# Submesoscale observations in support of satellite altimetry:
## results and perspectives in the Gulf of Lion

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IRD Institut de recherche pour le développement

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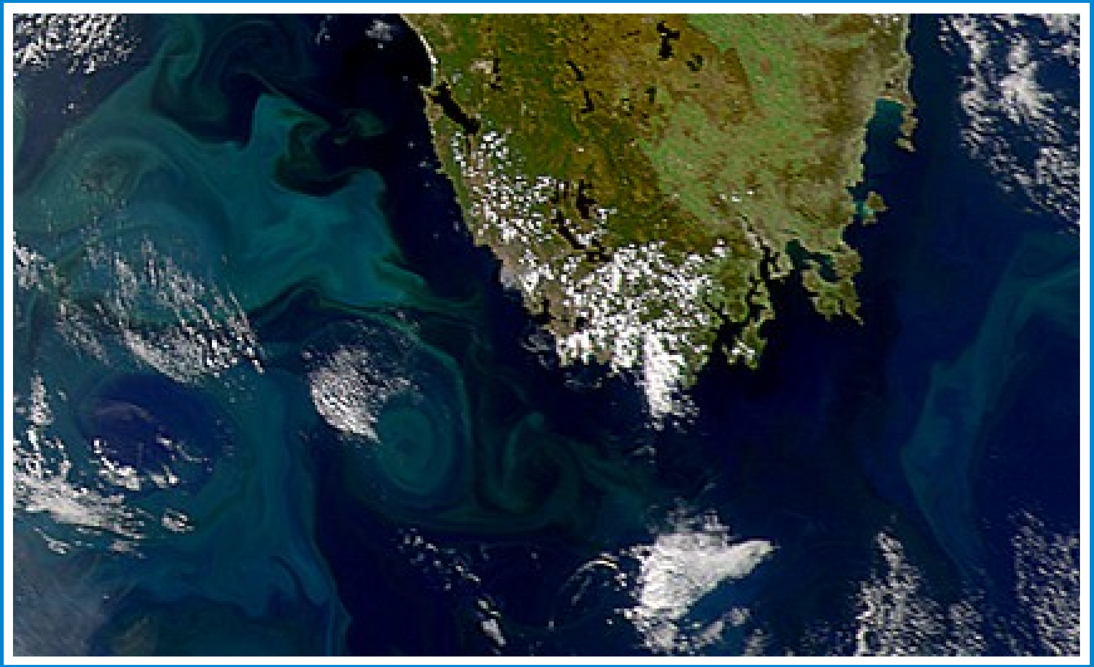
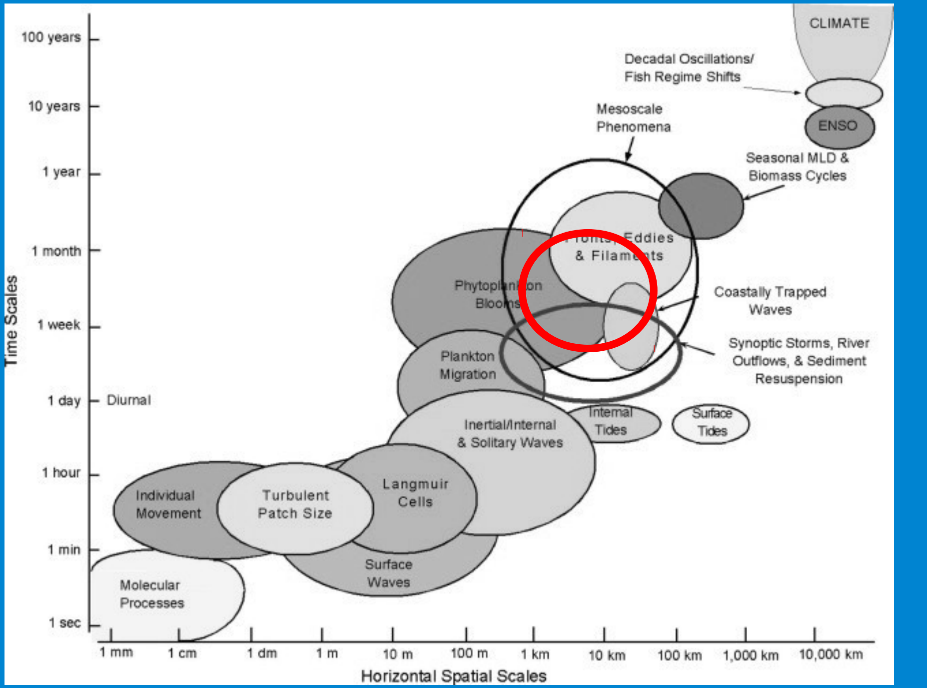
# Submesoscale structures



(from http://oceanservice.noaa.gov/)



(Dickey et al., 2003)

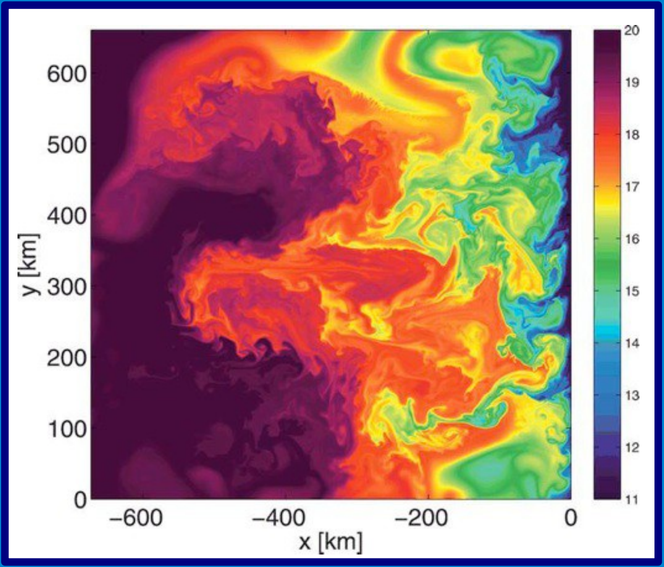
**Fronts, jets and eddies:**

- ➔ Horizontal scales ~(100m – 10km)
- ➔ Time scales ~(days – week)
- ➔ Ageostrophic dynamics

# Numerical models: Physics

- Advancements in computational power
- Development of regional models

➔ Several studies based on numerical models



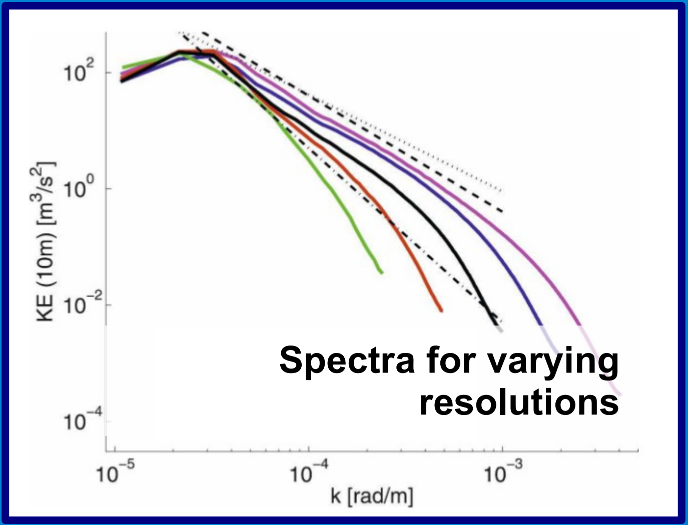
*(Capet et al., 2008)*

Highlighted submesoscale contribution to :

1) Ocean energy budget

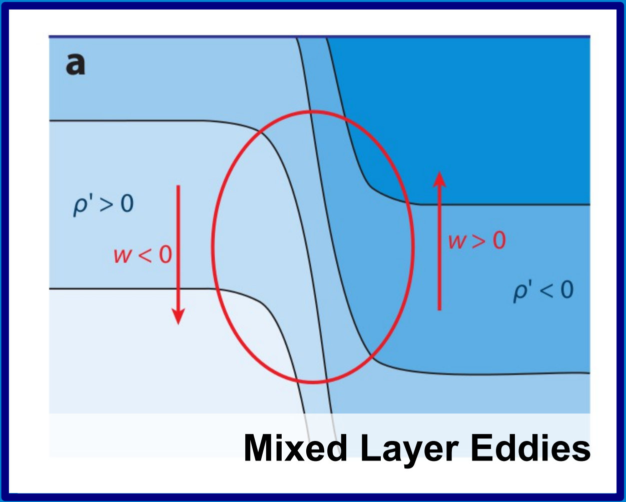
2) Restratification dynamics

3) Vertical velocities



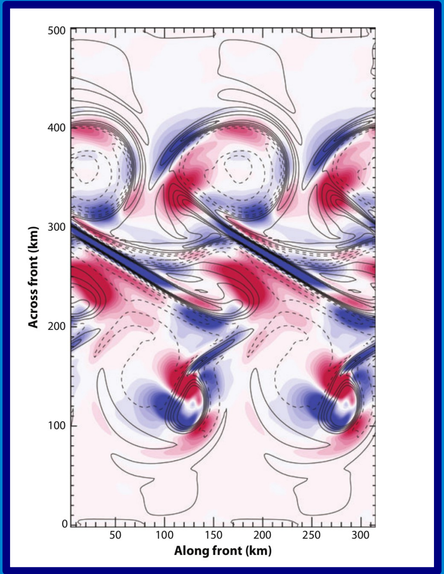
**Spectra for varying resolutions**

*(Capet et al., 2008)*



**Mixed Layer Eddies**

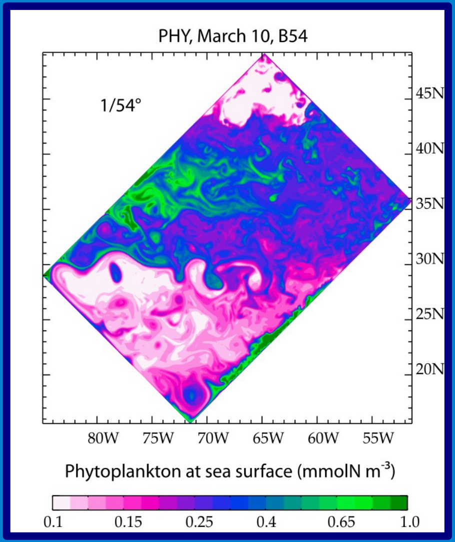
*(Klein and Lapeyre, 2009)*



*(Levy et al., 2001)*

# Numerical models: Biogeochemistry

## Impact of submesoscale dynamics on biogeochemical cycles:



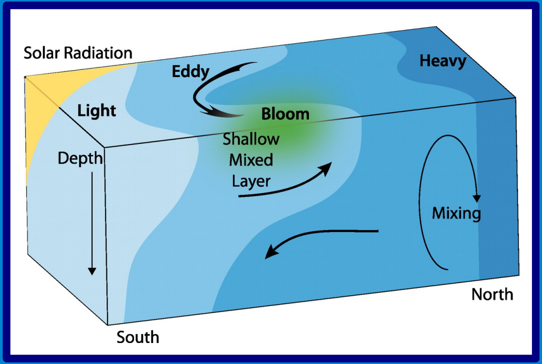
*(Levy et al., 2012)*

➔ **Nutrient inputs**

Mesoscale vs. submesoscale fluxes

Contrasting idealized vs realistic simulations

Net effects still unclear



*(Mahadevan et al., 2012)*

➔ **Primary productivity**

Important role of restratification

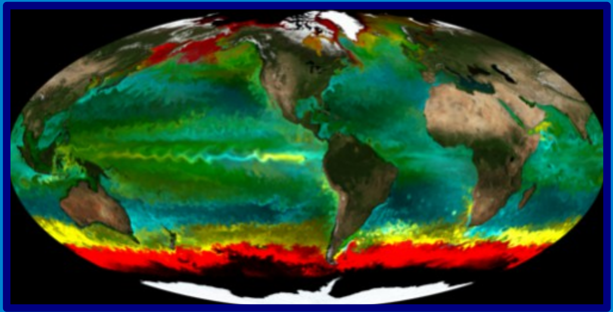
Onset of spring bloom

➔ **Submesoscale biological processes**

Non-linear interactions

Better understand their contribution

Improve parameterization in BOGCM

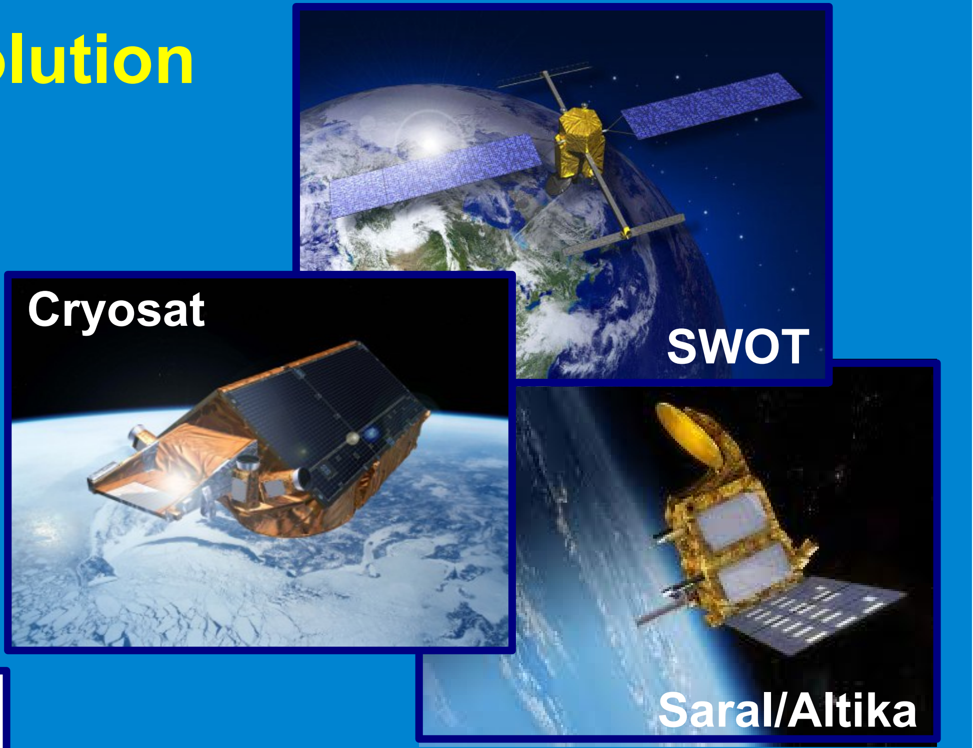


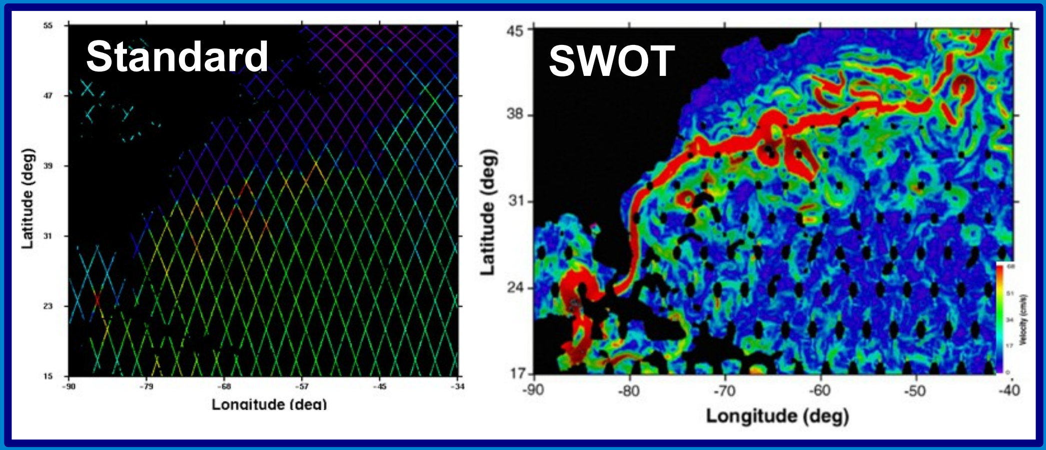
*(http://eaps-www.mit.edu/paoc/research/mick-follows-group)*

# Observations: Remote Sensing

➔ **SSH towards O(1-10 km) resolution**
(analogous to SST and Ocean color)

- **Existing missions (Saral/Altika, Cryosat...)**
- **Future Missions (SWOT, Sentinel 3, Jason-CS...)**





*(from http://smsc.cnes.fr/SWOT/)*

- **Global observations of surface submesoscale**
- **Improved accuracy in coastal regions**

**Need to validate/calibrate the signal**

**Link 2D to 3D dynamics**

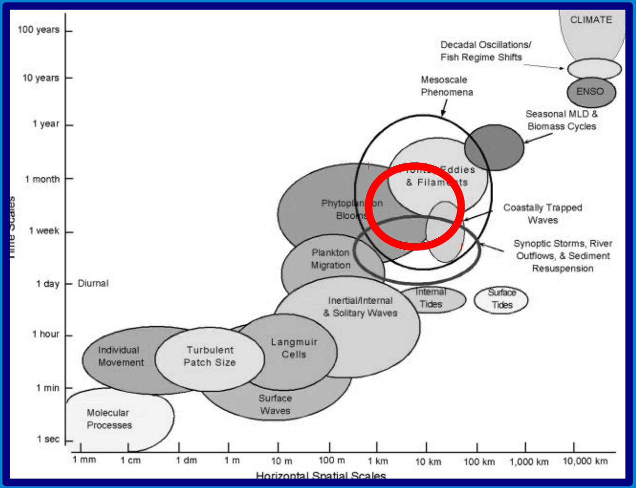
➔

**In-situ observations**

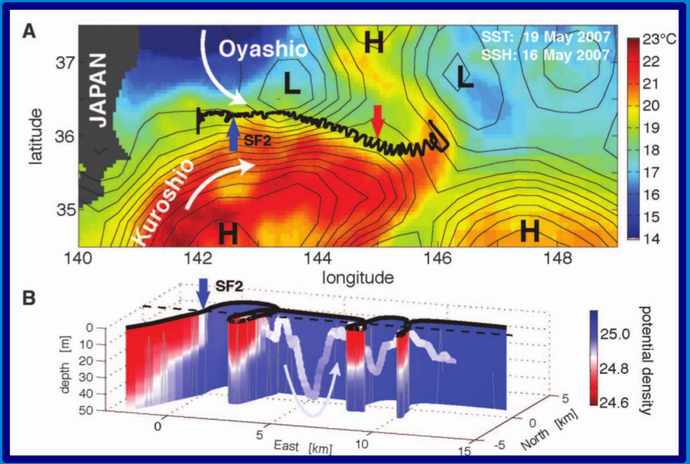
# Observations: In-situ

## Spatial and temporal scales:

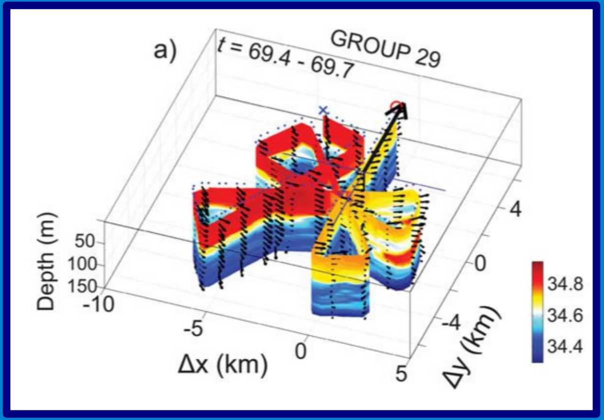
- Submesoscale structures are ephemeral and localized
- Submesoscale activity still a major observational challenge
- Studies based on direct observations still relatively limited but increasing



*(from Dickey et al., 2003)*



*(d'Asaro et al., 2011)*



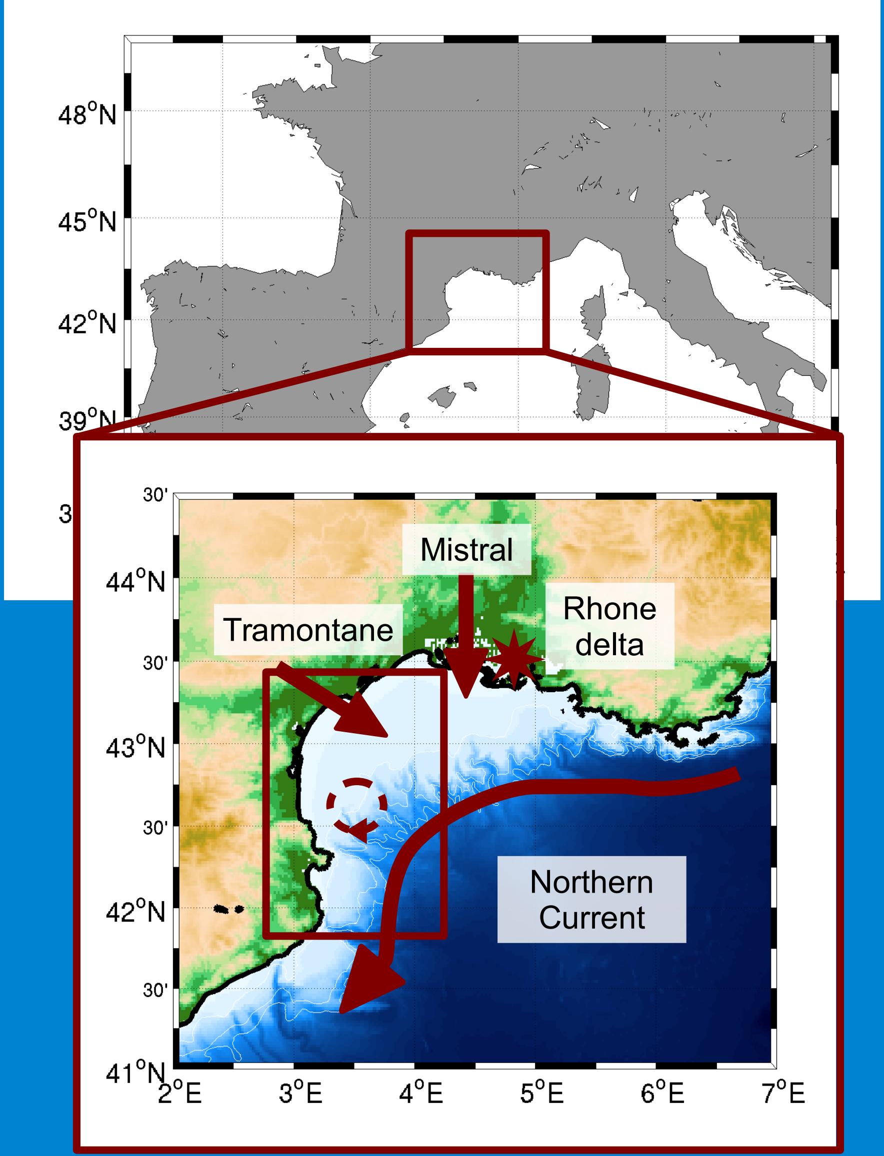
*(Hosegood et al., 2013)*

**Gulf of Lion: Latex10 (1-24 Sep 2010) and SeaGoLSWOT (29 Oct – 10 Nov 2014)**

# Outline

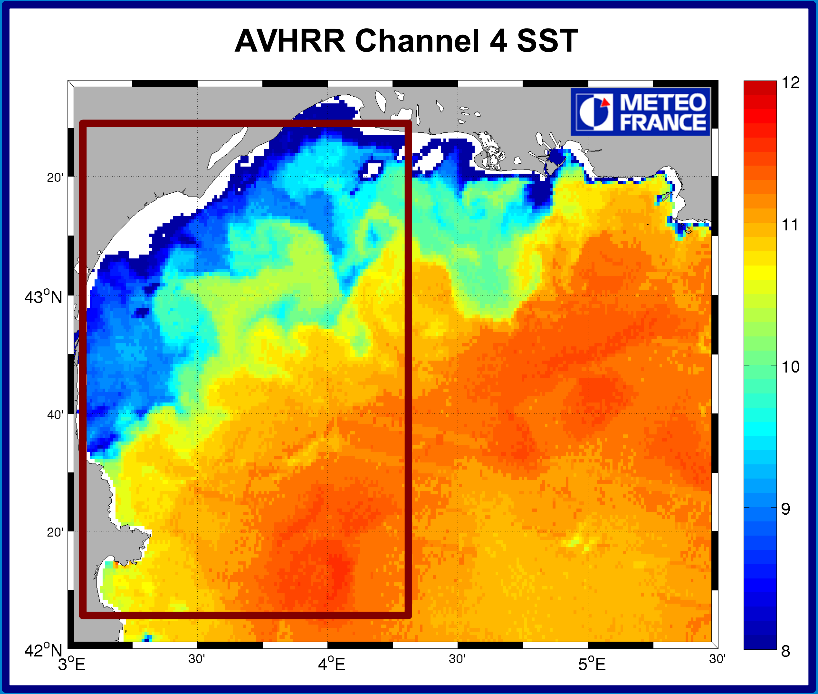
- **Results from Latex10 campaign:**
  1. In-situ Lagrangian Coherent Structures
     ***(in-situ to satellite)***
  2. Quantify horizontal diffusivity across a front
     ***(in-situ to models)***
- **Future perspectives:**
  3. Support to AirSWOT mission in the Gulf of Lion
     ***(SeaGoLSWOT campaign Fall 2014)***
  4. Long-term goal:
     Quantify submesoscale impact on global biogechemical cycles
- **Conclusions**

# The Gulf of Lion



- **Large continental shelf**
- **Three main forcings:**
    - ➔ **Mistral & Tramontane**
    - ➔ **Delta of Rhone river**
    - ➔ **Northern Current**
- **NC dynamical barrier to cross-shelf exchanges**
- **(Sub)mesoscale anticyclones in the western part**

# The Gulf of Lion



- Marked contrast between coastal waters (colder) and NC waters (warmer)
- Weak tidal regime
- Intense (sub)mesoscale activity favored by NC instabilities and strong wind forcing

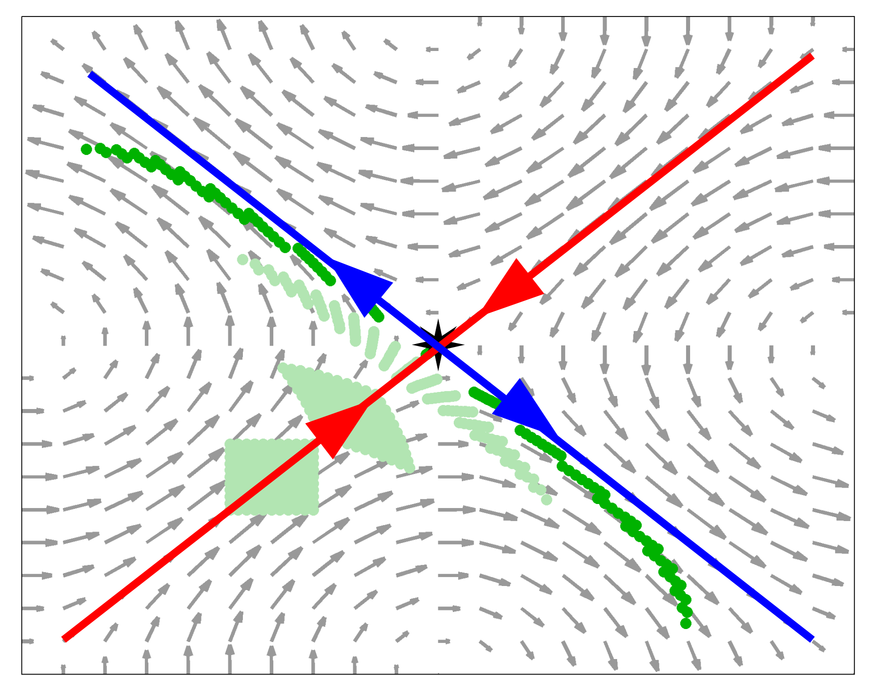
__Lagrangian Transport Experiment__

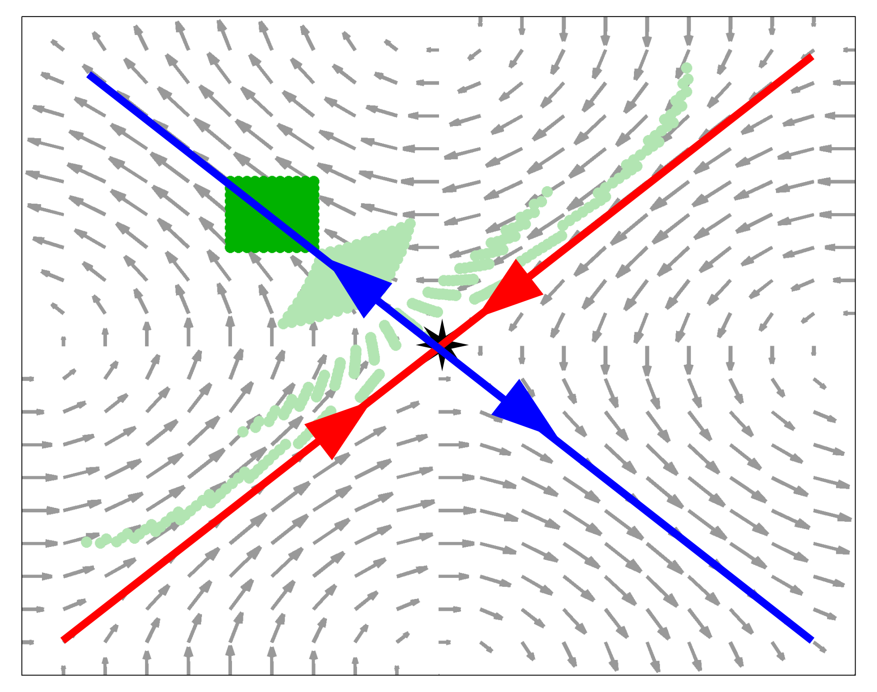
Latex10, September 1-24, 2010

Transport and biogeochemistry in the western part of the GoL

# Lagrangian Coherent Structures

- **Lagrangian Coherent Structures (LCSs) important diagnostic: identification of transport preferential directions and barriers**
- **Example: Particle dispersion around an hyperbolic point**





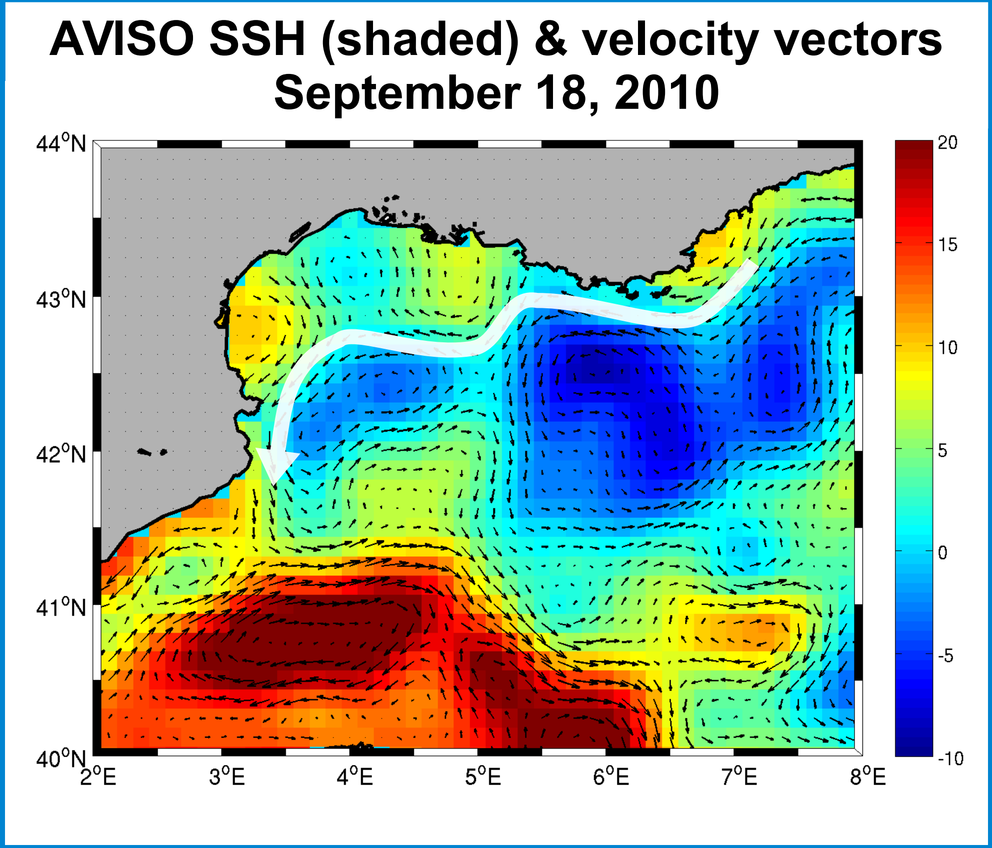
- **Particles move along and spread across converging direction:** <u>**Repelling LCS**</u>
- **Particles align along diverging direction (transport barrier):** <u>**Attracting LCS**</u>

# Altimetry LCSs

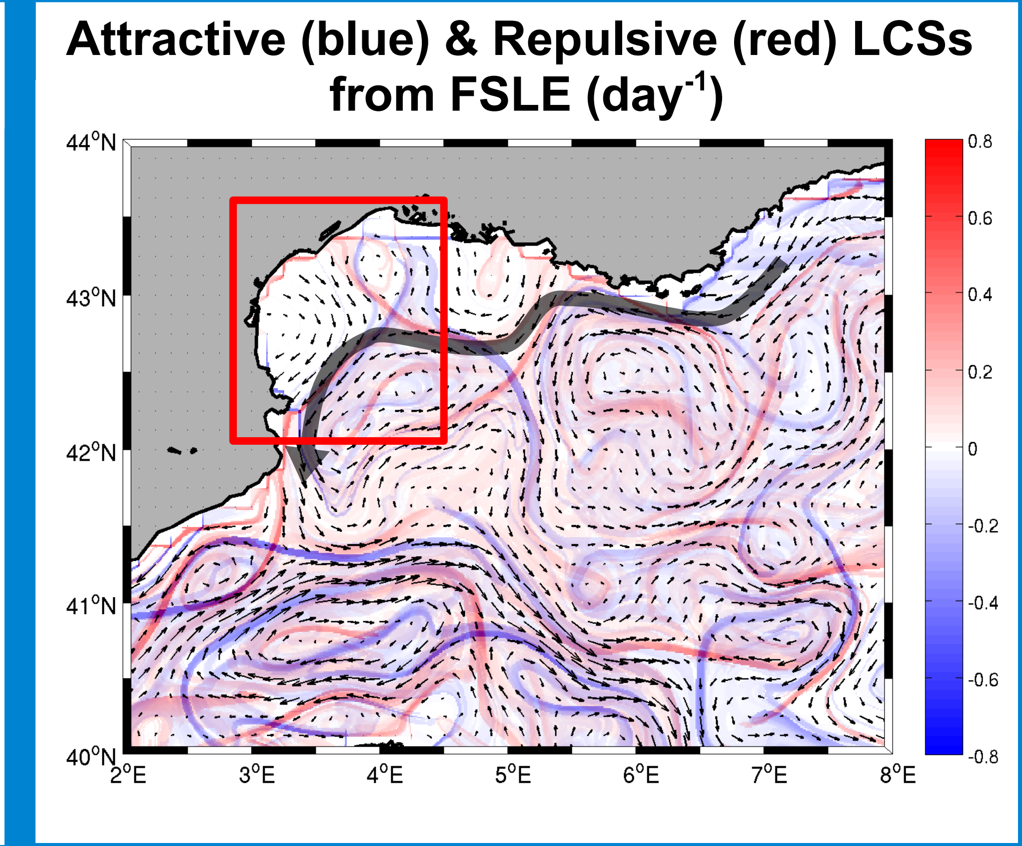
- **Altimetry LCSs from AVISO velocities using Finite-size Lyapunov exponents analysis (FSLE; *d'Ovidio et al., 2004*)**

- **Geostrophic surface velocity fields derived from SSH**

- **1/8 degree, daily**



**AVISO SSH (shaded) & velocity vectors September 18, 2010**



**Attractive (blue) & Repulsive (red) LCSs from FSLE ($day^{-1}$)**

# In-situ LCSs

## Latex10 Adaptive Sampling Strategy for detection of *in-situ* LCSs:

1. Position of large scale LCSs estimated from altimetry derived FSLE

2. *In-situ* deployment of drifters

3. Mapping of *in-situ* velocities (hull mounted ADCP)

## Deployment of 3 drifter arrays:

➔ **Lyap01** (September 12)

➔ **Lyap02** (September 18)

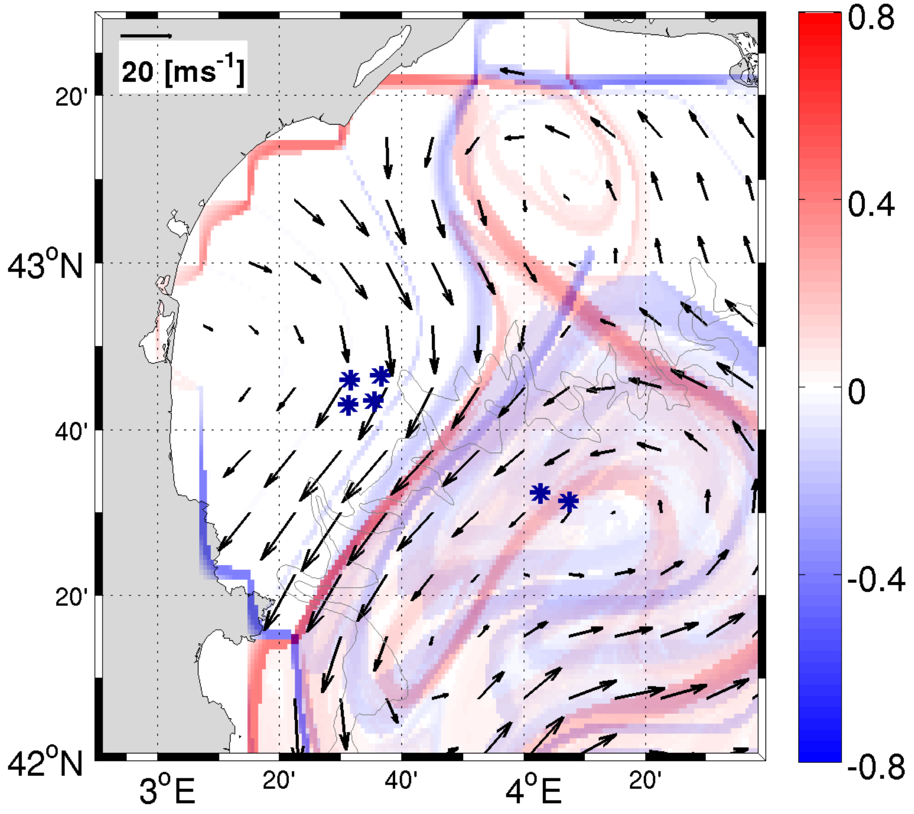
➔ **Lyap03** (September 21)

**LCSs from array dispersion patterns**

# Lyap01 – Sept 12 - 14

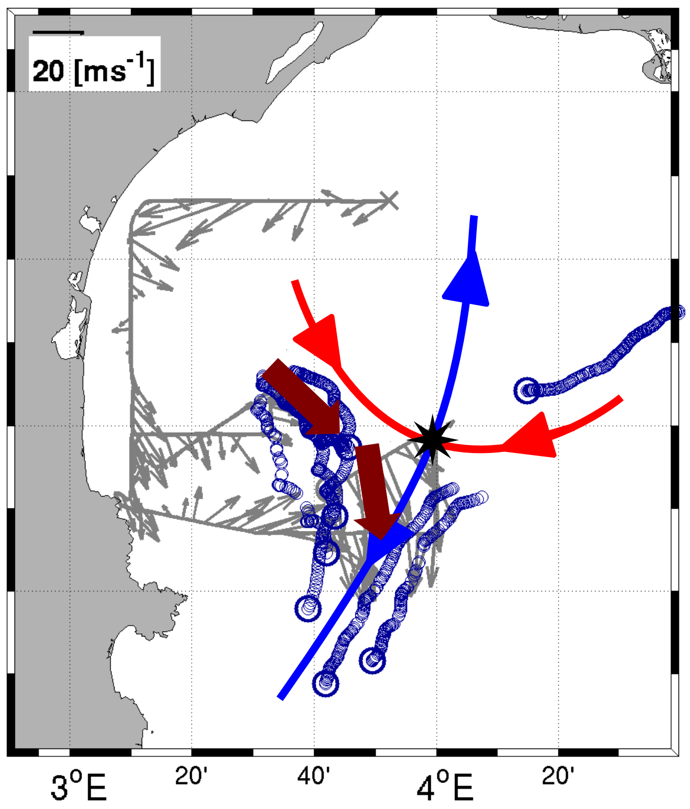
## September 12, 2010

- Altimetry geostrophic velocity vectors
- Attractive (blue) & Repulsive (red) LCSs
- Initial position of drifter array



## September 12-14, 2010

- Drifter trajectories
- *In-situ* LCSs
- 15m ADCP velocity vectors

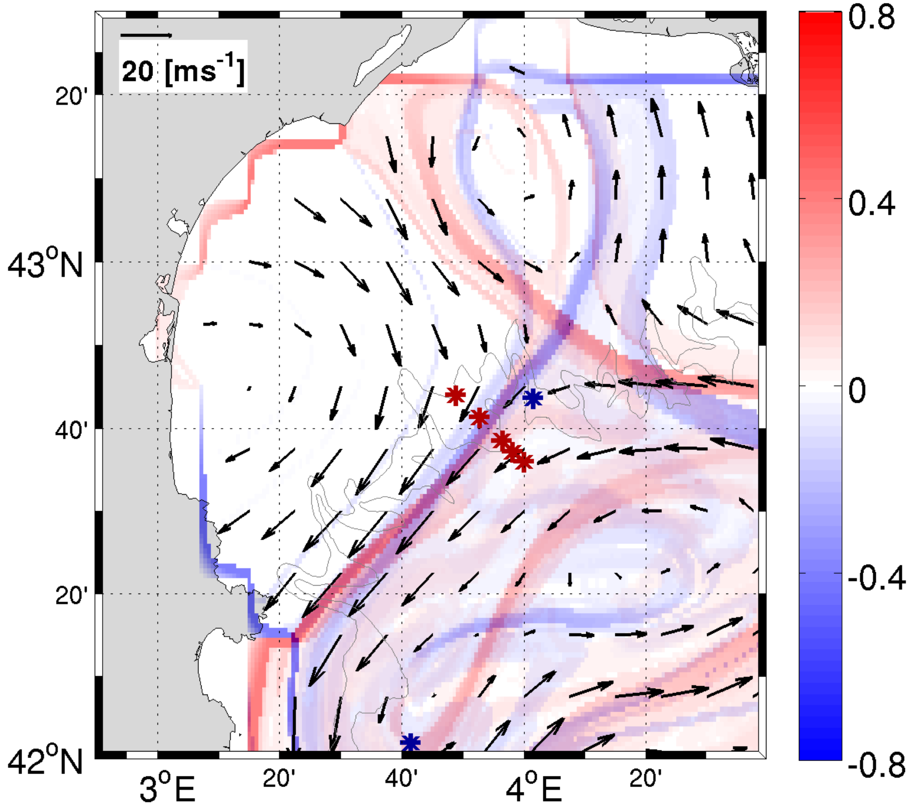


- **Repelling LCS on the continental shelf not detected**
- **Confirmed by ADCP velocities**

# Lyap02 – Sept 18 - 20

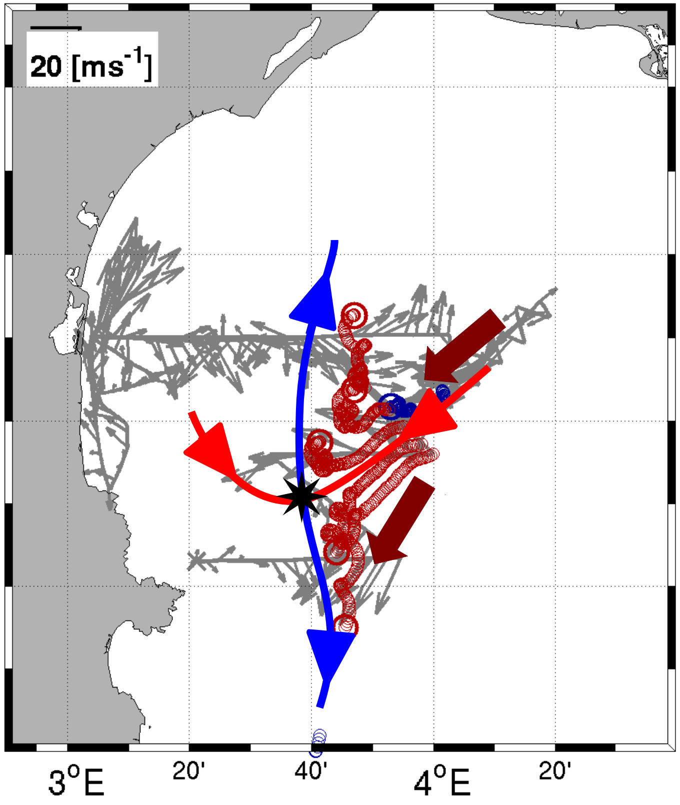
## September 18, 2010

- Altimetry geostrophic velocity vectors
- Attractive (blue) & Repulsive (red) LCSs
- Initial position of drifter array



## September 18-20, 2010

- Drifter trajectories
- *In-situ* LCSs
- 15m ADCP velocity vectors

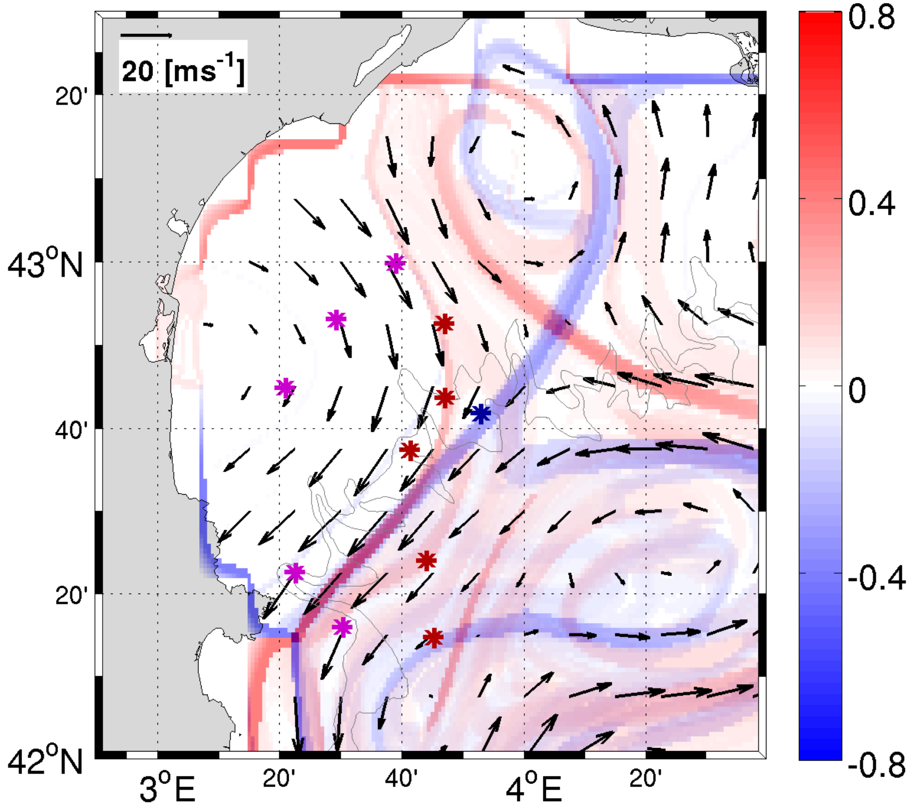


- Satellite structures similar to Sept. 12
- **Accurate identification of LCSs and hyperbolic point**

# Lyap03 – Sept 21 - 24

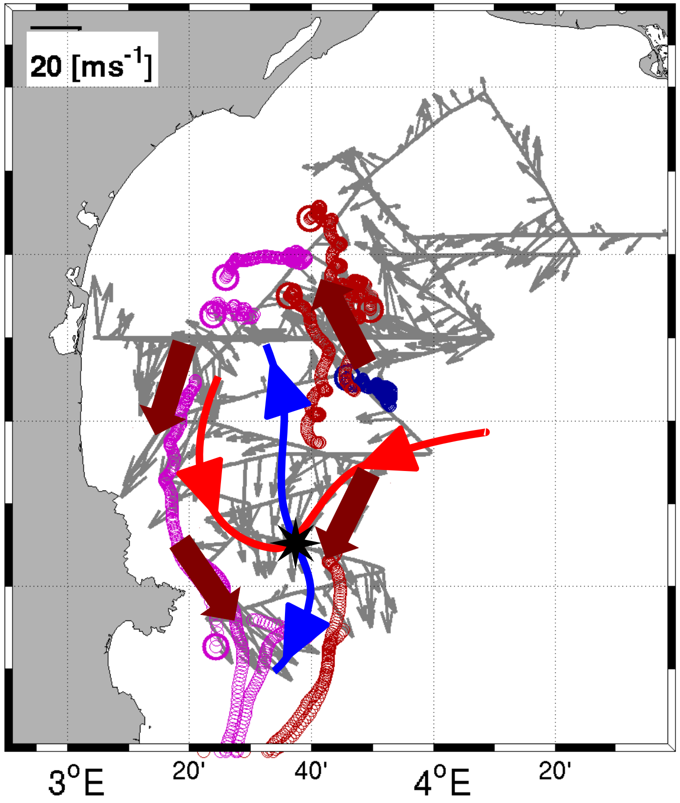
**September 21, 2010**

- Altimetry geostrophic velocity vectors
- Attractive (blue) & Repulsive (red) LCSs
- Initial position of drifter array



**September 21-24, 2010**

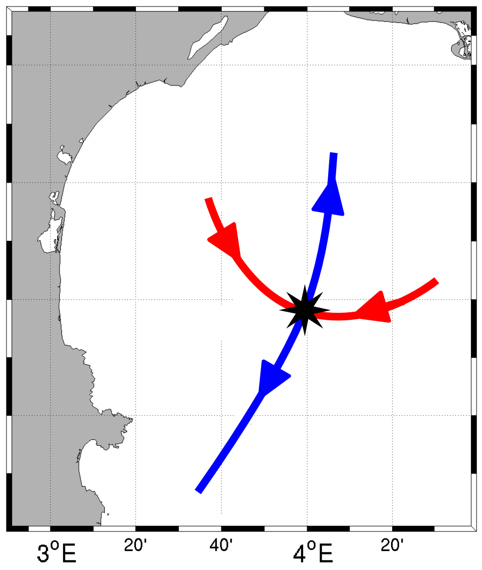
- Drifter trajectories
- *In-situ* LCSs
- 15m ADCP velocity vectors



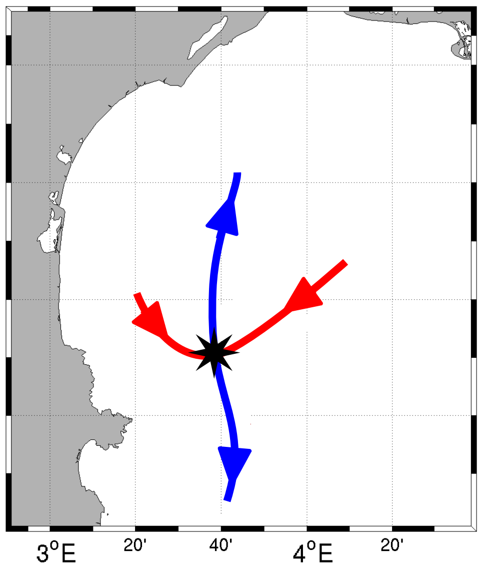
- **Satellite structures similar to Sept. 12**
- **Cyclonic circulation on the continental shelf**
- **ADCP indicate presence of southward coastal jet**

# Hyperbolic point migration

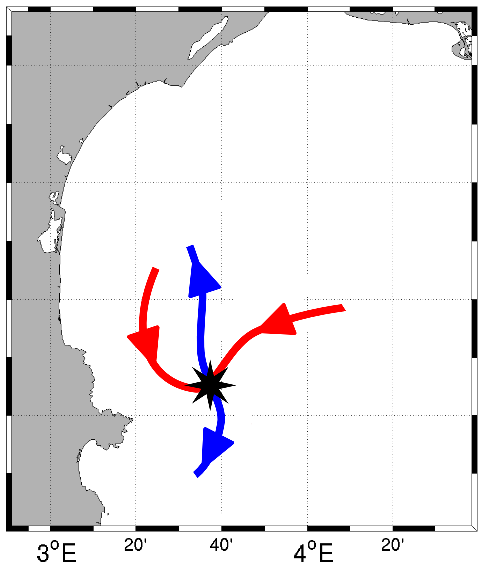
**Lyap01**



**Lyap02**



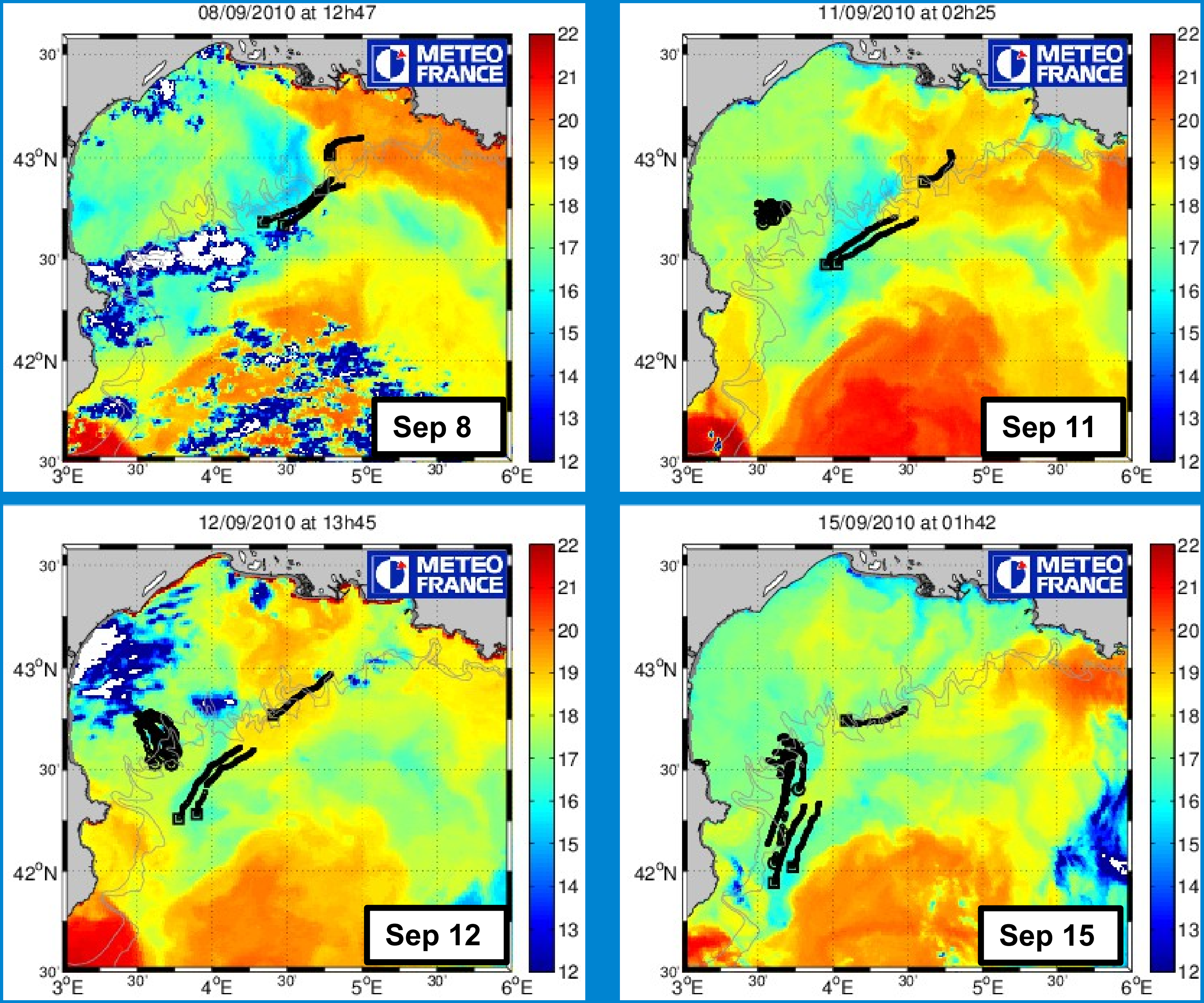
**Lyap03**



- In-situ LCSs tracked for two weeks (September 12-24)
- Hyperbolic point translational speed ~ 5 cm sec$^{-1}$
- Slower than advection speed: satisfied basic condition for FSLE analysis!!!

# LCSs and satellite imagery

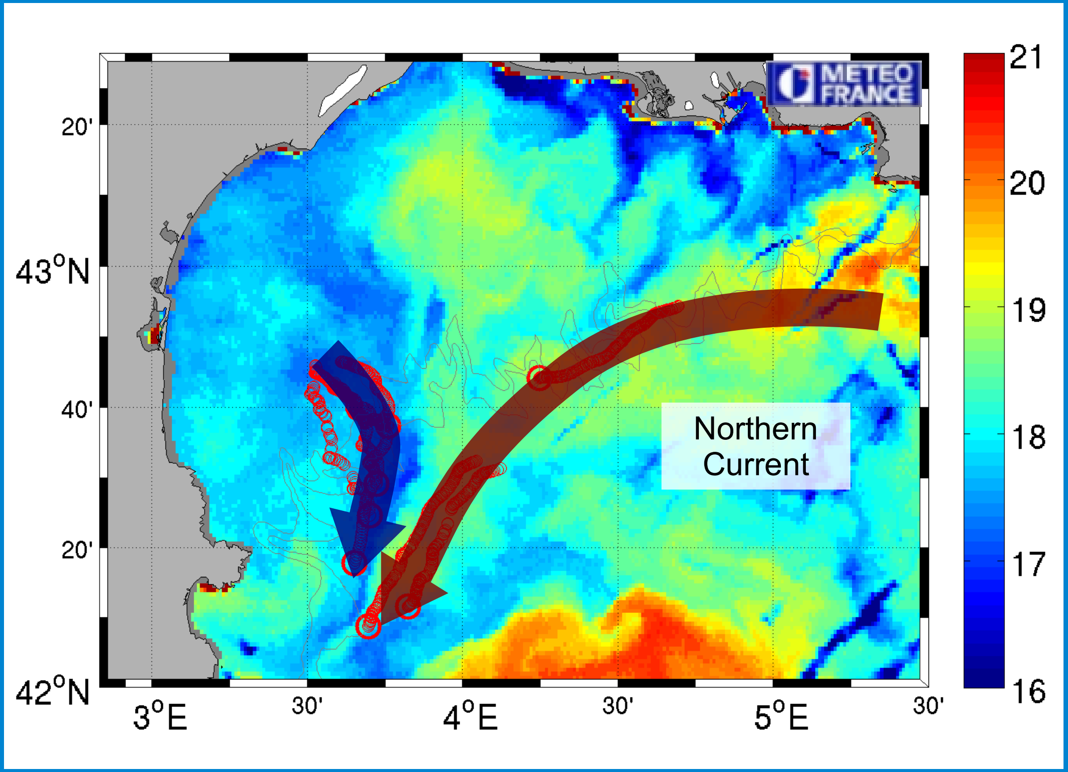
## AVHRR imagery + drifter trajectories (Sep. 8 to 15, 2010)



**Convergence of warmer (eastern outer shelf) and colder (western inner shelf) water masses**

# LCSs and satellite imagery

## AVHRR imagery + drifter trajectories (Sep. 15, 2010)



- In-situ LCSs associated with a front (NC and coastal waters)
- They identify coastal corridor along which water exit the GoL
- Importance of those structures to study cross-shelf exchanges

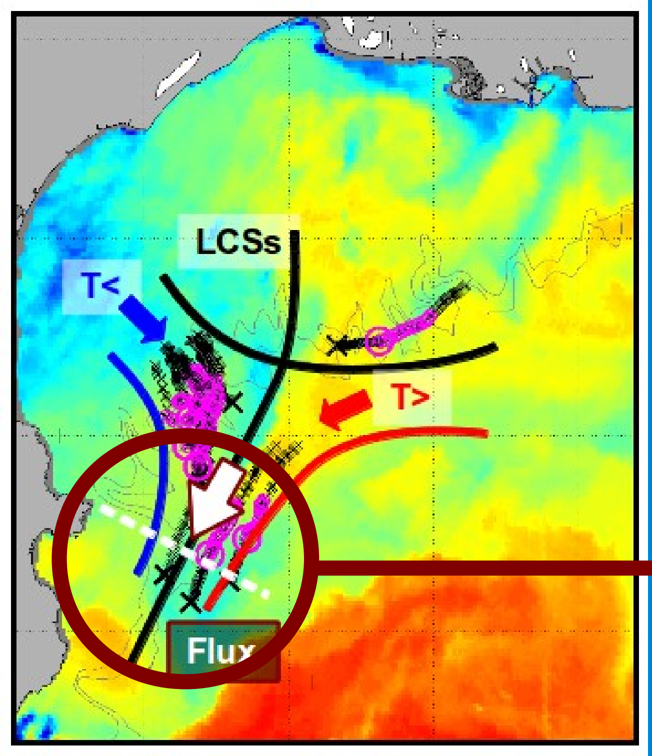
# Latex10 LCS Results

- **Adaptive sampling strategy allowed to detect and track *in-situ* LCSs for two weeks**
- **Translational speed of hyperbolic point satisfies assumption for FSLE analysis**
- ***In-situ* LCSs identified a corridor along which coastal waters left the continental shelf of the GoL**
- **LCSs good transport diagnostic in coastal regions**
- **Altimetry LCSs showed some limitations in the coastal region**

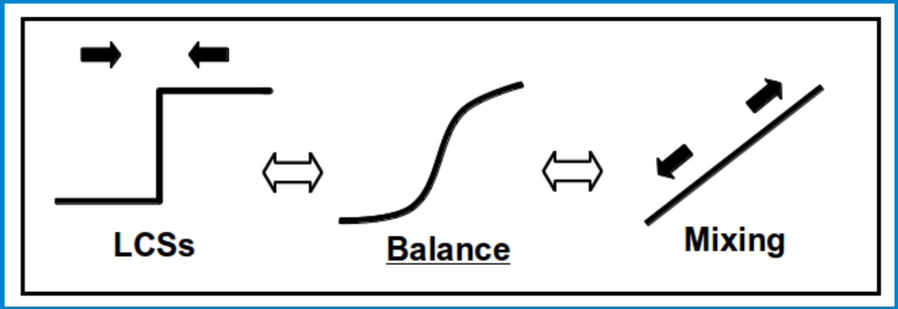
F. Nencioli, F. d'Ovidio, A. Doglioli, A. Petrenko
***Surface coastal circulation patterns by in-situ detection of Lagrangian Coherent Structures.***
*Geophysical Research Letters, 38, L17604, 2011*
doi:10.1029/2011GL048815

# Front-related parameters

## Using info from *in-situ* LCS:



1. **Computation of cross-shelf fluxes from ship ADCP (*work in progress*)**
2. **Computation of Kh coefficients from ship thermosalinograph**



- **Shape of T and S fronts across the attractive LCS results from balance between convergence and horizontal mixing**

- **Submesoscale Kh coefficients important for high-resolution models (physics + biogeochemistry)**
- **Few in-situ estimates** (i.e. Flament et al. 1985, Ledwell et al. 1998)

# Advection-diffusion equation

## 1D equation for a tracer *T*

$$\cancel{\frac{\partial T}{\partial t}} + u(x)\frac{\partial T}{\partial x} = K_H \frac{\partial^2 T}{\partial x^2}$$

$$-\gamma(x-\mu)\frac{dT}{dx} = K_H \frac{d^2 T}{dx^2}$$

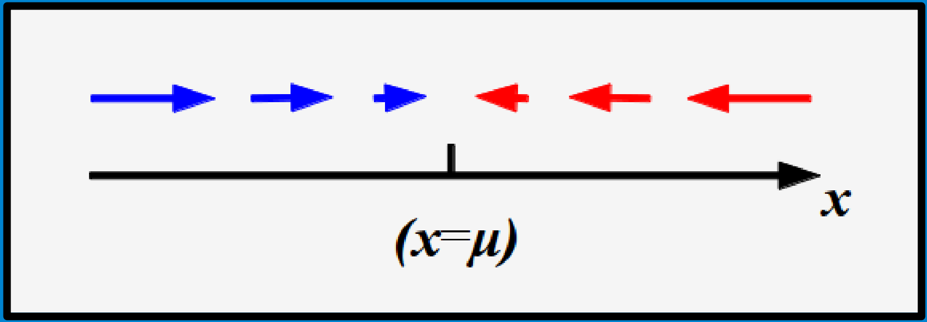
**Assumptions:**

- Front is at equilibrium (quasi-steady state)
- $x$ is the across-front direction

with

$\gamma$ : Strain rate (Lyapunov exponent)

$\mu$ : Position of front axis



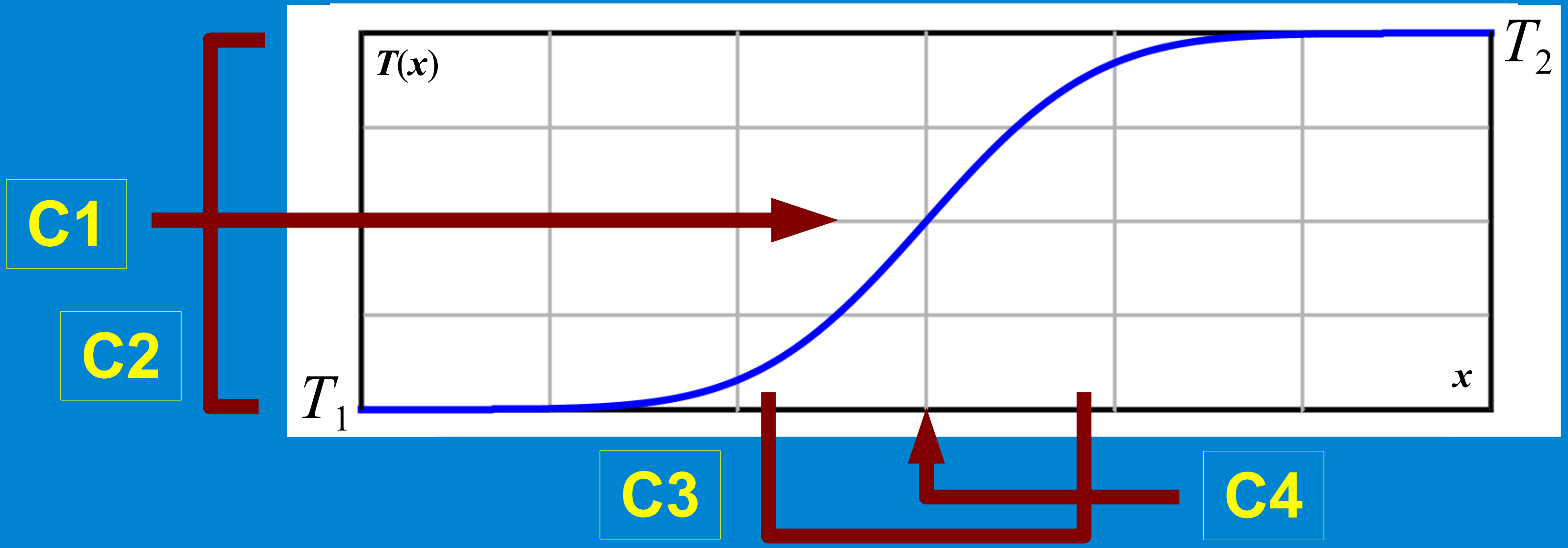
**Boundary Conditions**

$$T(x=-\infty) = T_1;$$
$$T(x=+\infty) = T_2;$$

$$\boxed{T(x) = \frac{T_2+T_1}{2} + \frac{T_2-T_1}{2}\,\mathrm{erf}\left(\frac{1}{\sqrt{2}}\sqrt{\frac{\gamma}{K_H}}\,(x-\mu)\right)}$$

# Analytical solution

$$T(x) = \underbrace{\frac{T_2 + T_1}{2}}_{\mathrm{C1}} + \underbrace{\frac{T_2 - T_1}{2}}_{\mathrm{C2}} \operatorname{erf}\left( \underbrace{\frac{1}{\sqrt{2}} \sqrt{\frac{\gamma}{K_H}}}_{\mathrm{C3}} (x - \underbrace{\mu}_{\mathrm{C4}}) \right)$$



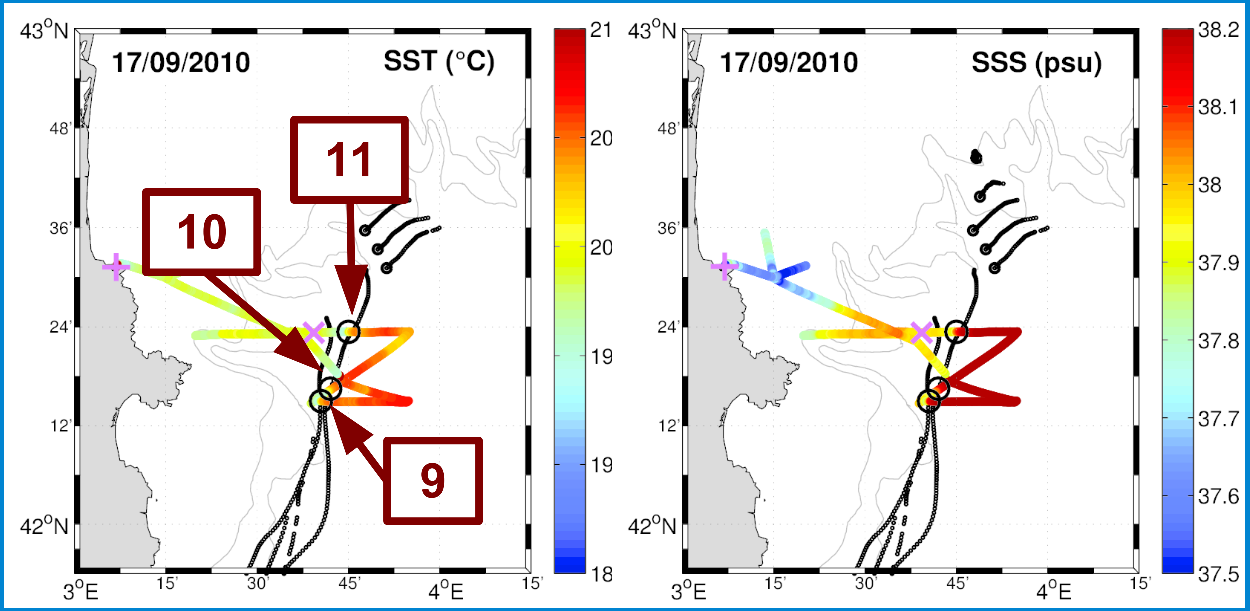
$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} \mathrm{d}t$$

- Coefficients computed by best fitting in-situ T and S transects

$$K_H = \frac{\gamma}{\left(2\,\mathrm{C3}^2\right)}$$

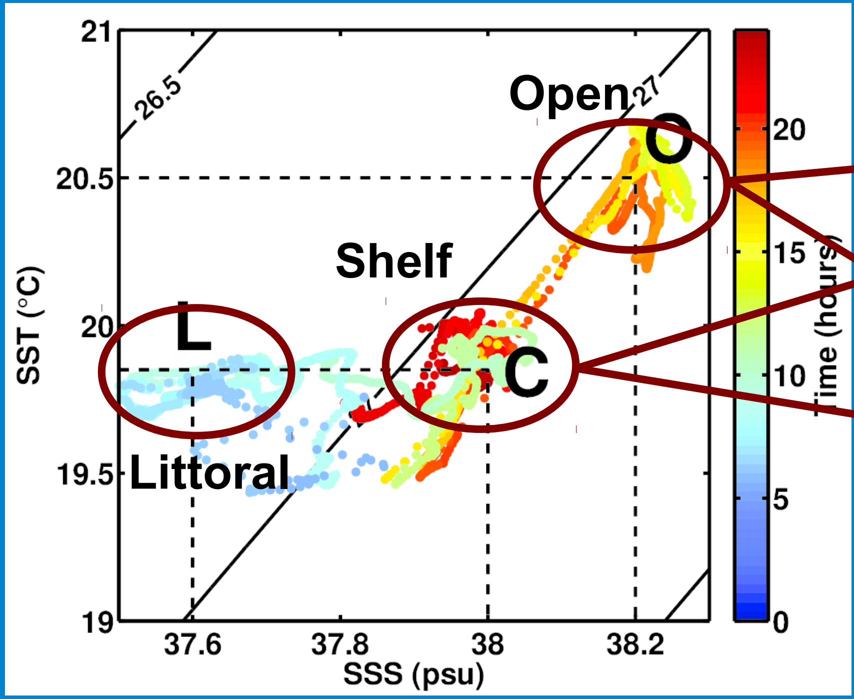
from drifter dispersion!!

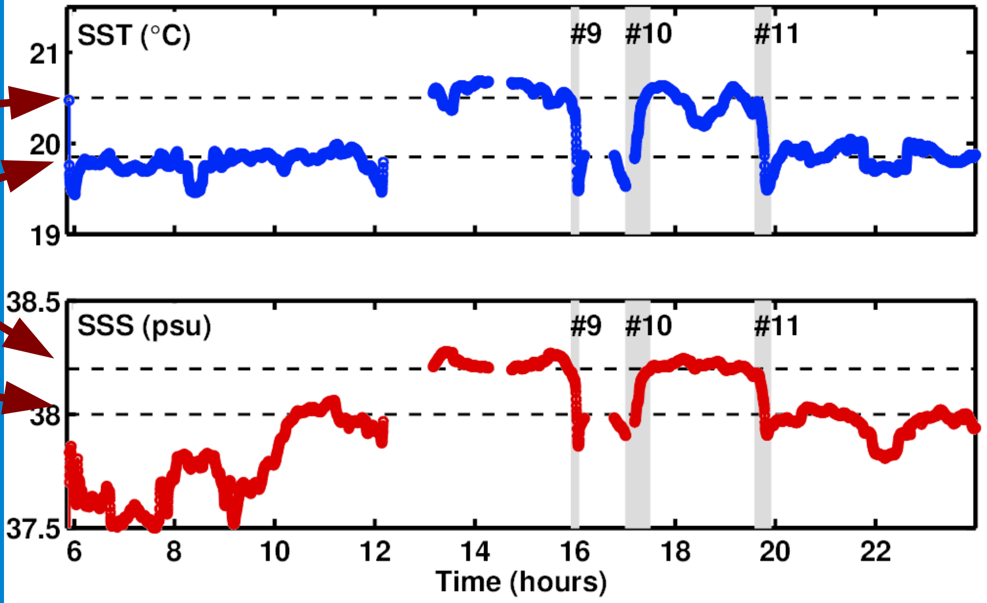
# Cross-front transects



## SST and SSS from ship thermosalinograph

- Total of 30 cross-front transects identified
- Transects projected to be normal to the front direction





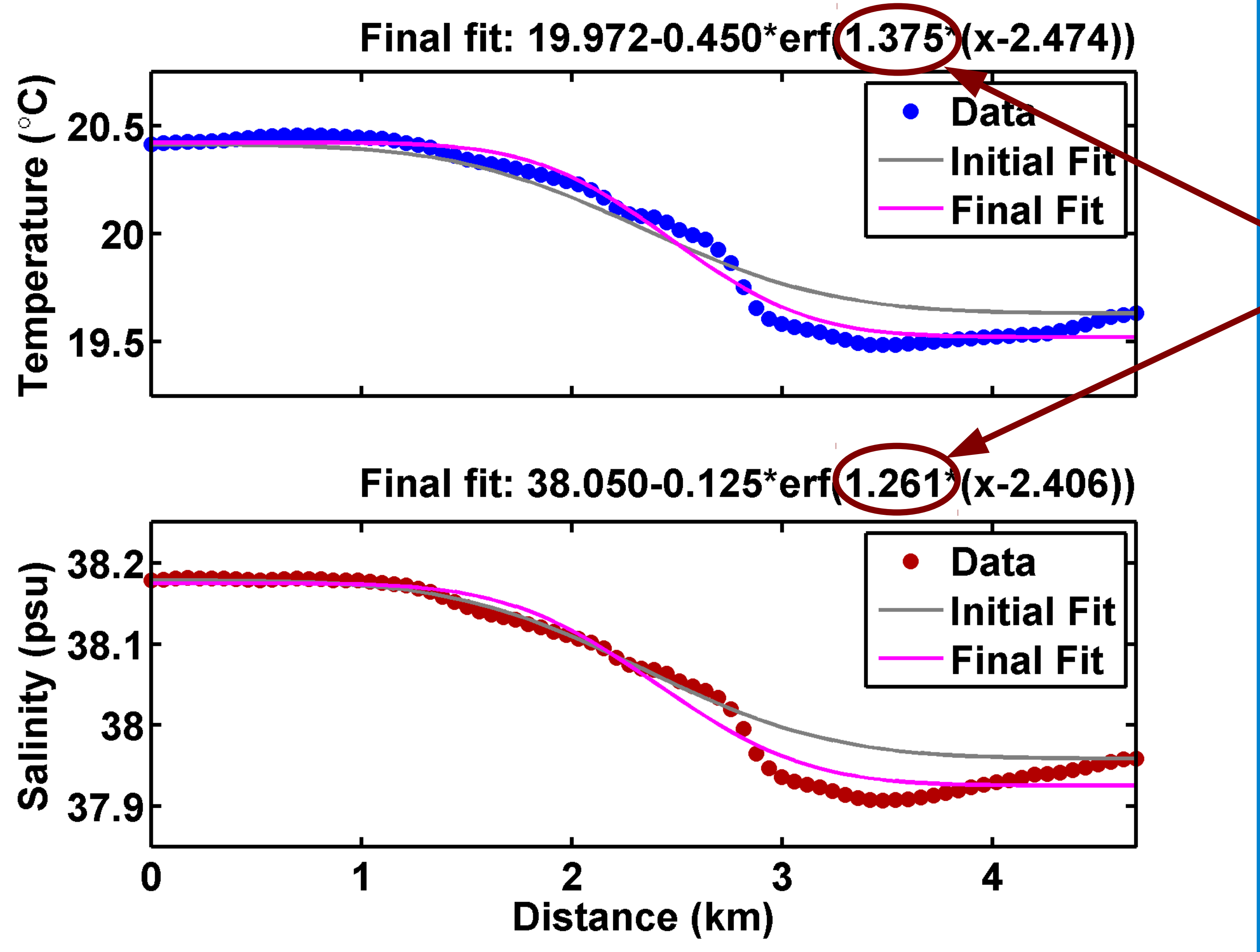
# Curve fitting

## Example: Transect 11

➔ Parameters from least square estimation using Nelder-Mead simplex direct search

**Front equation**

$$T(x) = C_1 + C_2\,\mathrm{erf}\,(C_3\ (x - C_4))$$


Final fit: 19.972-0.450*erf(1.375*(x-2.474))

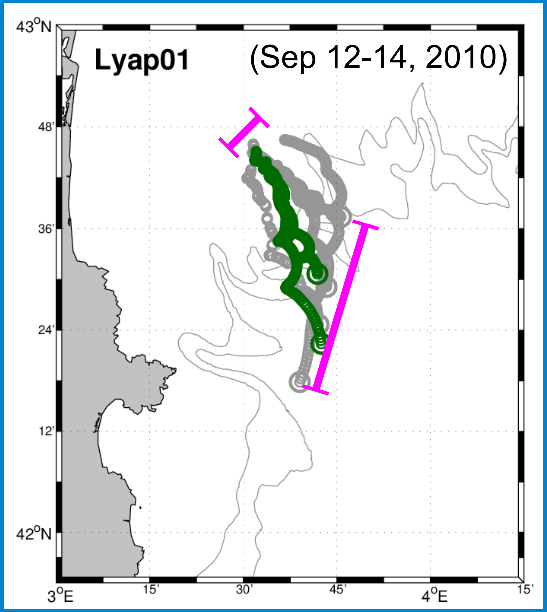
Final fit: 38.050-0.125*erf(1.261*(x-2.406))

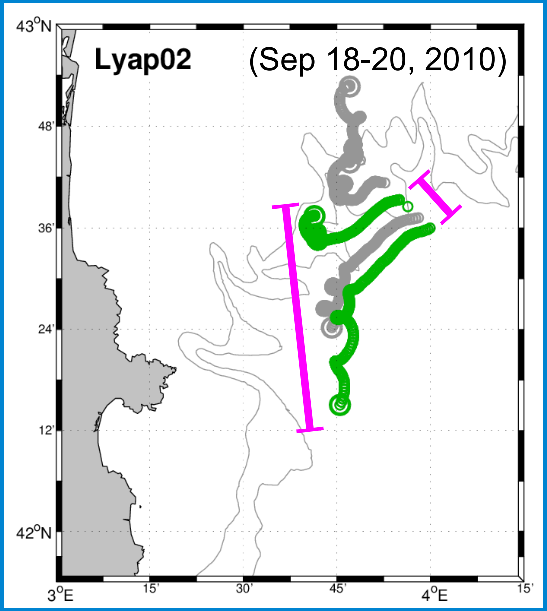
$$C_3 = \frac{1}{\sqrt{2}}\sqrt{\frac{\gamma}{K_H}}$$

- No fit for 11 out of 30 transects: limits of starting assumptions

**Not only horizontal convergence**

# Strain rate

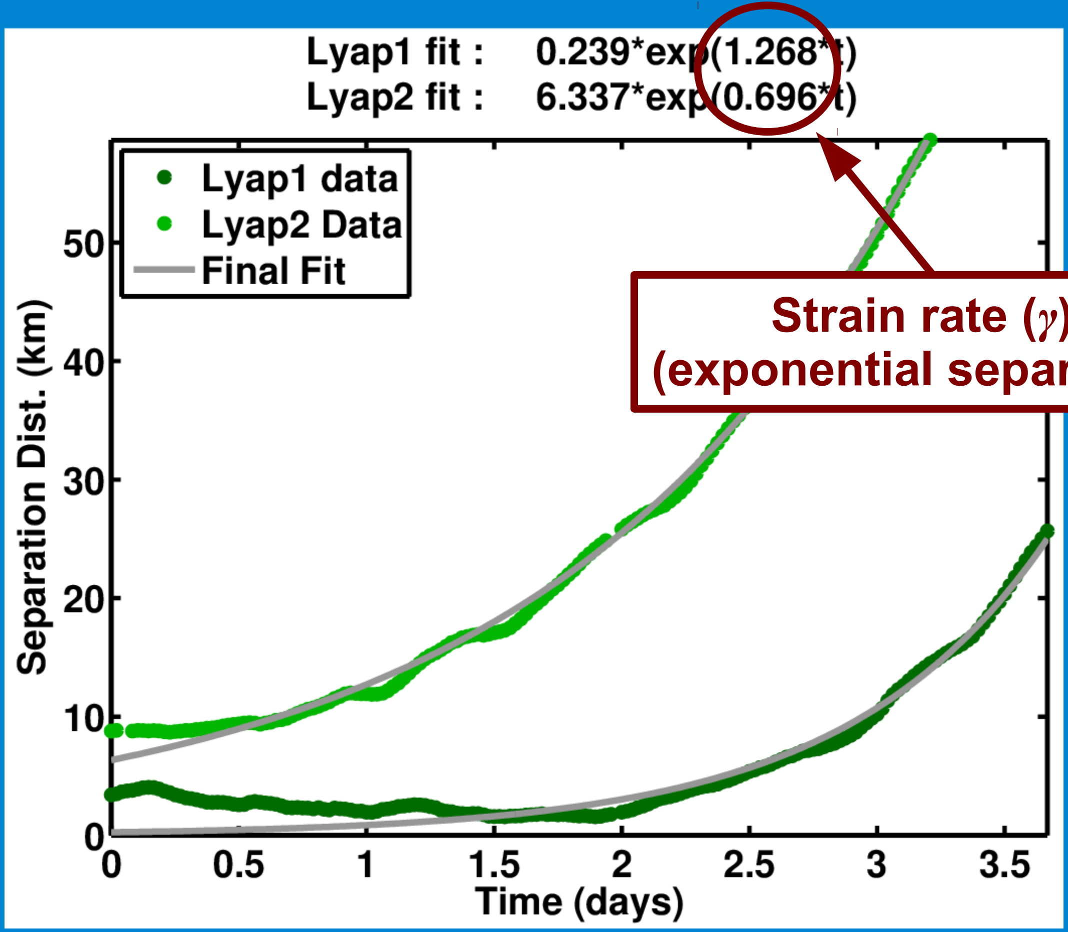




## Dispersion patterns of drifter arrays

- **For each deployment, computed fastest separation rate between buoy couples (analogous to Lyapunov exponent)**

$$\boxed{\delta_t = \delta_0 \exp(\gamma t)}$$

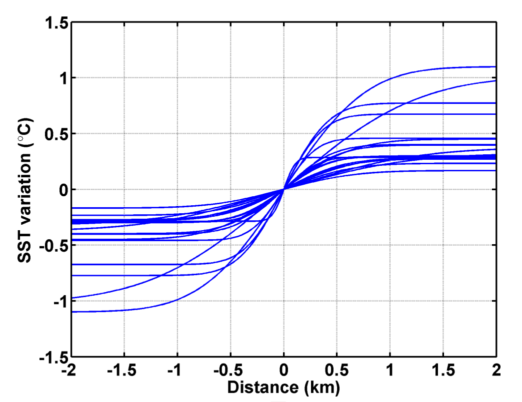


**Strain rate ($\gamma$)**
**(exponential separation)**

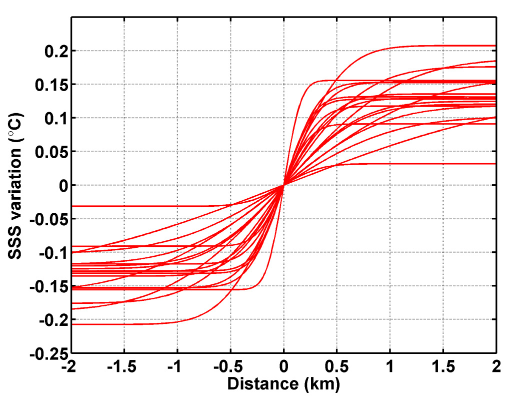
2. Kh

# Eddy diffusivity coefficients

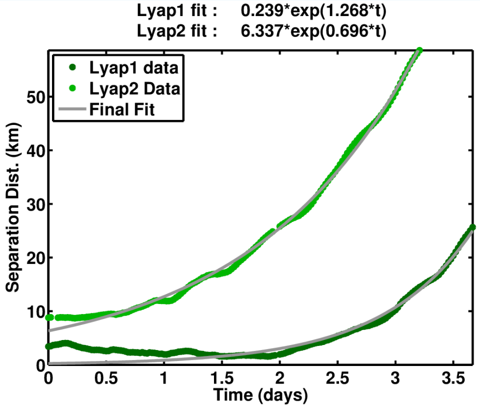
## T Front



## S Front

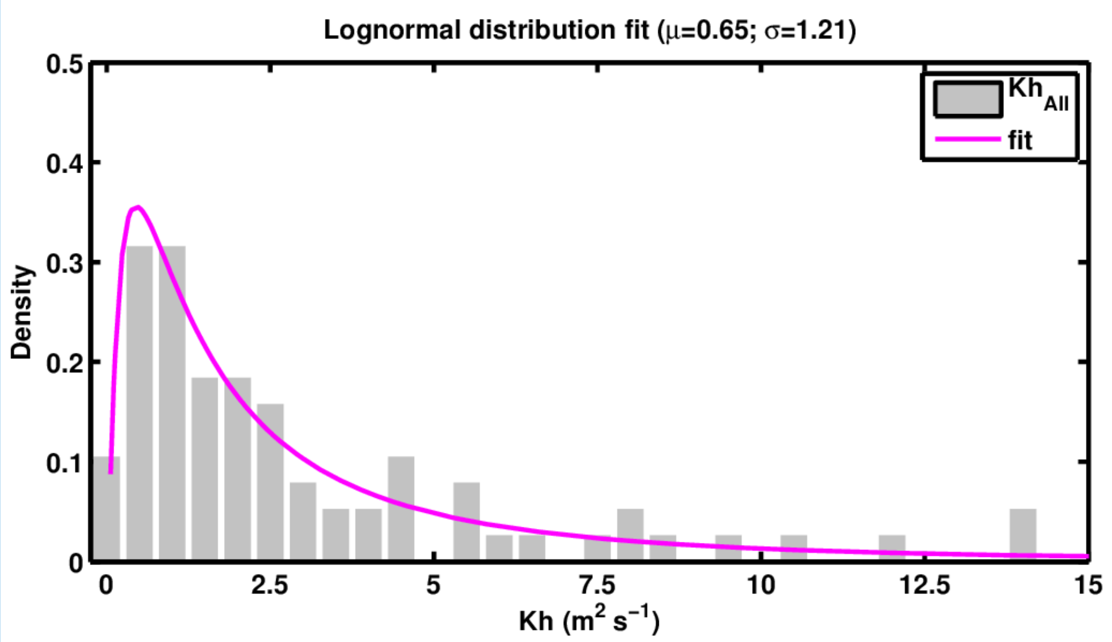


## Strain rate



$$K_H = \frac{\gamma}{\left(2\,\mathrm{C3}^2\right)}$$

## Eddy diffusivity coefficients



- Log-normal distribution
- 70% of estimates between 0.4 - 5 $m^2\ s^{-1}$
- Front widths range from 1 to 4 km
- $Kh_{SST}$ similar to $Kh_{SSS}$

# Latex10 Kh Conclusions

- ➔ **New approach to compute Kh from T and S sections across a front relatively simple and cheap**
  (i.e. compared to passive tracer release experiments)

- ➔ **In-situ estimates provide range of Kh values: Comparison with numerical models parameterizations**

- ➔ **Further dedicated in-situ experiments:**
  **Vertical sections to investigate impact of straining on ML instabilities**

- ➔ **Extend analysis of Kh over wider regions/the global ocean combining SSH and SST measurements**

F. Nencioli, F. d'Ovidio, A. Doglioli, A. Petrenko
***In-situ estimates of submesoscale horizontal eddy diffusivity across an ocean front***
*Journal of Geophysical Research - Oceans, In Press.*

**EOS Research Spotlight**

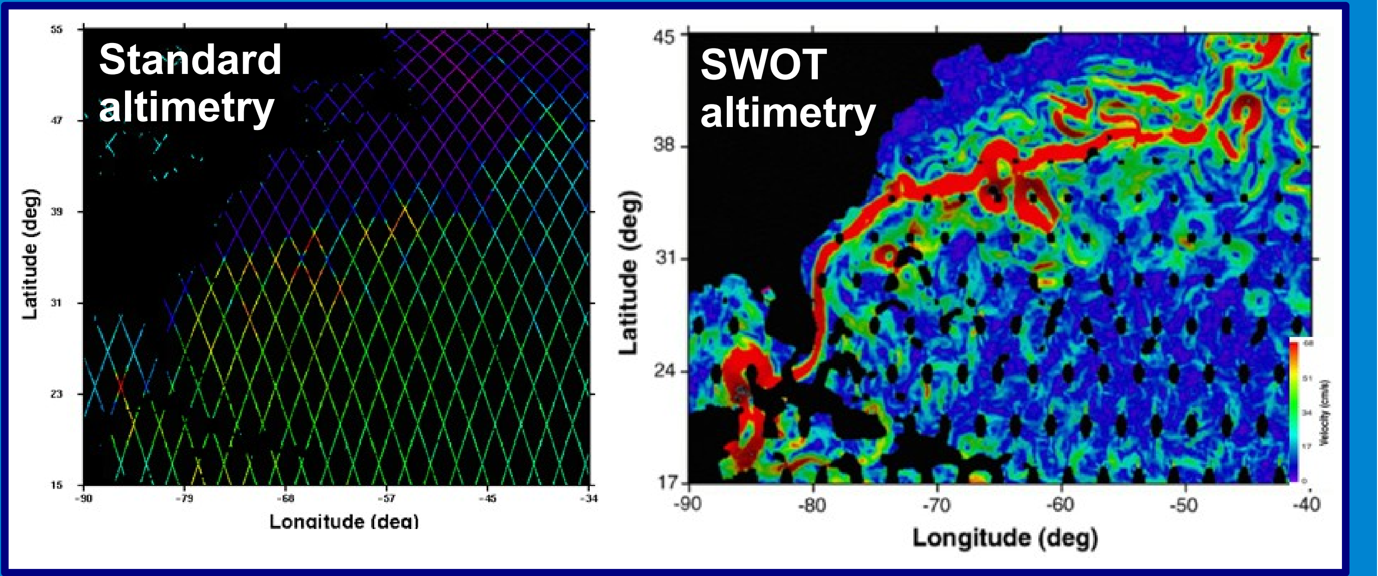
# SWOT: Surface Water and Ocean Topography

- **Wide-swath NASA/CNES satellite altimetry mission**
- **Launch in Fall 2020**
- **Hydrography + oceanography**

*(from http://swot.jpl.nasa.gov/mission/)*

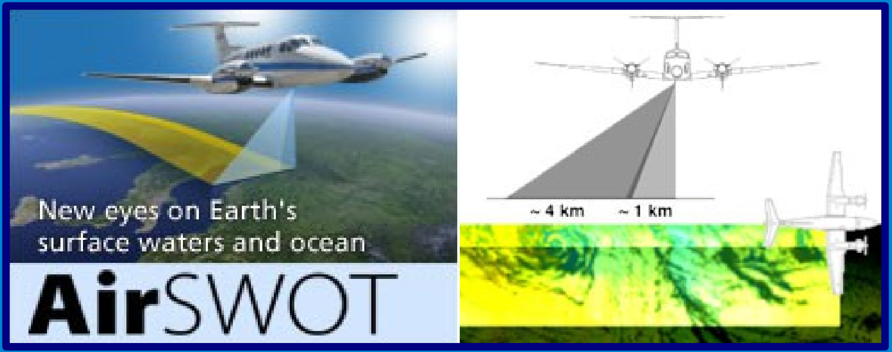
## Oceanography

- **SSH observations at a resolution of few km over a 100 km swath (sub)mesoscale regimes**
- **Important for coastal regions where traditional altimetry is inaccurate**



*(from http://smsc.cnes.fr/SWOT/)*

# AirSWOT



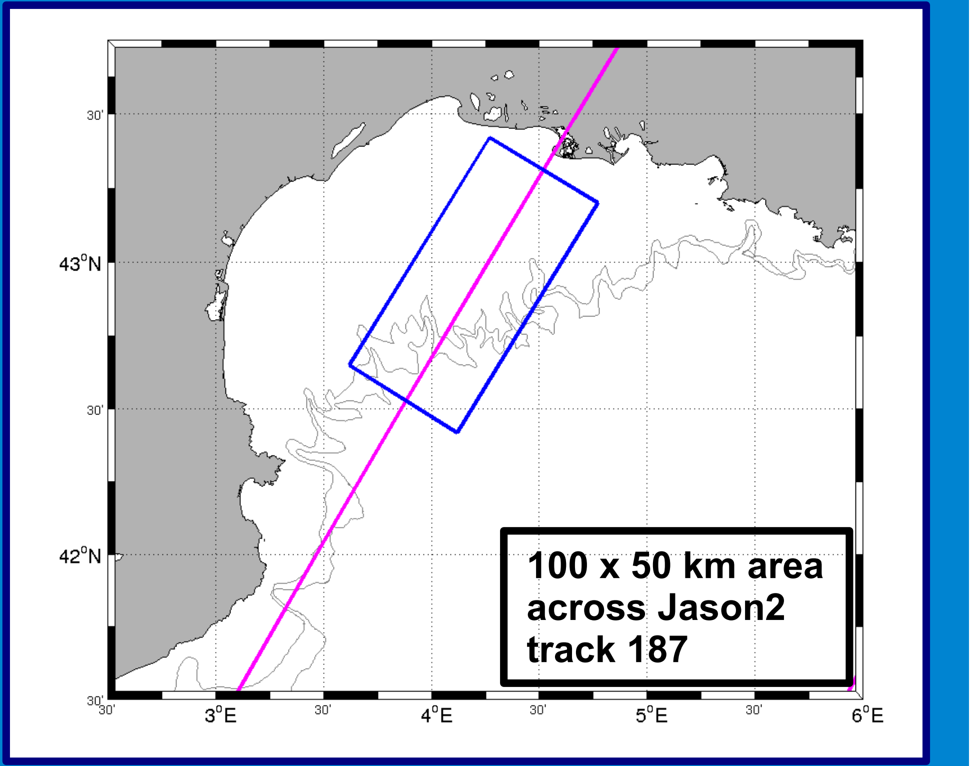
- **SWOT calibration/validation before satellite launch:**
  - ➔ **Airborne version of SWOT**
  - ➔ **Each flight with an ocean campaign**

➔ **Opportunity for (sub)mesoscale dedicated field experiments (support of high-resolution SSH maps)**

## SeaGoLSWOT campaign

(GoL: 29 Oct - 10 Nov, 2014)

- **“Checkout” AirSWOT mission**
- ***R/V Tethys II***
- **Ranked “A” by the CNFC**
- **Supported by CNES: “lite” campaign (34.8k Euros)**

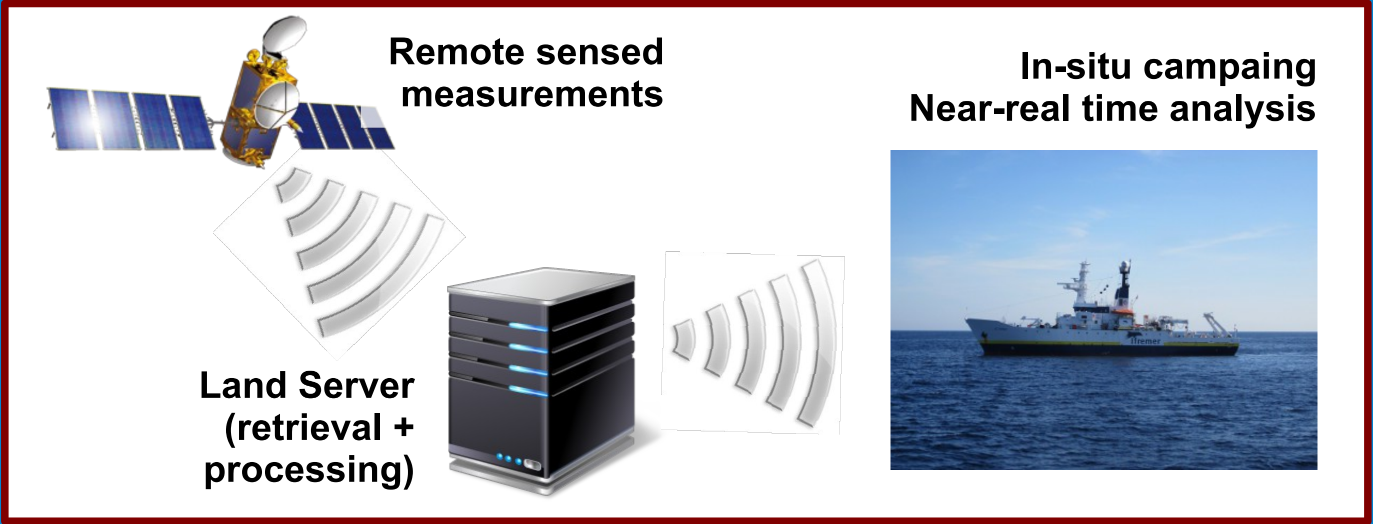


**100 x 50 km area across Jason2 track 187**

# SeaGoLSWOT strategy

**Objective: Series of 3D physical ecological mappings of specifc submesoscale structures**

## 1) Adaptive sampling strategy (Target the structures)



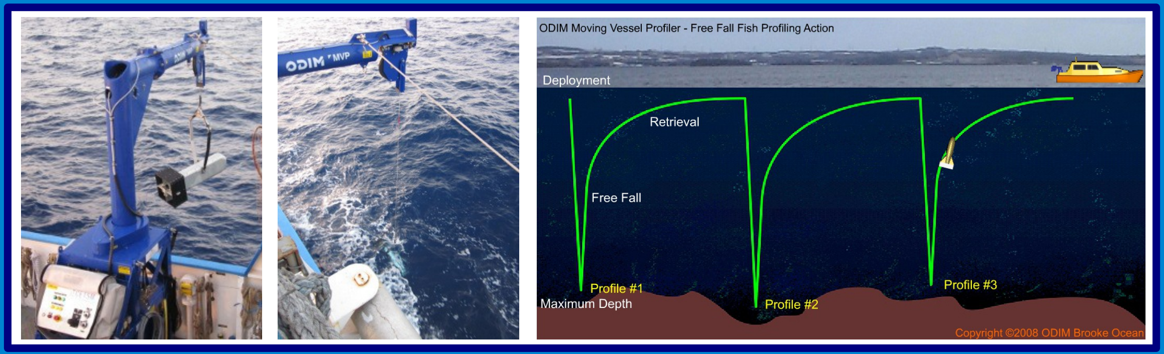
- **Already successfully setup in previous campaigns (Latex10, KEOPS2, STRASSE … )**
- **Simulations from high-resolution models used to test sampling patterns through *"in-silico"* campaings**

# SeaGoLSWOT strategy

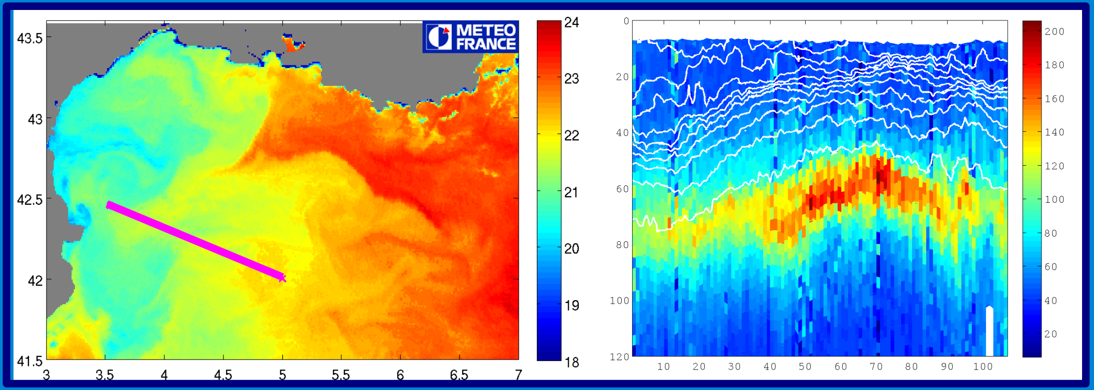
**Objective: Series of 3D physical ecological mappings of specifc submesoscale structures**

1) **Adaptive sampling strategy** (Target the structures)

2) **Ship-towed vertical profiler** (3D mapping)



**Moving Vessel Profiler**



- **High resolution vertical sections**
- **Combined with ADCP to investigate 3D dynamics**

# SeaGoLSWOT strategy

**Objective: Series of 3D physical ecological mappings of specifc submesoscale structures**

1) **Adaptive sampling strategy** (Target the structures)

2) **Ship-towed vertical profiler** (3D mapping)

3) **Limit the number of stops/stations**
   (Ecological measurements from automated platforms)

→ **Improved synopticity and resolution of observations**

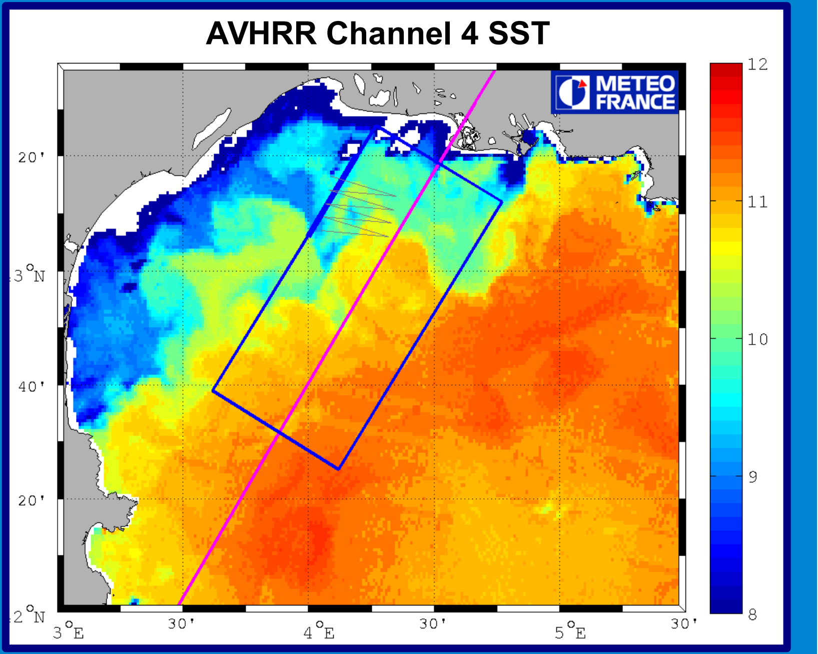
→ **Reduced costs for the campaigns**

- **Flow cytometry:**
  continuous phytoplankton community at the surface

*(http://www.cytobuoy.com)*

# Goals of SeaGoLSWOT

1. Provide AirSWOT measurements with ground truth of physics at ~1 km horizontal resolution
2. Evaluate the scales of variability of submesoscale altimetry signal
3. Explore the link between surface structures and subsurface dynamics
4. Investigate interactions between surface structures and vertical biogeochemical processes



- Further development of novel sampling strategies and instrument configurations

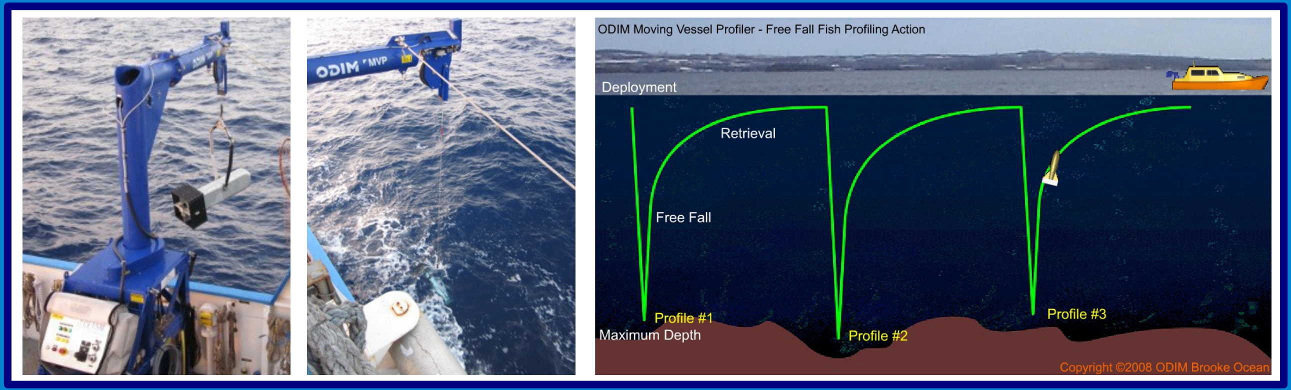
# Instrumentation

- **Clusters of SVP Lagrangian drifters + ADCP mapping**

**Surface velocities + LCS (Latex10)**

**➔ Goal 1:**
**Validate AirSWOT measurements**

- **Moving Vessel Profiler**



**Vertical sections**
**(CTD, Fluo., LOPC)**

**➔ Goal 3:**
**Interior dynamics**

- **CytoSense flow cytometer**

**Ecological communities**

**➔ Goal 4:**
**Physics-biology**

# Sampling operations

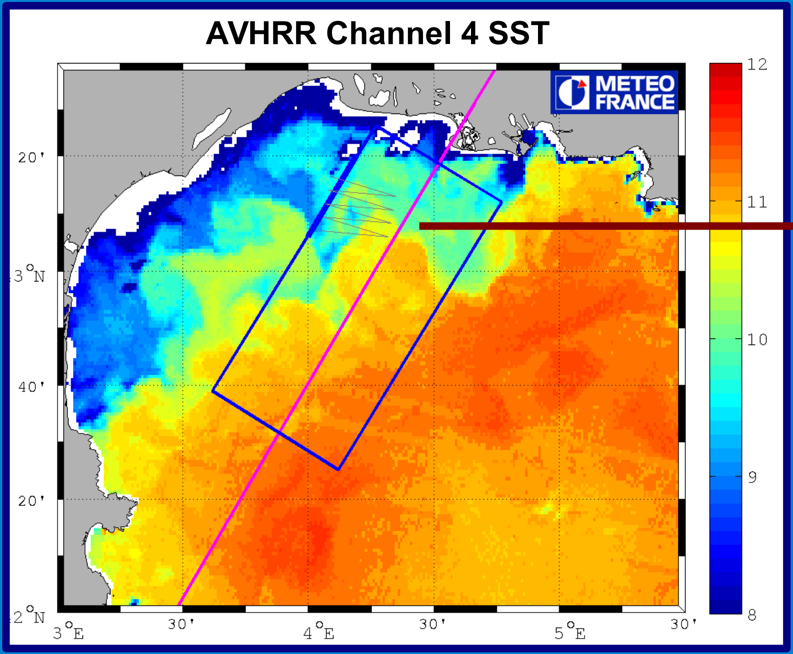
➔ **11 day campaign (Goal 2: Temporal variability) :**

**Repeat cycle every 3 days**

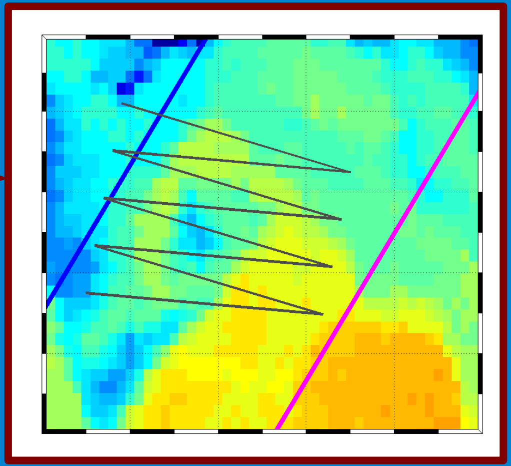
**(1) Identify (sub)mesoscale structure to focus**

**(2) Release drifter arrays**
(4 deployments total)

**(3) High-resolution mapping**
(one mapping every 12 hours)



**AVHRR Channel 4 SST**



➔ Optimal sampling patterns tested before the campaign using regional numerical simulations

# Biogeochemical Observations

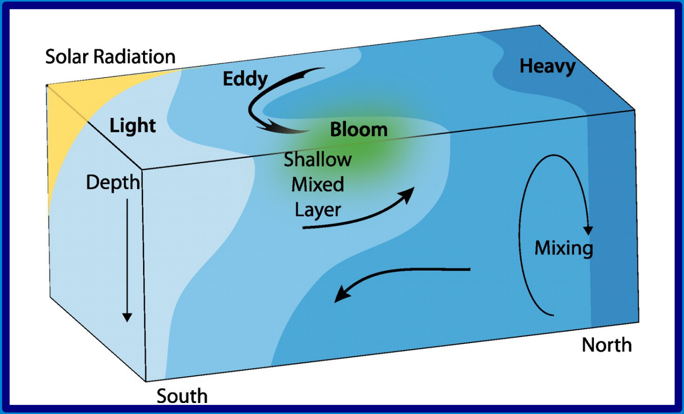
## Submesoscale impact on:

- **Biogeochemical cycles**
  (PP, Nutrient fluxes, C export …)
- **Structuring of ecological communities**
  (micro-environments)

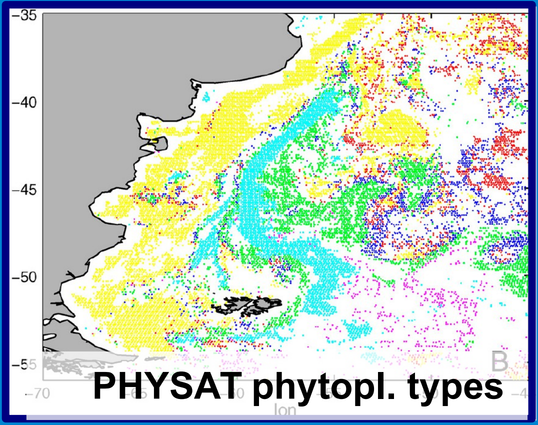
## Additional measurements required:

- **Multi-vessel campaigns**
  (Synoptic Mapping + Traditional sampling)
- **Automated platforms of observation**
  (Synoptic mapping of physical and biogeochemical properties)

**Optical sensors (bio-optical proxies)**

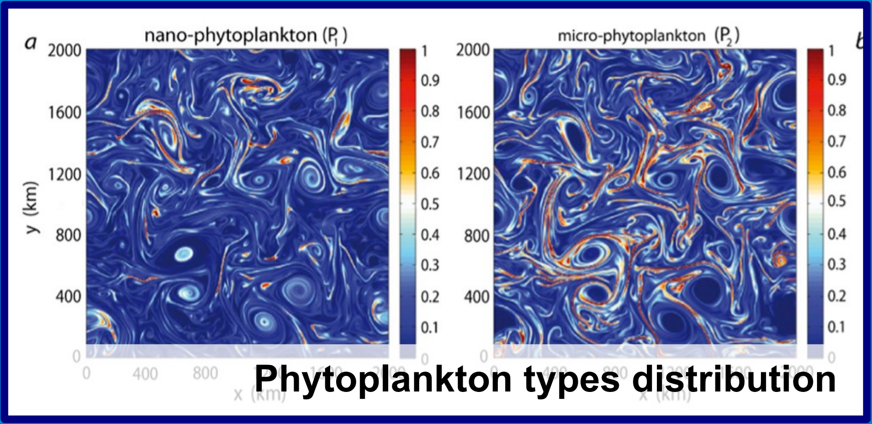


*(Mahadevan et al. 2012)*



**PHYSAT phytopl. types**

*(d'Ovidio et al., 2010)*



**Phytoplankton types distribution**

*(Levy et al., 2012)*

# Biogeochemical Observations

**Optical sensors with vertical profilers already tested**

**Further development in the next decade:**

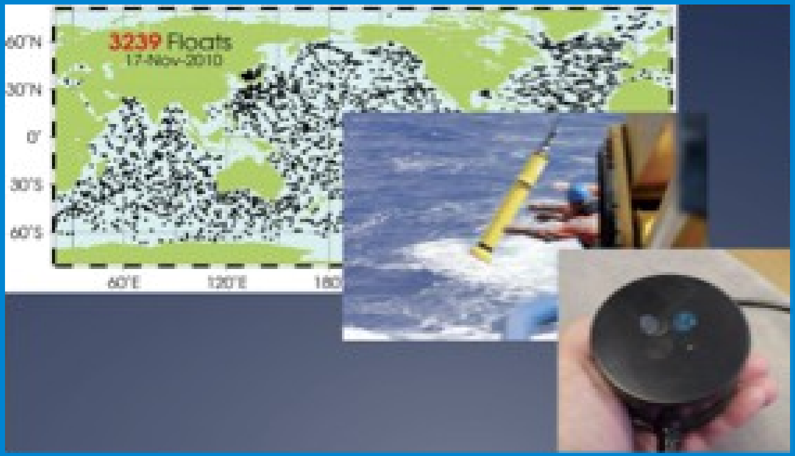
- ➔ **Technological** (e.g. nutrient sensors) **and technical** (e.g. new proxies) **advancements**
- ➔ **Complementary to Bio-ARGO program** (Large scale processes)

**SeaSoar**

*(www.chelsea.co.uk)*

**AC-S**

*(http://www.wetlabs.com)*

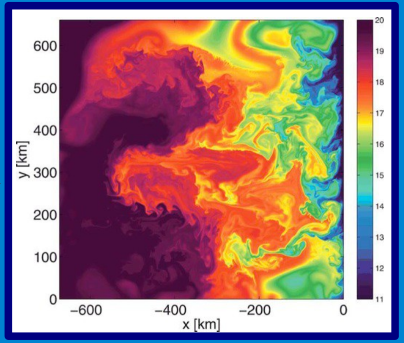


**Physical- biogeochemical observations needed to include submesoscale processes in BOGCM for a more realistic representation of the global carbon cycle**

# Submesoscale-dedicated campaigns

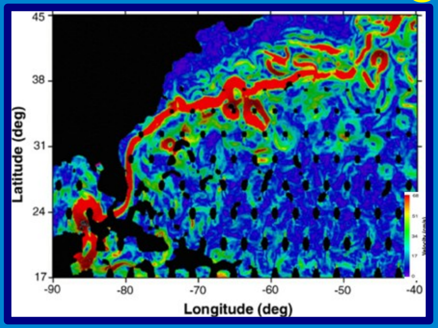
## Multi-platform integration

Numerical Modeling



In-situ observations

Remote Sensing



**Submesoscale field campaigns:**

**Info from models and satellites to adapt/optimize sampling strategy**

1. **- Improve representation of small scale processes:**
   - **ML instabilities under real wind and strain conditions**
   - **Small scale biogeochemical processes**

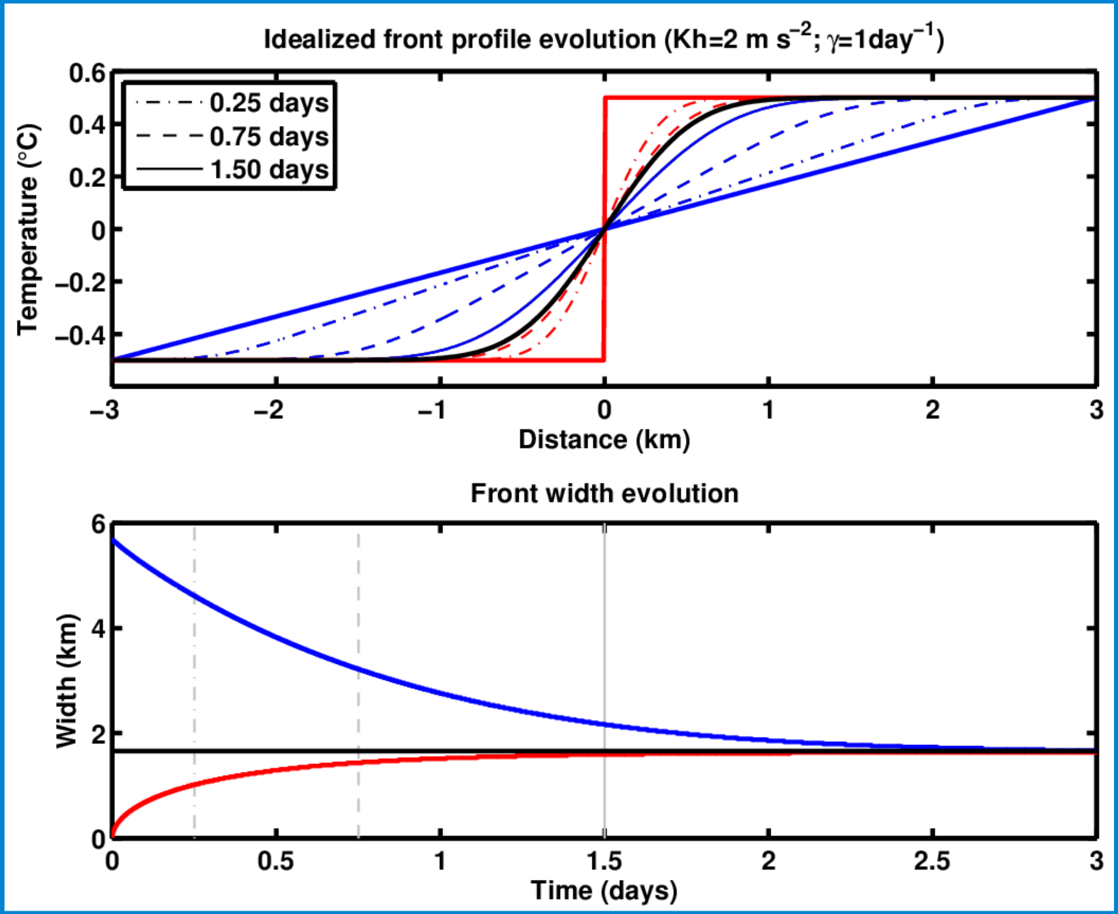
2. **- Provide ground truth for novel sensors**
   **- Identify 3D info retrievable from 2D high-resolution fields**

3. **- Extend results from in-situ observations to global scale**
   **- Term of comparison for BOGCM (global carbon cycle)**

# ***EXTRA SLIDES***

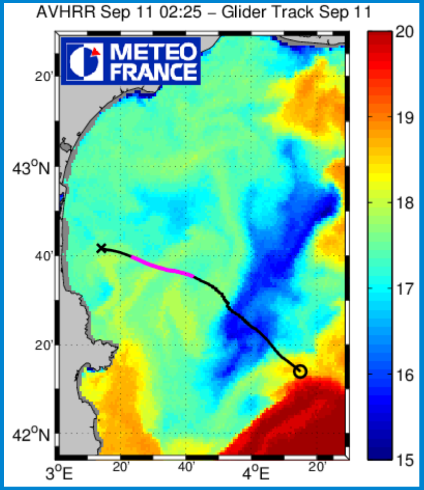
# Numerical solution

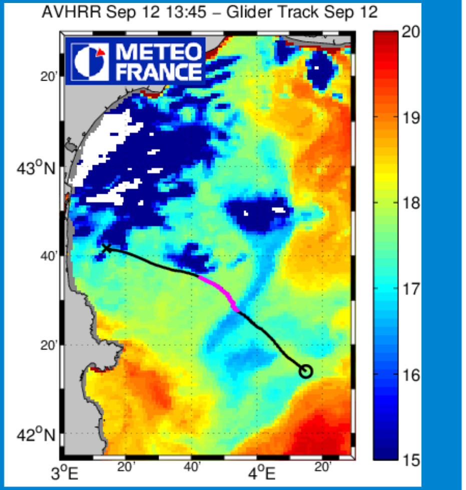
## First order upwind scheme

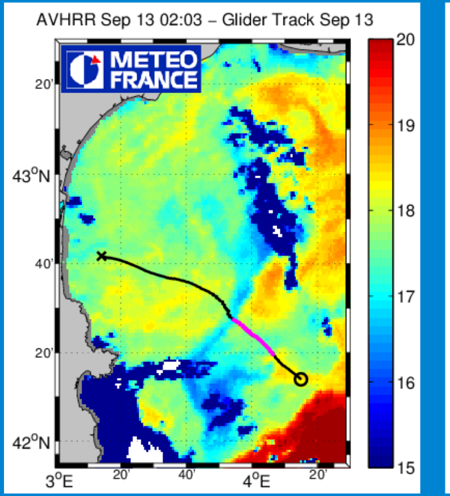


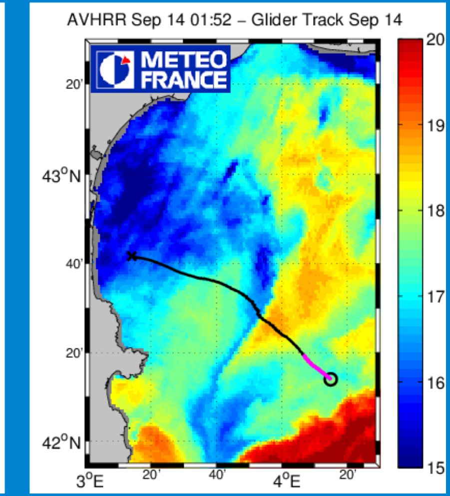
- Fast adjustment to equilibrium (within 1 day)
- However Kh proportional to square of width
- Even small errors in width could affect estimate of Kh

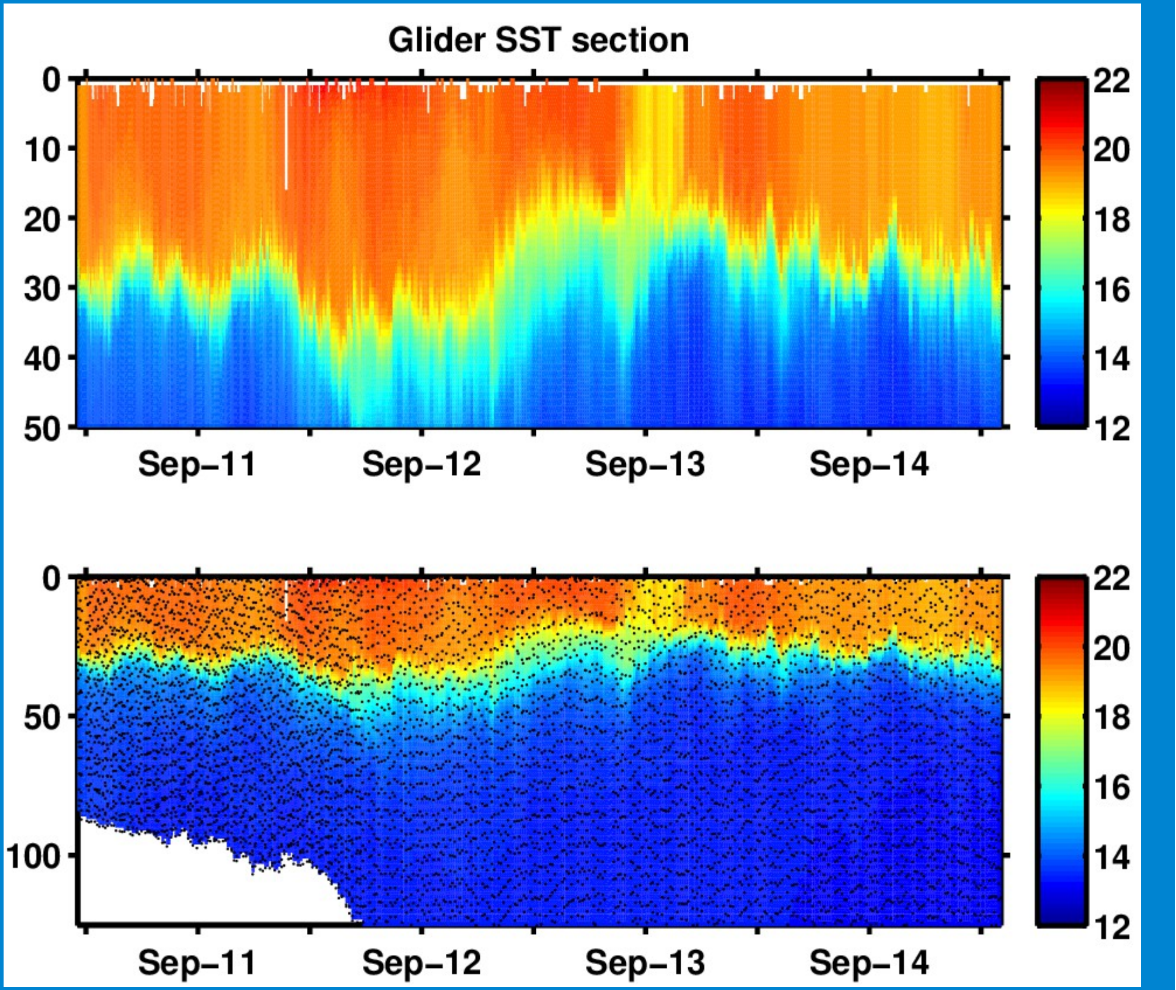
# Glider section


AVHRR Sep 11 02:25 – Glider Track Sep 11


AVHRR Sep 12 13:45 – Glider Track Sep 12

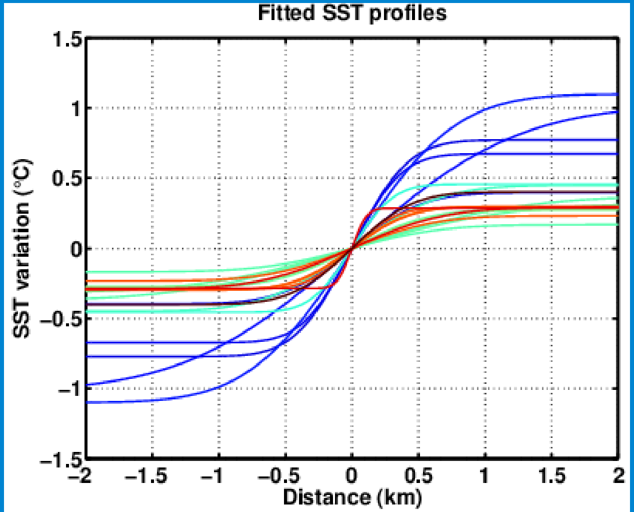

AVHRR Sep 13 02:03 – Glider Track Sep 13

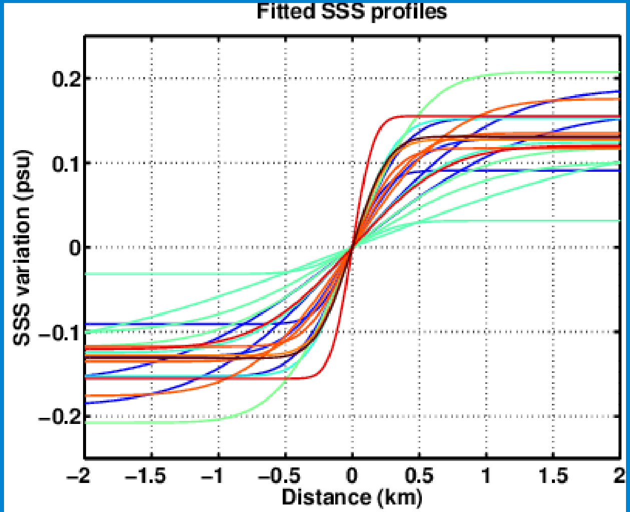

AVHRR Sep 14 01:52 – Glider Track Sep 14

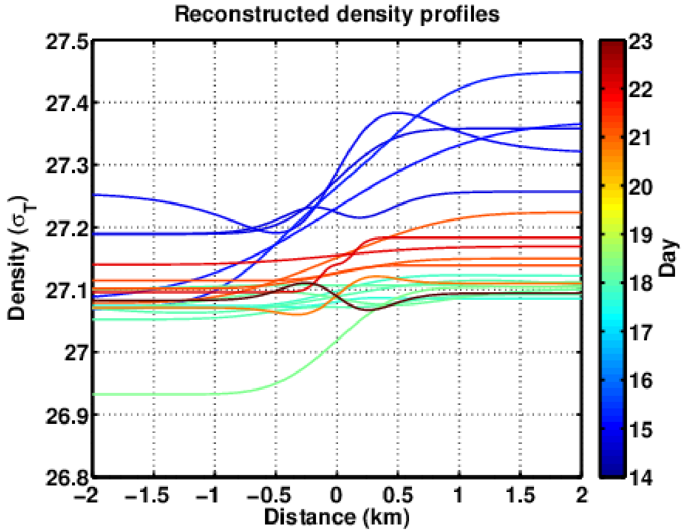

Glider SST section

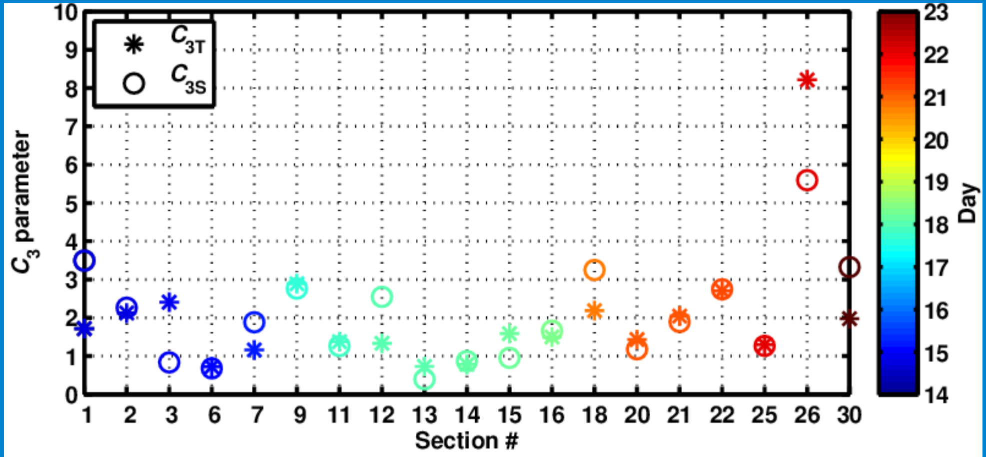
**2. Kh**

# Profiles



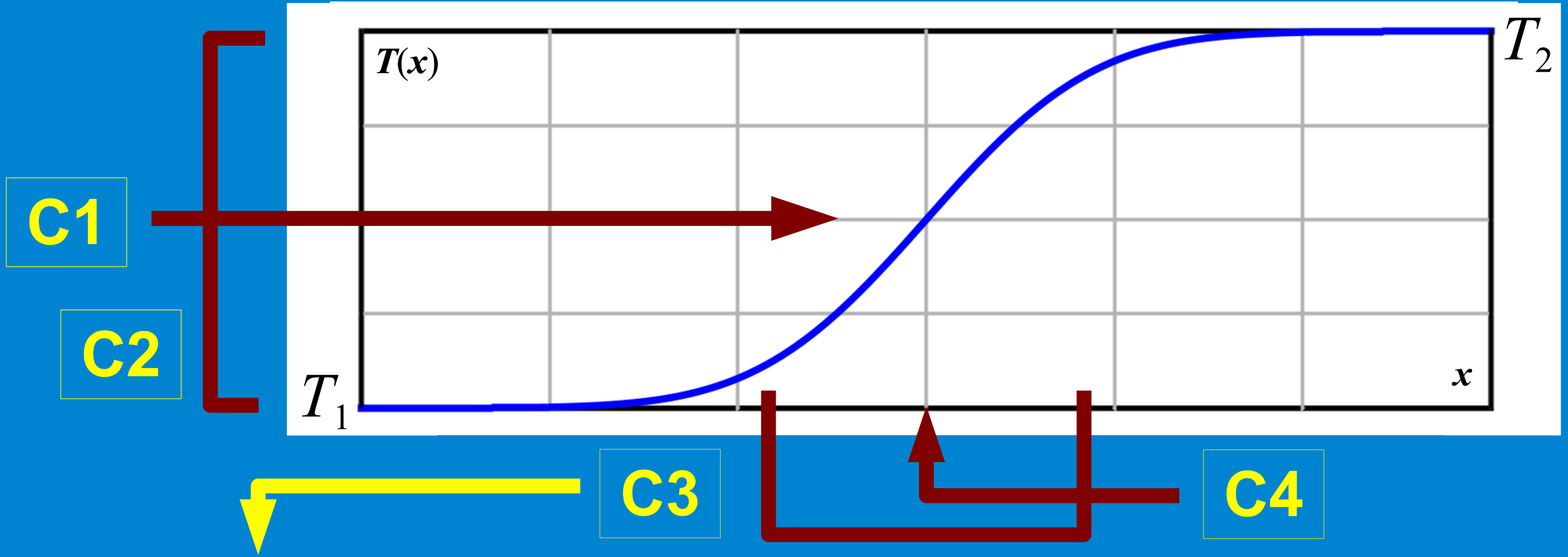




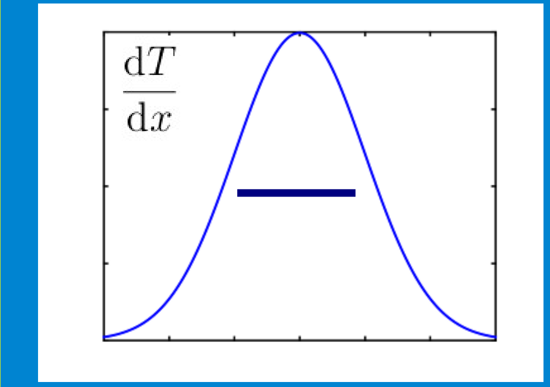


# Analytical solution

$$T(x) = \underbrace{\frac{T_2 + T_1}{2}}_{C1} + \underbrace{\frac{T_2 - T_1}{2}}_{C2} \operatorname{erf}\left(\underbrace{\frac{1}{\sqrt{2}}\sqrt{\frac{\gamma}{K_H}}}_{C3}\,(x - \underbrace{\mu}_{C4})\right)$$



$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,\mathrm{d}t$$



$$W_{front} = 2\sqrt{\frac{K_H}{\gamma}}$$

**68% of T variation**