On the inversion of sub-mesoscale information to correct mesoscale velocity

Lucile Gaultier, Jacques Verron, Pierre Brasseur, Jean-Michel Brankart

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The subject of this talk is on the inversion of sub-mesoscale information to correct mesoscale velocity. In other words we are using tracer observations from space to improve the estimation of the oceanic circulation. This topic is slighlty different from the previous one since we are using tracer observations from space to control dynamics.

I am currently working in LEGI Laboratory. One of our field of expertise is the use of observation to correct models and improve prediction.

Prerequisites

Altimetry

Data Assimilation

Sub-mesoscale

Tracer

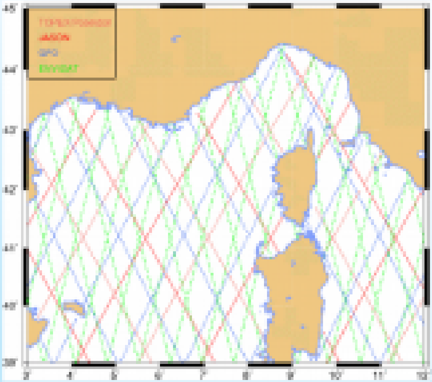
For a long time, the Team has developped usefull tools in Modeling and Data Assimilation using satellites data . With the developpement of high resolution tracer satellites, we are looking for new methods to use efficiently this huge amount of data and take into account the sub-mesoscale.
Altimetric satellites has provided valid data for more than 15 years. Using radars, the altimeter measures the sea surface height along its track.
Here is a map representing the tracks of altimetric satellites during 10 days. It is common to use the derived velocity assuming that the geostrophic hypothesis is valid (Large scale motion, Equilibrium of Rotation and Pressure forces).
In AVISO products, the tracks have been interpolated in time and space to build a map of ssh.
In the following study, the mesoscale velocity is the geostrophic velocity from altimetry (AVISO).

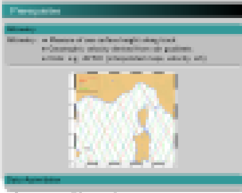
Recently, High Resolution Observation have brought to light the presence of sub-mesoscales in the Ocean. This kind of circulation happens at smaller scales than the mesoscale and is ageostrophic. Sub-mesoscale patterns in the ocean can easily be detected using High Resolution tracer observation. In the following study, I will refer to tracer as observable tracer. Nowadays, SST and Ocean Color are easily observed from space at high resolution.

Prerequisites

Altimetry

Altimetry :
- Measure of sea surface height along track
- Geostrophic velocity derived from ssh gradients
- Data: e.g. AVISO (interpolated maps, velocity, ssh)





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Prerequisites

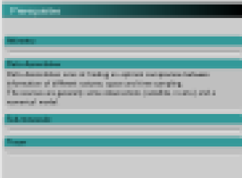
Altimetry

Data Assimilation

Data Assimilation aims at finding an optimal compromise between information of different natures, space and time sampling.
The sources are generally some observations (satellite, in-situ) and a numerical model.

Sub-mesoscale

Tracer



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Prerequisites

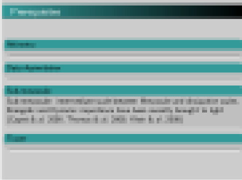
Altimetry

Data Assimilation

Sub-mesoscale

Sub-mesoscale: intermediate scale between Mesoscale and dissipative scales. Energetic and Dynamic importance have been recently brought to light (Capet & al, 2008, Thomas & al, 2008, Klein & al, 2008)

Tracer



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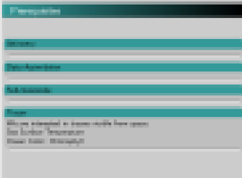
Tracer

We are interested in tracers visible from space:
Sea Surface Temperature
Ocean Color: Chlorophyll



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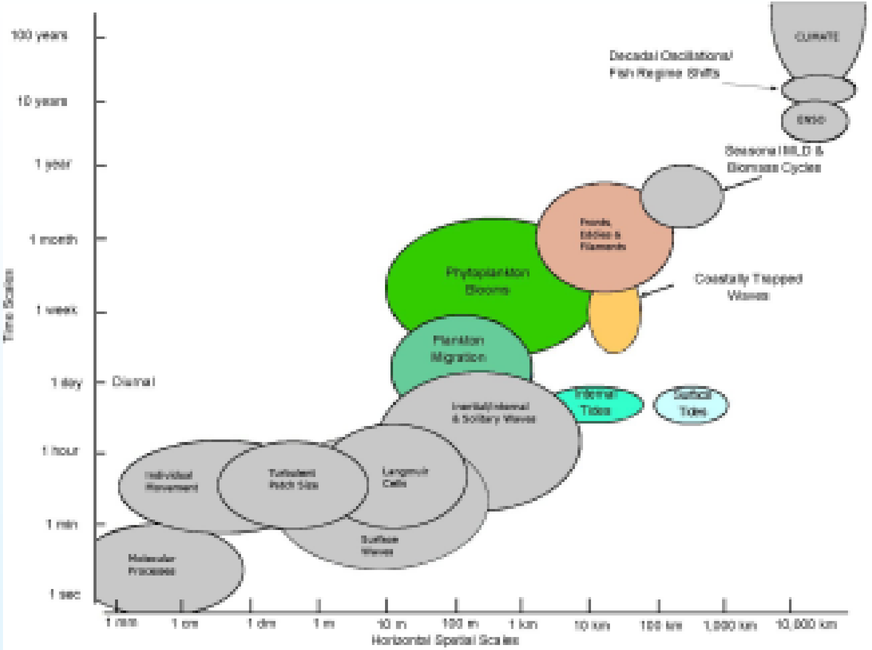
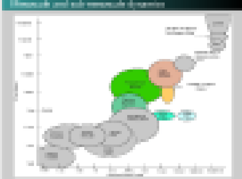
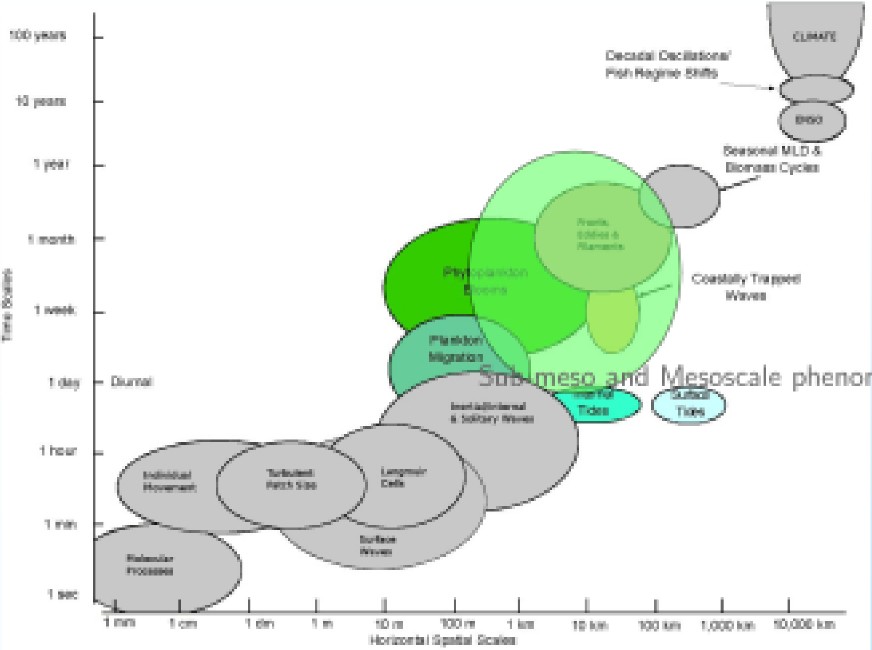
Mesoscale and sub-mesoscale dynamics



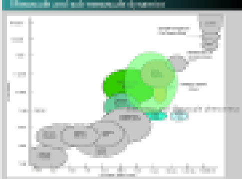


Many scales are present in the ocean, from climatology to molecular processes. The scales in which we are interested are located between 1km and 100 km, in the green circle. The sub-mesoscale dynamic is mainly observed from few hundred meters to 10 km.
At sub-mesoscales there is a strong interaction between the physics and the biogeochemistry so that the sub-mesoscale dynamics impact tracer fields.
Altimetric satellites can observe dynamics but are currently limitted to the mesoscale, and can provide at best one map a week, whereas tracer sensors have a fine resolution in space and time. We can get nearly a map a day with a resolution as low as 200m. We need to find a way to analyse this high resolution data set and extract dynamic information.
In the context of SWOT and SARAL projects, which will provide high resolution data (image), we are also looking for new methods to anlayse the huge amount of data.

Mesoscale and sub-mesoscale dynamics



Sub-meso and Mesoscale phenomena



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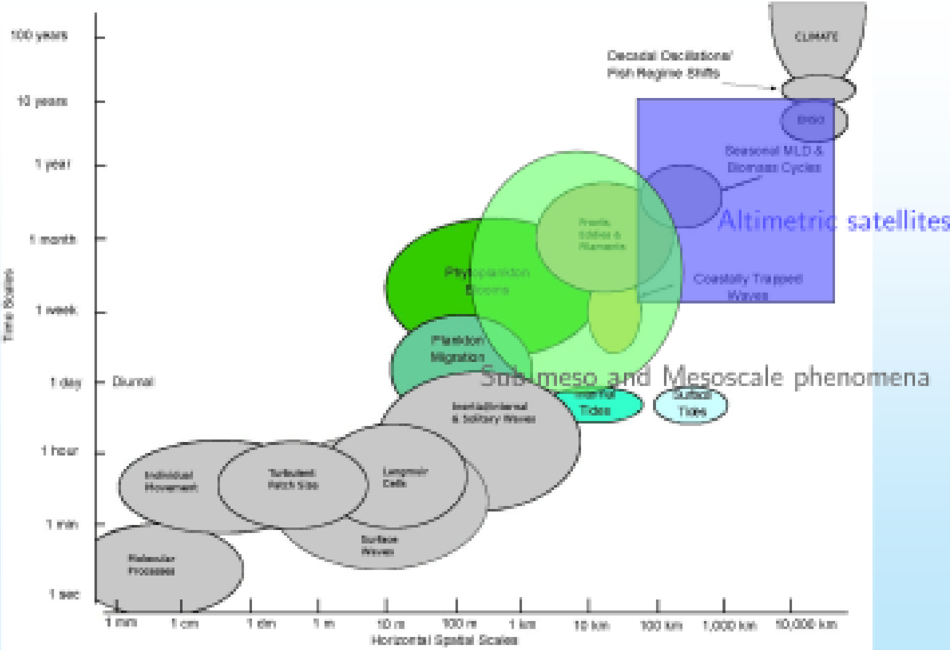

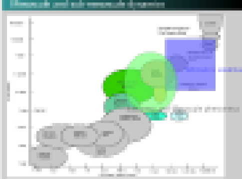

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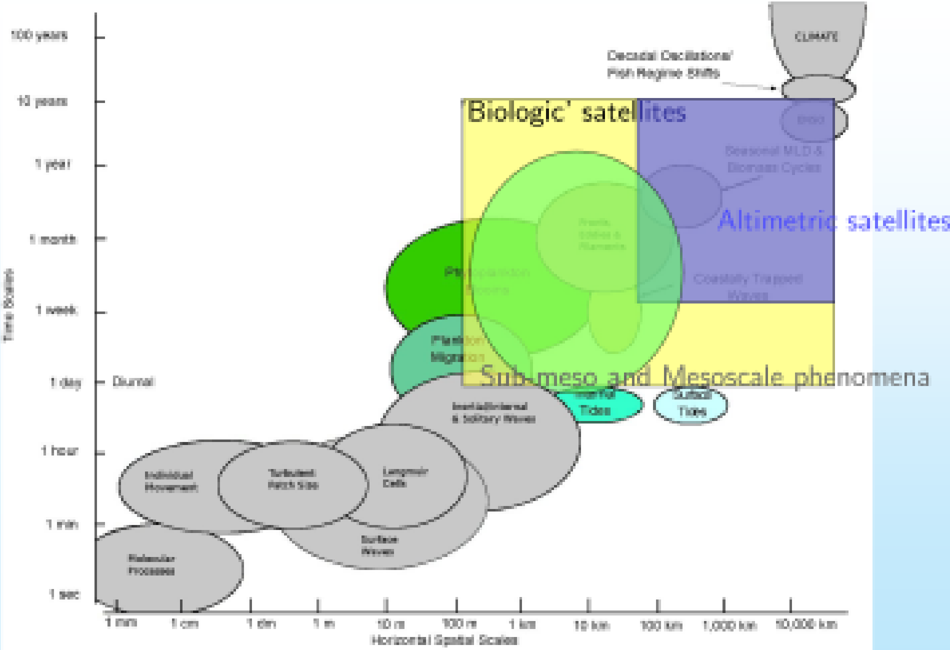

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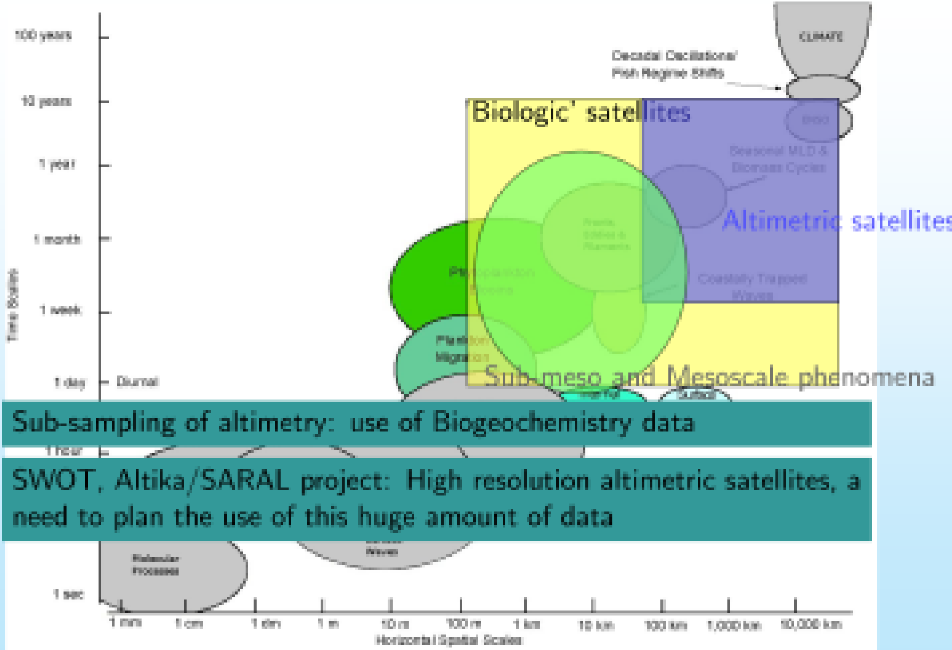
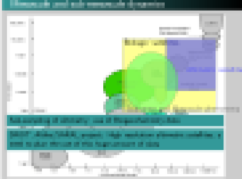


Sub-sampling of altimetry: use of Biogeochemistry data

SWOT, Altika/SARAL project: High resolution altimetric satellites, a need to plan the use of this huge amount of data



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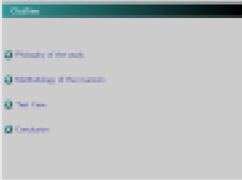
Outline

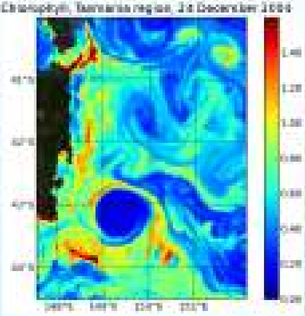
1. Philosphy of the study
2. Methodology of the inversion
3. Test Case
4. Conclusion



After presenting the philosophy of the study, I will present you some of the methodological aspect and show some actual results on a test case

Philosophy of the study

Sub-mesoscale tracer image



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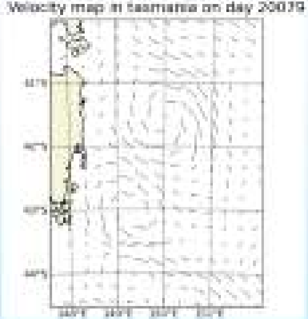
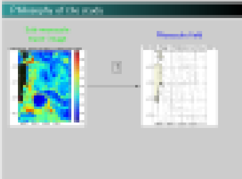
Mesoscale field

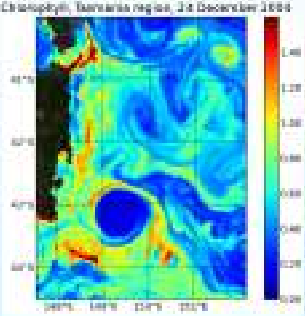




Our goal is to correct mesoscale velocity using a tracer image. Some studies brought to light the connecction between mesoscale velocities and tracer patterns, but correcting mesoscale velocity using tracers has never been done before. There is not much to say about the state of the art in this field since no such study has ever been done. We need to make up a new method from start to finish.

Philosophy of the study

Sub-mesoscale tracer image



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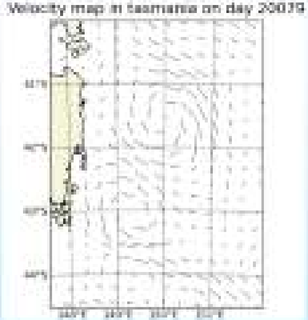
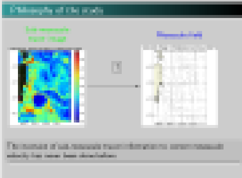
Mesoscale field



The inversion of sub-mesoscale tracer information to correct mesoscale velocity has never been done before



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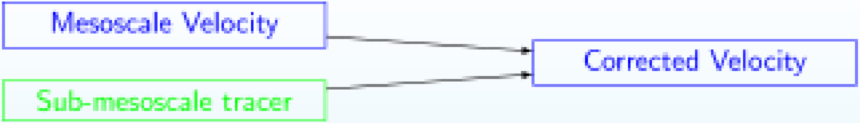
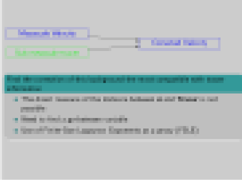


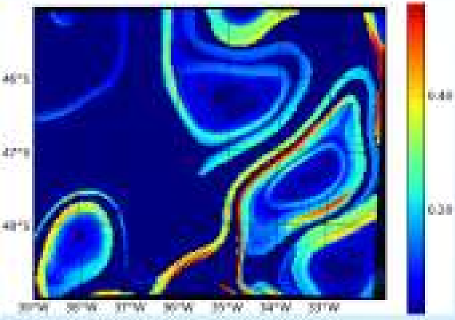
Find the correction of this background the most compatible with tracer information

- The direct measure of the distance between $\vec{u}$ and **Tracer** is not possible
- Need to find a go-between variable
- Use of Finite-Size Lyapunov Exponents as a proxy (FSLE)

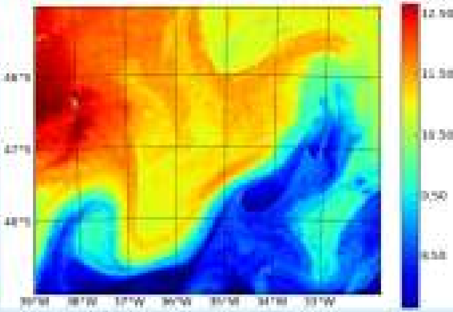


It is clear that we cannot calculate entirely the velocity but we can correct an estimation of the velocity. We need for our study an estimation of the velocity in our region, It will be refered as the background velocity. We need two information to correct the velocity: the background velocity and the information from the sub-mesoscale tracer. We look for the correction of this background the most compatible with the tracer info: we need to measure the gap between mesoscale information and tracer information. We cannot directly look at the difference between those two different physical variables. We need a go-between variable to enable this two representations of the region to discuss together. In the following study , we choose the FSLE as a go-between.

Are Lyapunov exponents a reliable proxy/image?

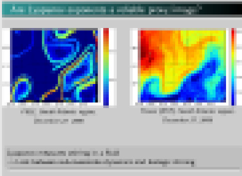


FSLE, South Atlantic region, December 27, 2006



Tracer (SST), South Atlantic region, December 27, 2006

Lyapunov measures stirring in a fluid
→ Link between sub-mesoscale dynamics and biologic stirring.



We need to check that the FSLE is a relevant proxy for this study. Indeed FSLE represents the stirring of the fluid. It is a connection between sub-mesoscale dynamics and biologic stirring. If we compare Lyapunov exponents image with tracer image, we can find similar patterns between the maximum lines of Lyapunov exponents and frontal tracer structure (that is to say the gradient). Both are Lagrangian tracer barriers. Lyapunov Exponent is going to be our go-between variable in the following study

Methodology

- Cost function:

$$J(u) = \|\lambda(u) - \lambda_{obs}\| + background\ \ term$$

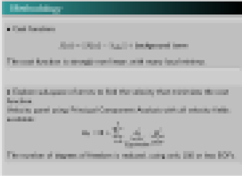
The cost function is strongly non linear, with many local minima.

- Explore sub-space of errors to find the velocity that minimizes the cost function.

Velocity panel using Principal Component Analysis with all velocity fields available:

$$\mathbf{u}_k = \bar{\mathbf{u}} + \sum_{i=0}^{n} \underbrace{a_k^i}_{Eigenvalue} \underbrace{\mathbf{u}^i}_{EOF}$$

The number of degrees of freedom is reduced, using only 100 or less EOFs.



The cost function is defined as the measure of the distance between the lyapunov exponents (that is to say the proxy of the velocity) and the tracer frontal structure. We look for the velocity that minimizes this cost function. The cost function is quite complex with many local minima and strongly non-linear so that it is very hard to find the minimum. We get a sample of the velocity by computing the sub-space of velocity errors, and we add this perturbation to the background velocity. The goal is to find the sampled velocity that gives us the lowest cost function. This velocity is refered as the corrected velocity later on.

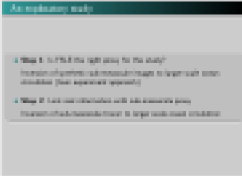
An exploratory study

- **Step 1**: Is FSLE the right proxy for this study?

  Inversion of synthetic sub-mesoscale images to larger scale ocean circulation (twin experiment approach)

- **Step 2**: Link real information with sub-mesoscale proxy

  Inversion of sub-mesoscale tracer to larger scale ocean circulation



The goal of our study is to invert tracer sub-mesoscale information to correct mesoscale velocity. The first requirement is that FSLE image is a suitable proxy, that is to say that FSLE image is invertible. If this step is successfull, we can link tracer information with FSLE image and do the full inversion. We can invert sub-mesoscale tracer information to larger ocean circulation, and therefore, prove the feasability of the inversion of tracer information.

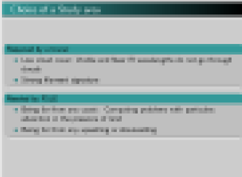
Choice of a Study area

Required by a tracer

- Low cloud cover: Visible and Near IR wavelengths do not go through clouds
- Strong filament signature

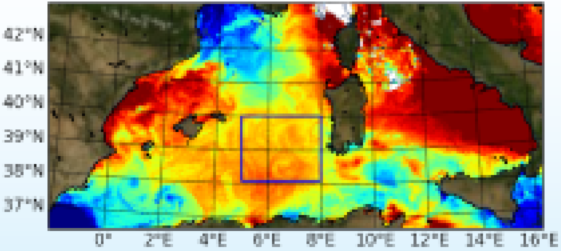
Needed by FSLE

- Being far from any coast : Computing problems with particules advection in the presence of land
- Being far from any upwelling or downwelling



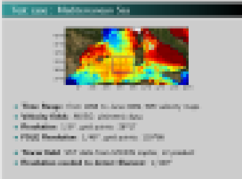
To implement the previously described method, I looked for an ideally located area. There are some technical requirements to detect well the tracer. We want the frontal structure to be easily detected. A low cloud cover is a first requirement to have enough data, but we also need the presence of submesoscale filaments and enough heterogeneity in the structure to detect the gradient. We also want Lyapunov exponents and the frontal structure of the tracer to have similar patterns. It means that we avoid coastal area, and the presence of upwelling and downwelling ...

Test case : Mediterranean Sea



- **Time Range**: from 1998 to June 2009, 595 velocity maps
- **Velocity fields**: AVISO, altimetric data
- **Resolution**: 1/8°, grid points: 26*17
- **FSLE Resolution**: 1/48°, grid points: 119*86

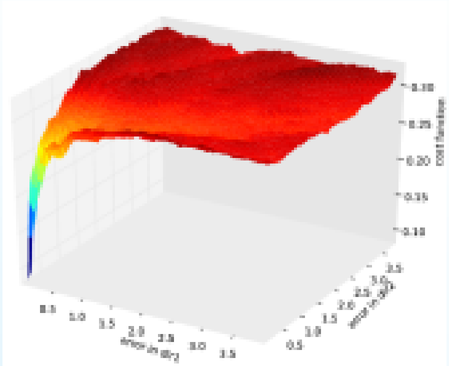
- **Tracer field**: SST data from MODIS captor, L2 product
- **Resolution needed to detect filament**: 1/100°

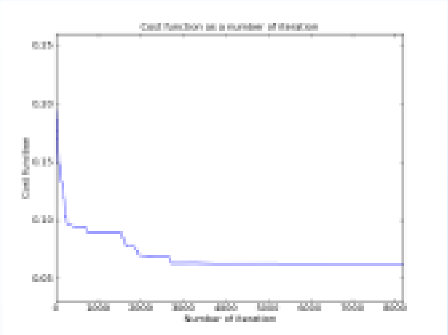


The area chosen for this test is the Western Mediterranean Sea, north of the African current. We have nearly 600 velocity maps to generate our sub-space of errors. The Aviso Velocity Resolution in this area is 1/8 and the derived FSLE Resolution is 1/48. The tracer used in the following study is SST from MODIS captor. SST initial resolution is 1/100 and is then degraded at FSLE resolution

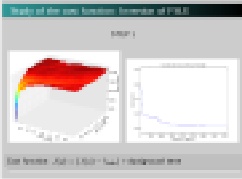
Study of the cost function: Inversion of FSLE

STEP 1





Cost function: $J(u) = \|\lambda(u) - \lambda_{obs}\| + background\ \ term$

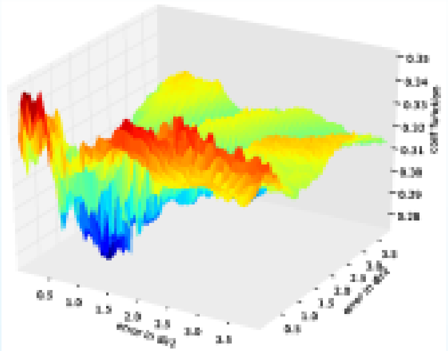


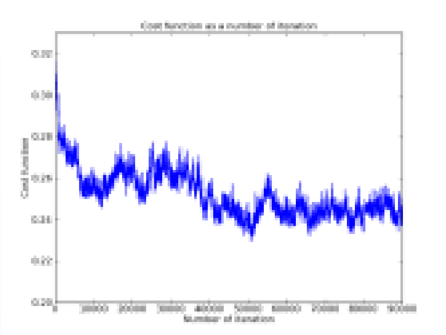
As I already told you, the first step of our study is to check that the inversion of our proxy FSLE is possible. The left picture represents the variation of the cost function along two directions of our space of errors. We can clearly see a global minimum. It means that we can identify the velocity that minimizes the cost function. The right picture represents the minimization of the cost function.
The proxy inversion seems possible. Therefore, We can go through the second step: the full inversion.

In the left picture the variation of the cost function along two directions seems far more irregular than in the first step. We can feel that it is going to be harder to find the velocity that minimizes the cost function. We can also see in the process of the minimization of the cost function that several local minima exists. It is not obvious to determine which one is the global minumum.

Study of the cost function: Full inversion

STEP 2





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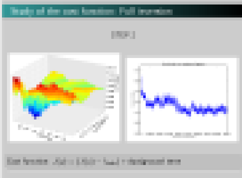

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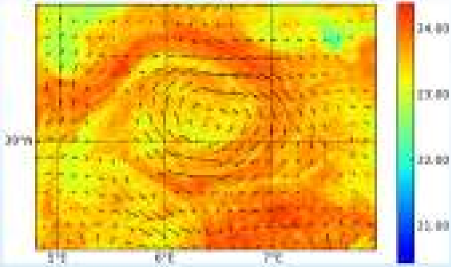
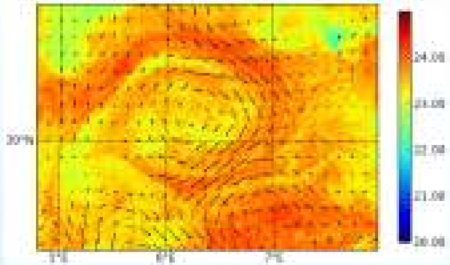
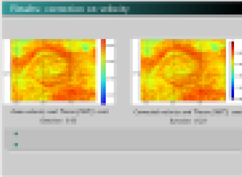
Results: correction on velocity



Aviso velocity and Tracer (SST), cost function: 0.33

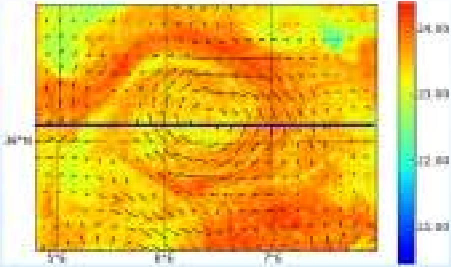


Corrected velocity and Tracer (SST), cost function: 0.23



The left picture is the superposition of the initial velocity with the Tracer. The right one is the corrected velocity with the SST. First of all we can see that the center of the gyre shifted a bit upward, and the velocity in the South East corner of the picture is more important and fits the gradient of the tracer.

Results: correction on velocity



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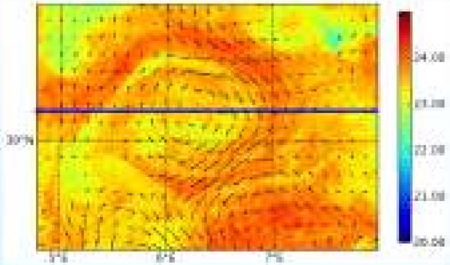
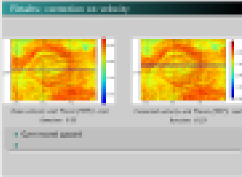


Corrected velocity and Tracer (SST), cost function: 0.23

- Gyre moved upward
-



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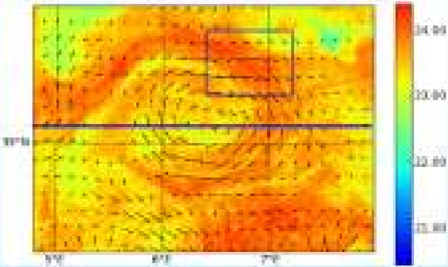

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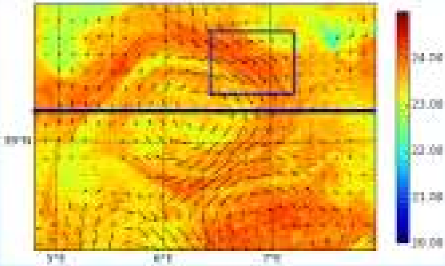
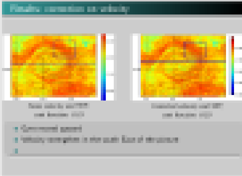


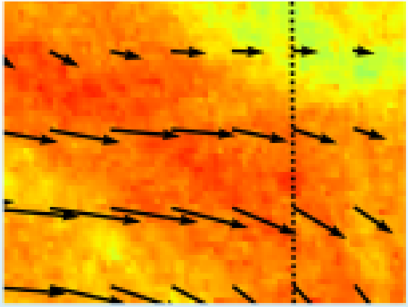
Corrected velocity and SST,
cost function: 0.23

- Gyre moved upward
- Velocity strengthen in the south East of the picture
-

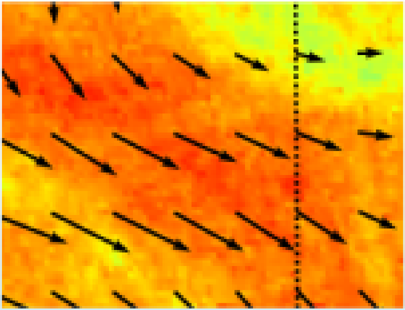


An important result is also observable in the blue rectangular. The philsophoy of this study is to work using Lagrangian barriers. If we look at a zoom along a frontal structure, we can see that the velocity does not cross the frontal structure of the tracer (the barrier). The correction applied on the velocity is coherent with the observation of the tracer. However we still need to estimate the error made on the corrected velocity.

Results: correction on velocity

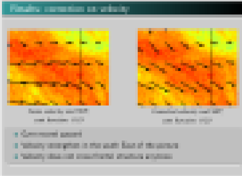


Aviso velocity and SST, cost function: 0.33



Corrected velocity and SST, cost function: 0.23

- Gyre moved upward
- Velocity strengthen in the south East of the picture
- Velocity does not cross frontal structure anymore



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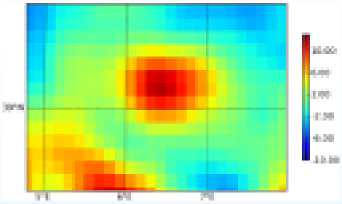
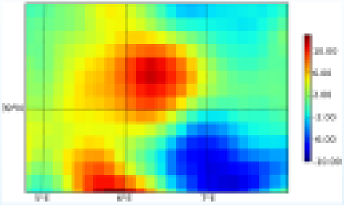
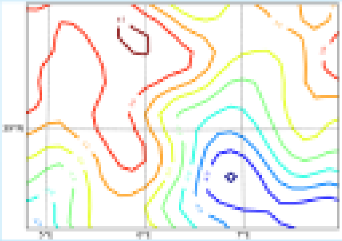
Correction to the ssh



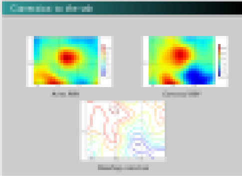
Aviso SSH



Corrected SSH

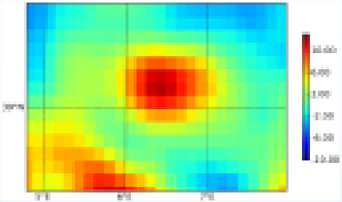


Resulting correction

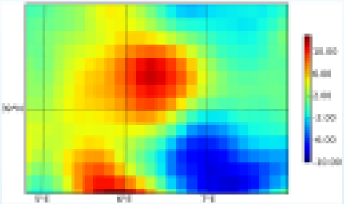


As the geostrophic Aviso velocity and the Sea Surface Height are related, We can calculate the resulting correction on the SSH. The left picture is the observed SSH , the right one the corrected SSH and the correction applied is the belowed picture (I mean the difference between the observed and the corrected SSH). The important correction applied on the South East corner is quite visible in the resulting correction. We can also observe the shift of the gyre.

Correction to the ssh

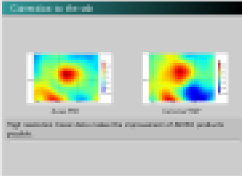


Aviso SSH



Corrected SSH

High resolution tracer data makes the improvement of AVISO products possible.



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Conclusion

Sub-mesoscale information are invertible to control larger scales dynamics

- Altimetry and tracer observation are complementary.
- Tracer information can compensate for the lack of SSH resolution in time and space.
- High resolution Sea Surface Temperature or Ocean Color data are usefull to control ocean physics.

Conclusion

Next

- Quantify the error made on the estimated velocity.
- Inversion of image in a coupled physico-biogeochemical model.

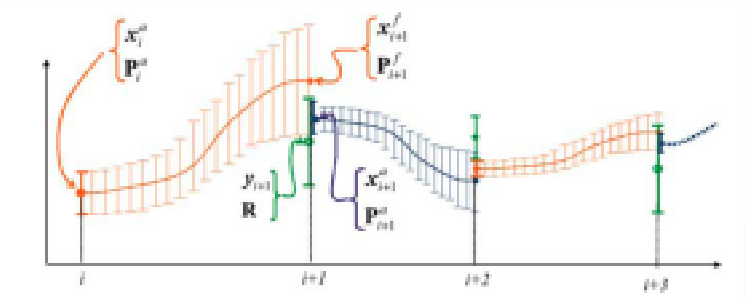
Prospects

- Data Assimilation of image in a coupled physico-biogeochemical model.

Altimetric data and tracer data are used together to build a better data set. This study shows how to make up for the sub-sampling in time and space of altimetry using Tracer information. We also prove that sub-mesoscale tracer information can control larger scale dynamics in the ocean. Still, we need to quantify the error made on this new estimation on the velocity. A similar study on a coupled physico-biogeochemical model should be interesting to improve the method and quantify the resulting error. An interesting prospect is to generalize the method and compute a full data assimilation of image in a couple physico-biogeochemical model.

Thank you for your attention

Data Assimilation



Conceptual representation of filtering with sequential assimilation, Brasseur, 2006

Sub-mesoscale

Sub-mesoscales are scales defined by a Rossby number of order one

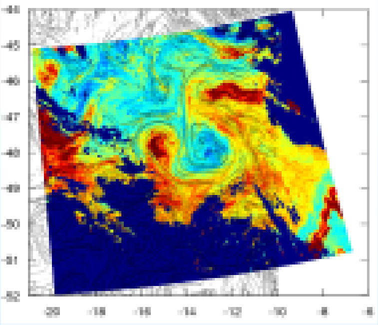
$$R_o = \frac{inertial\ force}{Coriolis\ force} = \frac{U}{fL}$$

It is caracterized by ageostrophic circulation: strain dominates over rotation.

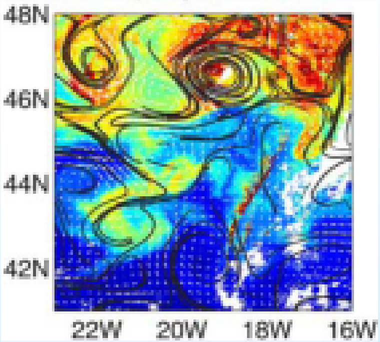
Three major ingredients:

- frontogenesis
- straining by the mesoscale turbulent field
- submesoscale baroclinic instability.

Connection between FSLE and tracer filaments



Chlorophyll, South Atlantic, d'Ovidio & al, 2004



Chlorophyll, Pomme area, Lehahn & al, 2008