Lagrangian Turbulence and Transport in Semi-enclosed Basins and Coastal Regions

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LONG-TERM GOALS

The long-term goal of this project is the development and application of new methods of investigation for the use of Lagrangian data and other emerging in-situ and remote instruments (drifters, HF radar, gliders and satellite) that provide information on upper ocean advection. Special attention is given to the development of new techniques for data analysis and prediction of Lagrangian transport in coastal flows.

OBJECTIVES

The project has the following specific objectives pursued during the last year of funding:

1) To characterize submesoscale dispersion in coastal areas from drifter data analysis
2) To apply methods for fusion of model outputs and data sets from drifters, gliders and satellite in order to improve transport prediction.
3) To provide a synthesis of performed work on the identification of transport pathways using dynamical system methods and Lagrangian data assimilation.

APPROACH

The work involves a combination of analytical, numerical and data processing techniques as well as participation to experimental work planning. The method development and application have been carried out in collaboration with L. Piterbarg (UCSC), researchers from University of Delaware (D. Kirwan), University of Toulon (A. Molcard), CNRS, Villefranche (V. Taillandier), CNR-ISMAR (K. Schroeder), University of Naples (E. Zambianchi). The experimental work has been done together with an international team lead by NURC-NATO (C. Trees, J. Chiggiato).

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WORK COMPLETED

1) Publication of a paper on velocity reconstruction from model outputs and drifter data to improve the prediction of sonobuoy trajectories (Chang et al., 2011).

2) Publication of a paper on relative dispersion computed from drifter data during two Marine Rapid Assessment Experiments (MREA 2007-2008) (Schroeder et al., 2011).

3) Submission and final revision of a paper on parameterization of submesoscale dispersion (Haza et al., 2011).

4) Submission and ongoing (minor) revision of a review paper on previous works on identifying transport pathways using dynamical system theory and Lagrangian data assimilation (Griffa et al., 2011).

RESULTS

i) Characterization of submesoscale dispersion in coastal areas from drifter data analysis

Lagrangian transport properties in coastal areas have been studied analyzing drifter data in the Ligurian Sea (North Western Mediterranean Sea), collected during four international experiments lead by NURC-NATO during 2007-2008-2010. We concentrate on the study of relative dispersion, i.e. the average separation of particle pairs, and we consider two complementary metrics of description: $D^2(t)$, thar describes the mean separation in time of particles initially launched at distance d_o, and the maximum FSLE (Finite Size Lyapunov Exponents) $\lambda(\delta)$ that describes mean separation rate of particles as function of scale δ. The study of relative dispersion is expected to provide general insights into the multi-scale nature of ocean dynamics, while bearing a direct relevance for many practical applications such as spreading of pollutants and biological quantities in the ocean.

Our study is mostly focused on the properties of relative dispersion in the submesoscale range, i.e. for scales smaller than the typical Rossby radius of deformation. The main question that we address is whether dispersion in this range is non-local, i.e. dominated by the strain of the larger mesoscale eddies, or local, i.e. dominated by active submesoscale features. Questions on distribution and role of submesoscale structures are very relevant, since submesoscales are likely to play an important role as a link between large scale quasi geostrophic flows and small scale quasi 3d processes (Mc Williams, 2008). Submesoscales are associated to processes of frontogenesis and ageostrophic instabilities, and they are expected to open a road to dissipation from large scale flows in the upper ocean, while also modifying their stratification and vertical transport (Capet et al., 2008; Lapeyre et al., 2006; Boccaletti et al., 2007). While submesoscales have been actively studied in the last few years using high resolution models, direct measurements are still scarce, due to the high resolution in space and time that is necessary to capture them. Drifter data appear well suited for the study, given the high resolution of the observations.

How can we diagnose the presence of submesoscales from relative dispersion measurements? Under some simplified assumptions, it can be shown that there is a relationship between the space spectrum of the flow and relative dispersion (Bennet, 1984). If the flow is dominated by mesoscale features, as in the paradigm of quasi-geostrophic turbulence, the submesoscale range is characterized by the enstrophy cascade and the spectra are steep, K^{-a} with $\alpha>3$. In this situation, relative dispersion is expected to be nonlocal and the corresponding $D^2(t)$ is expected to be characterized by an exponential, while λ versus δ is flat. If instead an active submesoscale field exists, it can be expected that the energy cascade will extend up to the submesoscale range, inducing less steep spectra, $1< \alpha<3<1$. In this case, $D^2(t)$ and $\lambda(\delta)$ are expected to be characterized by a power law behaviour.

In our recent paper Schroeder et al., 2011 we have studied relative dispersion using data from the 2007 and 2008 MREA experiments (Marine Rapid Environment Assessment). Drifter clusters have been repeatedly launched in the center of the Ligurian Sea and in one case in the coherent and well developed Northern current (Fig.1). The initial separation scales between drifters were less than 1 km, i.e. below the Rossby radius of deformation in the area (approximately 10-20 km). The computation of relative dispersion from these drifters (Fig. 2, right panel) indicates that the initial stage of dispersion is characterized by an exponential behaviour (the straight line in the semi-log plot) lasting for the first few days in time and for space scales up to 10-20 km, with an e-folding time scale of ~ 0.5-0.8 days. A similar result is also shown by the FSLEs (Fig.2, left panel) that show the presence of a plateau at scales in the range 1-10 km. This indicates that for this data sets the dynamics are mostly non-local, i.e. dispersion is controlled by large and mesoscale features, rather than by submesoscale eddies. These results are consistent with previous results at similar scales obtained in other parts of the world (LaCasce and Ohlmann, 2003; Koszalka et al., 2009)

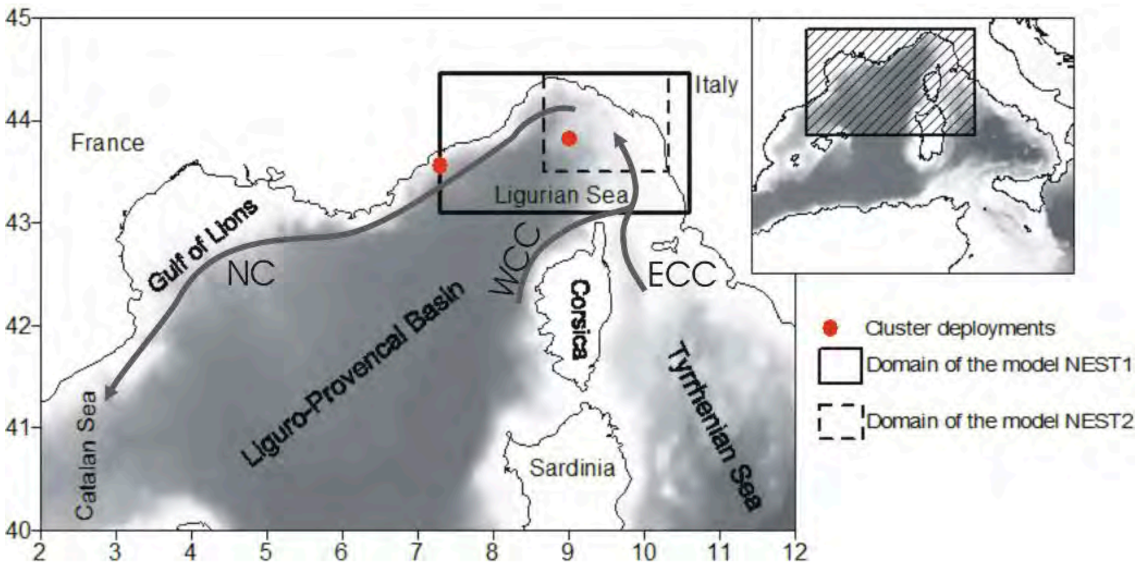

Fig.1. North Western Mediterranean region where the 2007-2008-2010 experiments have been performed. The red dots indicate the locations of cluster launches during MREA 2007-2008.

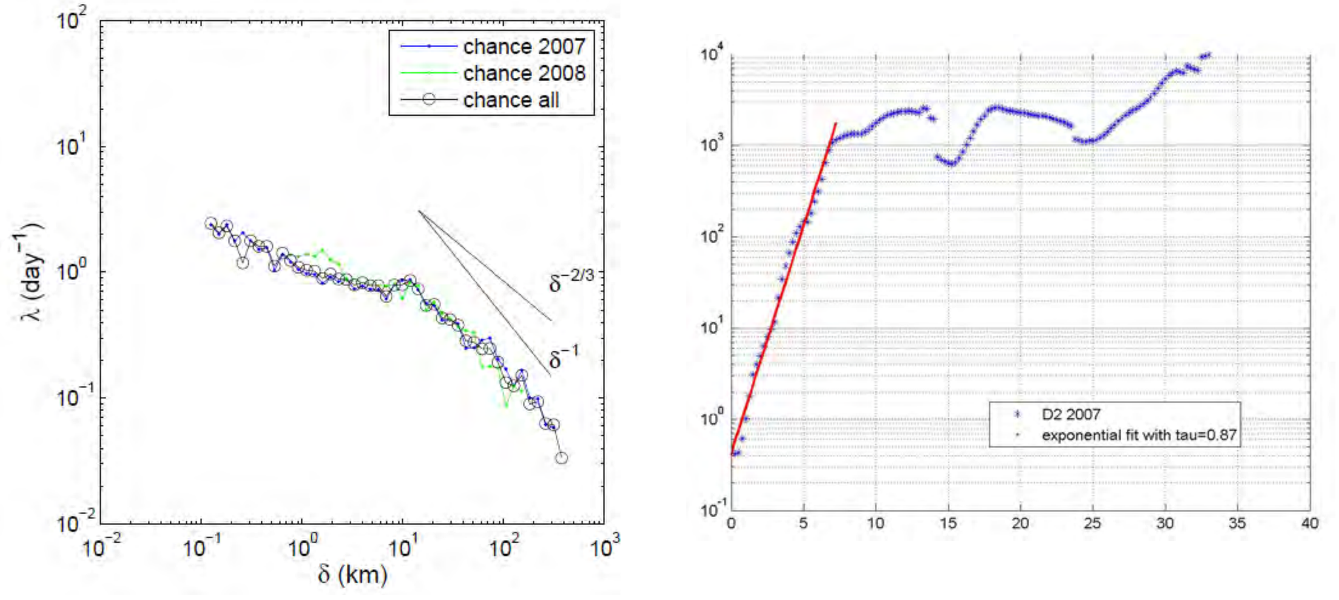

Fig.2. Plots of relative dispersion for the MREA 2007 and 2008 drifter data. Right panel: semi-log plot of $D^2(t)$ (blue stars) with superimposed a fit to a straight line (red) indicating initial exponential behaviour. Left panel: log-log plot of $\lambda(\delta)$, showing an approximate plateau in the range 1-10 km.

The investigation of relative dispersion has been continued considering results from two more recent experiments performed in 2010, the LIDEX and REP10 experiments. They have been performed in the South Eastern Ligurian Sea, an area characterized by very different dynamics, with less persistent currents and surface fronts generated by river outflows and water mass intrusions. The general strategy of the experiments was to identify a front from satellite images and deploy drifter clusters at both sides of the front using a deployment scheme that allows multiscale measurements from 100 m to 1 km (Fig.3).

Preliminary results obtained from the REP10 data set show a quite different scenario with respect to the MREA one. As shown in Fig.4, the initial behaviour of $D^2(t)$ is characterized by two exponential slopes. The first one occurs during the first few hours after launching and it corresponds to scales of order 100-500 m. The exponential is very steep, with an e-folding scale of ~ 0.03 days, i.e. more than an order of magnitude smaller than in the MREA case. The second exponential corresponding to the time interval between ~ 7-13 hours and space scales in the range of 500 m-5 km, has an e-folding scale of ~ 0.1 days, more in keep with the MREA values even though still significantly smaller. These preliminary results, if confirmed, would suggest the existence of two distinct regimes corresponding to two different scales of motion, likely indicative of submesoscale and mesoscale features respectively. This is different from the paradigms based on enstrophy or energy cascade in the submesoscale range, and it could open the door to interesting developments. We recall that some evidence of multiscale regimes in the submesoscale range are shown also by the recent works by Lumpkin and Ellipot (2010) and Berti et al (2011).

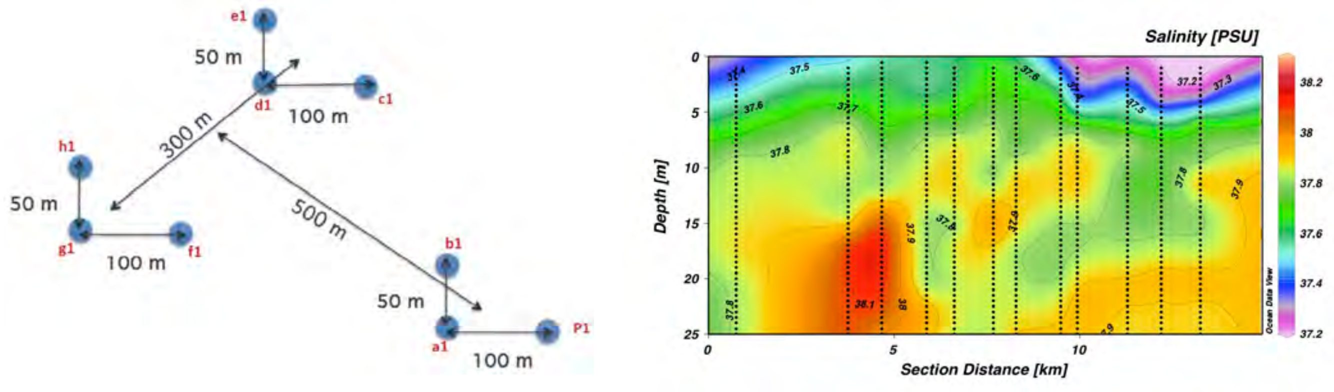

Fig.3 Left panel: schematic of drifter cluster deployment during the LIDEX and REP10 experiments in the South Eastern Ligurian sea. Right panel: example of salinity section during the experiments, showing the targeted shallow front.

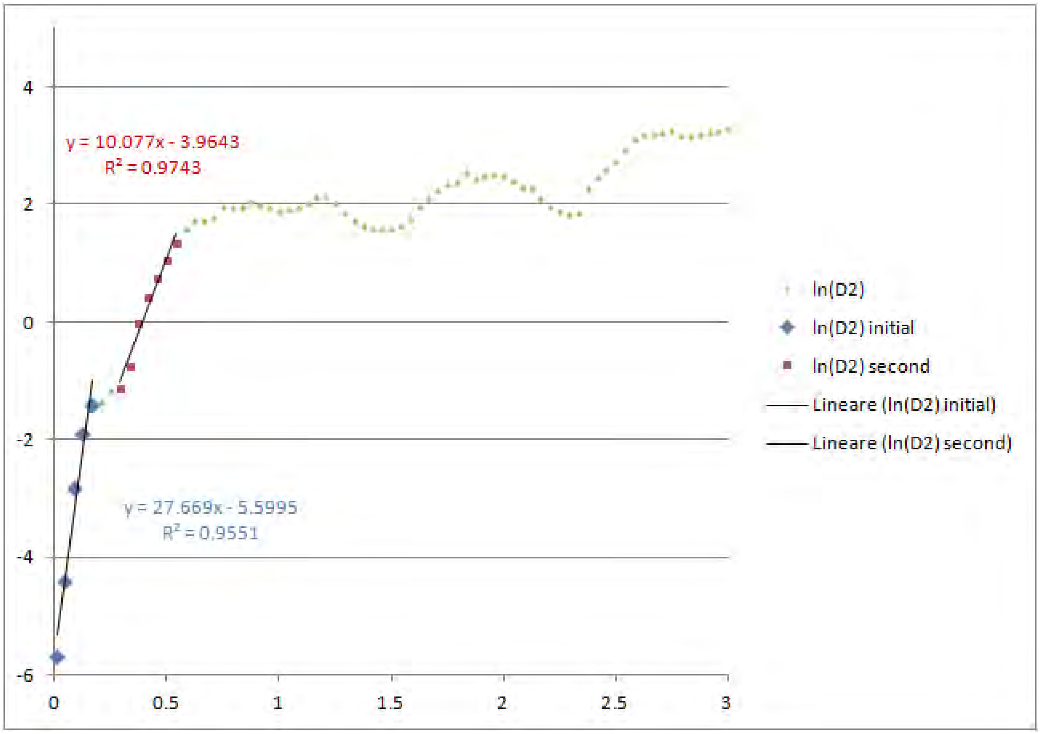

Fig.4. Plot of relative dispersion for the REP10 drifter data corresponding to initial distance of 100 m or less. Superimposed are two fits to two straight lines (black) indicating the two exponential regimes.

ii) Application of methods for fusion of model outputs and data sets from drifters, gliders and satellite

In many practical applications and operational settings, information are provided from models and observations of various nature. One of the most important questions and challenges is how to best combine these data sets in order to improve prediction of the ocean state, while retaining most of the useful information at various scales. We have used two complementary approaches.

The first one is the variational data assimilation approach that we have previously developed and applied in several examples to Lagrangian data (i.e. Taillandier et al., 2006). The second one is a fuzzy logic approach to data fusion in collaboration with L. Piterbarg. This latter approach is based on possibility (credibility) theory (e.g. Dubious and Prade, 1986) and its mathematical development has been carried out by L. Piterbarg. The approach allows for a more general treatment of uncertainties, since it is not based on the frequency interpretation of probabilities. It is expected to lead to non-linear estimates and fusion algorithms that are more flexible than linear methods, since it is not restricted by the assumptions of Gaussian-Markov properties. The following specific applications have been performed:

1) Estimating upper ocean velocity using surface drifters with models and HF radar data

The variational approach has been applied to the analysis of an NRL data set from a Litoral Warfare Advanced Development experiment (LWAD) off Taiwan (Chang et al., 2011). The data are composed of 30 SVP drifters and 29 sonobuoys with instrumented chains deployed in a small grid (approximately ½ degree square), complemented by numerical model hindcasts provided from a data assimilating model, the Naval Research Laboratory East Asian Sea 1/16 degree ocean model (EAS-16). The velocity field has been reconstructed by blending the outputs of EAS-16 with the data from the SVP drifters and then by statistically projecting the velocity correction over the upper water column. The corrected velocity fields have then been used to compute sonobuoy trajectories using an appropriate drag model, and the results are compared with the observed sonobuoy trajectories. A substantial improvement (error reduction of 50%) has been found with respect to model prediction without correction.

A new application has been recently started, finalized to blend information from drifters and velocity fields from coastal HF radars, in collaboration with the European TOSCA project.

The rational is the following. HF radars provide a unique source of velocity data over extended coastal regions, making them the instruments of choice to monitor coastal waters. It is important to keep in mind though that radar velocity measurements are relative to the very upper part of the water column and that they typically differ from actual in-situ measurements of transport for various reasons, such as resolution, coverage or influence of sea state. Typical differences between in situ and radar measurements are of the order of 5-10 cm/sec, and can go up to 20 cm/sec in some conditions. For this reason, it is important that HF radar data are complemented, compared and eventually corrected using instruments such as drifters, that directly sample current transport. For practical applications, for instance in case of accidents at sea, it is highly advisable to have a plan where drifter data are launched in the area of interest, and the drifter information are used together with the radar data.

The variational method has been used to blend drifter and HF radar data, using as a test case the data of the MREA/POET experiment, performed in 2007 in collaboration with NURC-NATO, CNR, University and Toulone and OGS. A WERA radar system in very high frequency (VHF) mode has been operated in the small coastal area of the Gulf of La Spezia (range of 7 km, resolution of 250 m) and the velocity fields have been compared with surface drifter data launched in repetead clusters (Molcard e al., 2009, Haza et al., 2010). While the first two clusters showed an excellent qualitative agreement with the radar data, with quantitative differences in radial velocity characterized by RMS of less than 5 cm/s, the third cluster showed a more marked difference, possibly because of the rough sea state.

Results from this third cluster have been used here to test the performance of the method applied to radar data. The radar velocities are corrected using drifter data, and rms corrections reach values of the order of 30 cm/sec, as shown in Fig. 5.

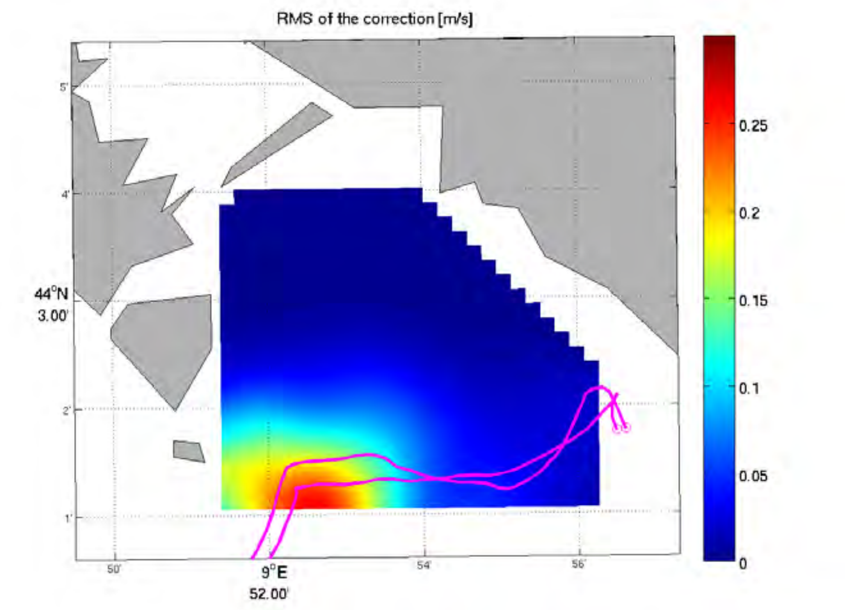

Fig.5 Colors indicate the RMS of the velocity correction applied to the HF radar data using the variational method based on the two drifter trajectories (in purple). Gray areas are land

2) Fusing tracer satellite data with model data and estimating uncertainties for glider data

A first application of fusion methods has been performed using tracer observations from satellite and model outputs (Mercatini et al., 2010). The results have been tested using synthetic data from an operational MFS model. The specific configuration of an isolated patch was considered, and the patch was assumed to evolve obeying to the advection and diffusion equation. The results were very encouraging showing a significant gain in the estimation of velocity and tracer concentration using the method.

Recent applications are concentrated on combining glider data with model outputs. Glider data have a great potential, since they provide a wealth of high resolution information on temperature, salinity and other variables in the ocean interior in addition to information on bulk velocity. On the other hand, their interpretation and optimal use still pose significant challenges, mostly because of the presence of small scale information (that are often not present or not correctly represented by the models) and because of the space and time aliasing of the signal induced by the glider motion. Ongoing work in collaboration with L. Piterbarg focuses on the determination of uncertainties in glider information, taking into account a) the glider motion in the ocean interior and b) the nature of the signal as a superposition of scales and dynamics such as geostrophic mesoscale eddies, submesoscale features and internal waves.

iii) Providing a synthesis of performed work on the identification of transport pathways.

The work performed during the last few years under this grant and other related ones has been summarized in a review paper submitted and presently in (minor) revision (Griffa et al., 2011).

The main overall goal of our work has been the investigation of transport pathways in the ocean, a very challenging and complex medium with scales of motion that range from thousands of kilometers to the dissipation scales. We have followed two main avenues to improve transport prediction. The first one is based on the powerful tools of dynamical system theory, that allow the identification of the barriers to transport and their time variability for a given flow. Various applications have been performed, and a few conceptual points can be drawn from them. Transport pathways appear indeed characterized by Lagrangian Coherent Structures (LCS) in flows at different scales, from offshore to coastal flows, and velocity fields from both radars and models appear suitable to be used to compute accurate LCS.

It is important to remark though that model based results, are dependent on specific applications. Topographically constrained and wind driven flows, such as in the Adriatic application, are easier for a model to reproduce with respect to open ocean flows dominated by strong nonlinearity, such as in the Kuroshio application. For this type of applications, improving model performance in terms of transport should be addressed using another important methodology that has been recently developed, namely the assimilation of Lagrangian data provided by floating buoys

A critical discussion of the two general approaches, i.e. dynamical system theory and Lagrangian data assimilation, is provided, indicating their common assumptions and their present limitations. Both approaches assume that transport is primarily controlled by mesoscale features, and that it is primarily 2-D. These assumptions are presently under investigation. Recent works show that submesoscale processes are likely to be relevant in many surface ocean flows in terms of energy cascade and vertical transport. Their role in horizontal transport and their influence on mesoscale pathways are still not clear. The results on LSC suggest that mesoscale is indeed dominant in transport and dispersion, but other results on relative dispersion from data and models provide a quite complex picture that still need to be unravelled. There might not be a generic answer to this question, and the relevance of submesoscale might be dependent on region dynamics. Even in regions where submesoscales are relevant, they might influence transport only locally, i.e. at their own scales. If this is the case, a possible avenue to take them into account is to parameterize their action, while maintaining eddy resolving models as a basis for computing mesoscale transport. Finally, possible avenues on transition to 3-D Lagrangian analysis have been discussed.

IMPACT/APPLICATIONS

The results on Lagrangian data assimilation and fusion have a significant impact for operational systems and they provide additional value to data from drifters, HF radars, satellites and gliders especially for coastal applications. The results on dispersion and transport pathways provide information on the behavior of tracer patches or floating instrument clusters, with implications for experimental and warfare planning and best sampling.

RELATED PROJECTS

Predictability of particle trajectories in the ocean, ONR, PI: T.M. Özgökmen, N00014-05-1-0095.

Optimal combining data for improving ocean modeling, ONR, PI: L. Piterbarg, N00014-11-1-0369

Ocean 3D +1, MURI ONR, PI: L. Pratt, N00014-11-1-0087

REFERENCES

Berti, S., Santos, F. D., Lacorata, G., Vulpiani, A., 2011. Lagrangian drifter dispersion in the southwestern Atlantic Ocean. J. Phys. Oceanogr. (in press).

Boccaletti, G., Ferrari, R., and Fox-Kemper, B. (2007). Mixed Layer Instabilities and Restratification. Journal of Physical Oceanography, 37, 2228-2250

Capet, X., McWilliams, J. C., Molemaker, M. J., and Shchepetkin, a. F. , 2008a. Mesoscale to Submesoscale Transition in the California Current System. Part I: Flow Structure, Eddy Flux, and Observational Tests. Journal of Physical Oceanography, 38, 29-43.

Chang, Y., D. Hammond, A. Haza, P. Hogan, H.S. Huntley, A.D. Kirwan, Jr, B.L. Lipphardt, Jr., V. Taillandier, A. Griffa, T.M. Ozgokmen, 2011. Enhanced Estimation of Sonobuoy Trajectories by Velocity Reconstruction With Near-Surface Drifters. Oc. Modelling, 36, 179-197

Haza, A.C., T.M. Özgökmen, A. Griffa, A. Molcard, P.M. Poulain, and G. Peggion, 2010. Transport properties in small scale coastal flows: relative dispersion from VHF radar measurements in the Gulf of La Spezia. Ocean Dynamics, 60(4), 861.

Koszalka, I., LaCasce J.H. and Orvik K.A., 2009. Relative dispersion statistics in the Nordic Seas. J. Mar. Res. 67, 411-433.

LaCasce, J., and C. Ohlmann, 2003. Relative dispersion at the surface of the Gulf of Mexico. J. Mar. Res. 61(3), 285-312.

Lumpkin, R., Elipot, S., 2010. Surface drifter pair spreading in the North Atlantic. J. Geophys. Res. Oceans 115, C12017.

Mc Williams J., 2008. Fluid dynamics at the margin of rotational control, Environ Fluid Mech, 8 441–44 DOI 10.1007/s10652-008-9081-8

Schroeder, K, A.C. Haza, A. Griffa , T.M.Ozgokmen, P.M. Poulain, R. Gerin, G. Peggion,M. Rixen, 2011, Relative dispersion in the Liguro-Provencal basin: From sub-mesoscale to mesoscale, Deep Sea Res., 58, 209-228.

Taillandier, V., Griffa, A., Molcard, A., 2006. A variational approach for the reconstruction of regional scale Eulerian velocity fields from Lagrangian- data. Ocean Modelling. 13(1), 1-24.

PUBLICATIONS (2010-2011)

Mercatini A., A. Griffa, L Piterbarg, E. Zambianchi, M. Magaldi, 2010. Estimating surface velocities from satellite tracer data and numerical models: implementation and testing of a new simple method, *Ocean Modelling*, 33, 190-203 [published, refereed].

Magaldi M.G., T.M. Özgökmen, A. Griffa, and M.Rixen, 2010. On the response of a turbulent coastal buoyant current to wind events, *Ocean Dynamics*, 60, 93-122 [published, refereed].

Taillandier V., S. Dobricic, N. Pinardi , P. Testor, A. Griffa, L. Mortier, G.P. Gasparini, 2010. Integration of ARGO trajectories in the MFS assimilation scheme, and impact on the regional analysis of the North Western Mediterranean circulation *J. Geophys. Res*., 115, C03007, doi:10.1029/2008JC005251 [published, refereed].

Haza, A.C., T.M. Özgökmen, A. Griffa, A. Molcard, P.M. Poulain, and G. Peggion, 2010. Transport properties in small scale coastal flows: relative dispersion from VHF radar measurements in the Gulf of La Spezia. *Ocean Dynamics*, 60(4), 861-882 [published, refereed].

Chang, Y., D. Hammond, A. Haza, P. Hogan, H.S. Huntley, A.D. Kirwan, Jr, B.L. Lipphardt, Jr., V. Taillandier, A. Griffa, T.M. Ozgokmen, 2011. Enhanced Estimation of Sonobuoy Trajectories by Velocity Reconstruction With Near-Surface Drifters. Oc. Modelling, 36, 179-197 [published, refereed]

Schroeder, K, A.C. Haza, A. Griffa , T.M.Ozgokmen, P.M. Poulain, R. Gerin, G. Peggion,M. Rixen, 2011, Relative dispersion in the Liguro-Provencal basin: From sub-mesoscale to mesoscale, Deep Sea Res., 58, 209-228 [published, refereed]

Griffa A., A.C. Haza , T.M. Ozgokmen, A. Molcard, V. Taillandier, K. Schroeder, Y. Chang, P. M. Poulain, Investigating transport pathways in the ocean, Deep Sea Res., submitted and in revision [submitted, refereed]

Haza, A.C., T. M. Ozgokmen, A. Griffa, Z. D. Garraffo, and L. Piterbarg, Parameterization of Submesoscale Transport in the Gulf Stream Region Using Lagrangian Subgridscale Models, Oc. Modelling, submitted and revised [submitted, refereed]