A method for predicting the displacement of Lagrangian fronts from near-real time altimetry

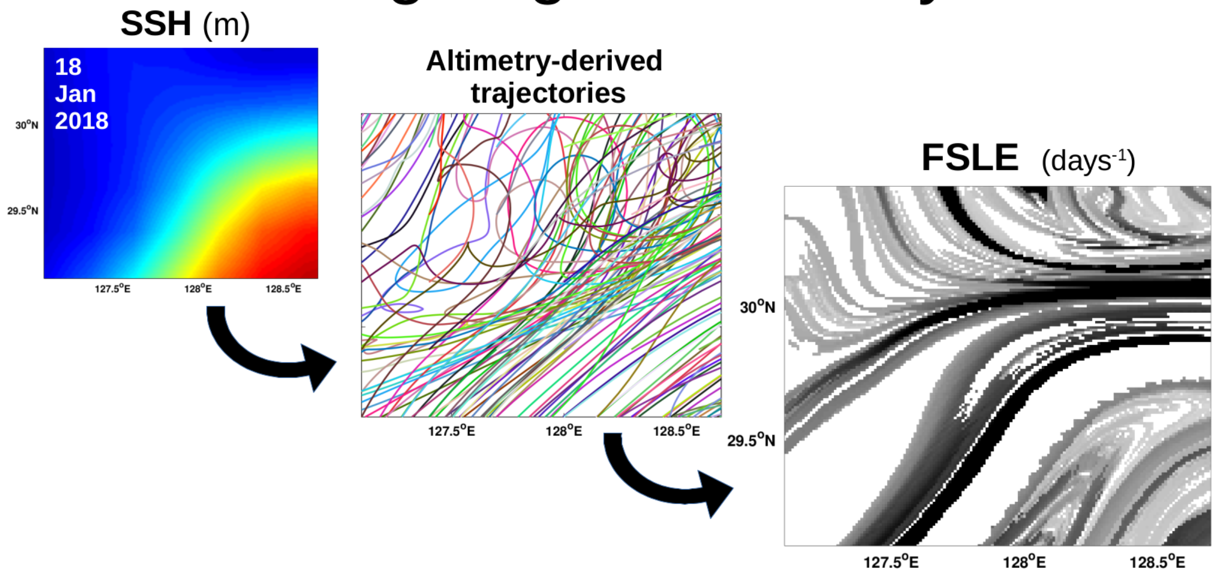
Gina Fifani[1,2], Francesco d'Ovidio[1], Alberto Baudena[3], Milad Fakhri[2], Yannice faugere[4], Rosemary Morrow[5], Laurent Mortier[1], Georges Baaklini[1,2]

(1)LOCEAN, SU, Paris, France
(2)CNRS-L, Batroun, Lebanon
(3)LOV, Villefranche-sur-mer, France
(4)CLS, Toulouse, France
(5)LEGOS, Toulouse, France.


I would like to first acknowledge all the co-authors who contributed to my thesis work under the co-direction of Francesco d'Ovidio (LOCEAN) and Milad Fakhri (CNRS-Lebanon).

In the following work we study the role of the Altimetry-based Lagrangian approach in environmental and applied problems, particularly in studying contaminants dispersion in the ocean.

Lagrangian Altimetry



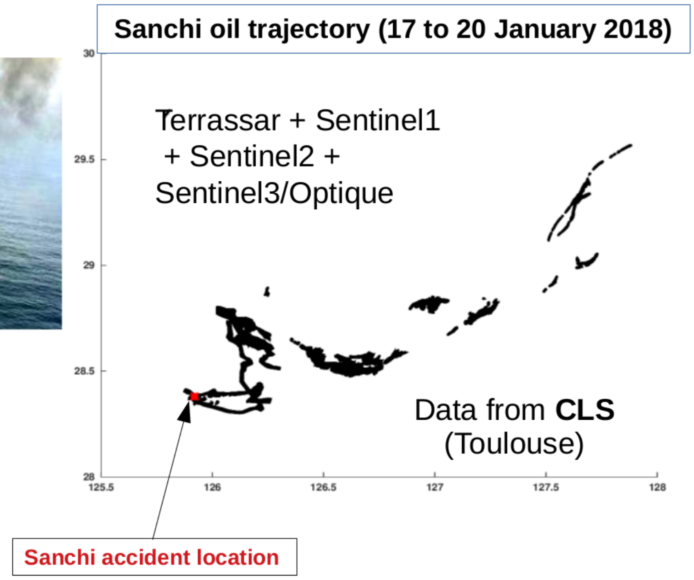
The Lagrangian approach is based on the analysis of particle trajectories advected in a fluid. In the case of altimetry, this approach can be employed by integrating numerically the surface currents and by creating in this way a set of trajectories of virtual surface drifters. The Lyapunov exponent (LE) is a Lagrangian quantity aiming at identifying transport fronts and barriers in the ocean known as Lagrangian fronts or Lagrangian Coherent Structures (LCSs). Lagrangian fronts can be computed from velocity field, including altimetry.

Regional application

Sanchi oil spill case study
(January 2018)

6 January 2018 → collision between the Iranian oil tanker **Sanchi** and the Hong Kong-flagged cargo ship **CF Crystal**

14 January 2018 → Sanchi oil tanker exploded and sank

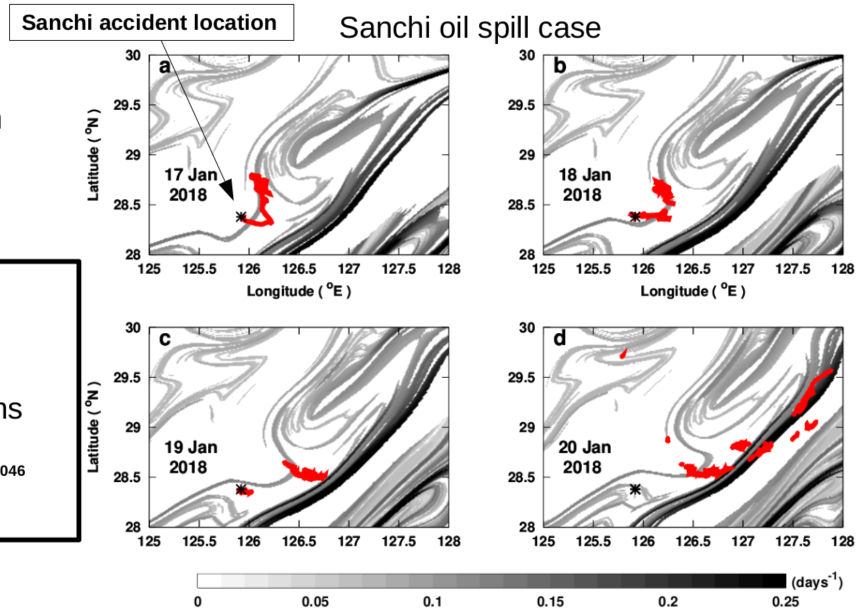


The Lagrangian-Altimetry approach has received considerable attention in environmental and ecological studies including phtoplanktonic and algal blooms, larvae transport and pollution dispersion. Besides its negative impact on marine ecosystems, water pollution may have dire consequences on human health with socioeconomic impacts. In this study, Sanchi oil spill case is firstly chosen in order to validate the efficiency of the Lagrangian-Altimetry approach in the analysis of the horizontal contaminants dispersion through the better understanding of the oceanic circulation. Sanchi accident occurred on 6 January 2018 in the Est China Sea after a collision between the Iranian oil tanker Sanchi and the Hong Kong-flagged cargo ship CF Crystal. After burning for almost one week, Sanchi oil tanker exploded and sank on 14 January as reported. Leaked Sanchi oil is mostly ultra-light crude oil, known as natural condensate and remains at the surface. CLS (Toulouse) provided the data for the oil propagation from 17 to 20 January 2018.

Finite-size Lyapunov exponent

FSLE (days^{-1})

Allows the detection of transport barriers in the ocean (Lagrangian Coherent Structures)



Velocity product:

CMEMS
NRT daily surface observations of global ocean
SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046
(~25 km)

The backward finite-size Lyapunov exponent (FSLE) is one of the altimetry-based Lagrangian tools that aim at identifying attracting and stirring features in the ocean also acting as transport barriers. These structures are often referred Lagrangian fronts or somehow equivalently Lagrangian Coherent Structures (LCSs). The daily application of the FSLE in the Sanchi area from 17 to 20 January 2018 is done using the altimetry-derived geostrophic velocity data in near real-time available at E.U. Copernicus Marine Service Information (CMEMS). Results above highlight the role and the efficiency of the FSLE underlined fronts (gray-scaled filaments) in governing the daily oil pathway (red pattern). The sharpest gray-scaled front attracts the leaked oil before stretching it along its direction on 20 January. Such a persistent front marks the presence of the Kuroshio Current in this area.

Prediction of fronts displacement

Lagrangian Coherent Structures: barriers that divide the flow into dynamically distinct regions.

L(x, t) = scalar function with LCS is given by the level set L(x, t) = 0.

Flux across LCS: $\Phi(t) = \int_{\mathrm{LCS}} \frac{\mathrm{d}L}{\mathrm{d}t} \mathrm{d}s$

$$\frac{\mathrm{d}L}{\mathrm{d}t} = \underbrace{\frac{\langle \hat{\mathbf{t}}, \nabla\sigma \rangle}{\langle \hat{\mathbf{n}}, \Sigma\hat{\mathbf{n}} \rangle}}_{\text{term A}} \underbrace{\left\langle \hat{\mathbf{t}}, \frac{\partial \hat{\mathbf{n}}}{\partial t} - J\hat{\mathbf{n}} \right\rangle}_{\text{term B}} + \underbrace{\mathcal{O}\left(\frac{1}{|T|}\right)}_{\text{term C}}$$

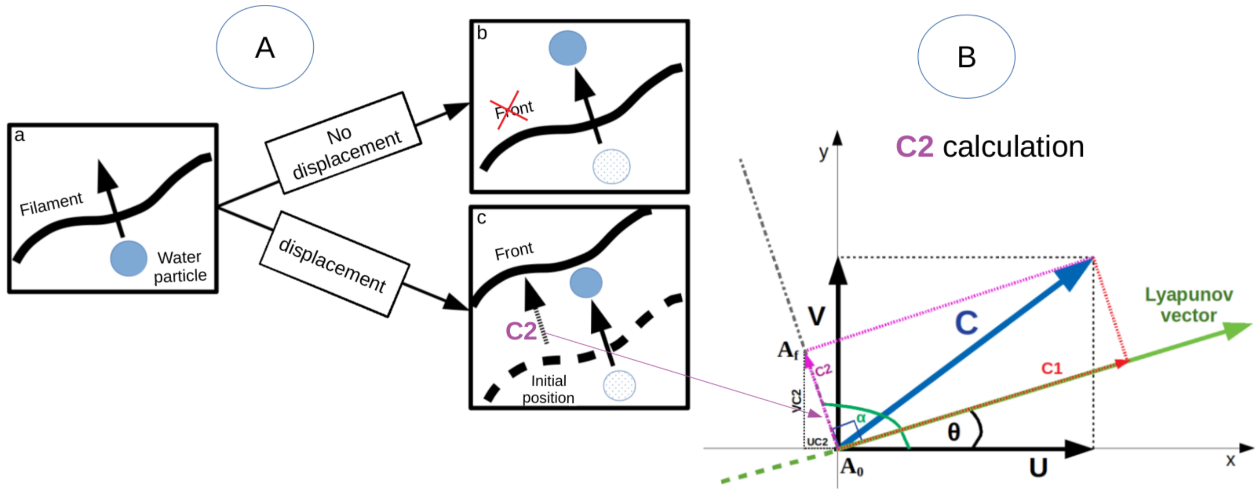
Shadden et *al.* (2005) (FTLE)

Term A: how well defined the ridge is, and goes to zero the sharper the ridge
Term B: the difference in the local rotation rate of the LCS from the local rotation rate of the Eulerian velocity field
Term C: a term which scales as 1/|T|, where |T| is the length of time over which the FTLE is computed.

While the tracer is extending along a Lagrangian front, the latter can also move. Such a displacement is an important information in the pollution management field. Near real-time analysis of pollution spreading like oil spill accidents require additional information on the future displacement of the Lagrangian fronts controlling the contaminant dispersion. Predicting the future displacement of these frontal structures is important because an effective response to a contaminant spill requires information on how the pollutant will progress, in which direction it will move and which regions will be at risk in the days following the disaster. Despite their spatial-temporal limitations, Forecast assimilation models remain today the only way to make the prediction by providing the future velocity fields. However they are not always available and their resulting predicted LCS may inherit the model errors.

Here we present a novel approach for predicting the short-term displacement of a Lagrangian front by the only use of the information of today's surface velocity field without the need for a reliable assimilation model. The approach attempts to exploit a mathematical propriety of a Lagrangian front, namely the fact that the flux is minimal/negligible across it. Such a theory is detailed in the paper of Shadden et al., 2005.

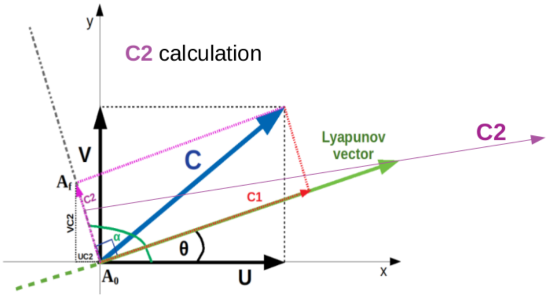
Prediction of fronts displacement

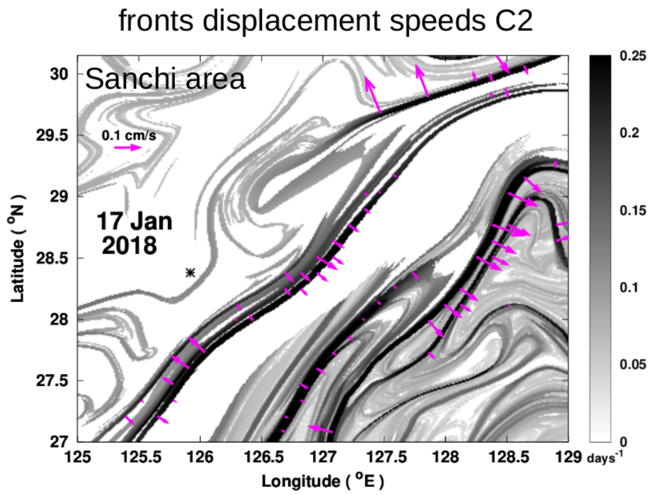


C2: front displacement speed **C**: altimetry-derived velocity vector

The short-term prediction method idea starts by resolving the following issue. We consider a water particle located on one of the front sides with a velocity speed directed across and orthogonal to the front. The latter speed corresponds to the movement of the particle. Nevertheless, a Lagrangian front is a transport barrier and the cross-front flux of water particles should be almost negligible. The only explanation for such a contradiction and the principle of the developed short-prediction method is that owing to the idea that the water flux is minimal across a well-defined front, the front should move with the water particle speed (continuous black arrows in figure A and C2 in figure B) orthogonal to the front (continuous black line in figure A and green arrow in B), otherwise the water particle will be able to cross the filament which will be no longer considered as a well-defined front or a transport barrier.

2 days prediction (17 to 19)

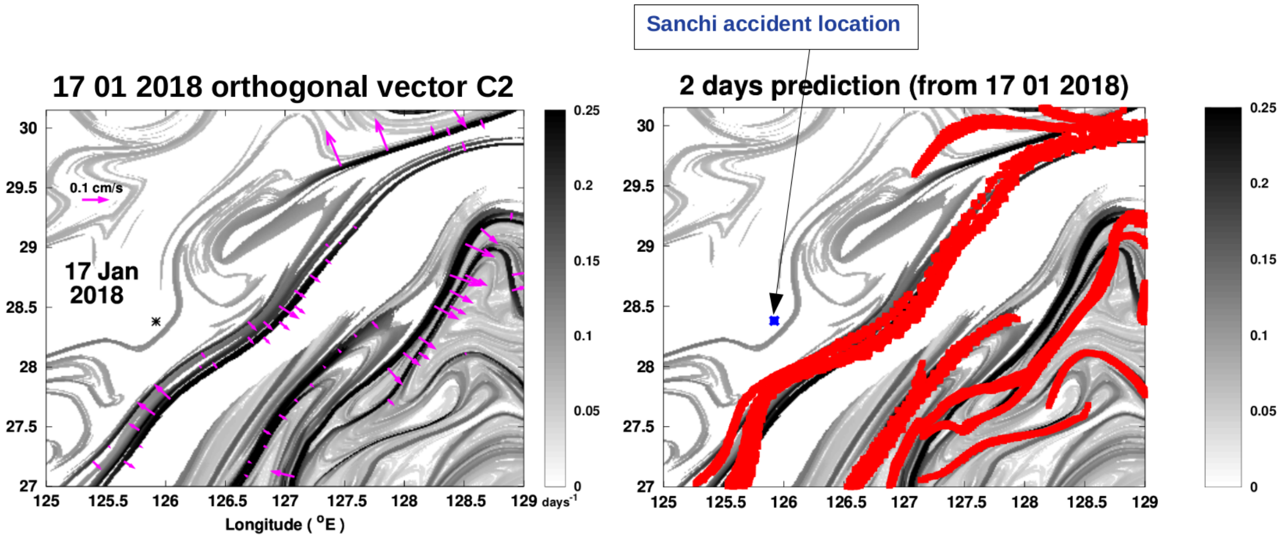




In order to make a 2-days prediction for the 17th of January fronts in the Sanchi areas, the calculation of C2 vectors (pink arrows in the slide above) is firstly done for the sharpest fronts in the area (λ>0.18 days-1) by the only use of the Lyapunov information of the 17th of January. Here we consider that we don’t have the future velocities that usually allow the computation the conventional FSLE.

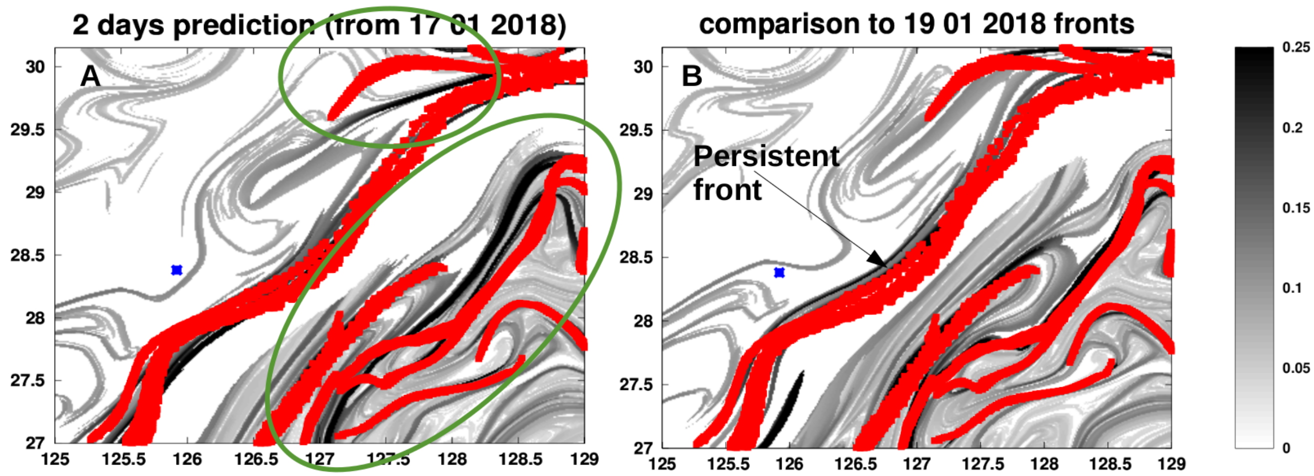
C2 vectors along a well-defined front are referred to the displacement speeds at which the front points will move in the very near future. After defining a 2 days period, the 2-days advection of the 17th of January fronts, thus the prediction of their displacement and their new positioning after 2 days (on January 19) become feasible.

2 days prediction (17 to 19)



The 2-days predicted positions of the 17th of January fronts are presented by the red lines in the figure to the right. In order to validate the experimentally observed displacements, we should wait for the availability of CMEMS velocity fields until 19 January 2018 so that the computation of the FSLE of the latter day can be done.

Comparison with day 19

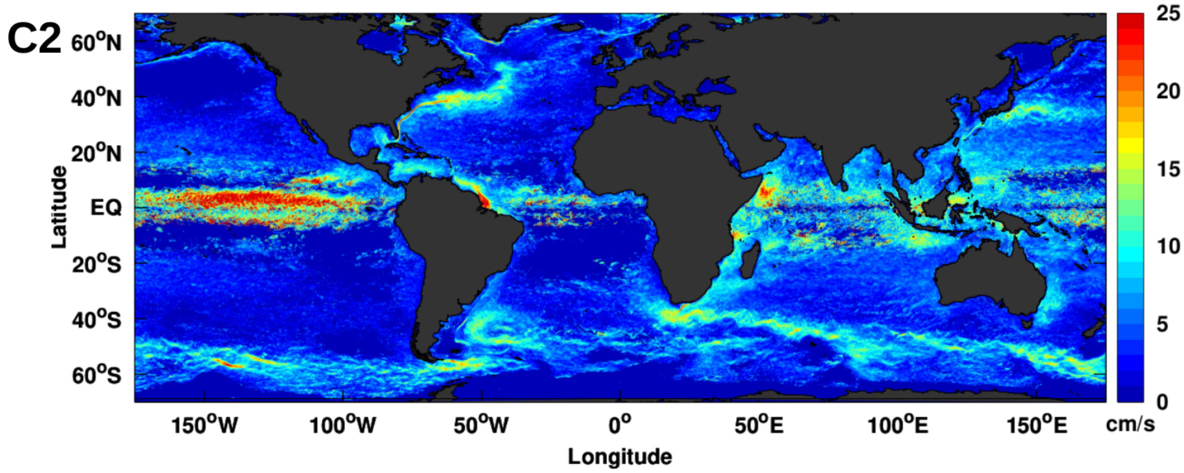


The gray-scaled fronts in the background of figure A are those underlined by the FSLE computation for the day 17 January 2018. Those in the background of figure B are those for 19 January underlined by the FSLE after using available CMEMS velocity data. Fronts in red in both figures (A & B) are the anticipated positioning of the 17th of January sharpest fronts (>0.18 days-1) after 2-days prediction by the novel method. The 2-days prediction of January 17's fronts displacement shows a remarkable consistency between the placement of the real fronts (in gray-scale) of 19th of January computed by the FSLE (figure B) and the positioning of the predicted fronts from 17 January (in red).

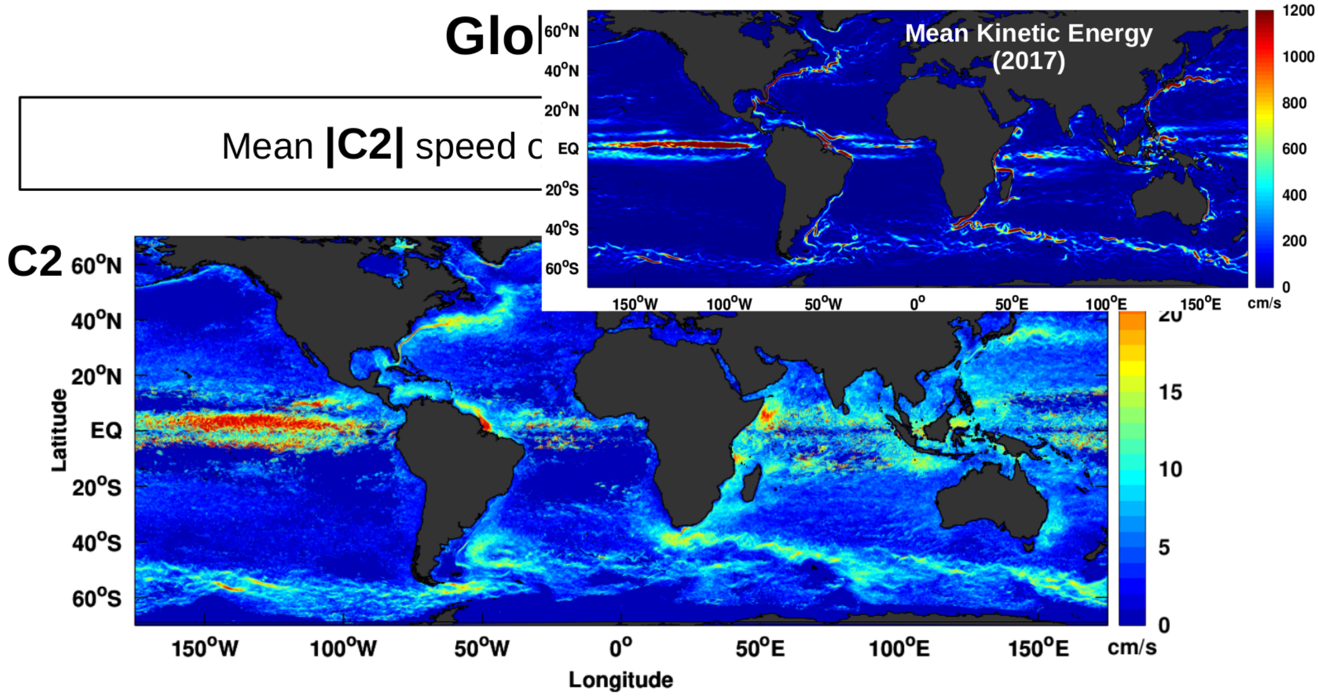
The few cases where the prediction results are not perfectly compatible with the real placement can be explained by different hypotheses, like the possible errors in the Lyapunov exponent computation which may affect the advection vector calculation. We should also remind that the current velocities could also rapidly change while we are using a constant velocity field, the reason why this method remains applicable for short-term predictions only.

Global application

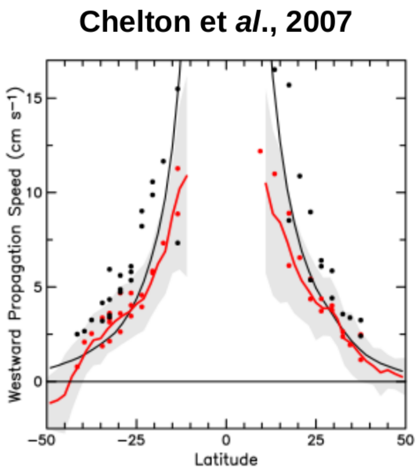
Mean **|C2|** speed of the sharpest fronts (λ > 0.18 days-1) displacement in 2017

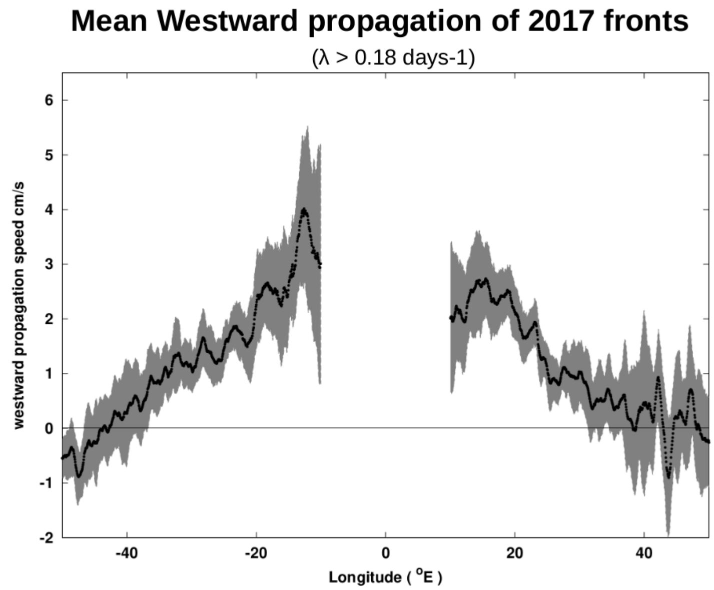


The ability to calculate the speeds at which the fronts in an area will move in the near-future does not only allow to make short-term predictions as done previously but can also be used for global statistical studies. After validating the method regionally, we present here a global application aiming at calculating the annual mean speeds (C2 vectors) at which fronts with λ > 0.18 days-1 move in 2017.



The regions whose fronts have high drifting speed (mean C2 norm > 10 cm/s) coincide with those of high mean kinetic energy associated with high mesoscale activities. The high variability detected in the Tropical zones, in particular between the latitude 20° S and 20° N, is strongly dominated by the linear nondispersive baroclinic Rossby wave propagation, which mainly explains the high displacement speeds of the tropical fronts (mean C2). However, elsewhere, the propagating energy involves the superposition of nonlinear vortices or eddies and larger-scale Rossby waves that are both responsible of the high |C2| means there.





Consistency: highest westward propagation is found in the tropics

According to Chelton et al. (2007), in terms of strength, eddies westward propagation speeds as well as the westward phase speed of the classical Rossby wave have very similar increasing trend towards the tropics in which the zonal phase speed of Rossby wave exceeds eddies speed. Our computation of the 2017 mean zonal component (UC2) of our calculated fronts displacement speeds (C2) gives a similar trend as in Chelton et al. (2007) with maximum mean values in the tropics.

Conclusions and persepctives

- Contaminants dispersion is a main threat to marine and human lives which requires an immediate response as pollutants can be rapidly transported in large distances by the complex ocean dynamics.

- Satellite altimetry provides a very accurate description of the ocean geostrophic velocity up to meso and larger scales at which altimetry supplies reliable near real-time current velocity fields.

- Lagrangian approaches for Lagrangian Coherent Structures detection seem to gain considerable attention in environmental studies. The Lyapunov exponent computation using altimetry-derived current velocities proved its efficiency in the detection of near real-time stirring features, the LCSs, governing Sanchi oil propagation while affecting its shape and direction.

- Near real-time LCSs detection allows to predict a part of the contaminant filamentation. However, the LCSs are not stationary features and their drifting mouvement could also affect the frontal propagation of the contaminant.

- Near real-time pollution studies need to be complemented by an anticipation of the future propagation of the pollutant the days following the discharge in order to support the pollutant management tools.

- We found that predicting a front displacement speed, and therefore its new positioning can be possible by a simple calculation, without the need for future current velocities, by the only use of the near real-time information.

- A global application of the method allowed the detection of regions of fast drifting fronts where any released pollution is subjected to a very quick dispersion rate. These regions coincide with those of high mean kinetic energy associated with high mesoscale activities.

- While some contaminants can reach and stay on the surface, others could drown or stay near the sea bottom where different oceanographic processes (caused by the bottom topography) can occur and affect the pollutant path. Further challenges remain considering the vertical component with a heavier oil spill type.