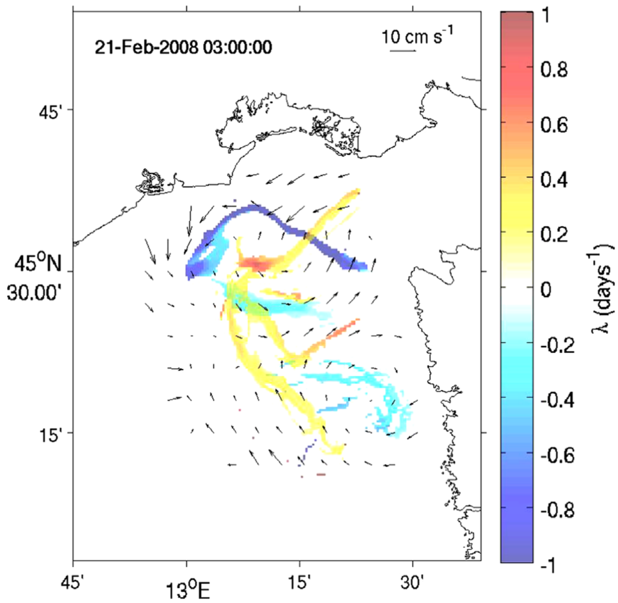

Fig. 5. FSLE (days^{-1}) map extracted from the calm wind period in February 2008. Black arrows indicate the mean surface current field during the calm wind period. The date specifies the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

coastline. The intensified inflow along the northern side of the GoT is also supported by recent numerical model findings (Malačič et al., 2012). The transport associated with this LCS is from West to East, which is reversed with respect to the calm wind case when waters flow cyclonically following the basin coastline. On the other hand, the meridional part of the flow field does not show intense structures, since the currents are rather uniform in direction and intensity and the advected particles do not experience the shear necessary to diverge or converge. When Sirocco relaxes the cyclonic gyre that is gradually restored so that the eastward current along Italy returns and the transport associated with the attractive LCS reverses back in the westward direction (not shown).

4. Discussion and conclusions

The surface transport in the Northeastern Adriatic Sea has been investigated by applying the FSLE technique on the current field detected by the HF coastal radar network active in the period from August 2007 to August 2008. The analysis is limited to the period from February to August 2008, when the spatial coverage of radar measurements was maximized under the three-site configuration. The interest is focused on the surface dynamics of this area associated with the typical wind regimes, Bora and Sirocco, compared to calm wind. Previous studies (d'Ovidio et al., 2009; García-Olivares et al., 2007) have confirmed the advantage of using the FSLE technique over more traditional Eulerian diagnostics for detecting the transport structures which separate dynamically distinct regions of a flow. Moreover, compared to other Lagrangian diagnostics, such as the analysis of sparse drifter trajectories, the FSLE technique allows us to retrieve information over broader domains, and thus is better suited for studies at the regional scale. Being the very first time that the FSLE technique is applied to the HF radar current fields of the Northern Adriatic Sea, it has been of crucial importance to investigate the sensitivity of the FSLE analysis with respect to the key parameters (initial distance, δ_i, and final separation distance of particles, δ_f) that control LCSs

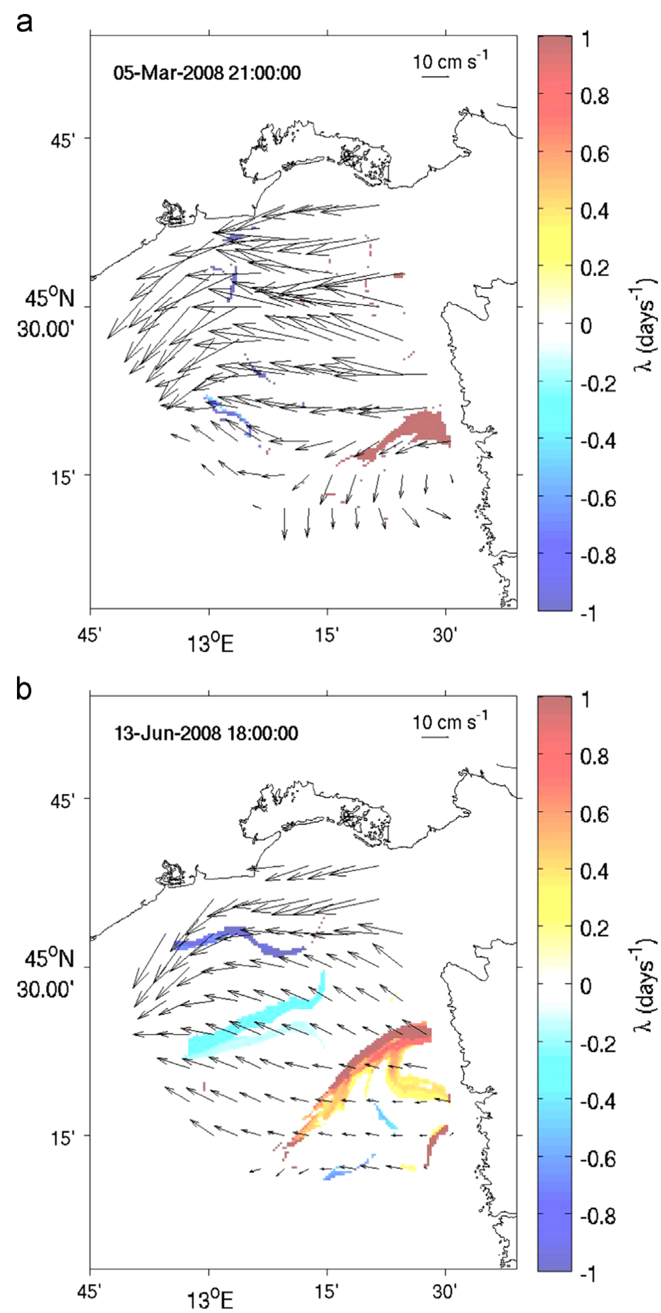

Fig. 6. FSLE (days^{-1}) maps extracted from the Bora episodes: (a) in March 2008 and (b) in June 2008. Black arrows indicate the mean surface current field during the wind episode. The date specifies the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

coverage and details visibility. Despite the very high variability of the radar current fields, the reasonably chosen values of these parameters have allowed us to identify and investigate the evolution of the strongest transport structures.

In summary, the FSLE analysis on the current field revealed the presence of recurrent surface transport structures during the different wind regimes considered (calm period, Bora and Sirocco). The current field during the calm wind period is characterized by the presence of multiple structures. Their persistence in time is longer when compared to the other wind cases analyzed. An attractive LCS crosses the GoT entrance where the gulf and the North Adriatic waters converge. A repulsive structure is present in

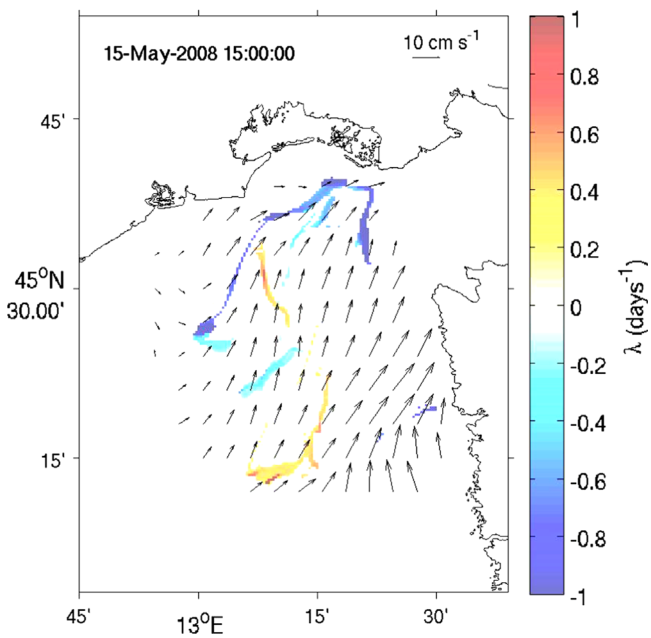

Fig. 7. FSLE (days^{-1}) map extracted from the Sirocco episode in May 2008. Black arrows indicate the mean surface current field during the wind episode. The date specifies the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

the central part of the radar field. The transport structures identified in strong Bora episodes show the displacement of the attractive LCS from the GoT entrance further west. Moreover a repulsive structure develops in front of the Istrian coast. On the other hand, during Sirocco events an attractive structure is present along the Italian coast. The transport associated with this LCS is from west to east, opposite to the calm wind case. This LCS indicates that Adriatic waters pile up along the northern coast.

As already pointed out, the surface circulation of the GoT is characterized by an outflowing transversal current developing from its southern border to the Tagliamento estuary, that merges with the westward flow along the Italian coast (Malačič and Petelin, 2009). This FSLE analysis identifies an attractive LCS in front of the GoT entrance, which is associated with the transport driven by this transversal current out of the GoT. This structure is present in all the considered wind regimes but its location with respect to the Italian coast and the direction of transport associated with it varies.

During calm wind periods the attractive LCS extends from the northern Istrian tip to the Tagliamento river and further west, representing the barrier to the outflow of GoT waters to the Northern Adriatic Sea. The advection associated with this LCS is westward, in agreement with the diagonal current pattern typical of the GoT: surface waters entering the gulf along the Istrian coast and exiting from the Italian side of the GoT in a cyclonic pattern (Malačič and Petelin, 2001).

During weak Bora events, the attractive LCS is displaced westward with respect to its position in calm wind periods. The spatial configuration of this LCS with respect to the gulf entrance shows the location where the GoT surface waters extend to meet the Northern Adriatic coastal flow. On the other hand during strong Bora events there is no more evidence of the attractive LCS in the radar field, indicating that the convergence area, and thus the boundary of westward outflow from the GoT, could be positioned beyond the western limit of the radar domain. A spatially coherent outflow from the GoT can indeed be observed from the radar measurements. This is in agreement with Malačič and Petelin (2009), who observed a similar outflow in response of intense wind forcing, and with Mihanović et al. (2011) who observed that Bora drives a sea level decrease in Trieste and, at the same time, a sea level rise in Venice.

To accurately identify the outflow barrier during strong Bora episodes, a wider current field would be necessary, either by extending westward the radar network or by using modeled current fields. In either weak or strong Bora cases a repulsive LCS develops in front of the Istrian coast. This structure represents a real transport barrier for the water masses present to the north and south of it. Any surface tracer present to the south of this repulsive LCS will not cross it and, therefore, the northward flow along the coast, characteristic of calm wind conditions, is temporarily halted. This determines a reduced connectivity between the Istrian coast and the GoT. This LCS could represent the southern boundary of the northern jet current exiting from the GoT and developing as a consequence of the Bora funneling between Dinaric Alps.

During Sirocco episodes the position of the attractive structure is found northeastward, as a consequence of the piling up of waters along the northern Adriatic coasts. Therefore there is no transport barrier in front of the GoT, indicating the occurrence of an extended inflow of North Adriatic waters into the GoT. Such an inflow in the gulf is also confirmed by the observed sea level rise in Trieste during analogous wind events (Mihanović et al., 2011). In this case, the local transport along this LCS is from west to east, and not in the opposite direction as during the typical cyclonic circulation of the North Adriatic area. The SW–NE orientation of the attractive LCS might indicate that the inflow comes from the open Adriatic rather than from coastal regions.

The application of the FSLE method on HF radar currents in the Northeastern Adriatic area can provide important information about horizontal transport dynamics. Such information could be greatly improved with the further development of a network of observation in the Northern Adriatic, which could lead to more refined transport analysis.

Concerning potential applications of the FSLE method, it could be directly used in the case of sea accidents or pollutant discharge to identify the possible pathways of dispersion from reliable near-real time velocity fields. This will allow us to identify the potential source area of the pollutant, and will provide a crucial information to circumscribe the intervention area and to guide the emergency operations.

Acknowledgments

The authors thank OGS, ISMAR-CNR and ISPRA for providing wind and sea level time series. The authors are grateful to Dr. Miroslav Gačić for supporting this work and for the stimulating discussion about the interpretation of the results. Gratitude is due to Dr. Annalisa Griffa for the precious suggestions during the development of the FSLE algorithm. Maristella Berta thanks MIO for the hospitality and financial support during her stay in Marseille for the advancement of scientific research. Maristella Berta shows her appreciation to Dr. Angelique Haza for sharing with the authors her experienced opinion about the results of this work.

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