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

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Abstract

This study focuses on the surface transport in the Northeastern Adriatic Sea and the related connectivity with the Gulf of Trieste (GoT) under 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 detected by the High Frequency (HF) coastal radar network. FSLE allow 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 calibration of the FSLE evaluation 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 and induces the inflow of Adriatic waters in the GoT. In this condition the attractive LCS extends mainly in SW-NE direction.
and, as in 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 present to the north and the south of it.

**Keywords:** Adriatic Sea, Trieste Gulf, radar, surface transport, FSLE, LCS

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 (Figure 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 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 blowing from Siberia, whose most severe manifestations are typical of the winter period [Yoshino, 1976]. The Sirocco blows from S-SE and by crossing the Mediterranean Sea it gets warm and wet. 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 central part, compensated by strong upwelling along the eastern margin, [Lazar et al., 2007; Orlić et al., 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 as a consequence of the funneling of Bora to the North and the South of Istria (these paths are called “Bora corridors”) [Lazić and Tosić, 1998]. This pattern has been identified both by drifters 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, sea level rise is often observed in the region during Sirocco episodes [Orlić et al., 1994].

Coastal processes and sea circulation of the North Adriatic Sea are of great interest because of the deep urbanization of its coastline and the intense exploitation of the local natural resources. This study focuses on the northeastern area, which corresponds to the shallowest area of the basin and thus it is extremely sensitive to wind forcing and riverine inputs (Po, Tagliamento, Isonzo; Figure 1). For these reasons, the surface currents developing in this part of the Adriatic Sea, has been continuously monitored by a coastal radar network in the framework of the NASCUM (North Adriatic Surface CUrrent Mapping) project. Since radars provide surface current measurements in near-real time, they represent a suitable tool during maritime rescue operations and they play a fundamental role for defining intervention procedures in case of environmental emergencies. 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 connectivity 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 (Figure 1). According to Malačić and Petelin [2001] and Bogunović and Malačić [2009] the circulation in the GoT is driven by the EAC intrusion at intermediate depth along the southern side of the gulf. This induces GoT waters to follow the gulf coastline with a cyclonic pattern and then 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 [Malačić and Petelin, 2009].

The surface transport in the area will be investigated through the Finite-Size Lyapunov Exponent (FSLE) technique. This method allows to estimate 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 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; indeed, at the same time 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 techniques, since it accounts for the spatio-temporal variability of the dynamical structures and not only their configuration at a given scale and time [García-Olivares et al., 2007; d’Ovidio et al., 2009]. Because of that, the identified LCSs are characterized by spatial scales at a finer resolution than the original flow field, resulting from the temporal evolution of the large scale dynamics [Hernández-Carrasco et al., 2011].

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) modelled
currents. 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, radar measurements have a clear advantage over large scale models and satellite data, in that the velocities obtained from the HF radar result from the entire energy spectrum of the local circulation. Thus, 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 a 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. On the one hand, the present work validates the accuracy of radar surface currents, on the other, it shows the precision of the FSLE method to detect coastal LCSs from radar velocities. To date, it represents the only example of the 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 analysing the high-resolution current measurements from the NASCUM 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 models fields used in pre-
previous studies. The sensitivity of the technique to different configurations of the
FSLE parameters will be discussed. Furthermore, the robustness of the identified LCSs will be examined in case the evolution of the flow field is faster than the advective time scale.

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. Meteo-mareographic station time-series

Time series of wind and sea level (SL) from the meteo-mareographic stations along the Italian coast, provided by ISPRA (Istituto Superiore per la Ricerca e la Protezione Ambientale\(^1\)), were used to identify the most relevant wind episodes of Bora and Sirocco over the radar area. Since the winds considered are characterized by very different blowing directions and the examined area is partially surrounded by heterogeneous coasts, a preliminary survey over several stations along the Northern Adriatic coast has been necessary to avoid using wind time-series affected by orographic deflection or screening. The Trieste station is located in a favorable position for detecting Bora events from the recorded wind time-series (Figure 1). On the other hand the Sirocco wind signal is too weak and intermittent at all stations along the Northern Adriatic coast. Thus, Sirocco events could not be accurately identified from wind stations. Nonetheless, due to the piling up of waters along the northernmost border of the Adriatic Sea, they are clearly identifiable as SL maxima in the time-series from the tide-gauge station in Venice (Figure 1). The sampling frequency of the wind time-series is one hour, and 10 minutes for the SL time-series.

\(^1\)http://www.mareografico.it/
SL signal has been low-pass filtered to remove tidal and subtidal fluctuations (cutting off oscillations with period shorter than one day).

2.2. Wind episodes identification

The FSLE analysis on sea surface currents is applied during periods characterized by strong, long-lasting events of Bora and Sirocco. 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 5m/s. The identification of Sirocco episodes has been achieved by selecting from the filtered time-series sea level signal rise events with amplitude larger than 20 cm. As a term of comparison, calm wind periods have also been investigated for reference. These are defined as periods of at least seven days with wind intensity lower than 3 m/s. The wind episodes are selected in the period limited to the widest available radar coverage (February 2008 - 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 Figure 2): the episodes of Bora of the 4-8 March 2008 and of Sirocco of the 14-19 May 2008, are the strongest wind manifestations for the entire period considered. They were also chosen 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 17-29 February 2008.

Since the coastal stations are located at the border of the radar field, the occurrence of these wind episodes has been further investigated (and confirmed) by the analysis of the ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) wind maps over the North Adriatic Sea, available for the period August 2007 - August 2008, with 2 km spatial resolution and 3 hours temporal resolution (not shown).
2.3. **HF surface currents**

The installed NASCUM network is composed of 3 CODAR (Coastal Ocean Dynamics Application Radar) Sea Sonde HF radar stations (dots in Figure 1), active from August 2007 to August 2008. Two stations are 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 × 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 (Figure 1).

The HF current dataset[^2] 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 Kovacevic et al. [2004]. The current signal includes also the tidal component, and thus represents the entire energy spectrum of the velocity field. Current fields show some missing values close to the baseline Bibione-Savudrija because of the geometrical reconstruction of the velocity vectors. Therefore, a linear interpolation has been applied in order to complete the gap in the grid nodes.

2.4. **FSLE application**

The FSLEs are evaluated by measuring the time needed for a particle pair to separate from a certain initial distance \( \delta_i \) to a given final distance \( \delta_f \). Thus, the procedure developed for this study has 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 $\delta_i$ and $\delta_f$ 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 $\delta_i$, 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. This ensures that all the space in the velocity field is sampled once and just once, as explained by d’Ovidio et al. [2004] and Lehahn et al. [2007]. On the other hand, the final distance influences the detection of the structures (with larger $\delta_f$, only the most stable and intense structures emerge).

Once these parameters are chosen, the FSLE 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 $\delta_i$ along the latitudinal and longitudinal directions. This choice allows 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 hours using both forward and backward integration in time, which allow to identify both the strongest repulsive and attractive LCSs during different wind regimes. Values of the FSLE $\lambda$ 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 $\tau$ is the time needed to separate two particles of the ensemble from $\delta_i$ up to $\delta_f$. The faster the divergence, the smaller is $\tau$, and the larger (in absolute value) is $\lambda$. 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 $\delta_f$ is reached, then $\lambda$ is non defined.

Maximum values of the $\lambda^+$ and $\lambda^-$ 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 sensitivity analysis

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, $\delta_i$ and $\delta_f$ respectively. Since there are no previous studies on FSLE analysis in the Northeastern Adriatic Sea, an overview on the sensitivity analysis performed on the $\delta_i$ and $\delta_f$ parameters for this particular case study is presented.

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]. Therefore, as a first trial, $\delta_f$ is fixed to 3 km and several FSLE maps obtained for different $\delta_i$ are compared (Figure 3). Starting from an initial distance between particles equal to the resolution of the radar velocity field (2 km) and successively reducing the parameter $\delta_i$, 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 $\delta_i$ the number of particles used in the analysis, and thus its computational requirements, increase. Considering the radar field resolution and the scales of interest, $\delta_i=0.4$ km represents a good compromise between map
resolution and computational efficiency to resolve structures within the range of few kilometers. Once the value of $\delta_i$ is set, an analysis on the sensitivity of the detected LCSs for different values of $\delta_f$ is also performed. Since mesoscale ranges within less than 3 km up to about 5 km, different values of $\delta_f$ were tested from 1 km to 5 km (Figure 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 $\delta_f$ 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, while for large $\delta_f$ only few particles separate up to this value and the resulting structures are formed by only few points of the map.

The suitable combination between the two parameters must be chosen taking into account that although $\delta_i$ can be chosen to be arbitrarily small, there exists an intrinsic limit on the details of the resulting structures associated with the surface shear information captured in the current field itself. Furthermore, $\delta_f$ should be upper bounded according to the residence time of the ensemble of particles in the flow field, i.e. their maximum separation achievable.

Thus, the best compromise between initial and final distance allowing to unambiguously visualize the strongest transport structures and to catch adequate details in the LCS patterns is found for $\delta_i=0.4$ km and $\delta_f=1.6$ km.

3.2. LCS patterns during wind episodes

To investigate the changes in the LCS patterns with different wind conditions, the most representative FSLE maps for each wind regime are presented in figures 5 to 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 (Figure 5). Several attractive and repulsive LCSs are identified and they cross each other within the radar velocity field. Despite the high temporal variability of the velocity field, the transport structures evolve with an independent and longer time scale, and thus are relatively persistent in time. 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. Although some temporal variability in the actual shape and position of this LCS is observed, due to the intrinsic variability of the currents with time, this structure is quite stable and persistent. The structure marks the convergence between GoT and Northern Adriatic waters. It 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. The convergence area corresponding to the anticyclonic vortex in front of the Istrian coast (southeastern corner of the radar field) has not to be interpreted as a typical pattern present in this wind conditions, since in other calm wind periods a cyclonic vortex can appear in the same area (not shown).

The FSLE analysis in the Bora case focuses on the March episode (Figure 6(a)). Before and after the Bora event, wind conditions are 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 observ-
tions from 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 (Figure 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, but it rapidly disappears as soon as the westward current pattern extends over the whole Northeastern Adriatic (Figure 6(a)).

The sudden disappearance of this attractive transport structure during Bora episodes, and its reappearance as soon as Bora ceases, indicates that the LCS does not vanishes 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 (Figure 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 than the one developing during the strong ones.

The FSLE analysis in case of Sirocco forcing focuses on the event in May 2008 (Figure 7). Regardless of the currents configuration before a Sirocco event, as
soon as Sirocco starts to blow it induces an homogeneous north-northeastward
current, consistent with the expected Ekman transport. 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.
An attractive LCS from SW to NE is evidenced, because of the convergence
of the southern open sea water masses along the Italian coast. The transport
associated with this LCS 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
are not experiencing the shear necessary to diverge or converge. When Sirocco
relaxes the cyclonic gyre gradually restores itself so that the eastward current
along Italy reestablishes and the transport associated to the attractive LCS
reverses back in westward direction (not shown).

4. Discussion and conclusions

The surface transport in the Northeastern Adriatic Sea has been investi-
gated 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 interest is focused on the surface dynamics of this area associated with
the typical wind regimes, of Bora and Sirocco. This study confirms the advan-
tage of using the FSLE technique over more traditional Eulerian diagnostics
for detecting the transport structures which separate dynamically distinct re-
gions of a flow. Compared to other Lagrangian diagnostics, such as the analysis
of sparse drifter trajectories, the FSLE technique allows to retrieve informa-
tion over broader domains, and thus is better suited for studies at the regional
scale. Unlike the previous FSLE applications, which are based on numerical
models or satellite datasets, this study represents one of the first application
of the FSLE technique on current fields extending over the entire energy spec-
trum. Furthermore, being the very first time that FSLE technique is applied
over HF radar current field 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, $\delta_i$, and final separation distance of particles, $\delta_f$) that control structures coverage and details visibility. Despite the very high variability of the radar current fields, through an accurate combination of these parameters, it is possible 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 wind, Bora and Sirocco). The current field during calm wind condition 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 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.

The analysis of FSLE maps for the main wind regimes has evidenced that the wind variability over the north-eastern Adriatic drives consistent changes in the spatial disposition and the temporal permanence of LCSs. The LCSs dynamics can be interpreted to retrieve important information on the transport patterns and water exchanges between the GoT and the Northern Adriatic during specific wind events, which could not be retrieved from Eulerian analyses of the velocity fields.

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 joins with the westward flow along the Italian coast.
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 from time to time.

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 [Malačić 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 extends 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 Malačić 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 and 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 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.

Being a shallow water sub-basin prone to severe wind events and intense
riverine outputs, the Northern Adriatic Sea, as a whole, has a quite complex
dynamics. Several biological and geochemical processes are driven or impacted
by the transport dynamics of this area. This, in turn, affects several human
activities such as fishery, maritime traffic or industrial settlement. Therefore,
a comprehensive description of the transport dynamics of such an active and
exploited basin needs to be achieved. 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 the network of observation in
the Northern Adriatic, which could lead to more refined transport analysis.

Nowadays, the dynamics of the GoT is not yet completely understood, there-
fore future radar measurements, either inside the GoT and further west toward
Venice, would improve the surface current coverage of the area. The applica-
tion of the FSLE method on modeled currents could extend the domain in which
LCS are estimated not only in the horizontal, but also in the deeper layers. This
could help to investigate and better understand the water exchanges between
the GoT and the Northern Adriatic Sea even below the surface. Future studies in the area should be associated with field campaigns in order to validate the current fields. Moreover, to obtain a comprehensive description of the dominant LCS in the Northeastern Adriatic, the FSLE method should be used in association with the advection of clusters of drifters. This will allow to compare in-situ trajectories with the transport structures identified from modeled or measured velocity fields. Future advancements in the investigation of the transport structures in the GoT will also include more quantitative analysis of water masses exchanges, which will integrate the information from the detected LCSs by using them as dynamical boundaries to compute fluxes in and out the gulf.

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

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References


Figure 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.
Figure 2: The wind periods selected: in the 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 lowest panel represents the sea level at Venice station with the selected Sirocco event (s).
Figure 3: FSLE (days\(^{-1}\)) trial maps for different \(\delta_i\): (a)2 km, (b)1.4 km, (c)1 km and (d)0.4 km. The parameter \(\delta_f\) is set to 3 km. Black arrows indicate the surface currents configuration at the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.
Figure 4: FSLE (days$^{-1}$) trial maps for different $\delta_T$: (a) 1 km, (b) 1.6 km, (c) 3 km and (d) 5 km. The parameter $\delta_i$ is set to 0.4 km. Black arrows indicate the surface currents configuration at the beginning of the trajectories simulation. The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.
Figure 5: FSLE (days$^{-1}$) map extracted from the calm wind period in February 2008. Black arrows indicate the surface currents configuration at the beginning of the trajectories simulation (specified by the date). The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.
Figure 6: FSLE (days$^{-1}$) maps extracted from the Bora episodes: (a) in March 2008 and (b) in June 2008. Black arrows indicate the surface currents configuration at the beginning of the trajectories simulation (specified by the date). The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.
Figure 7: FSLE (days$^{-1}$) map extracted from the Sirocco episode in May 2008. Black arrows indicate the surface currents configuration at the beginning of the trajectories simulation (specified by the date). The radar current field has been sub-sampled (one vector every five grid nodes) for graphical readability.