On the joint use of high resolution tracer images and altimetric data for the control of ocean circulation.

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December 09, 2013

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CNRS
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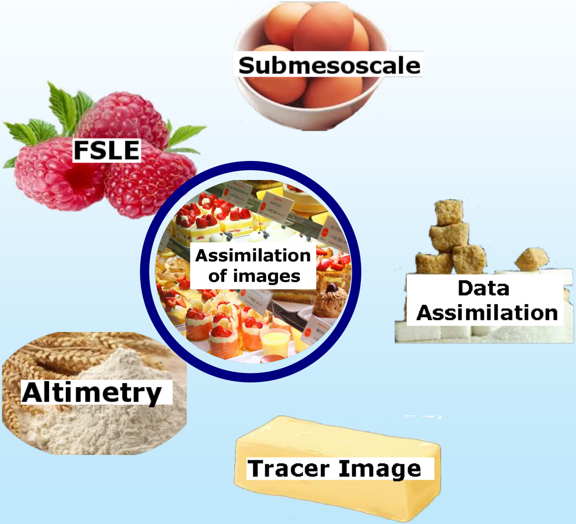
General objective

Benefit from the complementarity and the richness of several remote observations (altimetric and high resolution tracers) to improve the assessment of oceanic circulation.

Data image assimilation strategy

Explore the feasibility of tracer image inversion for the control of surface dynamics.

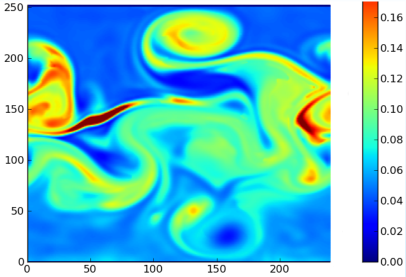
Ingredients



Submesoscale

- Intermediate scale between Mesoscale and dissipative scales.
- Filaments length: 1-10 km.

Sub-mesoscales generated by mesoscale dynamics
To what extend can sub-mesoscales control mesoscales?



Baroclinic instability in an idealized model (Chlorophyll)

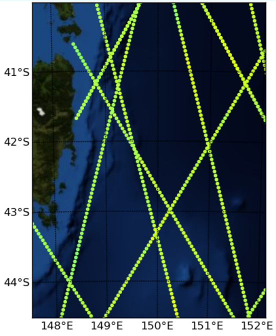
Importance of sub-mesoscales

➢ Impact on larger scale circulation
➢ Energetic importance
(Capet & al, 2008, Thomas & al, 2008, Klein & al, 2008, Ferrari & al, 2008)

Altimetry

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

Use of gridded SSH and velocity: interpolation between tracks



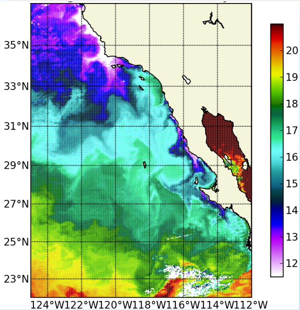
Jason and Envisat tracks (15 days)

➢ 3 satellites are necessary to capture mesoscale signal (Morrow and Le Traon, 2011).
➢ Sub-mesoscales cannot currently be seen by altimetric satellites (Fu and Ferrari, 2008).

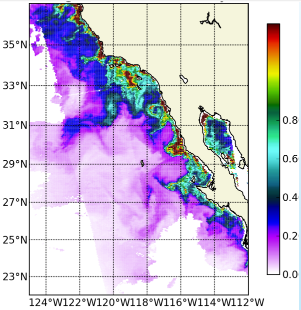
Tracer image

Interested in tracers visible from space

- Sea Surface Temperature (near IR, visible)
- Ocean Color: Chlorophyll (visible)



SST from MODIS sensor
(25-27 April 2011)

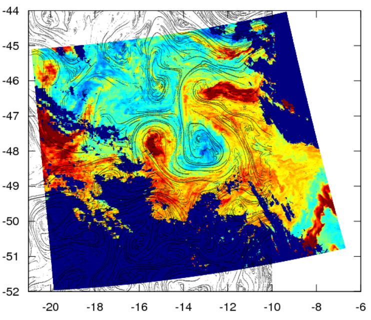


Chlorophyll from MODIS sensor
(25-27 April 2011)

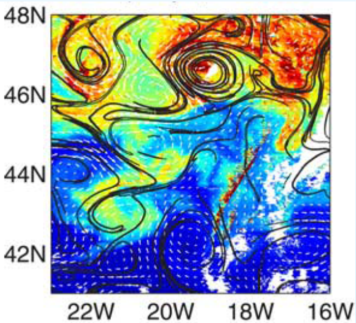
Sub-mesoscales filaments revealed by tracer images

FSLE: Finite-Size Lyapunov Exponents

Lagrangian tool that gives a measure of ocean stirring
Tracer observation and FSLE derived from altimetric velocity have shown similar patterns (Lehahn & al 2008, d'Ovidio & al 2004).



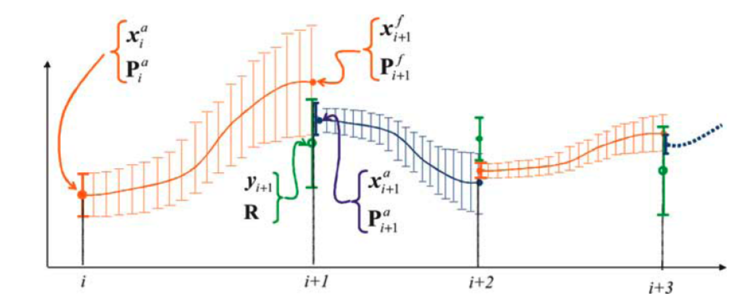
Chlorophyll, South Atlantic, d'Ovidio & al, 2004



Chlorophyll, Pomme area, Lehahn & al, 2008

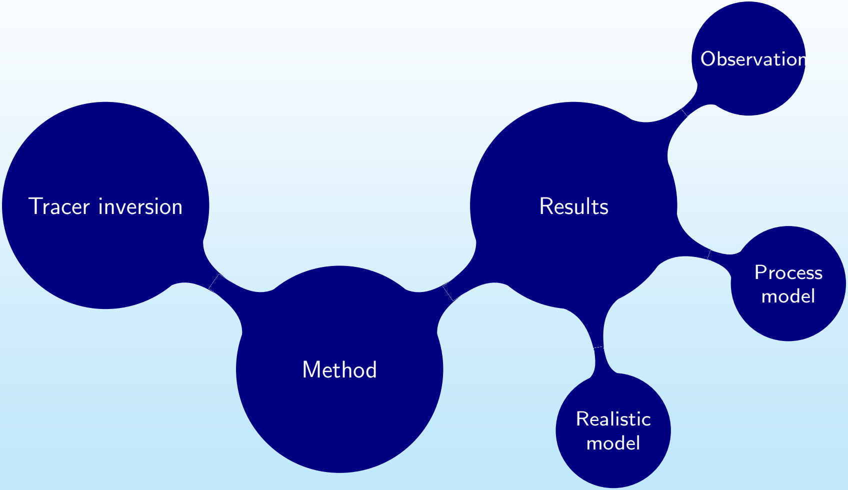
Data assimilation

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.

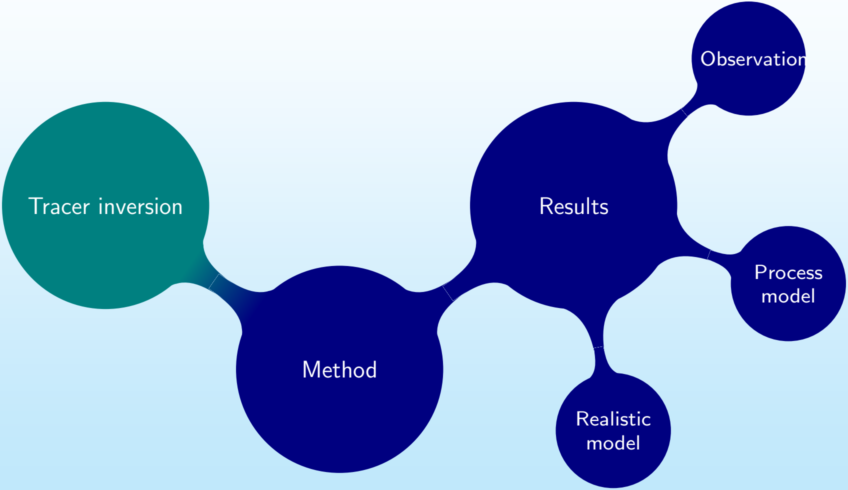


Conceptual representation of filtering with sequential assimilation, Brasseur, 2006

Path


Observation
Tracer inversion
Results
Process model
Method
Realistic model

Path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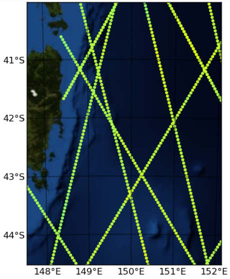
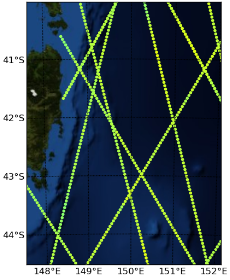
Complementarity of remote sensing



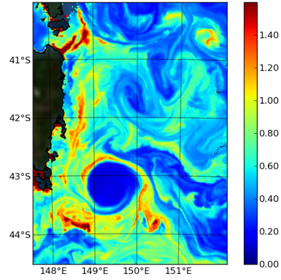
Jason and Envisat tracks, 15 days before and after December 22, 2004, Tasmania

Sub-mesoscales are not resolved by altimetry.

Complementarity of remote sensing



Jason and Envisat tracks, 15 days before and after December 22, 2004, Tasmania



Chlorophyll, December 22, 2004, Tasmania

Sub-mesoscales are not resolved by altimetry.

Sub-mesoscales are observed using satellite tracer sensors.

Joint use of altimetry and high resolution tracer observation to improve the dynamics.

Future observation

Project SWOT

- High resolution SSH image
- Detect small scale structure

Geostationary color

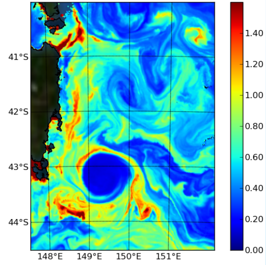
- Frequent and high resolution chlorophyll images
- Study of structures and biogeochemics

Complex observations
$\Rightarrow$ Interest in structure of data

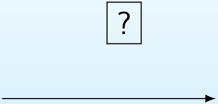
Context of the inversion

Feasibility of data image assimilation

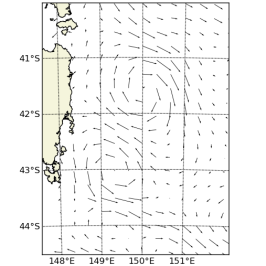
Inversion: fixed time assimilation



Chlorophyll image



Tasmania region, December 22, 2004

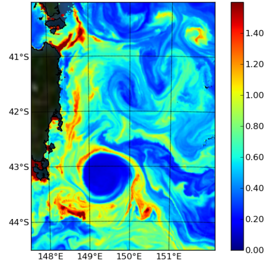


Velocity map

Context of the inversion

Feasibility of data image assimilation

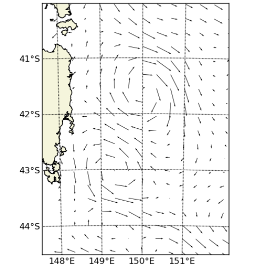
Inversion: fixed time assimilation



Chlorophyll image

?

Tasmania region, December 22, 2004

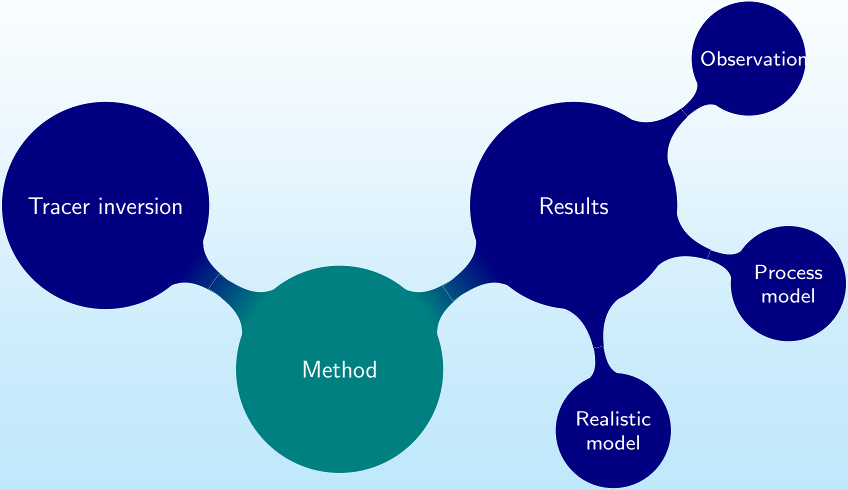


Velocity map

Use of a Data Assimilation approach

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

Path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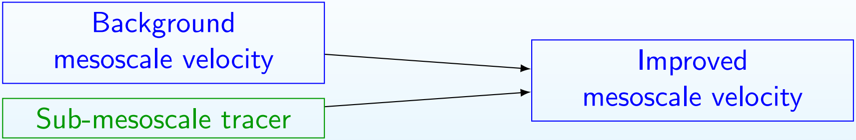
Need of a proxy

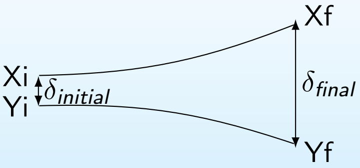


Find the correction of this background the most compatible with tracer information

- 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)

See Gaultier & al, 2012 for details

Physical meaning of Lyapunov Exponents



FSLE

$\lambda = \frac{1}{T} \times log(\frac{\delta_{final}}{\delta_{initial}})$

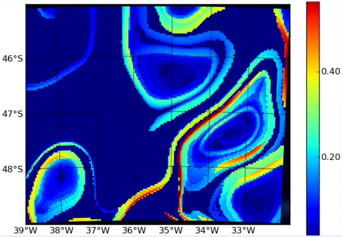
Inverse of the time T for particles to be separated from $\delta_{initial}$ to δ_{final}

Lyapunov Exponent constitute Lagrangian transport barriers between different regions

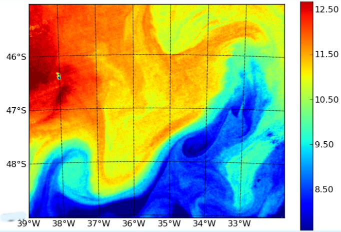
FSLE measures the separation rate of particles

Tracer cannot cross lines of maximum of FSLE

Proxy FSLE consistent



FSLE, South Atlantic region, December 27, 2006

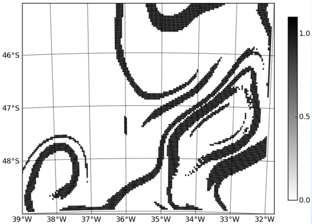


Tracer (SST), South Atlantic region, December 27, 2006

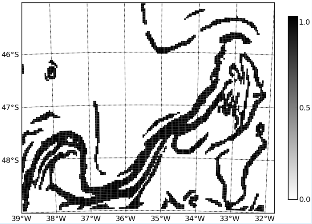
Lyapunov measures stirring in a fluid
→ Link between sub-mesoscale dynamics and biologic stirring.
(Lehahn & al, 2008, d'Ovidio & al, 2004)

- Binarisation of FSLE
- Binarisation of the norm of the gradient of tracer filtered image, image processing to reduce the noise (developed by LJK)

Proxy FSLE consistent



FSLE, South Atlantic region, December 27, 2006



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Overview of the method

Observation → Image

Sub-mesoscale tracer

MODIS observation of Sea Surface Temperature and/or Chlorophyll → Image of tracer filaments I_{tracer}

Dynamics

Sea Surface Height from Altimetry → Corresponding geostrophic velocity $\vec{u}$ → Image of FSLE $I_{FSLE}(\vec{u})$

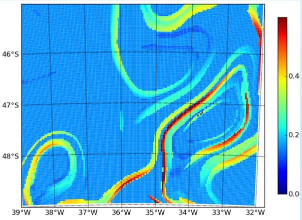
COST FUNCTION: $J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{tracer}\| + \mu\|\vec{u} - \vec{u}_{alt}\|$

Cost function

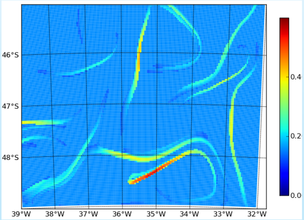
- Cost function:

$$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{tracer}\| + \mu\|\vec{u} - \vec{u}_{alt}\|$$

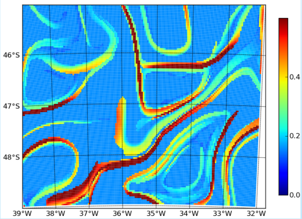
The cost function is strongly non linear, non differentiable, with many local minima.



$FSLE(\vec{u})$



$FSLE(\vec{\delta}_u)$



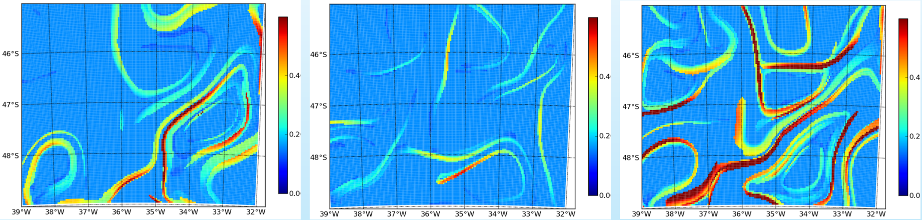
$FSLE(\vec{u} + \vec{\delta}_u)$

Cost function

- Cost function:

$$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{tracer}\| + \mu\|\vec{u} - \vec{u}_{alt}\|$$

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



$FSLE(\vec{u})$ $FSLE(\vec{\delta}_u)$ $FSLE(\vec{u} + \vec{\delta}_u)$

Minimize cost function using known and new methods

Build a subspace of error

Inspired by SEEK filter

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

Velocity panel using Principal Component Analysis (EOF 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.

Minimize J

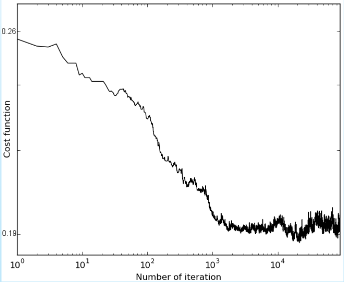
Need to use new methods : OSMIUM tool

Simulated annealing

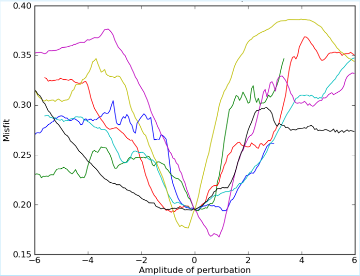
Excite a particle to get out of local minimum

Gibbs' Sampler

Sample potential solution around a minimum

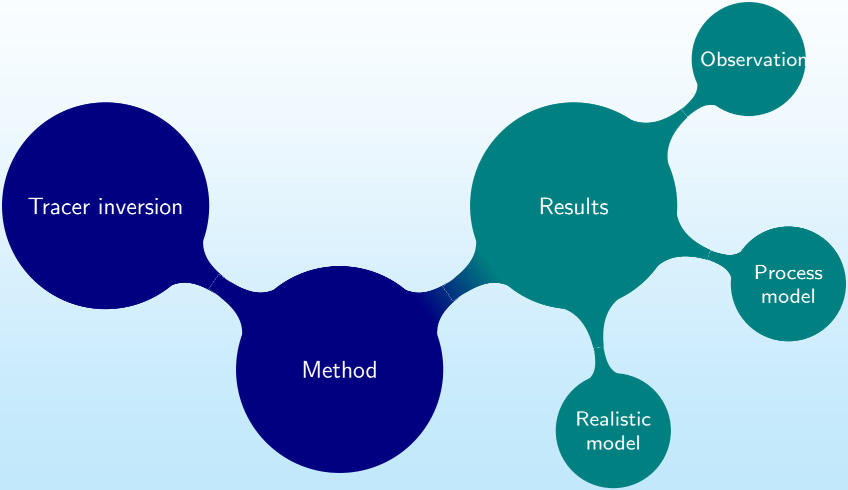


Cost function as a function of the number of iterations



Explore cost function around a solution

Path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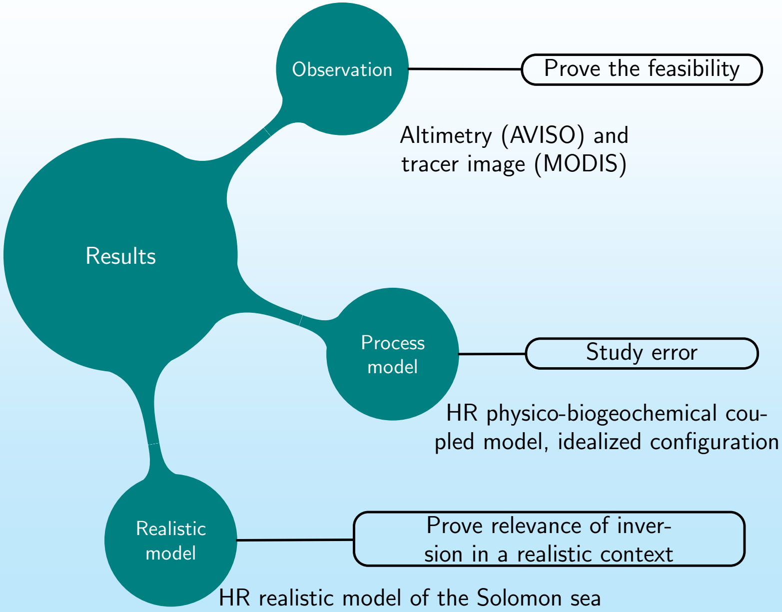
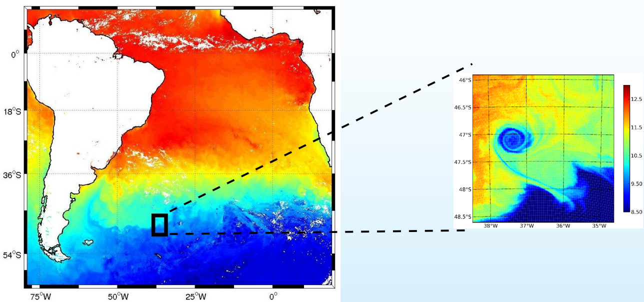
Strategy of the inversion study

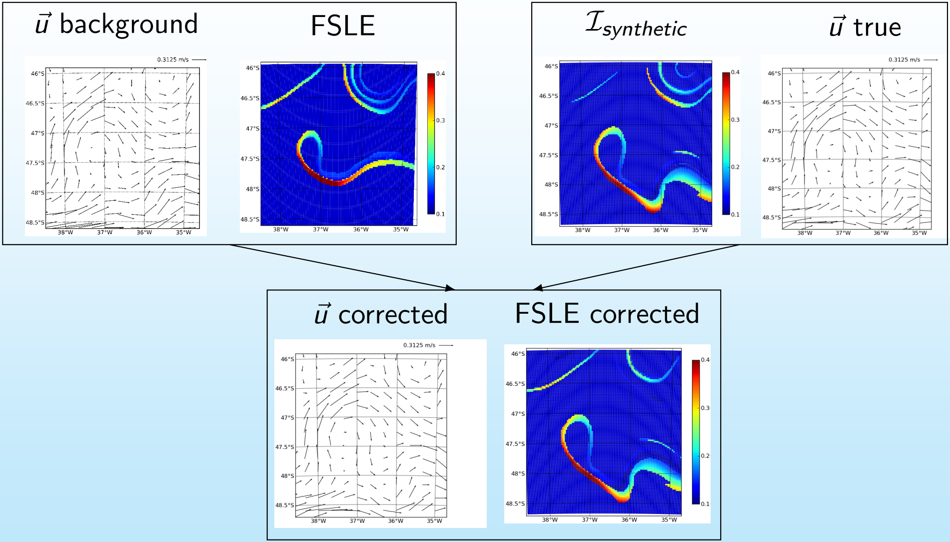


Test case : small area in the South Atlantic ocean



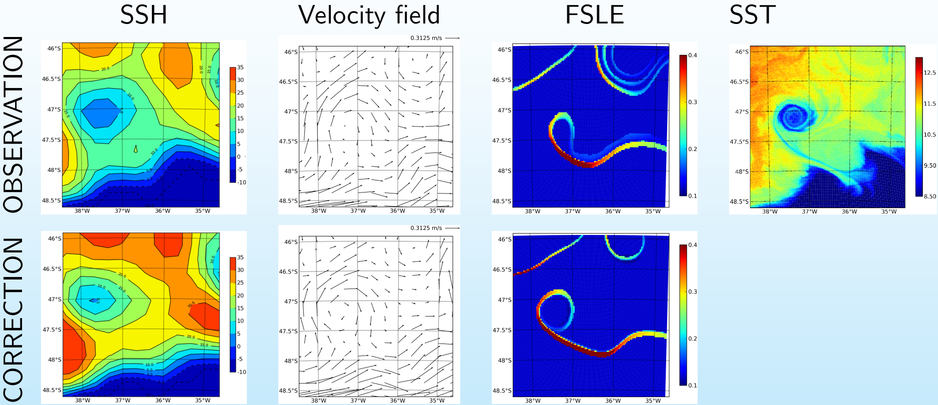
- **Time Range**: from 1998 to June 2009, 595 velocity maps
- **Velocity field**: AVISO, Altimetric data
- **Resolution**: $1/3^o$, grid points : 18*16
- **FSLE Resolution**: $1/50^o$, grid points : 130*120
- **Tracer field**: SST or Chlorophyll data (MODIS sensor, L2 product)

FSLE invertible



$$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{synthetic}\| + \mu\|\vec{u} - \vec{u}_{alt}\|$$

Corrected field



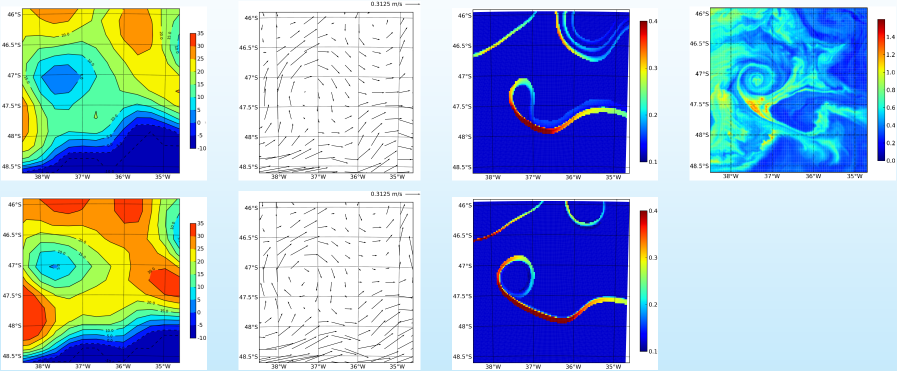
$$J(\vec{u}) = \alpha \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{SST}\| + (1-\alpha)\|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{CHL}\| + \mu\|\vec{u} - \vec{u}_{alt}\|$$

Corrected field

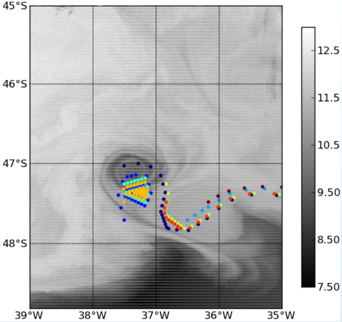
SSH | Velocity field | FSLE | Chlorophyll

OBSERVATION

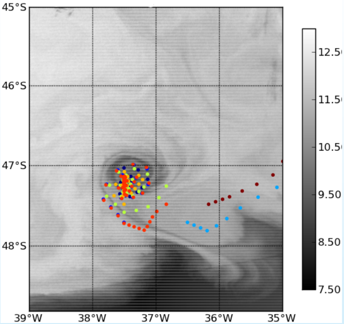
CORRECTION



$$J(\vec{u}) = \alpha \| \mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{SST} \| + (1-\alpha) \| \mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{CHL} \| + \mu \| \vec{u} - \vec{u}_{alt} \|$$



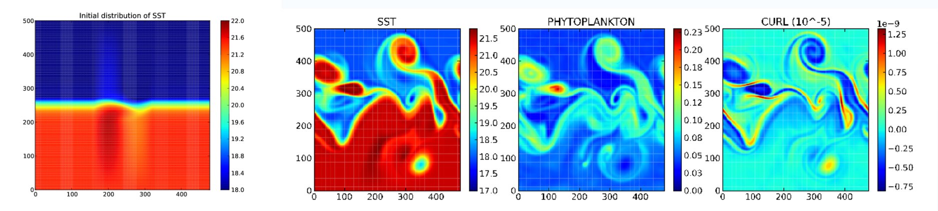
Lagrangian trajectories from the altimetric velocity field



Lagrangian trajectories from the velocity field corrected using tracers

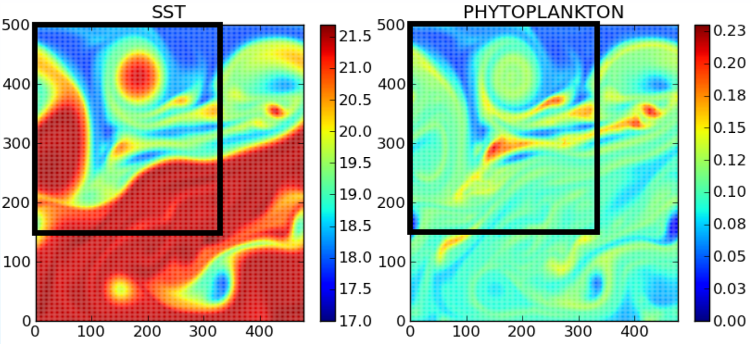
- The trajectory of six particles are represented over the SST
- These trajectories are similar to the filaments observed in SST

High Resolution coupled physico-biogeochemical model



Model configuration: Levy, 2002

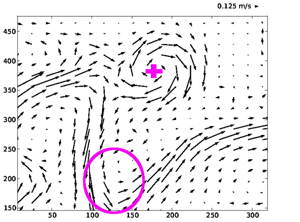
- NEMO dynamics coupled with LOBSTER biochemical model
- Channel domain: $478 \times 500 \times 4$ km ($240 \times 252 \times 30$ grid points)
- Horizontal resolution: 2 km
- Sub-mesoscale and mesoscale structures result from an unstable baroclinic jet



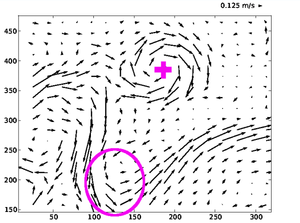
Inversion parameters

- Time range: 90 states of the model before the study date
- Background velocity: Velocity 5 days after the study date
- Corresponding FSLE: 2 km resolution
- Tracer Image: Chlorophyll and/or Sea Surface Temperature image of the study date at 2 km resolution

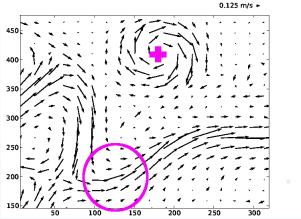
$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{CHL}\| + bg$



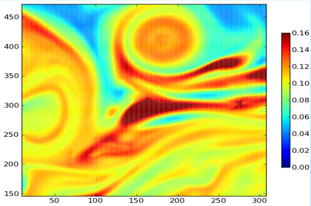
Background velocity



Corrected velocity

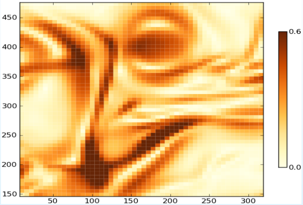


True velocity

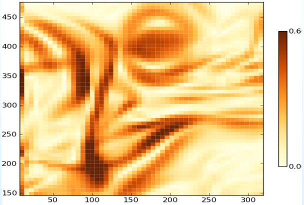


Chlorophyll

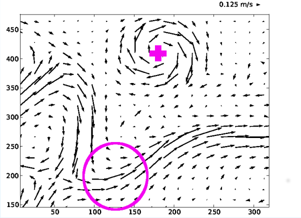
$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{CHL}\| + bg$



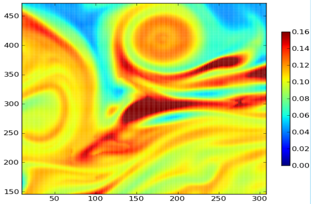
$||\vec{u}_{background} - \vec{u}_{true}||$



$||\vec{u}_{corrected} - \vec{u}_{true}||$



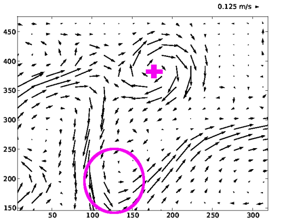
True velocity



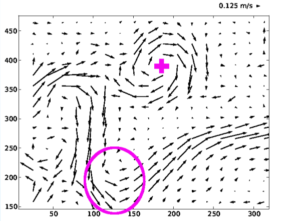
Chlorophyll

$\simeq$ 20% of the error on the background velocity is corrected.

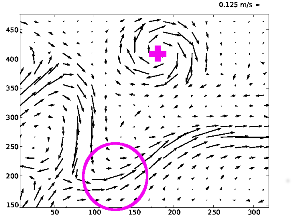
$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{SST}\| + bg$



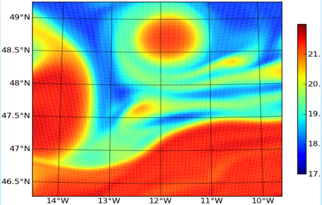
Background velocity



Corrected velocity

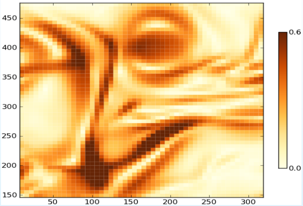


True velocity

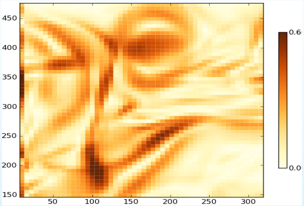


SST

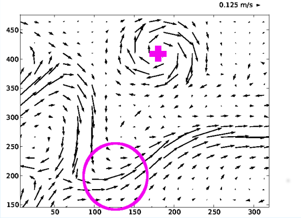
$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{SST}\| + bg$



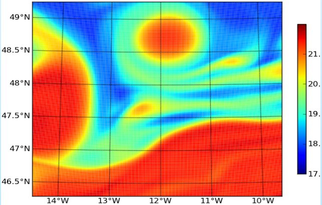
$||\vec{u}_{background} - \vec{u}_{true}||$



$||\vec{u}_{corrected} - \vec{u}_{true}||$



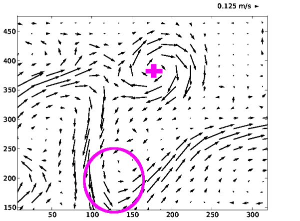
True velocity



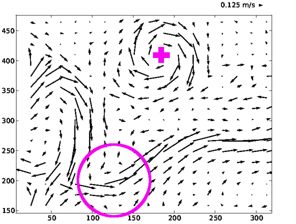
SST

$\simeq$ 45% of the error on the background velocity is corrected.

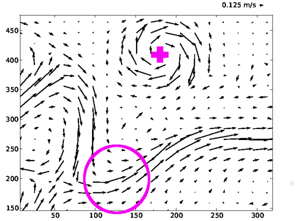
$$J(\vec{u}) = \alpha\|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{SST}\| + (1-\alpha)\|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{CHL}\| + bg$$



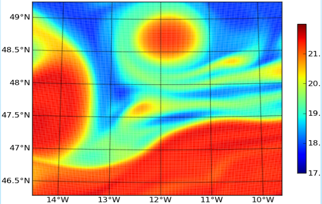
Background velocity



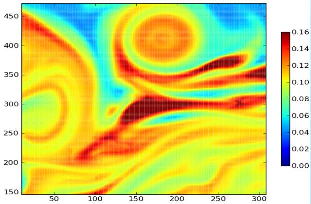
Corrected velocity



True velocity

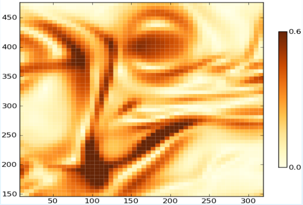


SST

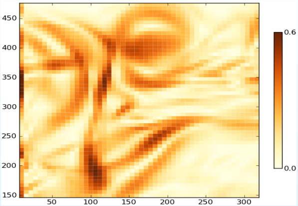


Chlorophyll

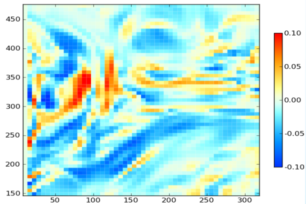
$$J(\vec{u}) = \alpha \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{SST}\| + (1-\alpha)\|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{CHL}\| + bg$$



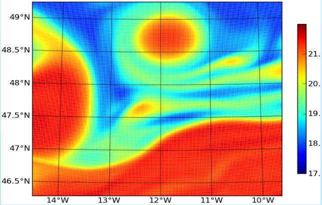
$||\vec{u}_{background} - \vec{u}_{true}||$



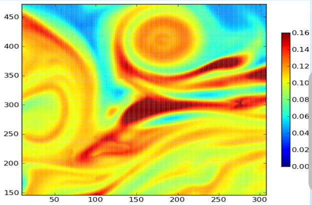
$||\vec{u}_{corrected} - \vec{u}_{true}||$



Chlorophyll contribution



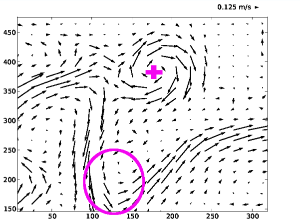
SST



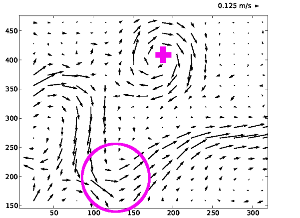
Chlorophyll

$\simeq$ 48% of the error on the background velocity is corrected

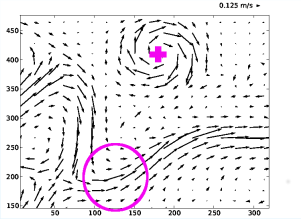
$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{struct}\| + bg$



Background velocity



Corrected velocity



True velocity

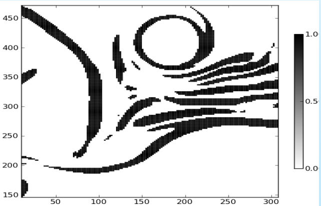
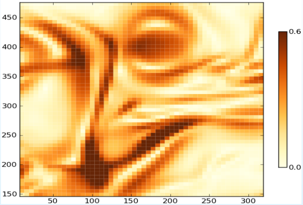
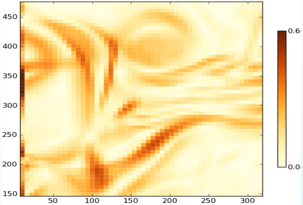


Image "structure"

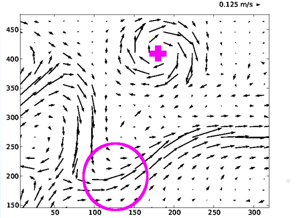
$J(\vec{u}) = \|\mathcal{I}_{FSLE}(\vec{u}) - \mathcal{I}_{struct}\| + bg$



$||\vec{u}_{background} - \vec{u}_{true}||$



$||\vec{u}_{corrected} - \vec{u}_{true}||$



True velocity

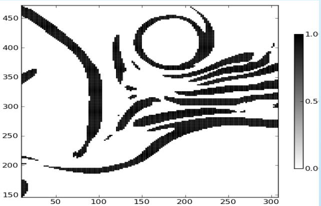
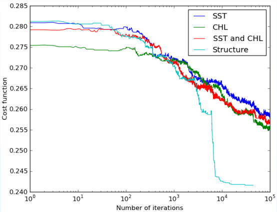


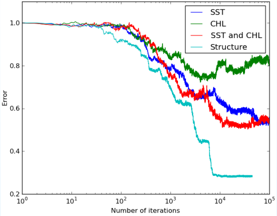
Image "structure"

$\simeq$ 72% of the error on the background velocity is corrected using the 'structure' image.
More information to be extracted from tracer structure.

Tracer contribution



Cost function as a function of iterations (semi-log)



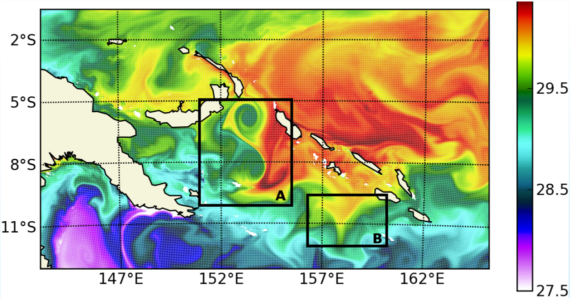
Error on the velocity as a function of iterations (semi-log)

Good Results even if the image processing is rough

- SST filaments are easier to detect and to use to correct dynamical fields
- Chlorophyll filaments help the convergence
- Merging SST and Chlorophyll enables us to detect structure from the dynamics only

Improving the image processing may improve the estimation of the velocity

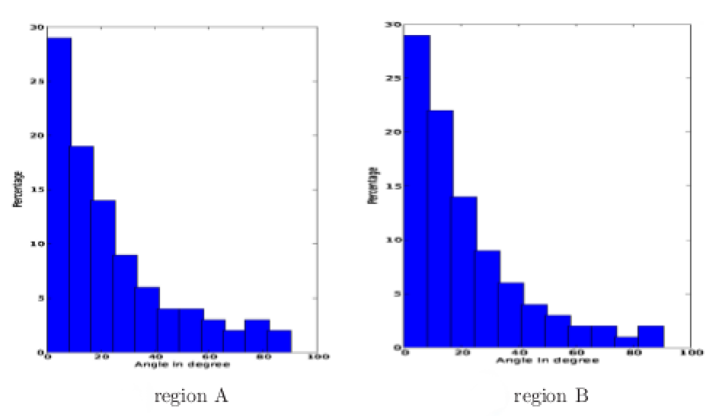
Realistic model of the Solomon sea



High Resolution realistic model of the Solomon Sea (Nathacha Djath)

- Dynamics : NEMO-OPA code, sub-mesoscale permitting
- Horizontal resolution : $\frac{1}{36}^{o}$
- Vertical resolution : 46 levels
- Forcing : ERA-INTERIM
- Time range : 1989-2006

Similarity FSLE-tracer



Angle between FSLE and SST, histogram

- ➢Similar histograms for other days
- ➢Similar histogram for SSS and SPICE

Inversion parameters

Sub-space of error

High-resolution model very turbulent: hard to build a consistent error sub-space.

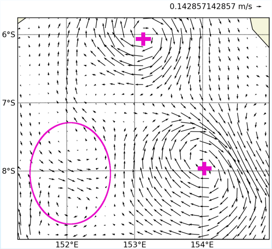
In the following, the sub-space is idealized.

➢ 50 data from the model preceding the chosen study date.

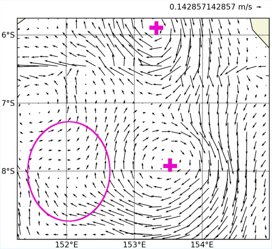
Inversion parameters

- Sub-space of error: EOF analyses on the variation of the model between 5 days
- Background velocity: Velocity 5 days after the study date
- Tracer Image: Sea Surface Salinity and/or Sea Surface Temperature image

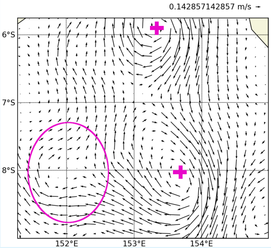
area A



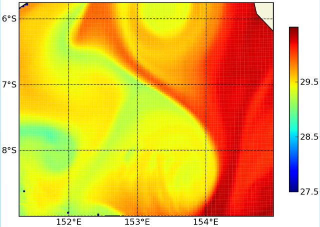
Background velocity



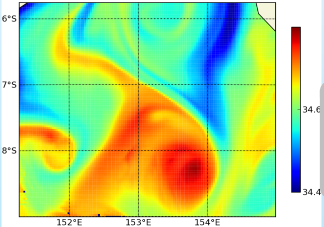
Corrected velocity



True velocity



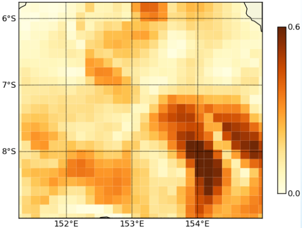
SST



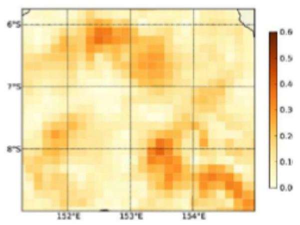
SSS

$\simeq$ 50% of the background error is corrected

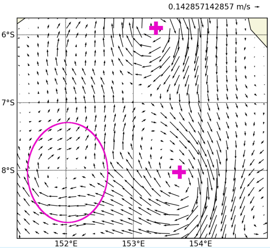
area A



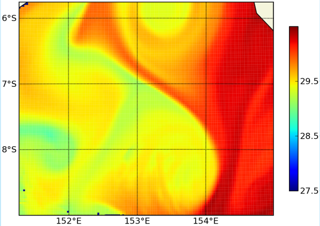
$||\vec{u}_{background} - \vec{u}_{true}||$



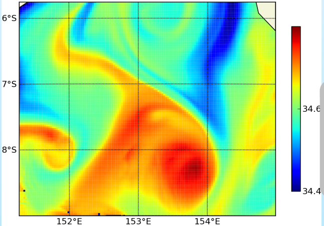
$||\vec{u}_{corrected} - \vec{u}_{true}||$



True velocity



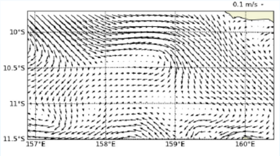
SST



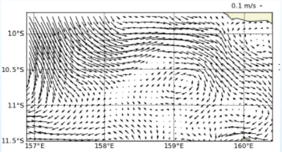
SSS

$\simeq$ 50% of the background error is corrected

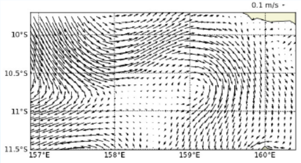
area B



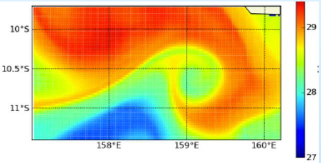
Background velocity



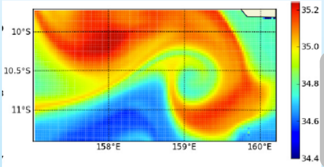
Corrected velocity



True velocity



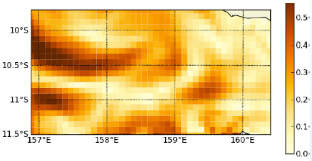
SST



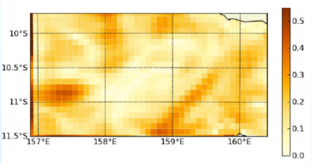
SSS

$\simeq$ 50% of the background error is corrected

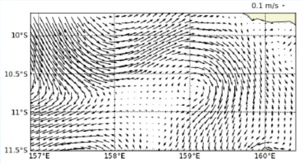
area B



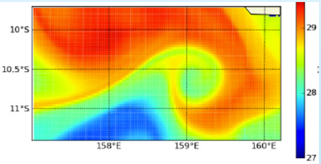
$||\vec{u}_{background} - \vec{u}_{true}||$



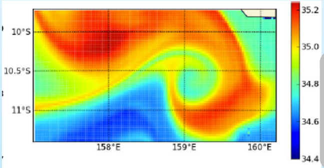
$||\vec{u}_{corrected} - \vec{u}_{true}||$



True velocity



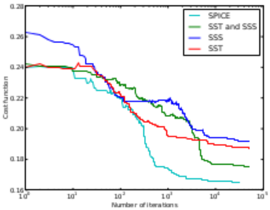
SST



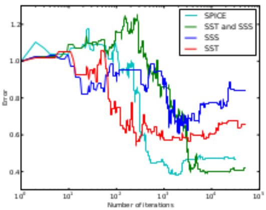
SSS

$\simeq$ 50% of the background error is corrected

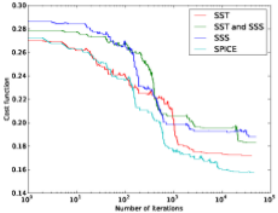
Cost function



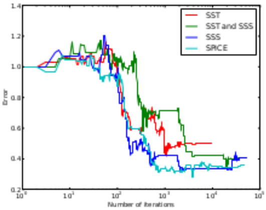
Cost function (area A)



Error on the estimate (area A)



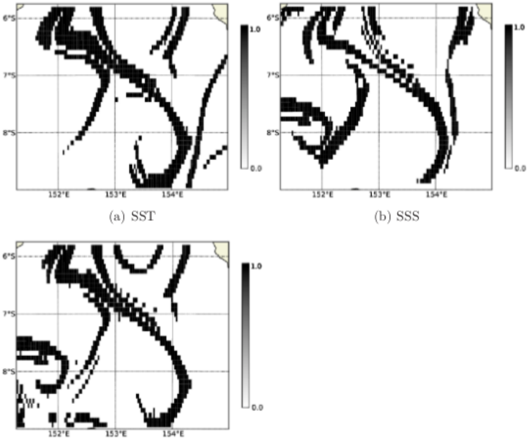
Cost function (area B)



Error on the estimate (area B)

➢area A: tracers are complementary
➢area B: one tracer is sufficient

Norm of the remaining error, area A



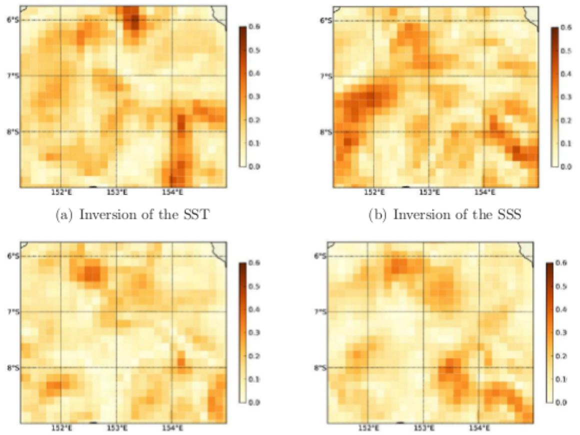
(a) SST

(b) SSS

(c) SPICE

- ➢ Information on dynamics reaveled by SST, SSS and SPICE differ
- ➢ Inversion of spiciness filaments give the best result

Norm of the remaining error, area A



(a) Inversion of the SST

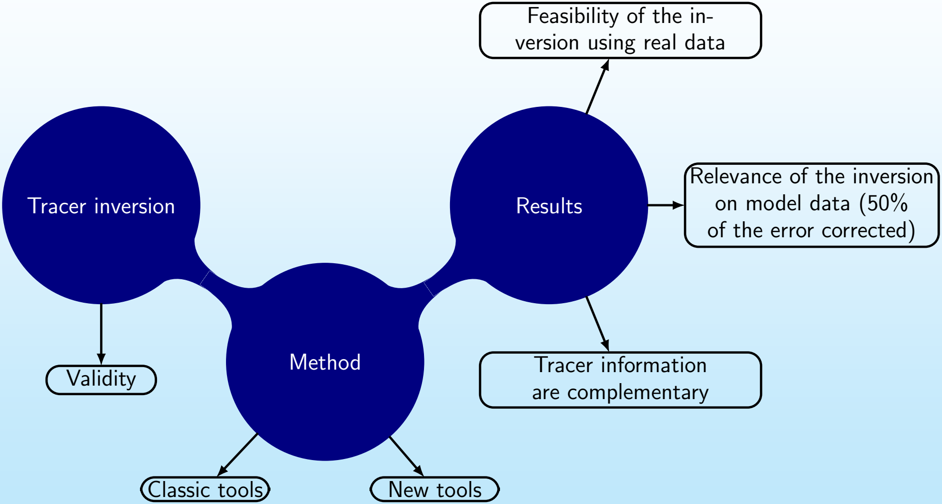
(b) Inversion of the SSS

(c) Inversion of the SPICE

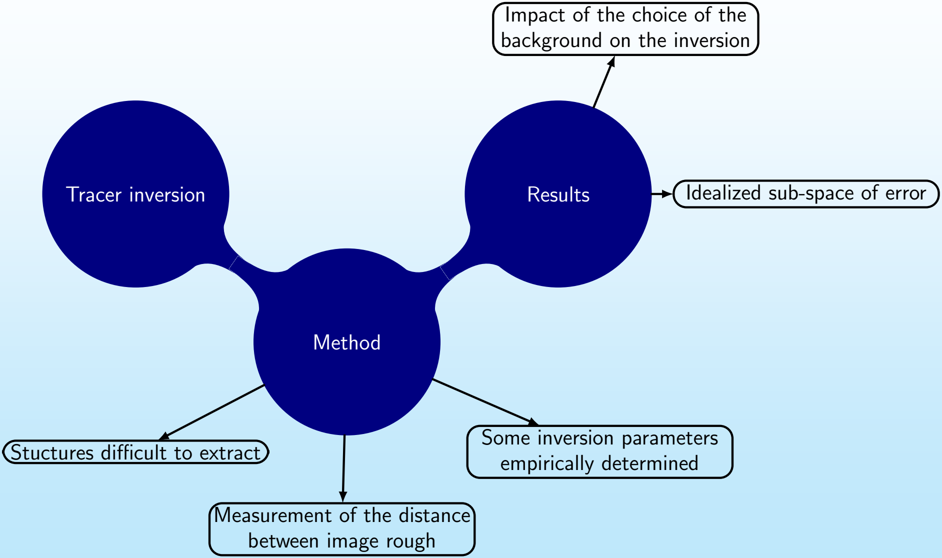
(d) Inversion of the SST and SSS

- ➢ Information on dynamics reaveled by SST, SSS and SPICE differ
- ➢ Inversion of spiciness filaments give the best result

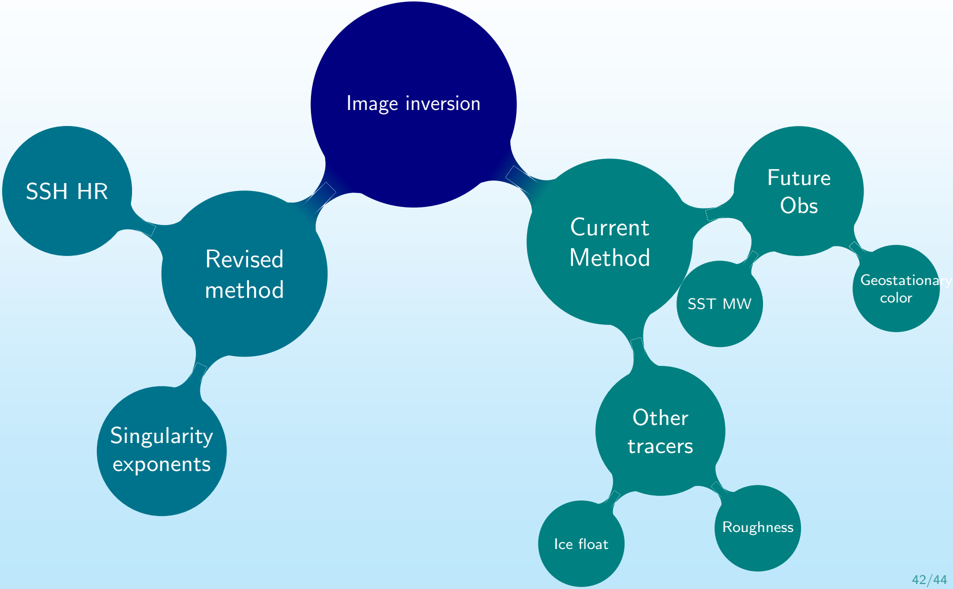
Conclusions



Limits


Impact of the choice of the background on the inversion
Tracer inversion
Results
Idealized sub-space of error
Method
Stuctures difficult to extract
Some inversion parameters empirically determined
Measurement of the distance between image rough

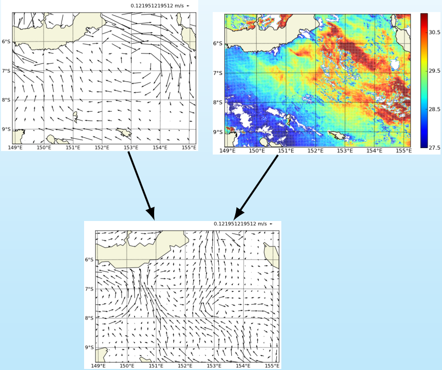
Richness of future image observation



Data image assimilation

Growing of complexities in model and observation

- Increase of non-linear effects
- Non Gaussian statistics



Data assimilation in a high resolution model

➢ At large scale, altimetry can control dynamics in the ocean.
➢ At small scales, using tracer images to control complex structures.

Thank you for your attention