Predictability of Particle Trajectories in the Ocean

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LONG-TERM GOALS

The long term goal of this project is to determine optimal sampling strategies for drifting observing systems, such as buoys and gliders, in order to enhance prediction of particle motion in the ocean, with potential applications to ecological, search and rescue, floating mine problems, and design of real-time observing systems.

OBJECTIVES

Our main objective is to develop Lagrangian techniques to improve our fundamental understanding of turbulent transport phenomena in the ocean. The objectives of the project serve the ONR thrust area of adaptive sampling and Lagrangian tracing. Another aspect of the research focuses on a better understanding of the nature of mesoscale and sub-mesoscale turbulent processes, which is relevant to ONR thrust area on sub-mesoscale variability associated with fronts, turbulence and mixing.

APPROACH

The work is based primarily on the analysis of output from coastal and ocean circulation models, as well as data from drifters and VHF radars deployed for real-time experiments. We also develop and/or employ Lagrangian models and techniques as needed.

WORK COMPLETED

1) Publication of a paper containing investigation of relative dispersion from a hierarchy of numerical models (Poje et al., 2010). To our knowledge, this is the most detailed investigation of relative dispersion from oceanic models to date.

2) Publication of a paper comparing temporal evolution of Lagrangian Coherent Structures computed from VHF radar to real drifters (Haza et al., 2010). To our knowledge, this paper contains the most comprehensive documentation of relative dispersion from observations. It is

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also only the second one displaying transport pathways from two independent observations and the validity of LSC in controlling transport pathways.

3) Submission of a paper estimating relative dispersion in the Ligurian Sea from drifters launched in the 2008 MREA (Marine Rapid Environmental Assessment) trials and on the basis of NCOM operationally run in that region (Schroeder et al., 2010).

4) Participation in the 2010 MREA trials organized by NURC/NATO (led by Jacopo Chiggiato) and Italian CNRs. Our main role was to design a multi-scale drifter launch strategy and take part in the decision about where to launch the drifters.

RESULTS

Many of our results are described at some length in already published papers over the past year (Poje et al., 2010; Haza et al., 2010; Magaldi et al., 2010) and in the 2010 annual report of the companion project entitled “Lagrangian Turbulence and Transport in Semi-Enclosed Basins and Coastal Regions”. Here we focus on the most recent work (Schroeder et al., 2010) and provide a synthesis on the investigation of relative dispersion from ocean models and data over the past years.

In addition, this is the final report of this specific project, which has been funded by ONR since 1998 and has allowed us to explore many different topics over the past 13 years, providing full or partial support for 26 journal articles, one book and two book chapters. We greatly appreciate this continuous support from ONR, without which these publications would not have been possible.

1) Relative dispersion from field and synthetic data in the Ligurian Sea:

Relative dispersion in the Liguro-Provencal basin (a subregion of the Mediterranean Sea, Fig. 1) is investigated using clusters of surface drifters deployed during two Marine Rapid Environment Assessment experiments covering different months in 2007 and 2008 respectively. The clusters have initial radii of less than 1 km, or an order of magnitude below the typical deformation radius (approximately 10-20 km). The data set consists of 45 original pairs and more than 50 total pairs (including chance ones) in the spatial range between 1 km and 200 km. Relative dispersion is estimated using the mean square separation of particle pairs and the Finite Scale Lyapunov Exponents (FSLEs). The two metrics show broadly consistent results, indicating in particular a clear exponential behavior with an e-folding time scale between 0.5 -1 days, or Lyapunov exponent in the range of 0.7-1 days^{-1}. The exponential phase extends for 4-7 days in time and between 1 km and 10-20 km in separation scale.

To our knowledge, this is only the third time that an exponential regime is observed in the world ocean from drifter data. This result suggests that relative dispersion is predominantly nonlocal, namely controlled mainly by mesoscale dynamics, and that the effects of the sub-mesoscale motions are negligible in comparison.

The results from drifter data have been complemented by an investigation using synthetic drifter data from the NCOM model that has been run in real time during the 2008 experiment at two different resolutions of 1.8 km (nest1) and 0.6 km (nest2), respectively (Figs. 1, 2). Results for both resolutions are qualitatively consistent with the drifter results, showing an initial exponential behavior with corresponding to a limiting FSLE value of 0.6 days^{-1} for NCOM-nest1 and 1 days^{-1} for NCOMnest2 (Fig. 3). The increase of the limiting FSLE value at increasing resolution (almost a doubling from nest1 to nest2) corresponds to an increase in the Okubo-Weiss parameter that quantifies the hyperbolicity of the velocity field, in agreement with the findings in our previous work (Poje et al., 2010).

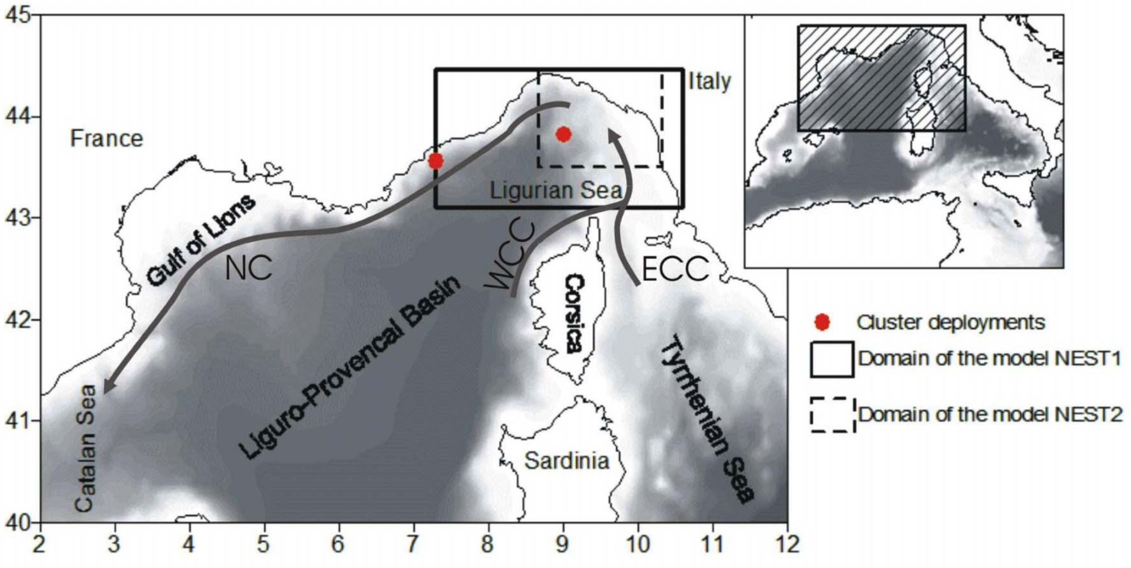

Fig. 1: Schematic of the Ligurian-Provencal basin (the inset to the right shows its location in the north-west Mediterranean Sea) and main currents; NC: Northern Current, WCC: Western Corsican Current, ECC: Eastern Corsican Current. The red dots show the cluster launch positions and the two boxes show the two domains of the NCOM model.

Model results have also been used to investigate sampling issues in computing relative dispersion. Reference estimates have been first computed using a data set consisting of a high number of original pairs (2000-3000 pairs available at separation scales of 1 km). These results are compared with those obtained from chance pairs released at 5-3 km. In this case, the pair number decreases strongly for small separation distances and the FSLE plateau is less clear with a limiting value that is up to a factor 2 bigger than the reference one. When instead original pairs are subsampled, decreasing their number down to 20-10, the FSLE plateau is more clear, and the estimates of the FSLE appear to oscillate around the reference value (Fig. 4). The results also imply that accurate estimation of relative dispersion is possible on the basis of only 12 drifter pairs. Nevertheless, since numerical models to do resolve turbulent processes at the sub-mesoscale range very well, it is not known yet how these estimates would translate to the real ocean, a-priori to oceanic experiments involving a large number of drifters.

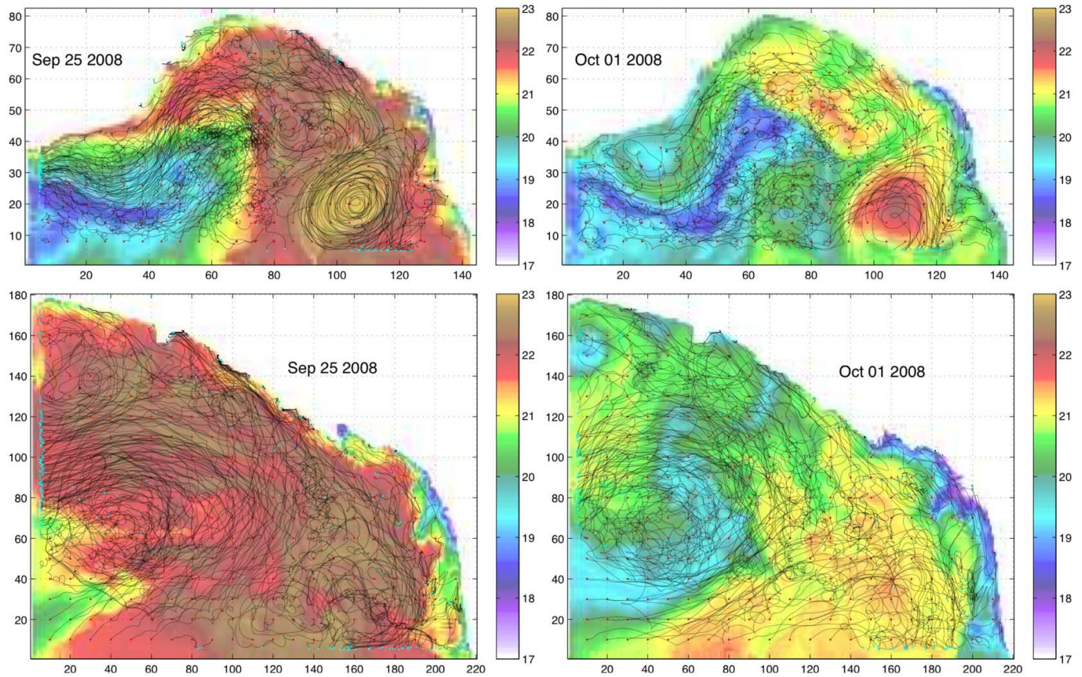

Fig. 2: Surface trajectories of synthetic particles advected using velocity fields from NCOM-nest1 (upper panels) and NCOM-nest2 (lower panels). Modeled surface temperature fields from 25 September 2008 (left panels) and 1 October 2008 (right panels) are superimposed.

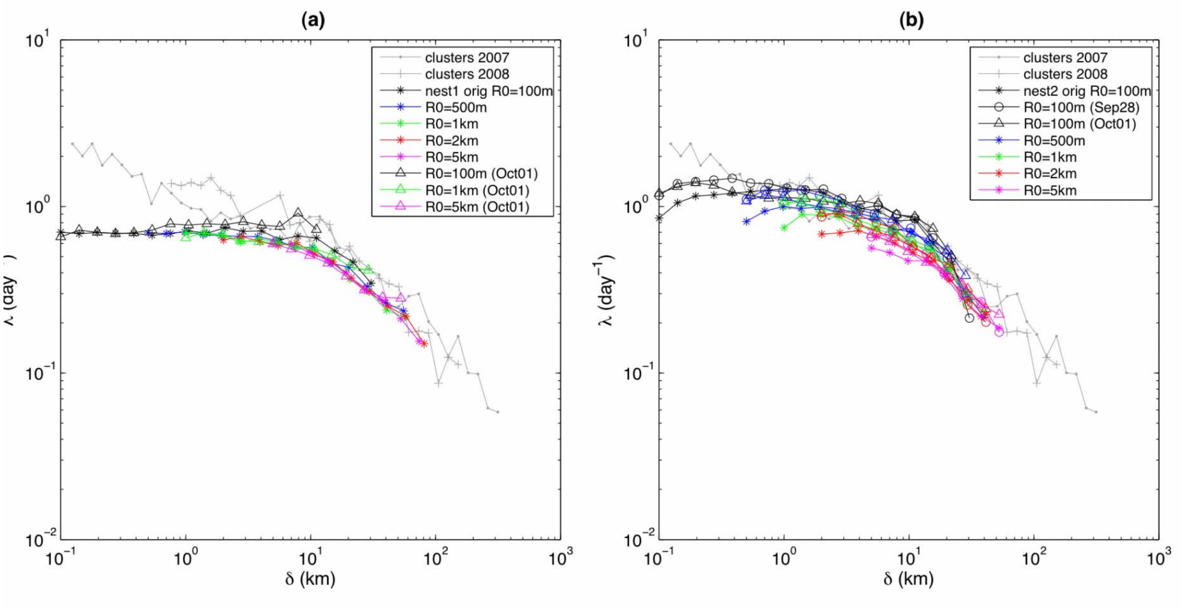

Fig. 3: FSLE curves using original pairs with 0.1 km, 1 km, 2 km and 5 km initial separation for (a) NCOM-nest1 and (b) NCOM-nest2. The FSLE curves from CODE drifters are plotted in the background.

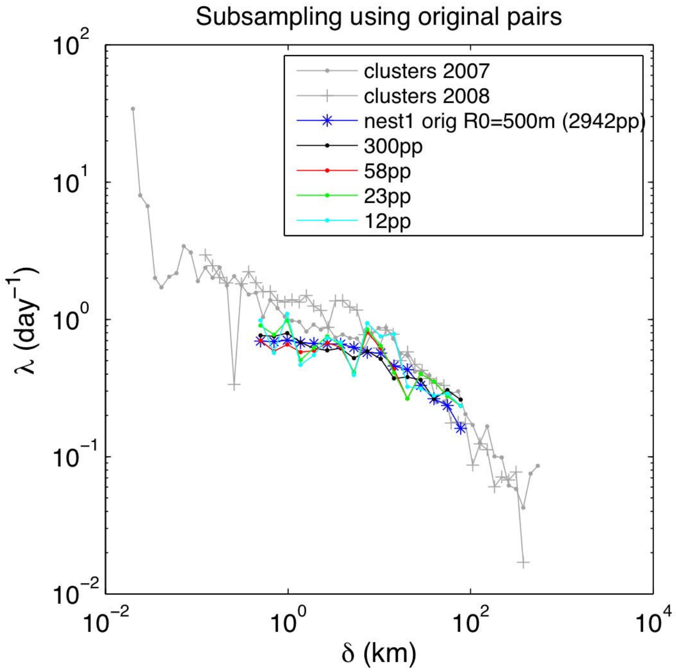

Fig. 4: Scale-dependent FSLE from NCOM-nest1 domain from sub-sampled original pairs. Results from 2007 and 2008 MREA clusters are shown in grey.

2) Synthesis of relative dispersion results in the ocean:

Over the past few years, we have conducted a number of studies in relative dispersion, which is intimately related to oceanic turbulence. In fact, scale-dependent FSLE plots provide a clear insight into the multi-scale dynamics of the ocean, and help quantify the net effect of all turbulent flow interactions on oceanic transport at different scales of motion. The driving force behind these investigations is the grand challenge posed of ocean flows in that they are composed of a wide range of interacting turbulent scales. In particular, existence of sub-mesoscale processes in the upper ocean have been put forward (e.g., Klein et al., 2008; Capet et al., 2008), but the interaction of sub-mesoscale and mesoscale motions has not been yet clearly understood. Thus, it is not clear which scales in the turbulent spectrum control the transport; *is there a dominant mechanism for transport, or transport depends entirely on the local turbulent process?*

This is an important question because if all scales of motion play a significant role in transport, then all scales have to be observed well enough to understand and model, which is clearly a difficult (even impossible) task for the foreseeable future.

If, on the other hand, the mesoscale features that are long-lived and contain most of the energy in the oceanic flows dictate the transport, while the imbedded sub-mesoscale motions are weak, small and transient enough perturbations as to not affect the pathways significantly, then present eddy-resolving ocean models and data assimilation methods relying on satellite altimeters with current spatial resolution capabilities would be largely satisfactory as prediction systems of ocean transport. Many of the Navy's prediction systems fall in this category, and would provide adequate means for ocean transport prediction.

Investigation of relative dispersion in the real multi-scale environment of ocean flows provides one of the avenues to investigate this fundamental problem, and drifters from clustered arrays appear to be valuable data sets to compute relative dispersion in various locations in the ocean.

The particular studies we have conducted have been reported in the following four papers: analysis of 1 km resolution operational NCOM in the Adriatic Sea (Haza et al., 2008), idealized 2D model, ROMS simulations of baroclinic instability and realistic Gulf Stream from HYCOM (Poje et al., 2010), coastal flows near La Spezia as measured by two VHF radars (Haza et al., 2010) and the Ligurian Sea circulation from drifters and operational NCOM (Schroeder et al., 2010). Also, new drifter launches have been conducted very recently (in the summer of 2010) under MREA programs, as reported in our companion annual report, but this data set is not analyzed yet.

All of these studies show a clear exponential regime for particle separations below the mesoscale range, which is suggestive of the fact that relative dispersion is predominantly non-local, namely the strain field created by the mesoscale dynamics dictates relative dispersion in the sub-mesoscale range.

This result has a number of implications. First and foremost, it puts not only the role of sub-mesoscale processes in ocean transport in doubt, but also fundamentally questions their existence in the ocean circulation, naturally leading to the following issues. Are the sub-mesoscale turbulent features pervasive in the upper ocean, or they are episodic in time, and maybe confined only to certain regions?

If they are pervasive, how can they be detected using current observational methods, if their effect on transport is quite small in comparison to that by the mesoscale features? If they do not influence ocean transport, in which other ways are they important? Can they coexist with mesoscale features? We believe that all of these questions are open and deserve to their own investigation as resources and technology allow.

Second, the result that a eddy-resolving models with only approximate representation (both in terms of exact location and speed, and also resolution) of the mesoscale features allows for statistical transport estimation at all scales in this region supports the applicability of Lagrangian transport view on the basis of 2D geometrical features to the ocean circulation, or at least, it does not contradict the perspective brought by this school of thought.

Third, this result paves the way toward a number of practical applications. The potential for neglect of an unknown degree of sub-mesoscale induced stirring and mixing allows a quick estimation of the initial behavior of pollutants in the upper ocean; we can expect that an initial patch will tend to grow in size exponentially with a doubling time of approximately 0.5-1 days, until it reaches a scale of approximately 20 km. Furthermore, accurate estimation of the pollutant's spreading should be feasible on the basis of eddy-resolving, data-assimilating ocean models (provided that the pollutant acts as a passive particle, or scalar field). This is very relevant for first action planning and mitigation in case of accidents at sea, providing information on the expected initial behavior of the pollutant.

IMPACT/APPLICATIONS

The investigation of the predictability of particle motion is an important area of study, with a number of potential practical applications at very different scales, including searching for persons or valuable objects lost at sea, tracking floating mines, ecological problems such as the spreading of pollutants or fish larvae, design of observing systems and navigation algorithms.

RELATED PROJECTS

Lagrangian Turbulence and Transport in Semi-Enclosed Basins and Coastal Regions, PI: A. Griffa, N00014-05-1-0094.

Statistical and Stochastic Problems in Ocean Modeling and Prediction, PI: L. Piterbarg, N00014-99-1-0042.

Optimal Deployment of Drifting Acoustic Sensors: Sensitivity of Lagrangian Boundaries to Model Uncertainty, PI: A. Poje, N00014-04-1-0192.

PUBLICATIONS (2009-2010)

Poje, A.C., A.C. Haza, T.M. Özgökmen, M. Magaldi and Z.D. Garraffo, 2010: Resolution dependent relative dispersion statistics in a hierarchy of ocean models. Ocean Modelling, 31, 36-50 [published, refereed].

Magaldi, M., T.M. Özgökmen, A. Griffa and M. Rixen, 2010: On the response of a turbulent buoyant current to wind events. Ocean Dynamics, 60, 93-122 [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, 861-882 [published, refereed].

Schroeder, K., A.C. Haza, A. Griffa, T.M. Özgökmen, P.M. Poulain, R. Gerin, G. Peggion, and M. Rixen, 2010: Relative dispersion in the Liguro-Provencal basin: from sub-mesoscale to mesoscale. Deep Sea Research – Part 1 [submitted refereed].