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Horizontal Lagrangian transport in a tidal-driven estuary—Transport barriers attached to prominent coastal boundaries

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ABSTRACT

Horizontal Lagrangian surface transport is studied in the Ria de Vigo, an estuary in NW Spain with tidal and wind-driven dynamics. Surface drifters and the surface flow from a high-resolution 3-D hydrodynamic model are compared to each other. In particular, our analysis is based on a classical comparison of real and artificial trajectories and on Lagrangian Coherent Structures (LCS) defined as ridges in spatial fields of the Finite-Time Lyapunov Exponent (FTLE). The trajectories of the drifters are in good agreement with the prediction of the model in two out of four cases. Further, FTLE ridges computed from the model velocity fields are found to mark transport barriers for the drifters. The results indicate that the model is able to represent the general circulation in the estuary. Main patterns in the Lagrangian surface transport in the model are shown for two typical meteorological situations, north wind and south wind. They can be interpreted as an imprint of a 3-dimensional circulation pattern in the Ria de Vigo and reveal in detail the separation of the time-dependent in- and outflow at the surface of the estuary.

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1. Introduction

Chaotic horizontal transport occurs in many oceanic flows, e.g., in a tidal-driven system at the coast (Riddlerzhof and Zimmerman, 1992), or at much larger scales in the open ocean (Abraham and Bowen, 2002). In order to analyze transport in these flows, concepts from dynamical systems theory have been successfully applied (Wiggins, 2005). The concept of Lagrangian Coherent Structures (LCS) provides a method to extract spatial geometrical structures that order transport in the flow (Haller, 2000; Ide et al., 2002; Lapeyre, 2002). LCS are the locally strongest repelling or attracting material lines and represent the cores of Lagrangian patterns. Being material lines, i.e., a line of fluid particles, they cannot be crossed by ideal tracers. Therefore, they are transport barriers separating the flow into different water masses, a fundamental and very useful property of this concept. LCS are surprisingly stable against errors in the velocity field (Haller, 2002; Hernández-Carrasco et al., 2011) and can still provide a sketch of the main circulation in a coastal region, when Lagrangian chaos impedes the direct comparison of trajectories. They reveal integrated Lagrangian information not obtainable from single steady Eulerian velocity fields (García-Olivares et al., 2007; d'Ovidio et al., 2009; Boffetta et al., 2001). The applications of LCS to oceanic flows range from the observations of the general ocean circulation (d'Ovidio et al., 2004; Beron-Vera et al., 2008) to very specific exchange processes across jets (Mendoza et al., 2010) or fronts (Mancho et al., 2008). The LCS method has been used to understand the spreading of plankton blooms (Olascoaga et al., 2006; Olascoaga, 2010; Pérez-Muñuzuri and Huhn, 2010; Lehahn et al., 2007) and to manage and predict the transport of contaminants and pollution in coastal waters (Lekien et al., 2005; Coulliette et al., 2007; Stirling, 2000), as well as to diagnose the mixing of oil spills (Mezić et al., 2010).

Only recently, coastal flows have been in the focus of studies using LCS, carried out in the Gulf of Eilat, Israel (Gildor et al., 2009), the Gulf of La Spezia, Italy (Haza et al., 2010) and in Monterey Bay, California, USA (Shadden et al., 2009). Coastal flows are especially challenging due to their complex 3-dimensional boundaries, a lack of isotropy, and a large variety of intermittent forcings and physical processes, such as unsteady wind influenced by the coastal topography. Yet, coastal regions are of great ecological and economical interest, and thus, intensified exploration of transport as a key process is necessary.

Our study region, the Ria de Vigo, is the southernmost of the four estuaries Rías Baixas in Galicia at the NW coast of Spain...
which is shown in Fig. 1. It has a typical V-shape and gradually deepens and widens towards its mouth. The Cies islands divide the mouth into a smaller northern mouth and a larger southern mouth (Gómez-Gesteira et al., 1999; deCastro et al., 2006). Being situated in the Iberian coastal upwelling system, the longterm circulation pattern with a time scale of some days to a week is determined by periods of northerly winds causing upwelling (typically in summer) and periods of southerly/westerly winds causing downwelling (typically in winter) (Wooster et al., 1976; Fraga, 1981; Nogueira et al., 1997). The circulation and the resulting transport have been studied experimentally (Piedracoba et al., 2005; deCastro et al., 2006; references therein) and by means of models (Taboada et al., 1998; Gómez-Gesteira et al., 1999; Montero et al., 1999; Torres et al., 2001; Miguez et al., 2001; Souto et al., 2003; Gilcoto et al., 2007). In case of upwelling, the cold, nutrient-rich upwelled water generates a high biological production and gives rise to an intense human use of the estuary in terms of aquiculture of fish and shellfish (Figueiras et al., 2002). However, contaminations and harmful algae blooms can threaten the productivity and the balance of the ecological system (Fraga et al., 1988; Tilstone et al., 1994).

In this study, we concentrate on the outer region of the estuary, where the interaction of the tidal flow with the wind-driven longterm flow along the coast leads to interesting chaotic dynamics. We investigate the horizontal surface transport in the Ria de Vigo from a coastal model are an extremely useful way to interpret the predicted transport. Coastal hydrodynamic models might not be

as accurate as direct measurements of the surface currents via High Frequency (HF) Radar (Molcard et al., 2009; Shadden et al., 2009; Ullman et al., 2006; Haza et al., 2010), but they can be available in coastal regions where HF Radar systems have not (yet) been installed and provide the possibility of a prediction of several days. While classical numerical tracer particle studies of contaminants, sediments or biological tracers are common (e.g., Montero et al., 1999; Carracedo et al., 2006; Ceréjo and Dias, 2007; Döös and Engquist, 2007; Cowen et al., 2006), only recently, flows of coastal models have been analyzed using the LCS concept (Haza et al., 2007; Branicki and Malek-Madani, 2010). We stress that we concentrate on the surface flow here, while decisive dynamics at the coast also happens in the vertical dimension.

The paper is organized as follows. In the following part we present the model and the drifter experiments. In the third part we describe the data processing and the computation of the LCS. The fourth part comprises the results including a discussion and finally we give a summary and an outlook in the fifth part.

2. Data

2.1. The hydrodynamic model

For our analysis we use the hourly output of the high resolution, 3-dimensional baroclinic hydrodynamic model MOHID (www.mohid.com) that is run operationally by MeteoGalicia (www.meteogalicia.es), the official Galician meteorological service. The MOHID model was developed at MARETEC at the Technical University of Lisbon and has shown its ability to simulate complex coastal and estuarine flows (Coelho et al., 2002; Martins et al., 2001). It solves the 3-dimensional incompressible primitive equations assuming hydrostatic equilibrium and the Boussinesq approximation. The turbulent vertical mixing coefficient is determined using the General Ocean Turbulence Model (GOTM) (Burchard and Bolding, 1999).

The model is implemented with three nested grids of increasing resolution. The largest grid has an extent of about 330 × 390 km² covering the entire Galician coast and parts of the Portuguese and Cantabrian coast with a resolution of 0.06 × 6.7 km. It receives boundary conditions from the POLCOMS model of the Spanish Operational Oceanographic System (www.eseeo.org) that itself forces by data of UK Met Office's data assimilating FOAM oceanographic model and Spanish AEMET's HIRLAM atmospheric model. Tidal data enters from Aviso's data assimilating FES2004 product via a barotropic grid of Western Iberia. Atmospheric forcing is provided by a WRF (Weather Research and Forecasting) Model at 12 km resolution with boundary conditions from NOAA’s GFS (Global Forecast System) model. The second grid has a resolution of 0.02 × 2.2 km and comprises the four estuaries Rias Baixas the southernmost of which is the Ria de Vigo. The finest model grid for the Ria de Vigo that we use in this study (Fig. 1) has a resolution of 300 m (156 × 153 grid points) and is integrated with a time step of 30 s. It receives boundary conditions from the second grid and is forced by WRF wind data at a resolution of 4 km. The operative scheme is composed by a preliminary spin-up of five days hindcast followed by a three day forecast. For the next prediction the new initial condition is generated by running the previous day, starting with the hindcast output and using assimilated local meteorological data during the integration. Freshwater river outflow into the Ria de Vigo is predicted by the SWAT (Soil and Water Assessment Tool, http://swatmodel.tamu.edu). An accurate bathymetry is crucial for the model, here it was constructed based on data from the Spanish Hydrographic Institute. The bathymetry is widely accurate, however, it must be mentioned that even at the high
resolution of 300 m, the accuracy might be limited at some extreme locations, e.g., details of the flow in the channel between the Cies Islands cannot be resolved.

The vertical dimension of the model grid is structured in 16 cartesian 2-level layers with an increased resolution in the surface boundary layer. We use the uppermost surface layer of the 3-D velocity output of the model to advect artificial tracers in 2-dimensional space. The depth of this layer varies between 1 m and 3 m as the tidal elevation adds to this layer, but generally corresponds to the typical length of the drogues of the drifters. For the artificial tracers we assume that the vertical velocities close to the surface are negligible compared to the horizontal velocities, since the water surface imposes a boundary condition of zero vertical flow (Branicki and Malek-Madani, 2010). This is especially justified for floating tracers. We tested the positions of the resulting LCS computed from the upper three layers and obtained only small differences. For these reasons, in the following we choose the uppermost water layer. For the further Lagrangian analysis the hourly velocity fields from the model are used.

The model was designed as an operational model that captures the general circulation in the Ria de Vigo, i.e., the propagation of the tidal wave in the complex bathymetry and the response of the flow to changing wind forcing, which drives the important long-term flow on the shelf with typical time scales of days to weeks (Piedracoba et al., 2005). Due to its hydrostatic approximation that neglects the vertical acceleration of fluid parcels (Marshall et al., 1997) it might not accurately represent some physical processes as, e.g., non-linear internal waves, Kelvin–Helmholtz instabilities under a fast spreading freshwater plume (Shaw and Chao, 2006) or upwelling filaments (Chao and Shaw, 2002). However, these processes do not dominate the circulation in the Ria de Vigo and hardly influence the drift of surface drifters. Internal waves have been reported to form on the shelf (Fraga, 1996), but there is no clear evidence that they enter the Ria de Vigo and alter the horizontal circulation.

2.2. Drifter experiments

Drifter experiments in the Ria de Vigo were carried out by the Technological Institute for the Monitoring of the Maritime Environment (INTECMAR) in Vilagarcía de Arousa, Galicia, Spain, in the framework of the AMPERA funded DRIFTER project ‘HNS, oil and inert pollution: Trajectory modeling and monitoring’. Data were collected for the project during 17 experiments over a period of 22 months from December 2008 to September 2010 in two Galician estuaries, the Ria de Arousa and the Ria de Vigo. The subset of data in the Ria de Vigo comprises 55 drifter trajectories. Drifters were deployed in clusters inside the Ria de Vigo, left in the water over night, and recovered the following day. Therefore, the mean duration of the trajectories is 19 h with a duration of 4 h for the shortest and 32 h for the longest drifter run. The total drifter time is 1077 drifter hours.

The original experiments were designed to compare different types of drifters and drogues for the management of contamination and oil spills. For this study, we selected four drifter runs out of the entire data set fulfilling two criteria (Table 1): the drifters must have sufficient current following properties (equipped with an effective drogue) and trajectories must be in the vicinity of LCS computed from the model flow. In Table 1 we show the four selected drifter runs with two types of drifters fulfilling these requirements: the MD02 drifter of Albatros Marine Technologies in three drifter launches, and the TRBUOY drifter of Marexi Marine Technology in one drifter launch. The MD02 drifter is a small coastal drifter that is robust due to its foam protection and, therefore, suitable for applications close to rocky coasts. Both drifters transmit their GPS position by sending SMS via the GSM system to a modem connected to a PC. GSM net coverage is limited to coastal areas impeding offshore use of these drifters. Wind slip could be estimated from a single experiment with moderate wind where a dye patch was present as a reference (Price et al., 2006). It turned out to be less than 4 cm/s for the MD02 drifter analyzed here. For the MD02 drifter the standard deviation of the GPS position was estimated to be approximately 13 m by means of an experiment where three drifters were fixed at a constant position for 3 h. This error is in the upper range of typical values reported by other studies (Ohlmann et al., 2005; Stevens, 2009). For the TRBUOY drifters the characteristics are expected to be likewise due to a similar construction as the MD02 drifter, although no systematic analysis of the uncertainties was made.

3. Data processing and methods

3.1. Drifter data

Drifter position data were recorded at a period of 10–15 min for most experiments and the period was decreased to 5 min for the last two experiments. All data were interpolated linearly to a time series with a 2 min time step and then lowpass filtered with a cutoff frequency of 1/15 min–1. Johnson and Pattiaratchi (2004) compare the power spectra of drifter trajectories to the spectrum of a stationary test and filter high frequencies with a signal to noise ratio smaller than 10. For our data this frequency threshold is around 1/16 min–1 corresponding to the cutoff frequency of the filter used. In order to compare the velocity of the drifters to the velocity from the model a further low pass filtering up to the Nyquist frequency of the model of 1/2 h–1 would be appropriate. However, this does not change the drifter trajectories significantly. Drifter positions at full hours and derived Lagrangian velocities are then compared to the FTLE fields and Eulerian velocities obtained from the hydrodynamic model.

3.2. Lagrangian Coherent Structures from model velocity field

In order to extract Lagrangian Coherent Structures we compute fields of the Finite-Time Lyapunov Exponent (FTLE) from the discrete hourly velocity data set of the hydrodynamic model. We use a standard method to obtain the fields of the FTLE by advecting a grid of artificial tracers for a finite time τ. Artificial tracers have an initial separation of 60 m corresponding to 5 × 5 tracer particles per model grid cell (300 m) and are advected with a fourth order Runge–Kutta scheme and a linear interpolation of the model velocity data to tracer positions in time and space. The FTLE fields \( A(\vec{x}, \tau) \) are computed as

\[
A(\vec{x}, \tau) = \frac{1}{\tau} \ln \sqrt{l_{\text{max}}(\vec{x}, \tau)}
\] (1)
where $\tau$ is the advection time and $\lambda_{\text{max}}$ the largest eigenvalue of the Cauchy–Green deformation tensor $\mathcal{A}(\mathbf{x},t,\tau)$, computed from the flow map of the artificial tracers (Shadden et al., 2005; Mancho et al., 2006). Tracers are advected forward and backward in time in order to obtain estimates of repelling (stable, divergent) and attracting (unstable, convergent) hyperbolic manifolds. We present the combined FTLE fields $A^+ (\mathbf{x},t,\tau)$ computed as d’Ovidio et al. (2004)

$$A^\pm (\mathbf{x},t,\tau)= A^+ (\mathbf{x},t,\tau)- A^- (\mathbf{x},t,\tau)$$

(2)

$A^+ (\mathbf{x},t,\tau)$ is the forward FTLE field where tracers are released at time $t$ and advected until time $t+\tau$, whereas $A^- (\mathbf{x},t,\tau)$ is the backward FTLE field where tracers are released at time $t$ and advected with the negative velocity field until time $t-\tau$.

Generally, the resolution of the FTLE fields is significantly higher than the velocity fields from the model due to the $5 \times 5$ tracer particles per model grid cell. The subgrid information in the FTLE field is contained in the time-dependent velocity field and can be considered real (Hernández-Carrasco et al., 2011). It stems from the integration of the velocity field along the trajectories of artificial tracers that have a length much longer than a grid cell. Moreover, subgrid flow structures can be contained in the temporal dependence of the velocity field.

In order to obtain meaningful FTLE fields, the finite advection time $\tau$ has to be chosen carefully according to two criteria. First, $\tau$ defines the time scale of the Lagrangian processes that will be mapped in the FTLE fields. If a certain Lagrangian structure with a typical time scale $\tau_1$ should be sampled, a much shorter advection time $\tau \ll \tau_1$ impedes the tracers to explore the whole structure, whereas for a much longer advection time $\tau \gg \tau_1$ tracers explore many different parts of the flow, so their integrated history becomes similar and the spatial FTLE field becomes more uniform (see Branicki and Wiggins, 2010; references therein for a detailed discussion). This dependence on the advection time $\tau$ can be analyzed in terms of the probability distribution functions (pdfs) $p(A^+(\tau))$ of the values occurring in the FTLE field. For small times $\tau$ the pdf is dominated by the distribution of the local instantaneous strain rate (Abraham and Bowen, 2002) and spatial FTLE fields do not show linear structures. For large times $\tau$ the pdf converges very slowly to its asymptotic form (Abraham and Bowen, 2002), which in the case of a delta function denotes a uniform FTLE field without any spatial information. Fig. 2 shows this evolution for the pdfs of FTLE fields in the Ria de Vigo. With increasing $\tau$ the standard deviation of FTLE values decreases and the mean of the pdf shifts to smaller values. For closed ergodic flows all Lyapunov exponents converge to the same value $\lambda_{\infty}$ for $t \to \infty$ and the variance vanishes (Abraham and Bowen, 2002; Waugh and Abraham, 2008; Lapeyre, 2002), however, the flow in the Ria de Vigo is an open flow and the infinite time limit is thus only hypothetical.

We use the pdfs of FTLE values here to investigate whether the choice of $\tau$ as a multiple of the tidal period significantly influences the resulting FTLE field. Obviously, in Fig. 2b the convergence of the pdf’s mean and standard deviation with increasing $\tau$ carries the imprint of the tidal semi-diurnal (and quarter-diurnal) frequency. This reflects that the separation of tracers in the flow does not evolve gradually, but intermittently with the tidal oscillations in the flow. Similarly, Orre et al. (2006) reports that relative and absolute dispersion in a tidal model in a Norwegian fjord depend strongly on the tidal cycles and mixing predominantly happens during times of high velocities between high and low tide. However, the evolution of the pdfs in Fig. 2 is smooth enough and does not imply a special preference for the choice of the advection time $\tau$. Meaningful LCS can thus be obtained with $\tau$ close to a typical time scale of the flow.

Second, the limited spatial extend of the velocity data is a strong limitation to the advection time, as tracers simply leave the region where velocity data is available. One way to deal with this problem is to calculate FTLE values at the moment just before the tracers reach the boundaries (Shadden et al., 2009), but this leads to a non-constant time $\tau$ for different tracers. Lekien and Leonard (2004) adapt $\tau$ to the persistence time of a dynamical regime obtained from Open-boundary Modal Analysis (OMA) of HF radar velocity data. Here, we simply keep $\tau$ short enough to prevent the tracers in the region of interest to reach the boundaries. FTLE values of tracers that left the region are not computed (Abraham and Bowen, 2002).

We choose $\tau = 24$ h for the FTLE fields shown. This time can be extended for calm meteorological situations, when the mean flow in the Ria de Vigo is small and sharp FTLE ridges do not appear until $\tau$ reaches several days. Finally, it must be mentioned that the studied coastal flow can be subject to several transitions, especially coupled with the wind forcing, so the choice of the advection time remains a subtle task (Branicki and Wiggins, 2010).
Once reliable FTLE fields are obtained, estimates of the manifolds, representing the LCS, are extracted as ridges in the forward and backward FTLE field separately (Shadden et al., 2005; Sadlo and Peikert, 2007). Then, the ridges are filtered using thresholds for the FTLE value and for the sharpness of the ridge, quantified by the second (negative) derivative of the FTLE field across the ridge (Sadlo and Peikert, 2007).

4. Results

In Section 4.1 drifter trajectories are compared directly to trajectories of artificial tracers. In Section 4.2 we present the properties of the obtained LCS in the Ria de Vigo and relate them to the drifter trajectories. Finally, basic circulation patterns in the Ria de Vigo are discussed in terms of LCS of the surface flow (Section 4.3).

4.1. Comparison of trajectories: drifters—model

At first, we perform a classical approach and compare trajectories of the real drifters to trajectories of artificial tracers that are advected with the model velocity data. Apart from the wind forcing entering the hydrodynamic model, we do not use any additional direct wind forcing on the artificial tracers. We are aware that the drifters could be modeled in a more sophisticated way, taking into account its vertical extension at the boundary of the wind and water flow. Possible effects are drifter displacement due to wind, wave-induced Stokes drift and sub-scale dynamics not resolved by the hydrodynamic model. Including these additional forcings can lead to a better agreement between the trajectories of modeled tracers and real drifters when appropriate data of the forcings are available (Furnans et al., 2008; Price et al., 2006). Such a detailed model of drifting objects is especially desirable for search and rescue missions or for operational pollution management. Here, however, the objective is to study the surface transport as predicted by the operational model and, therefore, we use the same ideal point-like tracers for the direct comparison of trajectories as for computing the FTLE fields. The uppermost layer of model velocity data is the most appropriate to compare to our Lagrangian data of real drifters. In the following the term ‘tracer’ is used shortly for ‘artificial tracer’ in contrast to ‘drifter’ for the real drifters.

Figs. 3–6 show the four drifter experiments considered due to the presence of LCS that interact with the drifter trajectories. The first panel (a) respectively shows the trajectories of real drifters and artificial tracers starting at the release point. The other two panels (b) and (c) compare the Lagrangian velocity of the drifters with the Eulerian velocities of the model in order to interpret the separation of trajectories. Drifter velocities are estimated from

Fig. 3. Experiment 1. (a) Trajectories of drifters and artificial tracers. (b) Comparison of the Lagrangian velocity of the drifters with the Eulerian velocity of the model interpolated to hourly drifter positions. (c) Scatter plot of Eulerian model velocity and Lagrangian drifter velocity components shown in (b) revealing the degree of correlation between both.

Fig. 4. Experiment 2. Corresponding diagrams as in Fig. 3.
finite differencing of the hourly position data and the Eulerian velocity of the model is a linear interpolation of the 2-dimensional model velocity field at the surface to the drifter position. Note, that the latter is not the Lagrangian velocity of the artificial tracers, but velocities are compared along the trajectories of the real drifters. Panel (b) shows that the modeled velocities are in a reasonable agreement with the measured drifter velocities. A strong tidal signal with a semi-diurnal period can always be seen in both data sets that identifies the tide as the main forcing for both. In panel (c) correlation coefficients $R_{corr}$ are around 0.8 for experiments 1 and 3, while in experiments 2 and 4 the agreement is lower with correlation coefficients of 0.68 and 0.64 respectively. An overview can be found in Table 2. We also quantify the deviation between drifter and model velocity components as $\Delta v_i = v_{drifter} - v_{model}$, $i=x,y$. The root-mean-square deviation $\text{RMS}(\Delta v) = \langle \Delta v^2 \rangle^{1/2}$ is a measure of the typical deviation between model and drifter velocities. It is in the order of 5 cm/s for our experiments (Table 2), similar to other studies where coastal drifters are compared to current data from High Frequency (HF) Radar (Ohlmann et al., 2007; Molcard et al., 2009).

Despite the reasonable agreement of the velocity data, the real and artificial trajectories in experiments 2 and 4 separate drastically. The drifter trajectories of these two experiments show how velocity differences between the artificial and real tracers at the beginning of the experiment (here mainly in the $x$-direction, Figs. 4b and 5b) lead to strongly diverging trajectories in the following 24 h. This divergence is partly due to the inherent behavior of Lagrangian chaos where small initial separations grow exponentially in time.

In order to quantify the accuracy of trajectory prediction (with velocity data from High Frequency (HF) Radar), Molcard et al. (2009) and Ullman et al. (2006) set the separation of drifters and artificial tracers $d(t) = |\bar{r}(t)_{drifter} - \bar{r}(t)_{tracer}|$ in relation to the total traveled distance of the drifters $D(t) = \langle |\bar{r}(t)_{drifter} - \bar{r}(0)_{drifter}| \rangle$.

The ratio $d(t)/D(t)$ denotes a relative error of the trajectory prediction and for identical trajectories it is zero. Similar Lagrangian error metrics have also been introduced by Toner et al. (2001).

### Table 2

Comparison of real drifters with artificial tracers.

<table>
<thead>
<tr>
<th>#</th>
<th>$d/D$</th>
<th>Separation rate (km/h)</th>
<th>Form of trajectories</th>
<th>$\text{RMS}(\Delta v)$ (cm/s)</th>
<th>$R_{corr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>4/12</td>
<td>Directional</td>
<td>5.2</td>
<td>0.78</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>3/24</td>
<td>Oscillating</td>
<td>4.5</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>5/12</td>
<td>Directional</td>
<td>7.2</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>3/24</td>
<td>Oscillating</td>
<td>6.9</td>
<td>0.64</td>
</tr>
</tbody>
</table>
We use this measure to further distinguish qualitatively the flows in experiments 1 and 3 from those in experiments 2 and 4 (Table 2). For experiments 2 and 4 the ratio \( d(t)/D(t) \) has relatively high values of the order of one, as the drifters are located in an oscillating chaotic tidal flow with several return points in the trajectories resulting in a small traveled distance \( D(t) \). In contrast, in the unidirectional (wind-driven) less chaotic flow in experiments 1 and 3 the traveled distance of the drifters \( D(t) \) is large, leading to small ratios \( d(t)/D(t) \) of 0.3 and 0.5. The total separation rate between modeled and real trajectories is almost a factor 2 higher for the directional flows with 4 km/12 h compared to the oscillating flows with 3 km/24 h, but is overcompensated in the ratio \( d(t)/D(t) \) by the large traveled distance \( D(t) \). Our separation rates are at the lower part of the typical range of 4–25 km/day found in open ocean studies as reported in Huntley et al. (2011).

Velocities and especially velocity gradients in our strong tidal flow can be expected to be as high as or higher than in the open ocean, so it is meaningful to compare our results to separation rates in the open ocean. An important difference, however, is the presence of the strong constraint the coastline imposes on our model flow and the well-defined forcing of the tides that in large parts determine the coastal model flow. This probably leads to the relatively low separation rates between drifters and modeled tracers that we find.

Based on the above comparison of drifter and model velocity data, we can consider a basic validation of the model and assume that the hydrodynamic model serves to approximately represent the flow in the Ria de Vigo. However, especially in two experiments we see that the flow is highly irregular and not unidirectional, so a small initial deviation between the drifter velocity and the model velocity can lead to a strong separation of the artificial tracers from the drifters. This strong dependence on initial conditions is an inherent property of chaotic systems. Therefore, instead of directly comparing trajectories, we concentrate on LCS as a more suitable approach to compare the drifter data set to the hydrodynamic model.

4.2. LCS in the Ria de Vigo

As described in Section 3.2 LCS are obtained from tracers advected with the Eulerian velocity field given by the hydrodynamic model. Fig. 1 shows an example of the model surface velocity field with a relatively unidirectional tidal in and outflow, that interacts in the outer parts of the estuary with the north-south flow on the shelf and with the Cies Islands off the coast. Fully developed eddies are absent, but some rotational structures appear as recirculations behind sharp capes. These have very short lifetimes of few hours, mostly less than a turnover time. Thus, in the investigated flow hyperbolic separation points are predominantly situated at the coast and are rarely found in the calmer center of the bay. Artificial tracers mostly separate due to a drift towards a coastal boundary or an island. Therefore, most LCS are connected to the coast with one end and extend a distance into the flow that depends on the advection time \( \tau \) (Shadden et al., 2009; Lekien and Leonard, 2004; Lekien et al., 2005).

Fig. 7 shows a case of pronounced repelling LCS in the Ria de Vigo with the above mentioned characteristics for a long advection time of \( \tau = 60 \) h. Such long advection times are feasible for a slow mean flow when artificial tracers stay inside the area of interest. We plot a square of artificial tracers at their initial positions consisting of three regimes separated by repelling LCS that mark three different water bodies. The distinct final positions of the three tracer regimes demonstrate the predicting character of the LCS: the green tracer regime (1) leaves the estuary northwards and enters the Ria de Aldan Bay, while the cyan regime (2) is caught at the north coast of the Ria de Vigo close to Cape...
The dynamics in the flow is represented by the time dependent FTLE field and the extracted LCS, shown here in snapshots. Animations of the FTLE fields reveal the full dynamics including the tidal oscillations of the LCS (see on-line supplementary data, Appendix A). Moreover, in regions where LCS are absent the temporal dynamics of the background FTLE field is a good estimate of the underlying flow, or simply said, the background FTLE field moves almost exactly with the flow.

The main feature in Fig. 9 is an attracting (unstable/blue) LCS (L1) connected to Cape ‘Cabo Home’ (C) that marks the line of convergence between water entering the north mouth and water from inside the Ria de Vigo. Both drifters deployed inside the Ria de Vigo stay essentially east of this LCS along the entire experiment while being advected to the south. The drifter trajectories are also consistent with another attracting (unstable/blue) LCS (L2) emerging from the eastern most cape at the north coast. This LCS marks the abrupt movement in the drifter trajectories 4 h after the release stemming from the change of direction of the tidal flow at low tide, see Fig. 9a and animation in supplementary data. The repelling (stable/red) LCS (L3) connected to San Martino Island (A) separating the outflow through the south mouth from the flow towards the island is crossed by one drifter. This suggests a slight shift between the location of the LCS in the model and the real flow. The other drifter follows the prediction by the model.

Fig. 10 shows experiment 2 at the north coast of the Ria de Vigo. LCS appear due to recirculations behind capes but are less pronounced as the tidal flow is basically oscillating parallel to the coastal boundary. Drifters stay between an attracting (blue/unstable) LCS (L1) and a repelling (red/stable) LCS (L2). The observed LCS turn out to be typical for tidal dynamics in the inner parts of the Ria de Vigo.

Fig. 11 shows experiment 3, a closeup of the separation of drifters in the tidal channel between San Martino Island (A) and Monteguido Island (B). Wind and flow direction are similar to experiment 1 (Fig. 9). Drifters were deployed in the channel during falling tide in order to check the LCS of the outflow. We want to highlight that even at the small scale of the order of 1 km the initial LCS are principally consistent with drifter trajectories. This agreement might be explained by the well defined flow in the small zone of interest due to a strong constraint imposed by the surrounding coastal boundaries. The repelling LCS (L1 and L2) between the initial positions of the drifters correctly predict that one drifter passes the channel, the second runs aground on San Martino Island (A) and the third drifts south, passing the island on the eastern side. Only later, the westernmost drifter crosses an attracting (unstable/blue) LCS (L3) twice indicating a deviation of the model from the real flow.

Fig. 12 shows experiment 4 in calm conditions, i.e., without a directed longterm flow on the shelf outside the estuary. Mixing of neighboring water bodies and the resulting LCS are mainly due to an oscillating tidal flow around the Cies Islands. Drifter trajectories are consistent with a repelling (red/stable) LCS (L1) separating water inside the Ria de Vigo from water that moves westwards around the eastern cape of San Martino Island. In the second half of the experiment drifters move to the center of the basin without the influence of any further pronounced FTLE ridges.

We compared drifter trajectories of four experiments to estimated transport barriers (LCS) from the model flow, and we find that overall LCS serve to predict and visualize the transport at the surface in the real flow in a global way. The used methods to estimate transport barriers (LCS) from FTLE fields turn out to be appropriate for the analyzed flow. Uncertainties of the positions of the transport barriers can be observed in at least two cases when a drifter crosses a pronounced transport barrier. Shadden et al. (2009).

Fig. 9. Drifters and LCS in experiment 1. Current positions of the two drifters are shown as green circles, starting at the release point (black square) and moving along the trajectories with hourly resolution (green line with black dots). The background field is the combined FTLE field \( \Lambda^\pm(x,t) \) in units 1/h. Advection time is \( \tau = 24 \) h. Extracted repelling (attracting) FTLE ridges are drawn in red (blue). The failure of one of the drifters for some hours is indicated by a black line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
estimates an error for the position of the transport barrier based on crossing events. Here, the error would be in the order of 1 km, corresponding to approximately three grid cells of the model flow. In general, the model cannot be expected to represent the real flow.

Fig. 10. Drifters and LCS in experiment 2. Legend as in Fig. 9. Drifters move in a zone with small dispersion between two FTLE ridges that are connected to a cape at the north coast.

Fig. 11. Drifters and LCS in experiment 3. Legend as in Fig. 9. Initial LCS correctly indicate that one drifter goes offshore through the channel, the second runs aground at San Martino Island (A) and the third is drifted south around the eastern cape of San Martino Island. Later, the westernmost drifter crosses an attracting (unstable/blue) LCS twice. The noisy structure at the bottom of the FTLE field appears because forward advected tracers leave the region of available velocity data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
exactly, as the bathymetry is complex and the wind forcing included in the hydrodynamic model does not respect local effects like shadowing of the mountains with a height up to 500 m surrounding the estuary. However, temporal sequences of drifter positions plotted over the LCS positions allow for a visual comparison of drifter trajectories to integral geometrical structures of the model flow. As a principal result, the subdivision of the flow into dynamically different water bodies can be roughly predicted by the model. In contrast, the direct comparison of trajectories of drifters to simple artificial tracers reveals high discrepancies, as velocity differences between model and real flow accumulate in the integration.

4.3. LCS during north and south wind conditions

The results demonstrate the relevance of the extracted LCS for the real flow. However, LCS are highly dynamic and intermittent, especially in transient meteorological conditions (Branicki and Wiggins, 2010). It is thus desirable to obtain more general information about the Lagrangian transport at the surface beyond the special cases of the four experiments. Wind forcing and the induced flow on the shelf play an important role for the circulation in the outer parts of the Galician Rias (deCastro et al., 2000). At the western Galician coast two wind directions are dominant that can also be related to upwelling and downwelling processes: northerly winds (often during summer) and southerly/westerly winds (often during winter). Here we extract LCS in these two meteorological conditions and show a Lagrangian sketch of the short-time surface circulation in the Ria de Vigo. Fig. 13 shows LCS of the two typical flow patterns selected as examples for its pronounced north–south mean flow on the shelf indicated by white arrows. The LCS are time dependent and oscillate with the tide but they are computed for a time \( t = 24 \, \text{h} \), twice the tidal period, and can be considered to represent the Lagrangian pattern of the short-time residual flow. Their persistence time is in the order of days, comparable to the persistence time of the flow pattern due to the wind forcing. In contrast to Eulerian measures, the LCS reveal the spatial information where surface water masses from the shelf and from the estuary converge or separate. The Cies Islands (A and B, Fig. 1) and Cape ‘Cabo Home’ (C, Fig. 1) play a key role for this circulation, since pronounced LCS are attached to these coastal boundaries. The inner and outer parts of the Ria de Vigo are not strictly separated, but surface water enters (leaves) the inner parts of the estuary during south wind (north wind).

During south wind conditions (Fig. 13a), the most important repelling (stable/red) LCS mark the flow separation at the Cies Islands (L1) and at Cape ‘Cabo Home’ (L2). Only the water body in-between the LCS (L1) and the coast enters the Ria de Vigo at the south and most of the water leaves the estuary through the north mouth again. Attracting (unstable/blue) LCS connected to the Cies Islands in the north (L3) show that the outflow stays attached to the coast, drifting north into the Ria de Pontevedra. During north wind conditions (Fig. 13b), the flow is almost inverse to the flow during south wind conditions. A prominent attracting (unstable/blue) LCS (L4) impedes surface water to enter into the inner estuary from the north. The water body between Cies Islands and Cape ‘Cabo Home’ passes on both sides of San Martino Island and is drifted offshore. Under both conditions, a transport barrier extending in north-south direction and connected to the Cies Islands clearly separates the flow that interacts with the inner part of the Ria de Vigo from the flow that passes by on the shelf. Note the two bays Ria de Aldán and Ria de Baiona which are almost cut off from the rest of the surface water exchange by LCS in both cases. These zones of retention can be of special importance for ecological studies as high concentrations of contaminants or biological tracers can persist in these areas. Even though the discussed LCS under north wind and south wind conditions are subject to a certain variability, they correspond to typical flow patterns in the model appearing under similar meteorological conditions.

Fig. 12. Drifters and LCS in experiment 4. Legend as in Fig. 9. Even though the trajectories of drifters and artificial tracers deviate strongly in this experiment (Fig. 6), the repelling (stable/red) LCS close to San Martino Island computed from the model is consistent with the drifter trajectories. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
conditions. Their relevance for the trajectories of real surface drifters has been demonstrated for the four experiments (Section 4.2).

5. Discussion and conclusions

In this work we studied Lagrangian surface transport at submesoscale (1–10 km) in a tidal estuary by comparing trajectories of surface drifters to Lagrangian Coherent Structures (LCS) computed from the output of a coastal hydrodynamic model. Similar to recently reported results (Shadden et al., 2009), we find that drifter paths are better characterized by LCS than by single artificial tracers. The drifter experiments show that the positions of the LCS have uncertainties of about 1 km as the model tends to underestimate the dynamics. Nevertheless, the LCS give an idea of the fundamental structure of Lagrangian transport imposed by the prominent coastal boundaries that can be expected in different meteorological cases. This demonstrates the importance of the Lagrangian view on the output of coastal models and the power of the LCS method in the analysis for these flows.

We are aware that care must be taken when analyzing a coastal flow only horizontally. Vertical flow most often cannot be neglected as upwelling and downwelling processes or typical vertical estuary circulation imply. Vertical flow can lead to divergence in the 2-dimensional surface flow that changes the FTLE fields (Haza et al., 2010). We also observe the occurrence of negative FTLE values (see Fig. 2a) corresponding to zones of horizontal convergence. Furthermore, Branicki and Malek-Madani (2010) have suspected that a part of LCS extracted from estuary model flows can be artifacts due to coarse boundary conditions and imprecise forcings. In our case, the relatively accurate tidal forcing determines a large part of the dynamics, but coarse wind data and unresolved coastal topography, as well as the assumed approximations for the hydrodynamic equations can certainly limit the reliability of the model output. Nevertheless and in spite of these limitations, the LCS can reveal a surface footprint of the total 3-dimensional transport given by the model. The LCS analysis applied to model data can be especially interesting in regions where direct measurements of the velocity field (e.g., HF Radar) are not available.

Due to its importance in fishery and seafood production the Ria de Vigo is a region of intensive biological and ecological studies where the transport of nutrients, plankton, fish eggs, larvae, etc., plays an important role. Visualized surface transport patterns can be a useful hint for such studies. They can help to take horizontal transport processes into account as an explanation for biological observations (Pérez-Munúzuri and Huhn, 2010; Lehahn et al., 2007).

Future work could deal with a closer look at the position error of the LCS which can be determined by lines of drifters deployed across a predicted LCS. Moreover, the challenging task of 3-dimensional LCS in coastal models has been addressed by Branicki and Malek-Madani (2010) and reliable results would be valuable for many ecological transport problems.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version of http://dx.doi.org/10.1016/j.csr.2012.03.005.

References


Fig. 13. Examples of LCS in the Ria de Vigo for two typical meteorological situations: (a) south wind in winter and (b) north wind in summer. White arrows denote the approximate direction of the mean flow on the shelf. LCS (denoted L1–L4) allow to distinguish the water entering, leaving and passing by the Ria de Vigo.
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