GLOBAL MAPS OF ALTIMETRY-DERIVED SUBMESOSCALE FRONTS AND FILAMENTS FROM LYAPUNOV EXPONENT CALCULATION

Francesco d'Ovidio [(1)], **Marina Levy**[(2)], **Rosemary Morrow** [(3)], **Renaud Dussurget**[(3)]

[(1)] *ISC-PIF,57-59 rue Lhomond, F-75005, Paris, France and LOCEAN-IPSL, Université Pierre et Marie Curie, BC 100, 4 place Jussieu, F-75005 Paris, France*
Email:dovidio@locean-ipsl.upmc.fr
[(2)] *LOCEAN-IPSL, Université Pierre et Marie Curie, BC 100, 4 place Jussieu, F-75005 Paris, France,*
Email: Marina.Levy@locean-ipsl.upmc.fr
[(3)] *LEGOS, 18 avenue Edouard Belin 31401 Toulouse Cedex 09, France,*
Email: Rosemary.Morrow@legos.obs-mip.fr
Email: Renaud.Dusserget@legos.obs-mip.fr

ABSTRACT
Submesoscale filaments are ubiquitous in high resolution observations of the ocean surface. By stirring water masses with contrasted properties, they affect a large number of biophysical processes, ranging from the vertical circulation to the structure of phytoplankton communities. Filaments are characterized by very high horizontal aspect ratio (~km for the width, ~100 km for the length) and temporal variability of the order of the day. Due to the presence of clouds obscuring remote optical sensors and to the cost of in situ surveys, filament direct observation is very sparse, and the filament dynamics at the global or even regional scale mostly unknown. In order to circumvent this observational problem, some diagnostics have been developed that try to reconstruct synoptic submesoscale information indirectly. This is achieved by identifying a mechanism able to create filaments from a resolved, global component of the ocean dynamics. The Lyapunov exponent technique exploits the mechanism of horizontal stirring, that creates submesoscale tracer filament from mesoscale turbulent structures. By applying this technique to altimetry data, this approach is able to produce maps of filament location and stirring intensity at submesoscale resolution for the global oceans. In a joint collaboration between the CTOH-LEGOS in Toulouse, LOCEAN-IPSL and the Institute of Complex Systems (ISC) in Paris, we are constructing maps of Lyapunov exponents from satellite-based surface velocity fields, producing filament-resolving (4-10km), daily maps. These will be obtained using AVISO altimetry-derived geostrophic velocities, and using the CTOH geostrophic and Ekman near-surface currents. This product (available for both near-real time and historical applications) will provide the first systematic, uninterrupted, global survey of the submesoscale ocean structure. Its intended applications are the design of next generation filament-resolving platforms, the near-real-time support to campaign studies, and the study of the submesoscale ocean climate variability.

1. THE CHALLENGE OF THE OCEAN SUBMESOSCALE

The presence of filaments appear in virtually any high resolution survey of the ocean surface. These structures, well visible for instance in ocean colour or sea surface temperature satellite image, are typically of mesoscale length (100km), of much smaller width (10 km), and extend vertically below the mixed layer. Filaments play an important role in the ocean biogeochemistry, affecting both lateral and vertical transport, as well as mixing. Through lateral stirring, filaments disperse tracers like nutrient, phytoplankton, and zooplankton larvae; by redistributing heat and salinity anomalies over regions of mode water formation, they affect the low frequency variability of the ocean dynamics. Thin filaments of density anomalies induced by lateral stirring may trap inertial waves, becoming hot spots for small scale mixing, and, when characterized by strong density gradient, they are able to create intense upwelling/downwelling cells. The timescale associated to filaments is of the order of days/weeks, comparable to the one of plankton ecology, so that filaments may be expected to be one of the aspects of the ocean turbulence that has a strongest interaction with biotic processes.
For all these reasons, historical and real-time information of filaments dynamics is of great

importance for understanding the ocean dynamics and planning in situ experiments. Nevertheless, obtaining global or even regional information about filaments is a challenge for both in situ and remote sensing platforms. A submesoscale-resolving in situ survey of a filament should sample for about a month regions 100 km large at a ~km and ~day resolution, which can be obviously achieved for individual filaments only. On the other hand, high resolution sea surface temperature and ocean color images are heavily affected by clouds and provide a sparse and unpredictable coverage in both space and time. Altimetry is not affected by clouds, but is too coarse grained.

2. RECONSTRUCTING THE SUB-MESOSCALE DYNAMICS OF THE GLOBAL OCEANS

In order to overcome this problem, some methods have been recently developed, that try to reconstruct filament position and intensity in an indirect way [1] . One of this methods is the Lyapunov exponent calculation, that extracts filament information from relatively coarser-grained velocity fields like altimetry-derived geostrophic velocities [2,3]. The technique is based on the observation that in the ocean filaments are often the consequence of a tracer being stirred by a relatively larger structure of the velocity field. This is best seen with an example. Consider a chlorophyll or surface temperature filament winding around a mesoscale eddy. This filament is not necessarily created by submesoscale velocities, but it can be the effect of a large scale chlorophyll or SST front colliding with the mesoscale eddy. In this case, the mesoscale structure of the velocity field contains all the information for reconstructing the filament. In particular, by integrating the velocity field, the advection of a numerical tracer can mimic the stirring effect of the eddy, and the tracer submesoscale filaments winding around the eddy can be estimated.

Lagrangian methods like the Lyapunov exponents can therefore extract sensible tracer submesoscale information from mesoscale velocity fields and complement traditional diagnostics like the eddy kinetic energy. However, in respect to these traditional diagnostics, Lagrangian methods have a much higher degree of complexity and are several orders of magnitude slower, since they involve the construction of particle trajectories. For these reasons, we are currently reprocessing the available altimetry database systematically and prepare a historical and near-real-time database of location and intensity of tracer filaments induced by the mesoscale turbulence.

3. DATA AND METHOD

The reprocessed dataset is the AVISO global multisatellite sea surface height archive. These data are based on all the altimetry anomalies measurement available at each time plus the Rio05 [4] mean dynamic topography (constructed from in situ and remote sensing observations). Both near-real-time and delayed products are available. The Lagrangian trajectories needed to compute the Lyapunov exponents are based on a fourth order Runge-Kutta integrator. The filament maps are built at various resolutions (see the Timeline below). At each grid point of a map, the backtrajectories of nearby points are constructed and the time needed for reaching a prescribed final separation is measured. Calling $\boldsymbol{\delta_0}$ and $\boldsymbol{\delta}$ the inital and final trajectories' separation and $\boldsymbol{\Delta t}$ the time needed to reach the separation $\boldsymbol{\delta}$, the local Lyapunov exponent is defined as:

$$\lambda(x,t)=\frac{1}{\Delta t}\log\left(\frac{\delta}{\delta_0}\right). \qquad (1)$$

For more details on the Lyapunov technique and validation see [5] and [6].

The use of a geostrophic velocity field with added Ekman component is also under test. The Ekman component is computed from Quickscat surface wind data, and is added to altimetry velocities (see [7]).

4. PRODUCTS

4.1 Delayed-time

We are reprocessing the historical datasets of delayed-time altimetry data. We plan to release daily maps of Lyapunov exponents at both 10km and 4km resolution with a spatial resolution of 4 days. These resolutions will be sufficient to detect the position and the dynamics of the filaments induced by altimetry-resolved mesoscale turbulence on advected tracer. The delayed-time product is intended as (i) a submesoscale-resolving complement of

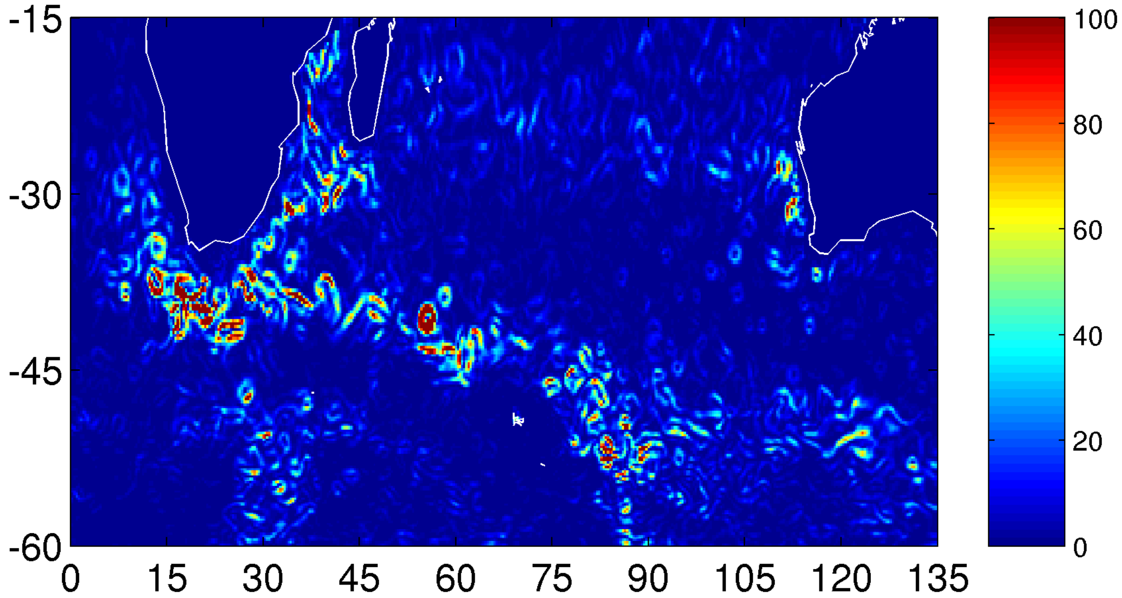

Figure 1: A traditional diagnostic of altimetry data (eddy kinetic energy, 30 km resolution). The eddies present in the velocity field can be detected. The resolution is limited by the resolution of the altimetric map that currently does not

traditional diagnostics like eddy kinetic energy for ocean circulation analysis and (ii) for intercomparison of altimetry with high resolution features in SST or chlorophyll images. The validation of this product can be found in [6] and [5].

4.2 Near-real-time

A near-real time operational product will also be provided for campaign studies. This product is intended in support to in situ sampling of (sub-)mesoscale fronts and filaments. These near-real time maps of Lyapunov exponents have been used during the LOHAFEX fertilization campaign (see Reports at www.lohafex.com) for choosing and monitoring an eddy with a well isolated core in the South Atlantic. Although the

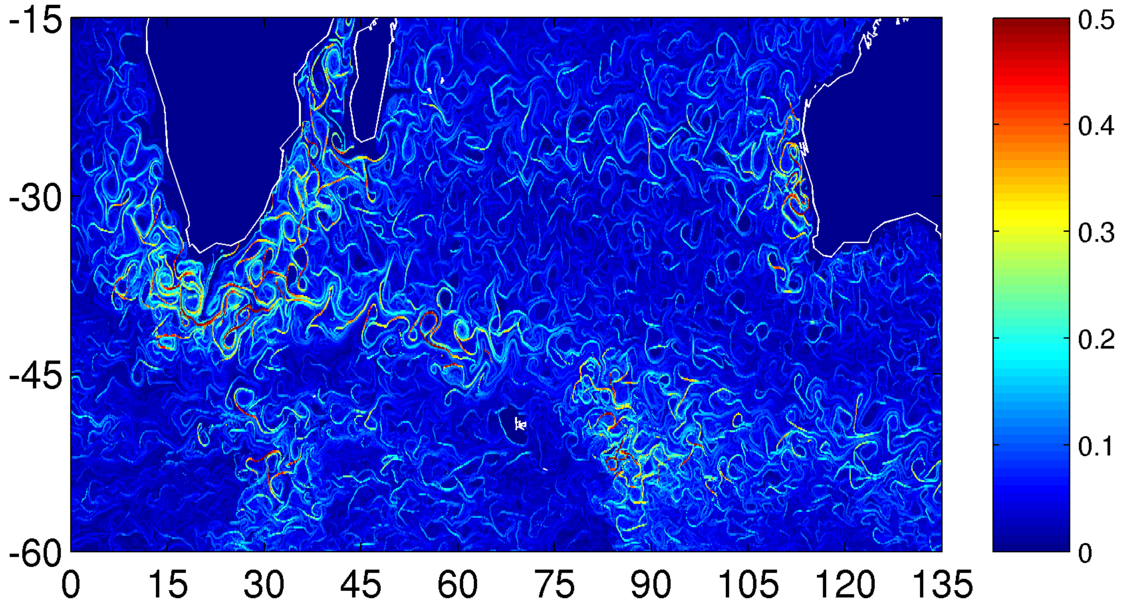

Figure 2: Same region and data of Fig. 1 but reprocessed with a Lagrangian diagnostic (the Lyapunov exponent calculation, 1 km resolution). By advecting numerical trajectories with the altimetric velocity field, the submesoscale filaments induced by the mesoscale eddies of Fig. 1 can be estimated. The value is in day^{-1} and represents the inverse time scale for the filament formation (see Data and Method).

campaign had mainly biogeochemical objectives, several physical measurements have been performed along a filament that slowly unwinded from an eddy core, including the release of Lagrangian drifters. The high frequency of the uninterrupted in situ spatiotemporal sampling (~km, ~day) and the duration of the campaign (one month), combined with the possibility of targeting a filament from its genesis up to the end of its life cycle, make of the LOHAFEX campaign an ideal case for testing the use of Lyapunov in near-real-time applications. Moreover, the chlorophyll induced by the fertilization of a water patch contained in the filament proved to be an excellent Lagrangian tracer, well visible from a MODIS image during a cloud-free day. The analysis of this campaign data is currently in progress.

4.3 Ekman component

Prolonged perturbations of geostrophic currents may have a large impact on advective properties, even if the mesoscale structure of the velocity field is, instantaneously, only marginally modified. We are testing the response of the stretching to Ekman transport by analysing with the Lyapunov technique near-surface velocities obtained by altimetry plus Quickscat-derived Ekman component.

5. TIMELINE

We plan to deliver a test product at relatively low resolution (10 km, 10 year re-analysis) for the end of 2009, together with a test near-real-time product (4-7 day of delay, Southern Ocean). We plan to have operational level, regional near-real-time product at 4 km for the first half of next year, and a complete high resolution re-analysis of the entire altimetry dataset for the end of 2010. A global high-resolution near-real-time product will be available for beginning 2011.

6. PERSPECTIVE

The exploration of the submesoscale ocean dynamics (~km, ~day) is one of the next challenges for both modelling and observational efforts. Novel platforms and sensors are being specifically developed for this. However, in order to deliver the most informative data, these next-generation observations need to be focused toward the key uncertainties of the submesoscale dynamics. The identification of these uncertainties is an important objective that has to be achieved now, developing diagnostics able to deal with datasets not specifically designed for the submesoscale, and designing case study experiments. The reconstruction of submesoscale information from available datasets is of critical importance also for a second aspect, namely the creation of historical datasets able to complement future observations and shed some light on the submesoscale climate variability. Methods like the Lyapunov exponents do not provide an exhaustive information, since are based on a single mechanism of filament formation (in the case of the Lyapunov technique, the horizontal stirring induced by mesoscale turbulence). Nevertheless, with the Lyapunov exponent some submesoscale information can be systematically retrieved from altimetry and - with the help of in situ measurements and satellite images - unambiguously validated for a time window that spans more than a decade.

REFERENCES

1. Boffetta, G., G. Lacorata, G. Redaelli, and A. Vulpiani (2001). Detecting barriers of transport: a review of different techniques. *Physica D* **159**, 58-70.
2. d'Ovidio, F., V. Fernandez, E. Hernandez-Garcia, and C. Lopez (2004). Mixing structures in the Mediterranean Sea from finite-size Lyapunov exponents. *Geophys. Res. Lett*. **31**, L17203.
3. Waugh, D.W., E.R. Abraham, and M. Bowen (2006), Spatial variations of stirring in the surface ocean: a case study of the Tasman sea. *J. Phys. Oceanogr.* **36**, 526-542.
4. Rio, M.-H., P.-M. Poulain, A. Pascual, E. Mauri, G. Larnicol, R. Santoleri (2007). A Mean Dynamic Topography of the Mediterranean Sea computed from altimetric data, in-situ measurements and a general circulation model. *J. Mar. Sys.* **65**, 484-508.
5. d'Ovidio, F., J. Isern-Fontanet, C. López, E. García-Ladona, E. Hernández-García (2009). Comparison between Eulerian diagnostics and the finite-size Lyapunov exponent computed from altimetry in the Algerian Basin. *Deep Sea Res.* **56**, 15-31.
6. Lehahn, Y., F. d'Ovidio and M. Lévy (2007). Stirring of the northeast Atlantic spring bloom: A Lagrangian analysis based on multisatellite data. *J. of Geophys. Res.*, C08005.
7. Sudre, J. and R. Morrow (2008). Global surface currents : a high-resolution product for investigating ocean dynamics. *Ocean Dyn.* 58 (2), 101-118.