THE ROADS OF THE SEA - CAN WE PREDICT THE MOTION OF PARTICLES CARRIED BY OCEAN CURRENTS?

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Abstract

Ocean currents play a fundamental role in the transport of substances and species. Being able to monitor and predict their effects is of great relevance for a number of applications, such as correct management of the coastal ecosystem, manage control in case of discharges of pollutants and understanding of pathways of invasive species. While transport by ocean currents is under many aspects very complex and dominated by turbulent and chaotic processes, it has been shown in recent works that it is often possible to find a hidden structure, at least for mesoscale motion, that guides the movement of the avected quantities. Barriers of motion exist in the ocean, related to the main "Lagrangian coherent structures", i.e. to structures such as gyres, jets and eddies. In this paper, we provide examples of methods to identify such barriers and applications in the Mediterrean Sea . The limits of these methods, that are based on the assumption that the velocity field is well known, are also discussed, and possible remedies in terms of Lagrangian assimilation are discussed.

1 Introduction

Currents are the roads of the sea. They transport physical properties such as temperature and salinity (T,S), chemical properties, pollutants, particulate and sediments as well as biological quantities such as phytoplankton, zooplankton, larvae and jelly fish. Being able to understand and predict transport by ocean currents is therefore crucial for a number of applications. They include climatic applications, for instance understanding heat transport or pathways of species invasions, as well as applications for a correct management of the coastal ocean ecosystem and for damage control in case of accidents at sea such as discharges of pollutants.

Transport predictions is very challenging for a number of reasons (Piterbarg et al., 2007). To understand it, consider the basic equation of Lagrangian transport, i.e. the equation that describes particles advected by the current,

$dx/dt= u(x,t)$,

where x is the position of a particle and u is the velocity. The equation shows that the trajectory of a particle, $x(t)$, is the integral of the velocity $u(x,t)$. This implies that even small errors in the prediction of u tend to accumulate and grow in the prediction of $x(t)$. Since in practice small errors in u are unavoidable, due to incomplete knowledge of forcing, topography, coastline and to the influence of small scale unresolved processes, we can expect that this will result in significantly amplified errors in trajectories. Also, the equation is inherently nonlinear, since u depends on the position x, and it has the property of being very often chaotic. This implies that even for very simple Eulerian flows u (in presence of time dependence) trajectories are highly sensitive to initial conditions. Predicting them is therefore very difficult, since even a slight difference in initial conditions in space and time can result in significantly different behaviours.

Even though Lagrangian prediction is highly challenging, a number of methods have been put forth in the past decade that have helped increasing our skills in this direction. Different methods have been suggested for different applications. Methods based on statistical approaches are particularly suited for climatic problems. They consist in separating the mean component of the currents from the turbulent and fluctuating component and parameterizing the turbulent part for instance using stochastic methods (Aliani and Molcard, 2003 ; Veneziani et al., 2005 ; Doglioli et al., 2006). Other methods are more suited for the prediction of specific events, and they are typically based on dynamical system theories. The basic concept here is that even though the motion of a single particle is extremely challenging to reproduce because of the high dependence on initial conditions and on the details of the flow, the description of the general pattern of transport is much more approachable. It has been suggested that ocean transport is dominated by main "coherent structures" (Hadden et al., 2005), such as vortices, eddies and jets, that are separated by invisible barriers, i.e. regions that particle trajectories cannot cross. Methods from nonlinear dynamical system have been proposed to locate such barriers, that can be used to provide information on the general fate of a particle launched in a certain area. Details on the specific trajectory might be difficult to determine, but its general behaviour is expected to be determined by such barriers. A special relevance is given to the concept of hyperbolicity and in particular to the presence of hyperbolic points that separate different structures. Various methods can be used to identify such points, ranging from direct identification in terms of flow invariants to methods based on local dispersion properties, such as Finite Time (FTLE) or Finite Size (FSLE) Lyapunov Exponents (Shadden et al., 2005 ; Artale et al., 1997).

Dynamical system methods appear to have a great potential for practical ocean applications. Nevertheless it is important to point out that they are "diagnostic" tools, in the sense that they can be used with great results only as long as the velocity field u is known with a certain degree of accuracy. This is the case for instance for velocity fields from extensive HF (High Frequency) radar measurements, or from accurate ocean circulation models. In many cases, though, predictions from circulation models are still incomplete and the structures can be considered known only with some approximation. In order to increase our knowledge of such structures and our prediction capability, assimilation methods can be used, that combine information from real time data with model results. In particular, since we are interested in Lagrangian predictability, we can expect that assimilation of Lagrangian data will be especially fruitful. For Lagrangian data we mean data from floating instruments that follow the current with good approximation, either at the ocean surface (drifters) or in the ocean interior (SOFAR, RAFOS and Argo floats) communicating their position via satellite or acoustically. In the last few years, new methods for Lagrangian data assimilation have been proposed in the literature and tested using simplified models (Molcard et al., 2003 ; Taillandier et al., 2006 ; Kutsnetsov et al., 2003). Some of these methods have been recently applied to in situ data and the results appear very promising in terms of flow correction and increasing transport prediction skills.

In this paper we provide a brief summary of results that have been obtained in the last few years at CNR-ISMAR in collaborations with a number of national and international laboratories aimed at increasing the predictability of particles in ocean flows. We focus on two main issues. In Section 2, we review the development and implementation of methods from dynamical system theory focusing especially on the FSLE tool (Haza et al., 2007) to highlight flow feautures and barriers. We provide some examples of applications in the Adriatic and Ligurian Sea, testing the result using independent Lagrangian data. The presented results are among the very first examples of application of the theory to real ocean flows. In Section 3, we provide a summary of work aimed at improving flow prediction using Lagrangian data assimilation. The development of a method based on a variational approach is briefly reviewed and examples in coastal flows are shown, using different types of Lagrangian data from Argo floats moving at 350 m to drifters at the surface. These results are the first successful applications of Lagrangian data assimilation using in-situ data, and the method is now transitioned toward operational systems. The potential of these findings for practical applications and the strategies for further development are discussed in Section 4.

2 Computing transport barriers using FSLEs

The Finite Size Lyapunov Exponents (FLSEs) are a diagnostic tool that can be used to identify the main transport barriers and flow structures such as eddies, jests and boundary currents. They correspond to maps of relative dispersion in the flow field, and are relatively simple to implement. In order to compute FSLEs the velocity field u has to be known, either from high resolution measurements (HF radar) or from model. The computations of FSLEs is performed seeding particles in small clusters (typically of three particles each) throughout the flow domain and numerically advecting them forward and backward. Formally FSLEs are defined as the time that takes for particles initially separated of a given distance d0 to reach a distance d1=a d0 where a is a specified factor. Forward advection highlights regions of high dispersion characterized by small values of FSLEs, while backward advction identify convergence regions.

An example of computation of FSLEs using results from an NCOM NRL model in the Adriatic Sea (Haza et al., 2007) is shown in Fig.1 (left panel). The red (blue) lines indicate concentration (dispersion) lines. The superposition of lines indicate “ridges”, i.e. areas that act as transport barriers between different flow regions and that cannot be crossed by particle trajectories. Hyperbolic points are indicated by the crossing of blue and red lines, as indicated by the circle in Fig.1 off the Gargano Cape. These points are central to understand Lagrangian pathways, since they separate different structures and are characterized by directions in which stretching can cause particles to diverge from the structures (unstable manifolds) as well as to converge (stale manifolds). Particles located close to a hyperbolic point can easily separate, following the different manifolds.

FSLEs cmputations have been performed and tested during two recent field experiments in collaboration with NURC-NATO, NRL, Universitá of Miami, Universitá of Toulone and OGS. The two experiments took place in the Adriatic Sea (DART06, Haza et al., 2007) and in the Ligurian Sea (MREA07-POET, Schroeder et al, 2010) respectively. During DART06, FSLEs have been computed using the NCOM-NRL circulation model with 1 km resolution, and FSLE maps (Fig.1, left panel) were used in real time to guide drifter launches from ship. The goal was to identify regions of high hyperbolicity so that the launched drifters would tend to quickly separate, inducing a maximum coverage of the area. The presence of an hyperbolic point in the area off the Gargano Cape have been suggested before by the analysis of historical drifter data (Veneziani et al., 2007), but the hyperbolic point is known to be present only at certain times, and to depend on the flow structure. For this reason, model results are needed to pinpoint the exact time and location of the point. During DART06 three launches of drifter pairs have been performed guided by model forecasts, and two over three show the presence of an hyperbolic point that induces drifter trajectories to quickly separate and diverge. An example is shown in Fig.1, right panel, where the observed drifter trajectories (green and purple lines) appear to separate quickly, one going to the north and the other to the south, in agreement with the model results, as shown by the numerical trajectories in black. During the third launch, instead, the drifters did not separate and moved together toward the north. This launch actually acted as an inadvertent “control” experiment in the sense that the circulation model was indeed predicting at the time that the presence of the hyperbolic point was cancelled by a strong wind episode. The ship, though, due to logistic reasons performed the drifter launches in any case, and the observed and numerical trajectories did not show separation. This clearly indicates that a) the hyperbolic point is not present at all time and b) the model forecast is able to correctly capture its time dependence.

The second experiment took place in the Ligurian Sea and had two components: a large scale component with drifter launches in open ocean (Schroeder et al., 2010), and a more coastal component in the Gulf of La Spezia with significantly smaller scales of the order of 5-7 km (POET experiment, Molcard et al., 2009, Haza et al., 2010). During POET, clusters of five drifters were launched in the Gulf. Results from two launches performed two days a part from the same initial conditions are presented in Fig.2 (upper panels), showing a dramatically different trajectory behaviour. During the first launch (left) the drifters move coherently in a cyclonic way exiting the Gulf after 12-15 hours. During the second launch, instead, the drifters quickly separate and end up sampling the whole Gulf, exiting after more that 20 hours. During POET, a VHF coastal radar was operated in the area providing maps of velocity fields at resolution of 250 m every 30 minutes. FSLEs maps were computed from the radar velocity and used to understand and quantify the different type of dynamics acting during the two launches. Snapshots of FLSLEs during the two launches are shown in Fig.2 (lower panels). During the first launch, a clear ridge is depicted that separate the area of the Gulf in two different regions. The drifters move along the evolving ridge and do not cross it as they flow through the Gulf . This can be partially seen by comparing the drifter trajectories and the FSLE snapshot in Fig.2 (left panels) but it is much more clear considering the animation depicting drifter motion superimposed to the evolving FSLE maps (http://www.rsmas.miami.edu/personal/ahaza/radar/LaSpezia$_{f}sle_{c}lusters.gif).Duringthesecondlaunch(rightpanel),$

The results show that even at small coastal scales, where the dynamics are complex and driven partially by the large scale boundary current intruding in the Gulf and partially by local forcing, Lagrangian transport can be interpreted in terms of barriers between dominant structures well captured by FLSEs.

3 Improving transport prediction using assimilation

The results in Section 2 provide positive indications on the feasibility of forecasting the main transport properties, since they suggest that particle motion is mostly dominated by barriers between the main coherent structures, rather than by smaller scale flow feautures. As a consequence, when the main coherent structures are well represented and forecasted by the models, we can expect that also particle transport is well represented at least in terms of general behaviour, even though the details of single trajectories might be missing. On the other hand, the nature of these coherent structures is still only partially understood and in many cases circulation models are only partially able to capture them. A common problem with models, for instance, is related to the propagation velocity of the structures, so that there might be phase shift errors involving the exact location of the structures at a given time.

A very effective avenue to improve model performance is to use real time data to correct model results using methods of data assimilation. In particular, in our case, since we are interested in transport prediction, we can expect that Lagrangian data from floating instruments that directly sample current advection will be especially useful.

A new method to assimilate Lagrangian data have been developed by CNR-ISMAR in collaboration with the Universitá of Miami. The method is based on correcting the velocity field at the level where the instruments are transported by the currents (i.e. in the interior ocean for Argo floats and at the surface for drifters) by requiring minimization of the distance between observed positions and positions of numerical trajectories launched in the model (Molcard et al, 2003 ; Taillandier et al., 2006a). Once the velocity field is corrected, the other variables of the model, i.e. the mass variables T,S and the sea surface height (SSH), are adjusted using some simplified dynamical requirements such as geostrophy and mass conservation (Ozgokmen et al., 2003). The method has been implemented using a variational approach and it has been first applied to Argo floats (Taillandier et al., 2006b) in the Mediterranen Sea as part of the MFS (Mediterranean Forecasting System) project. Mediterranean Argo floats (MedArgo) are programmed to drift at a parking depth of 350 m, resurfacing at approximately 5 day intervals, and providing information on their position and on TS profiles. Lagrangian assimilation uses the position information to correct the drift at 350m. An example of results obtained assimilating MedArgo floats in the region close to the Balearic Islands is shown in Fig.3. Results without assimilation (left panel) can be compared with results with assimilation (right panel). The superimposed orange-brown lines indicate the observed drift of one float during 10 days, the arrows indicate velocity vectors and the color indicate the salinity field S. As it can be seen, the assimilation of the Argo float data induces a jet along the eastern coast of the island that was not present without assimilation, in keeping with the observed float drift. Notice also that there are differences in the S fields between the two panels, due to the dynamical adjustment performed during the assimilation. The Lagrangian assimilation of MedArgo has been recently performed in the framework of a multivariate system, i.e. as part of the MFS observing system including T,S profiles from MedArgo and XBTs and satellite SSH and SST (Tallandier et al., 2010). Results are very positive and the Lagrangian MedArgo assimilation is now in the process of being transitioned to the operative MFS system.

Further investigations are presently carried out on the assimilation of surface drifters. Assimilation of surface drifters is expected to be more challenging than for Argo floats mostly because they sample the very surface of the ocean (from 15 to 1 or 2 m), that is characterized by small scales fluctuations and dynamics that significantly deviate from geostrophy. This poses two significant question. The first one is related to which scales should be filtered and which ones retained in the model correction, while the second one is related to the correction of the mass variables, that has to be performed differently than in the case of Argo floats. A simple geostrophic balance in fact cannot be used since the upper meters are strongly influenced also by Ekmn dynamics, so that a more complex dynamical decomposition has to be adopted. So far, we have been working on the first step of assimilation, i.e. the velocity correction at the surface using drifter data, and we have not attacked the problem of mass correction yet. Results on surface correction are very promising (Taillandier et al., 2008), as shown in the example in Fig.4 for the Adriatic Sea. The left (central) panels show results from the ROMS model without (with) correction, for a snapshot of velocity (top panels) and for numerical trajectories (bottom panels) launched along a section. The small red lines in the top panels indicate two day trajectories of four drifters used for the correction. As it can be seen, the velocity correction appears small, but it has a significant impact on trajectories. The trajectories of the non corrected model in fact appear retained inside the boundary current, while they tend to exit from it in the case of correction, more in keep with what suggested by MODIS satellite data (left panel) indicating significant intrusion from the boundary current in the interior. Of course this is not a quantitative test of results yet, and work is in progress to quantify the improvement using independent data

4 Summary and discussion

In this paper, we have discussed methods to improve the prediction of particles transported by ocean currents. Results are very encouraging and they show that, even though the problem is extremely challenging, significant improvements can be obtained using appropriate techniques. On the other hand, a number of questions are still open as discussed in the following.

The results in Section 2 strongly suggest that the motion of particles is controlled by barriers between the main coherent structures in the flow, such as mesoscale eddies, jets and boundary currents. The size of these structures depends on the flow environment and in particular on the Rossby radius of deformation, ranging from tens of km in the open sea in the Adriatic and Ligurian sea, to few km in small coastal gulfs such as the Gulf of La Spezia. Flow feautures smaller than these mesoscale structures do not appear to directly influence the main characteristics of particle transport, even though they can influence the details of single trajectories. This result, if confirmed in other regions of the world ocean and shown to be general, is expected to be extremely important for what concerns practical applications. The result in fact implies that the resolution of circulation models can be limited to correctly reproduce mesoscale structures, while capturing submesoscale or smaller processes is not crucial for the problem of Lagrangian transport, that is central to many practical applications of operational prediction systems. Looking at the existent literature, results in other parts of the world show similar and compatible results, for instance the studies of relative dispersion in the Gulf of Mexico and in the Norwegian Sea (LaCasce and Ohlman, 2003). On the other hand, other results in the Califonia Current seem to suggest that submesoscale and smaller scales might be relevant for flow advection properties (Capet et al., 2008). This might be related to the fact that the California Current is characterized by supwelling and significant vertical motion, that is often dominated by submesoscale structures. Overall, the central issue of the role of submesocale and smaller features is still open and it requires significant further investigations. Different regions of the ocean might have to be treated differently (Griffa et al., 2008), and it is crucial to understand what are the physical reasons for these differences and the consequences for the transport of biogeochemical properties and their modeling and prediction.

For what concerns assimilation methods, the results in Section 3 show that they can be extremely useful to correct model forecasts, for instance repositioning and shaping coherent structures that are not correctly reproduced by the models. Assimilation has been successfully implemented in the case of Argo subsurface floats, and it is now in the process of being transitioned to operational systems. Work is in progress for surface drifters and the main questions to be addressed are conceptually related to the ones discussed above. We have to decide weather or not the signature of small scale processes present in the data have to be maintained and used in the assimilation or filtered away, and which type of dynamics have to be used, beyond geostrophy. In order to do that, an increased knowledge of air sea interaction processes is necessary, as well as an improved understanding of the role played by vertical motion in the mixed layer. Finally, it should be pointed out that while Lagrangian data are certainly a natural choice to improve transport prediction, other types of data can also be used, and fusion between models and various data is expected to be very important in the future. As an example, work has already started to use satellite data (SAR and visible) to improve transport prediction in case of accidents at sea such as oils spill events (Mercatini et al., 2010).

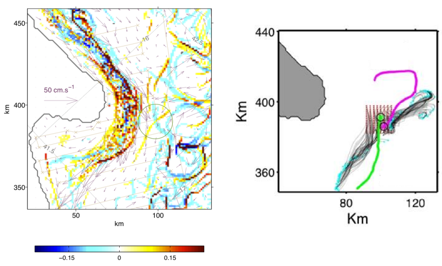

Figure 1: Figure 1. (left) Forecasted surface velocity from NCOM model during DART06 experiment. Superimposed are the 2-day model based FSLE field and the location of a hyperbolic point (green circle). (right) 2 day trajectories for real drifters (green and purple) and numerical drifters (black lines)

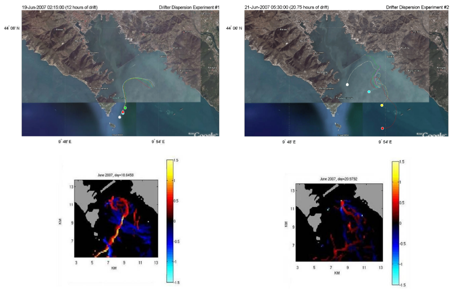

Figure 2: Figure 2 Top panels show the trajectories of two drifter clusters launched from the same location two days apart in the Gulf of La Spezia during the POET experiment (June 2007). Bottom panels show FSLE maps computed from VHF radar at the time of the launches

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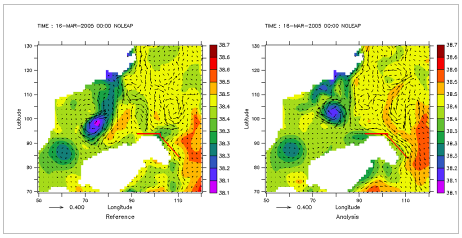

Figure 3: Fig 3 Left (right) panel shows an example of OPA model results in the Balearic Sea without (with) assimilation of Argo float trajectories. Arrows indicate vector velocities, color the salinity field and the superimposed brown-orange lines indicate the observed 10 day drift of the assimilated float

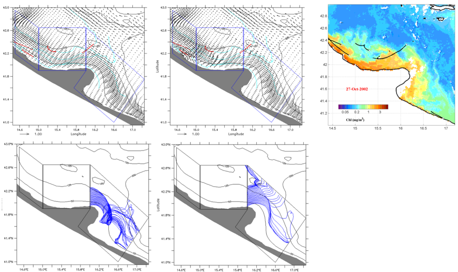

Figure 4: Fig.4 Left (central) panels show an example of ROMS model results in the Adriatic Sea without (with) velocity correction from surface drifters. Top panels depict the velocity field, with superimposed the 2 day trajectories (red lines) of the drifters used in the correction, while the bottom panels depict numerical trajectories launched along a section. Left panel shows a Modis satellite image taken at the same time as the model results.

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