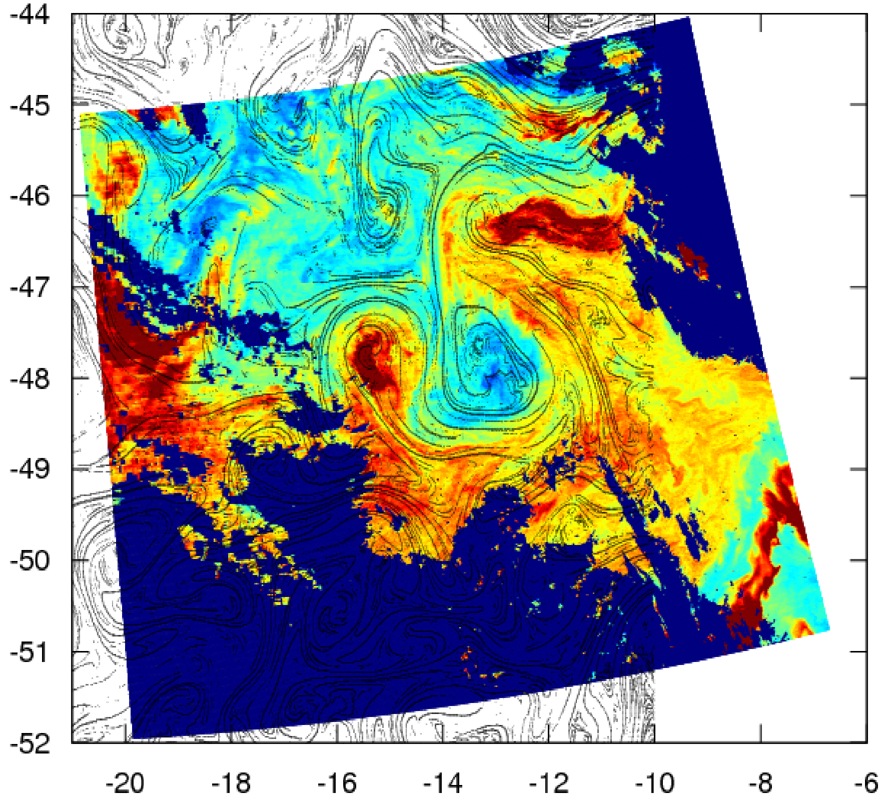
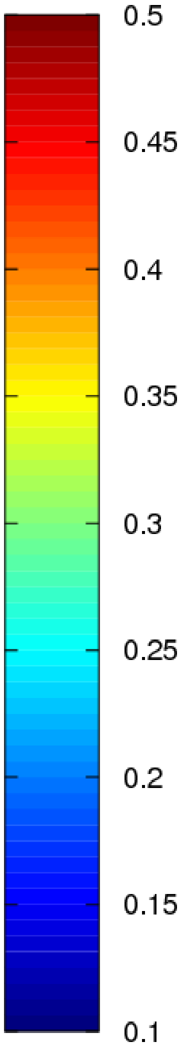
The geometry of lateral stirring

Lyapunov vector from altimetry data

Francesco d'Ovidio
CNRS/LOCEAN-IPSL, Paris, France





Thanks to: M. Lévy, S. De Monte, C. Cotté, R. Morrow J. Isern-Fontanet E. Hernandez-Garcia, A. Despres, G. Reverdin, S. Alvain

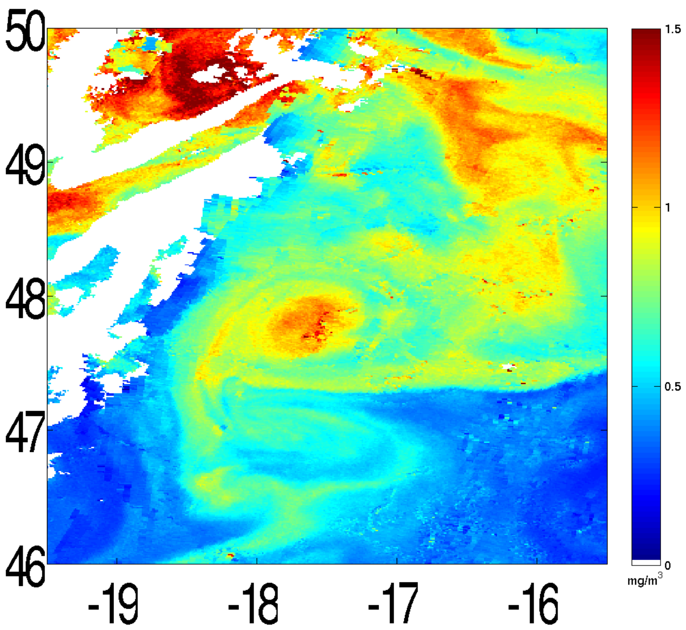
MOTIVATION

Importance of the (sub-)mesoscale:

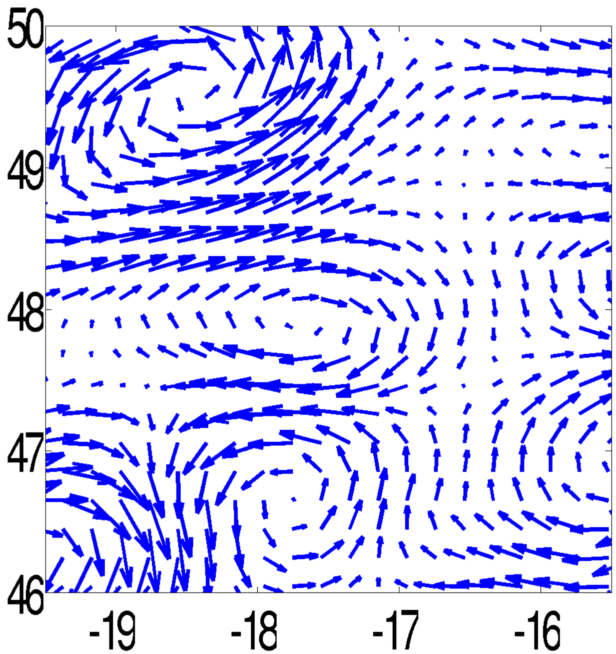
1. submesoscale not resolved by global circulation models and global observation networks
What processes are we neglecting in global budgets? (when/where?)

2. same temporal variability as plankton ecology
“Resonant” biophysical regime

3. same temporal variability as in situ survey
How can we overcome this synopticity problem?



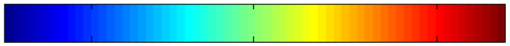
Limit: coverage (clouds)



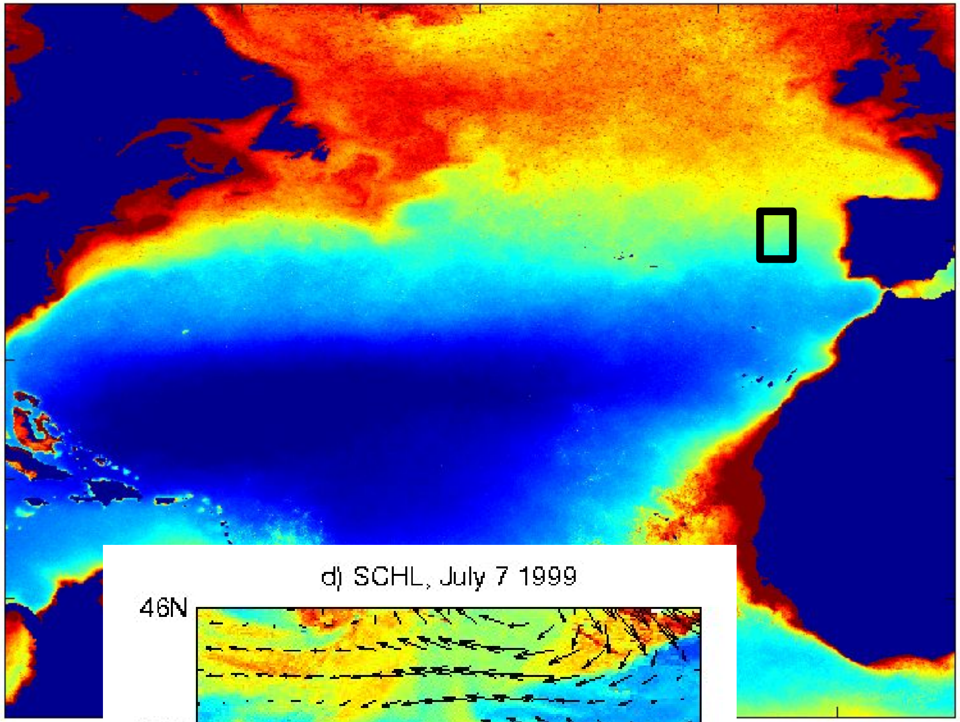
Limit: spatial/temporal resolution

Plankton patchiness

SeaWiFS chlorophyll

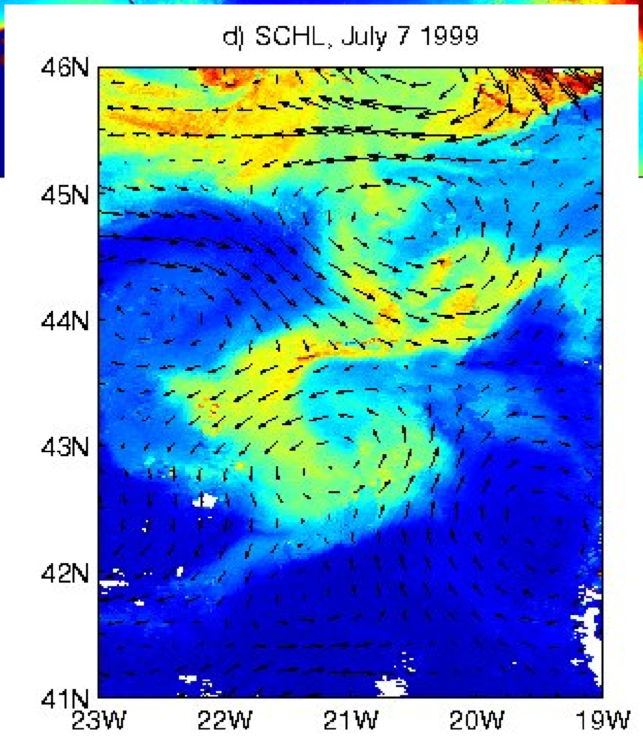


1000 km



Large scale variability
North Atlantic
(1998-2003, mean)

100 km



Meso/submeso
scale patterns
Northeast Atlantic
(daily images)

OUTLINE

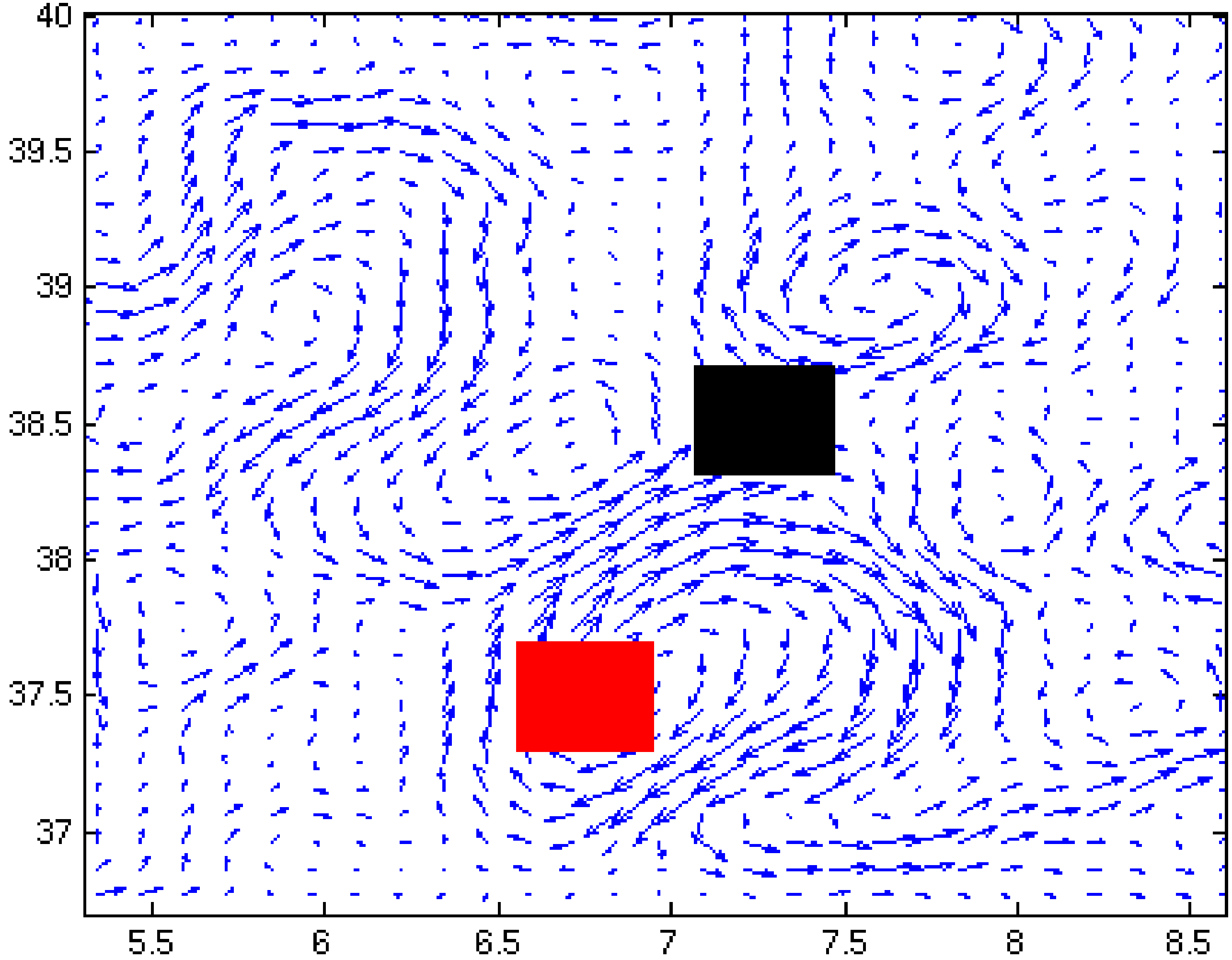
1. Stirring from altimetry: Lyapunov exponents and vectors
- the role of mesoscale temporal variability
- reconstruction of chaotic stirring by Lyapunov analysis
- kinematic vs. tracer fronts

2. Validation
- satellite SST
- In situ

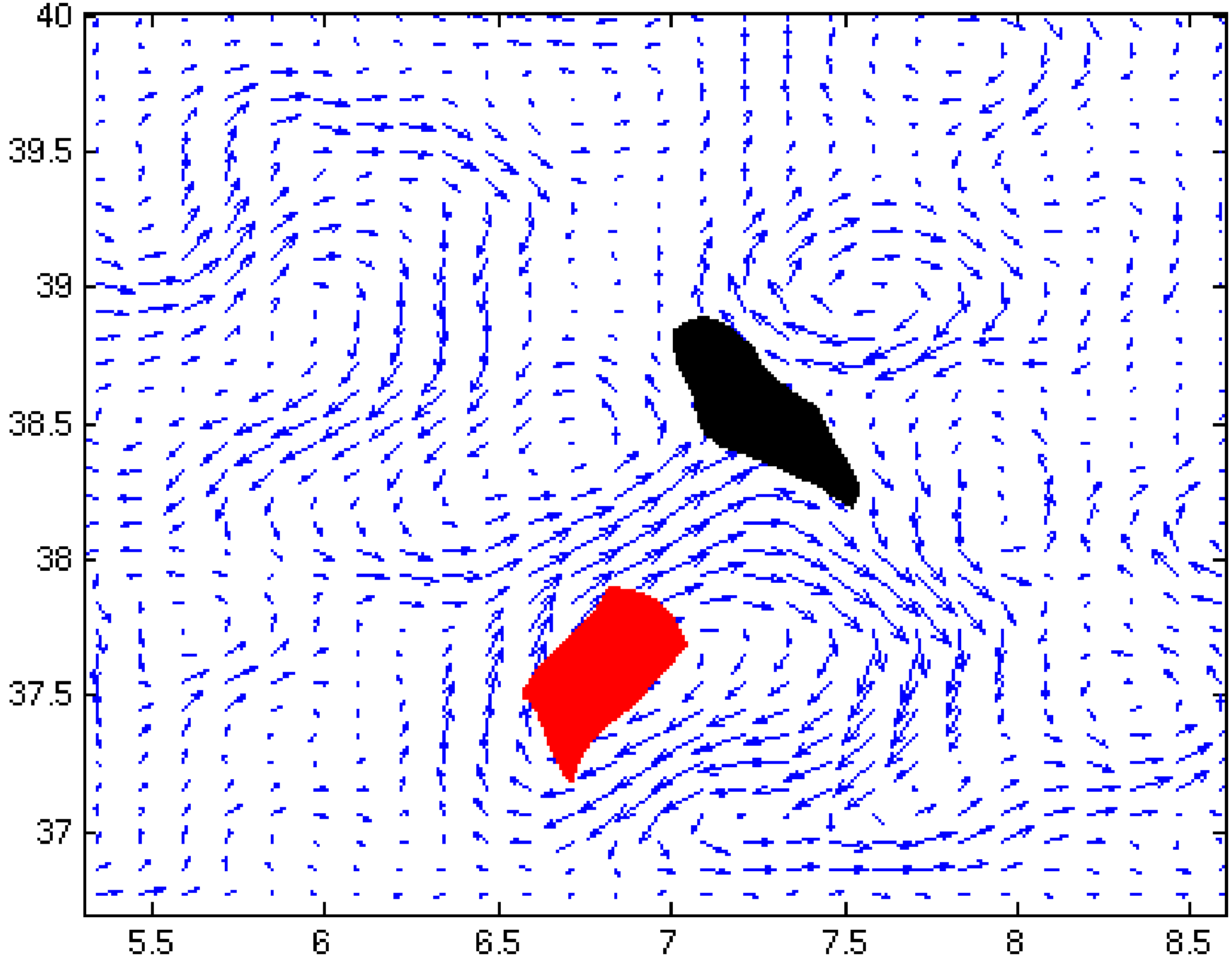
2. Example of application
- Fluid dynamical niches
- megacosm experiments

A slightly more realistic example: a numerical tracer stirred by altimetric velocities

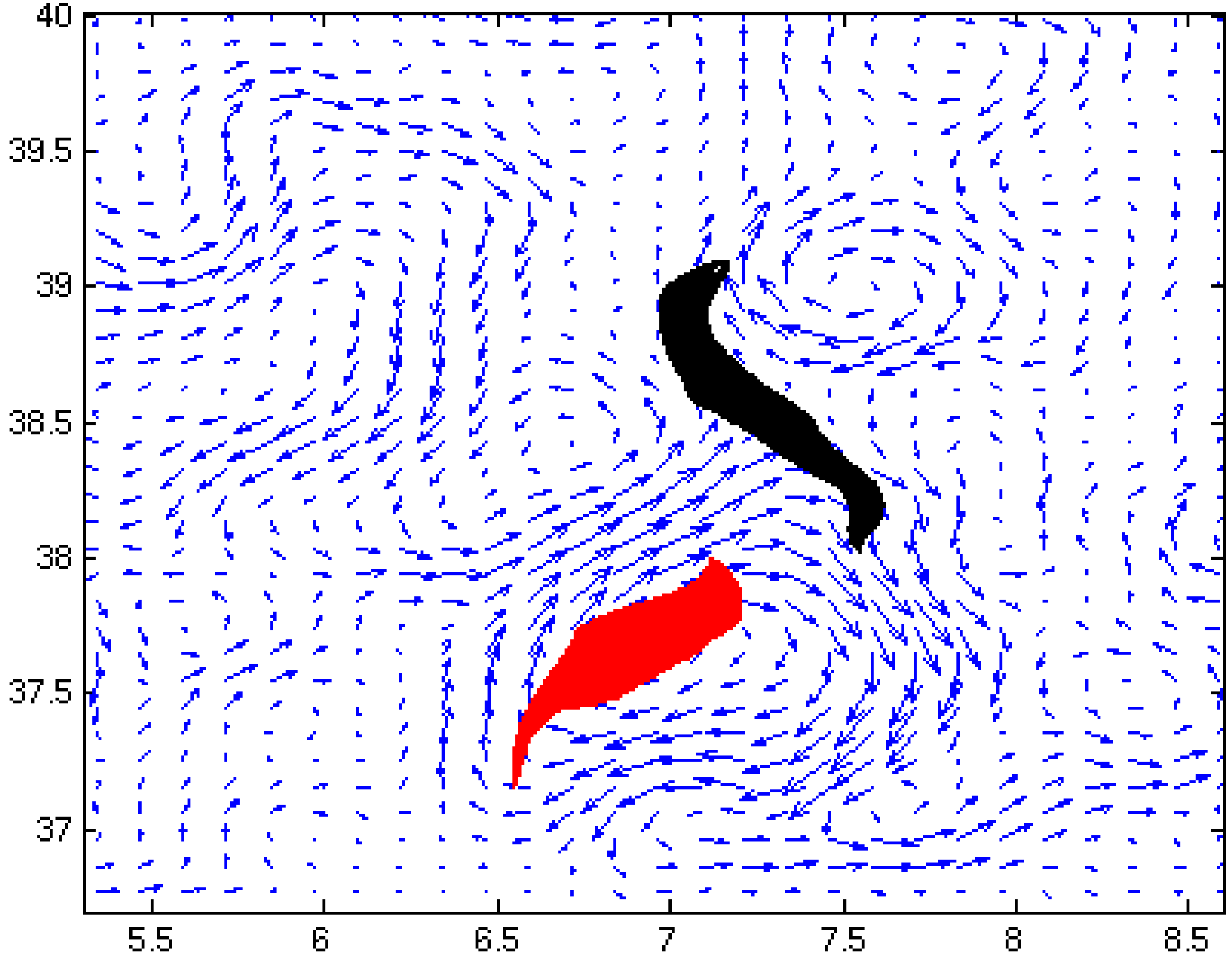
day 1



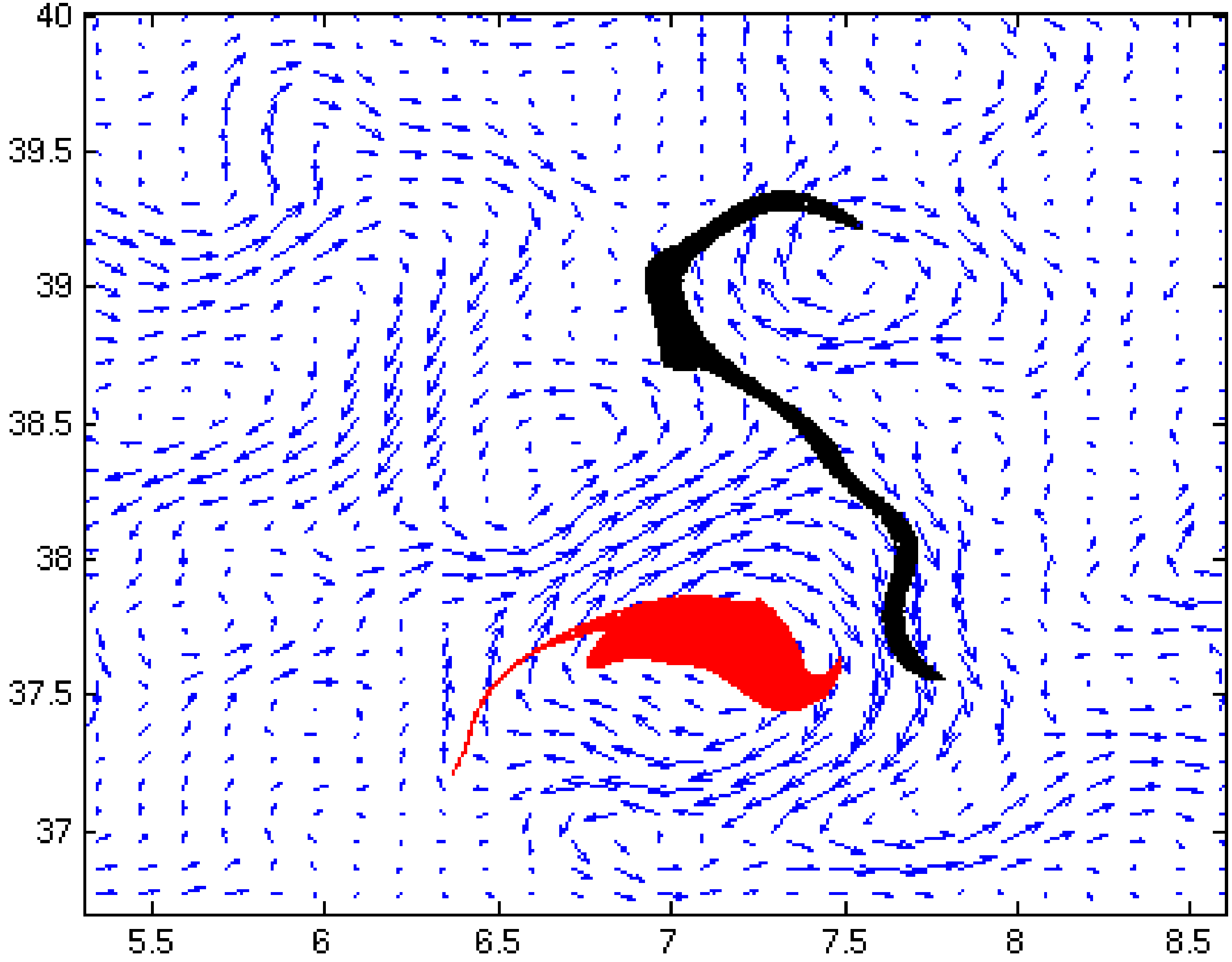
day 2



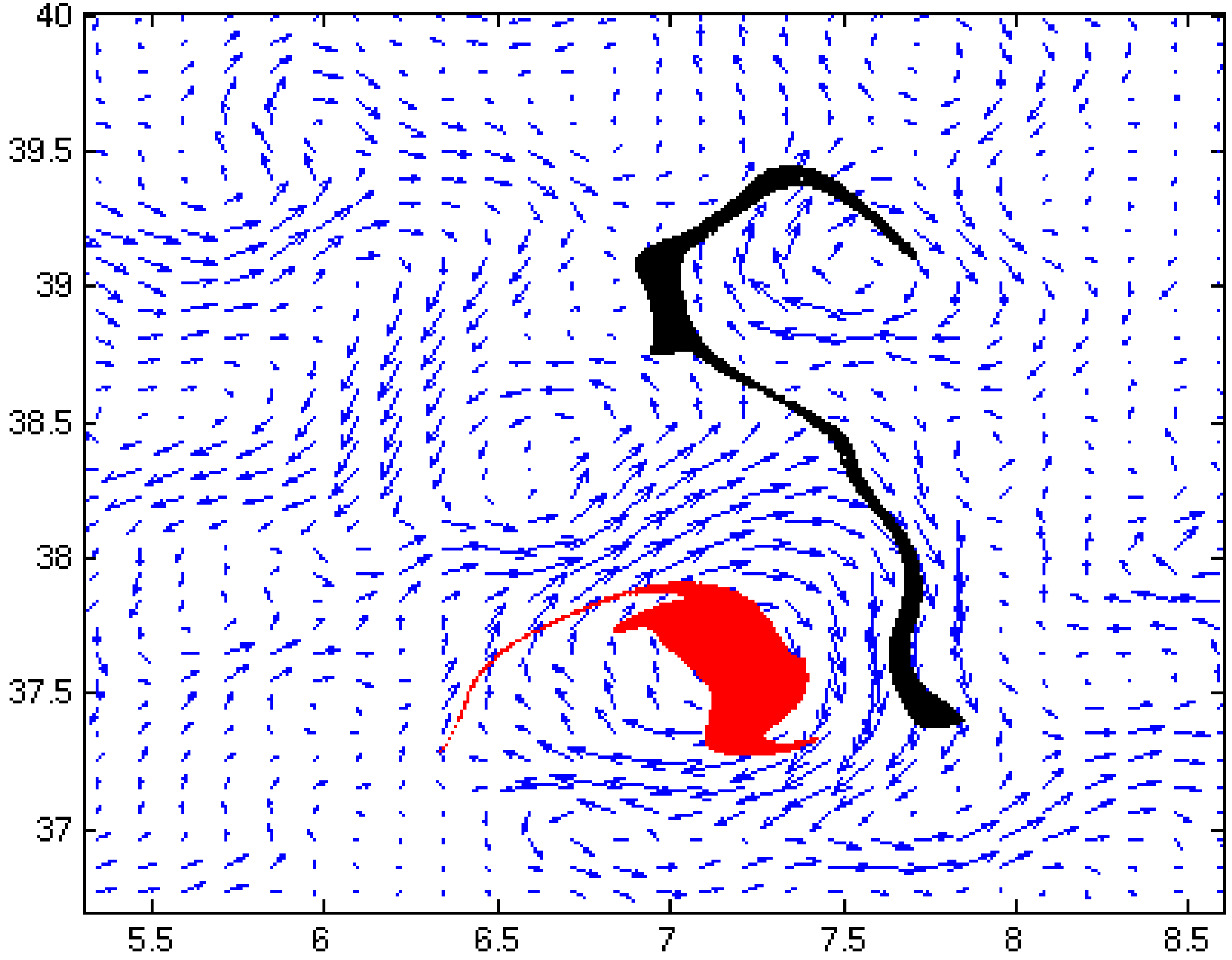
day 3



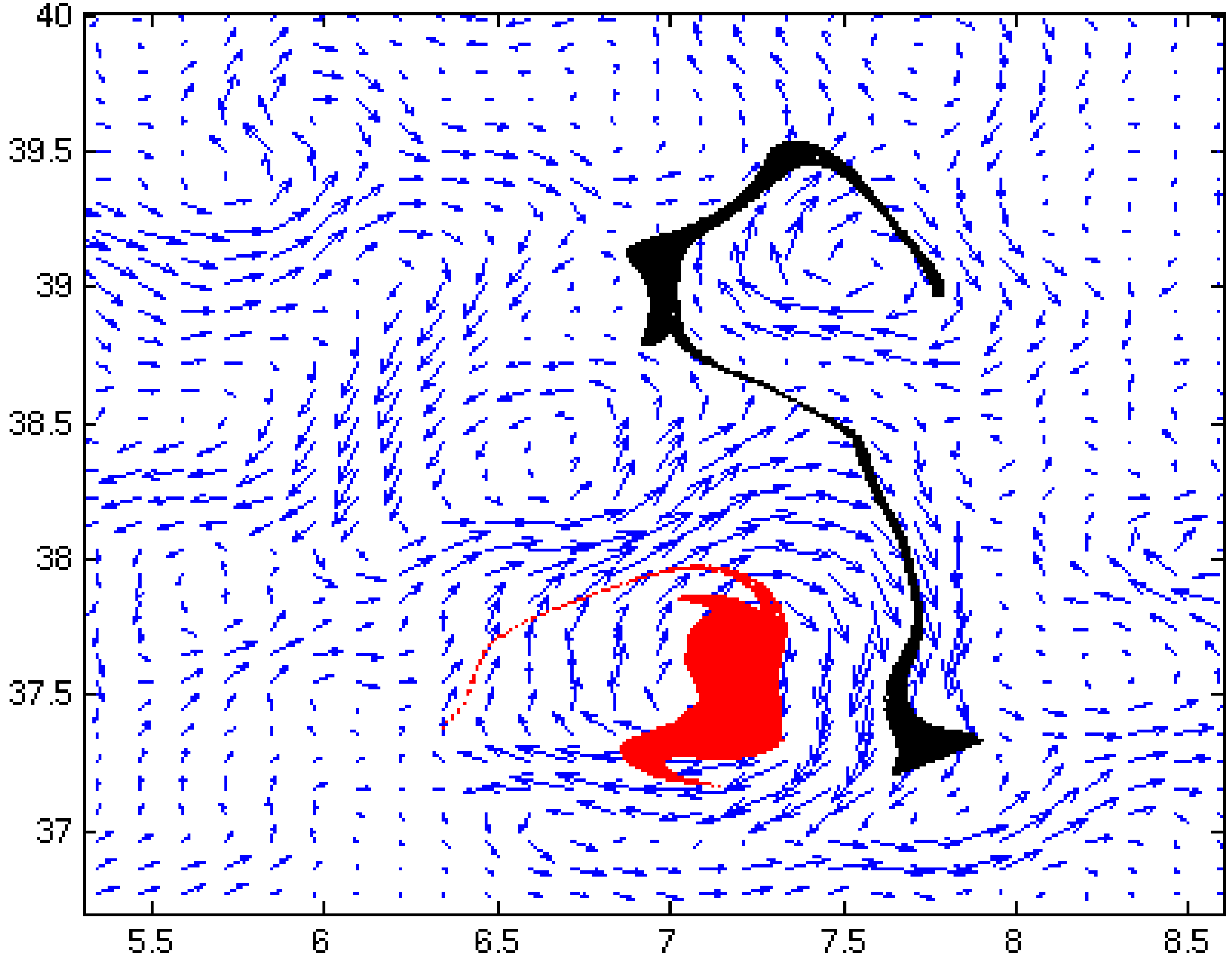
day 4



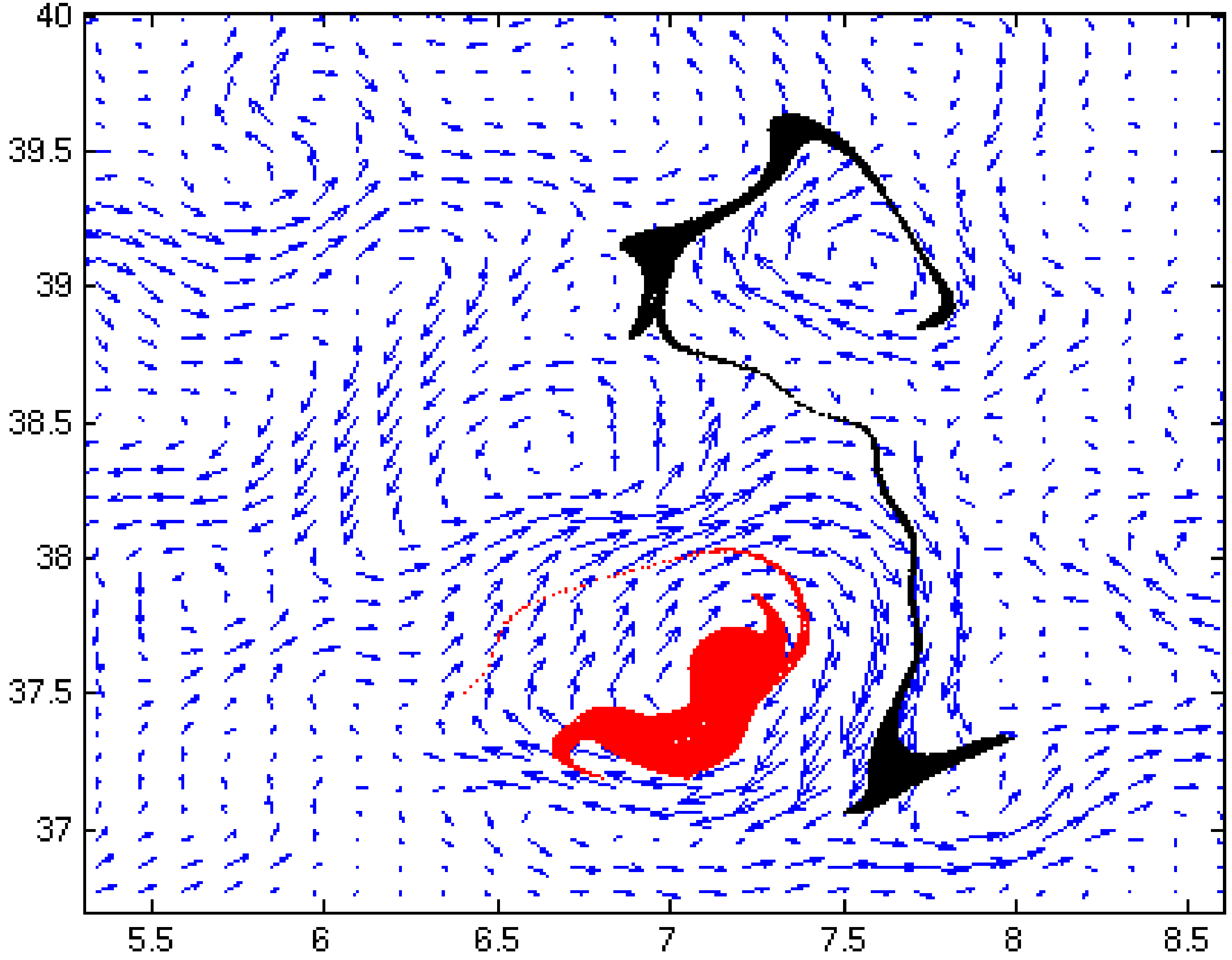
day 5



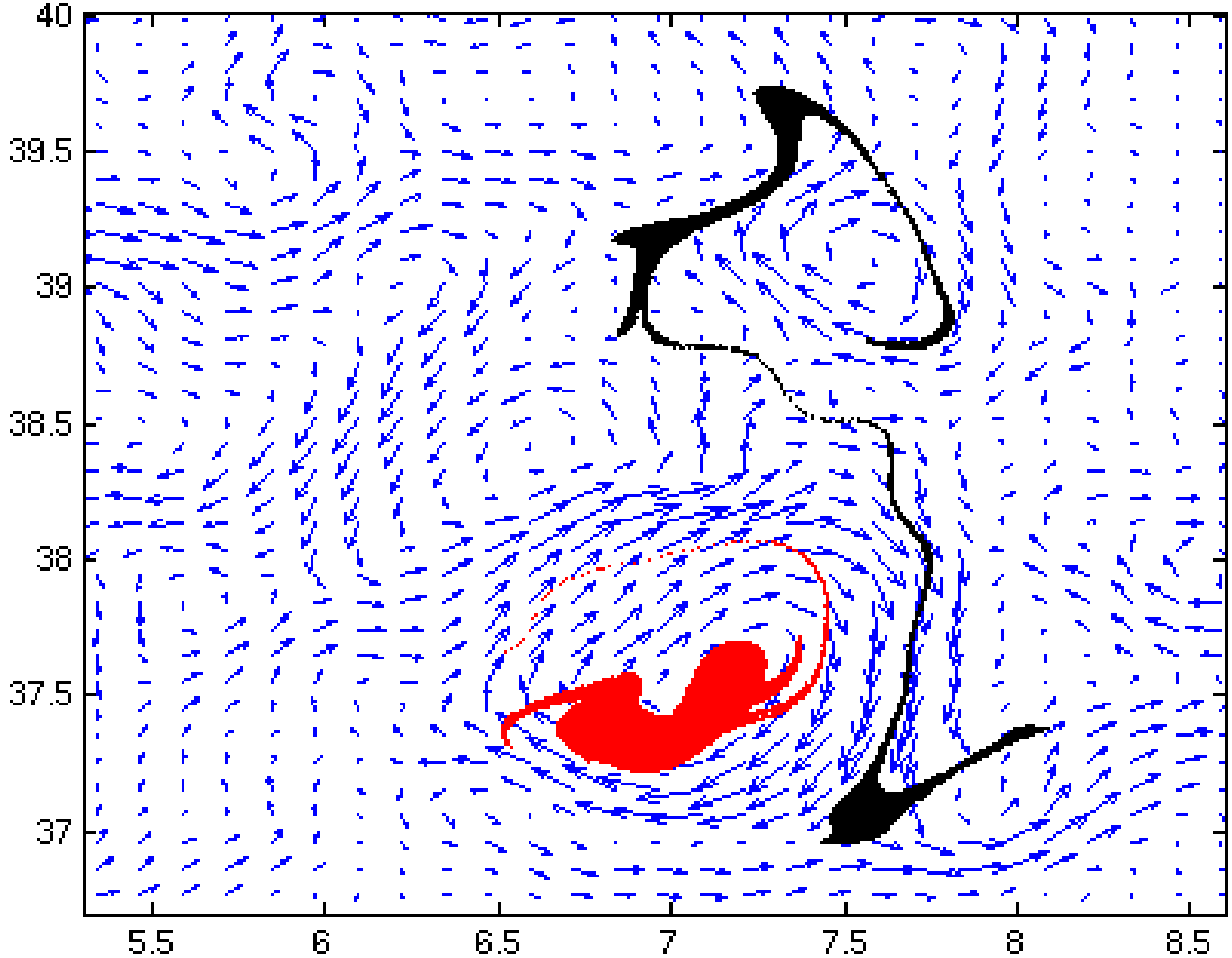
day 6



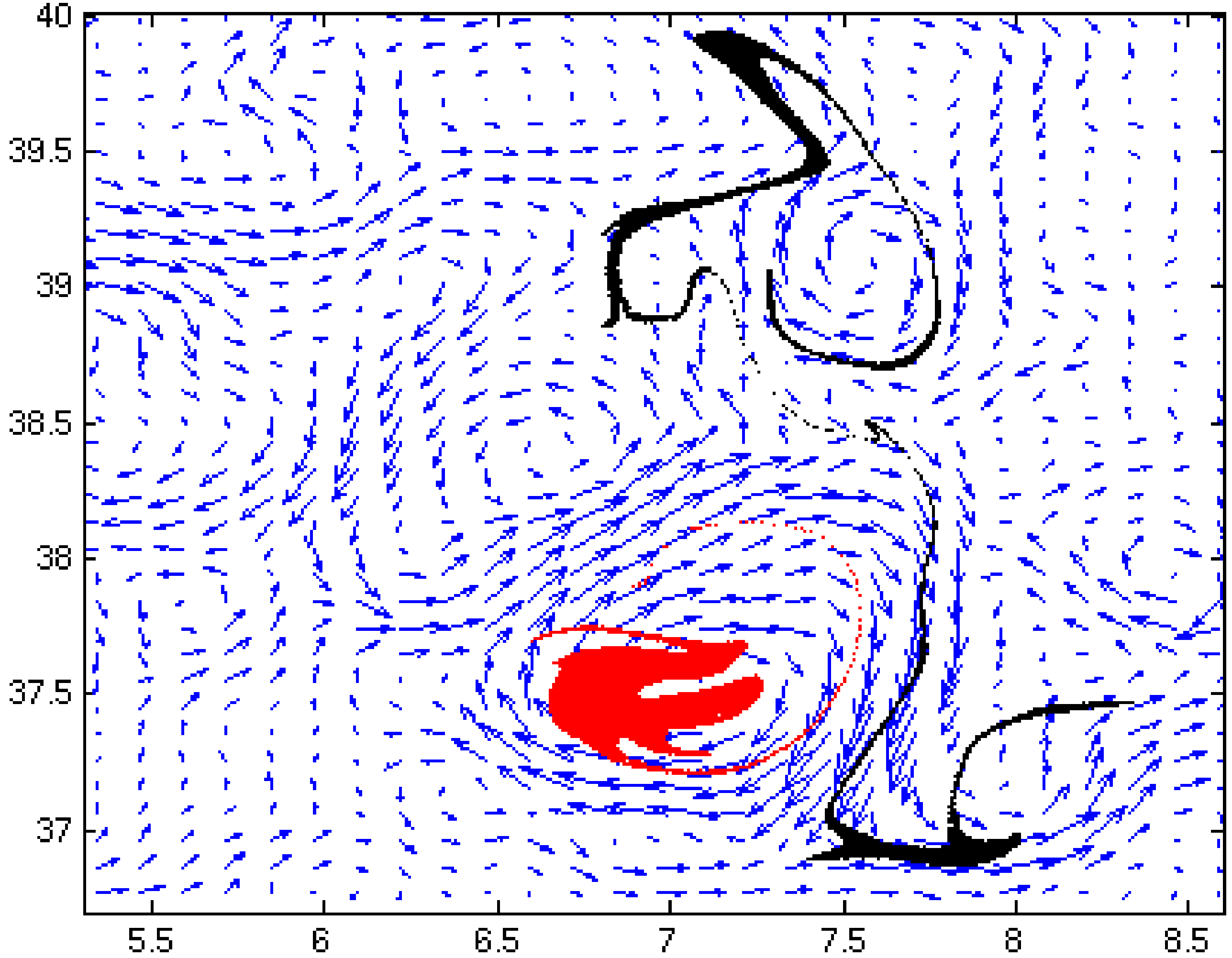
day 7



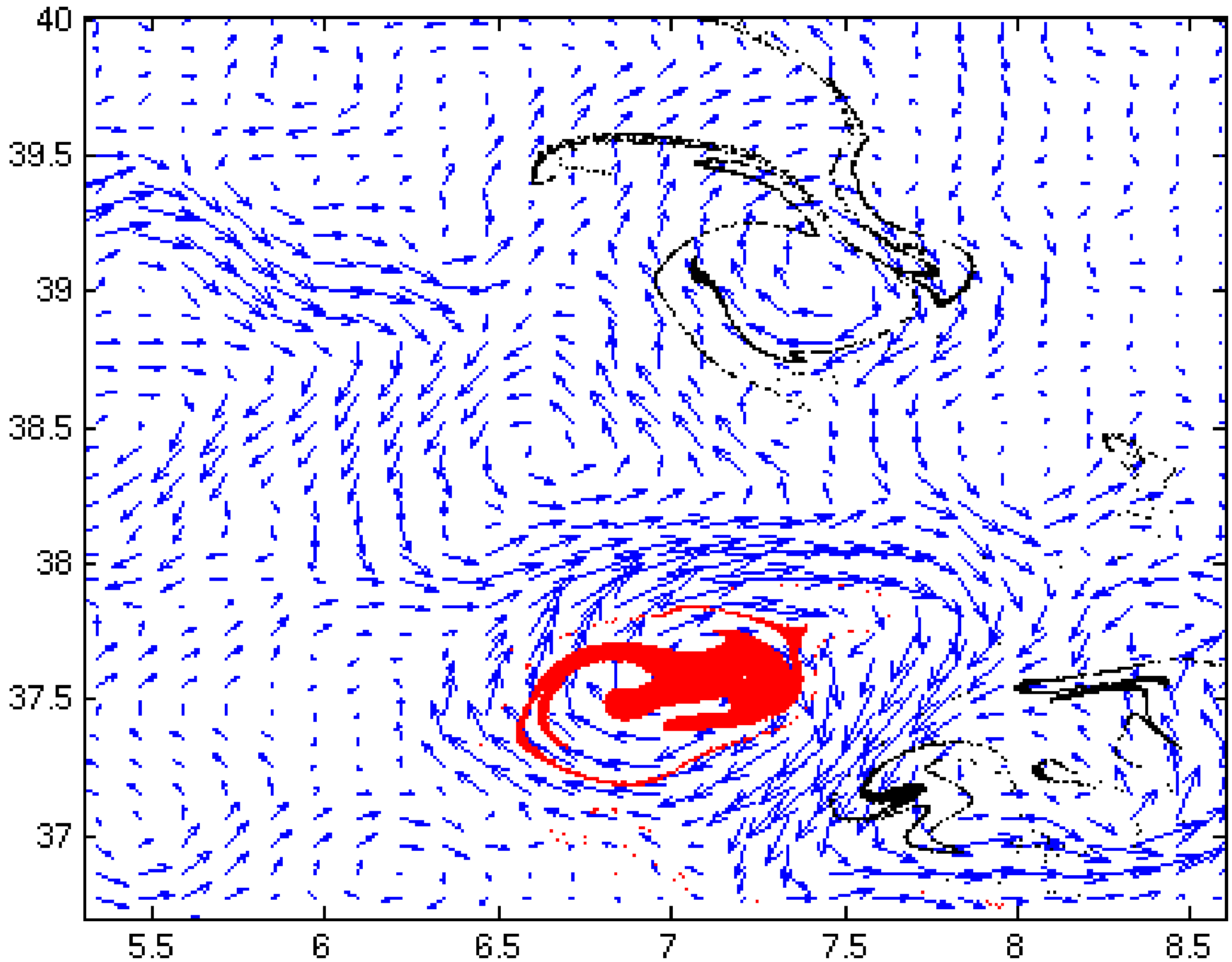
day 8

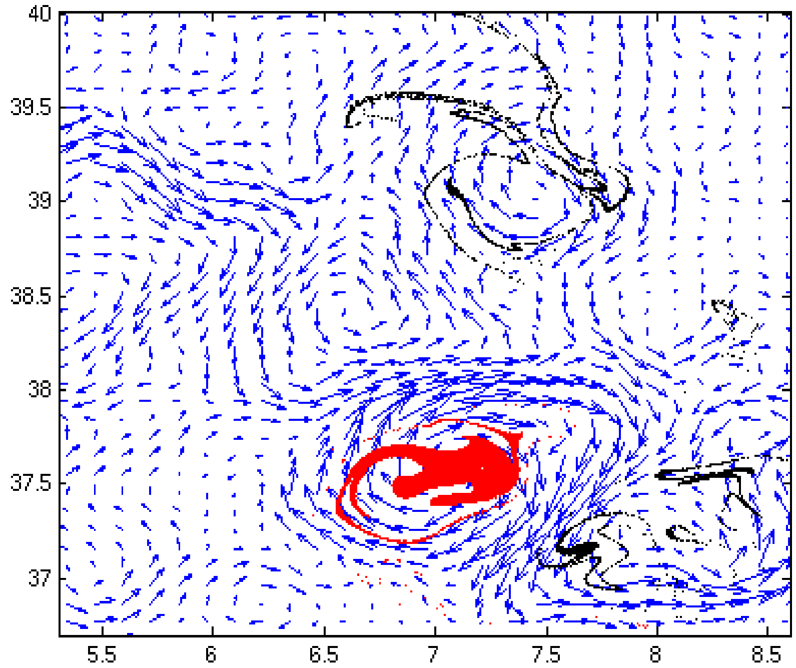


day 9



day 20





A mesoscale velocity field is able to generate submesoscale filaments

These tracer filaments do not align necessarely with the instantaneous streamlines.

These tracer filaments are reminiscent of SST and CHL patches

How can we detect tracer fronts? -> Lyapunov analysis

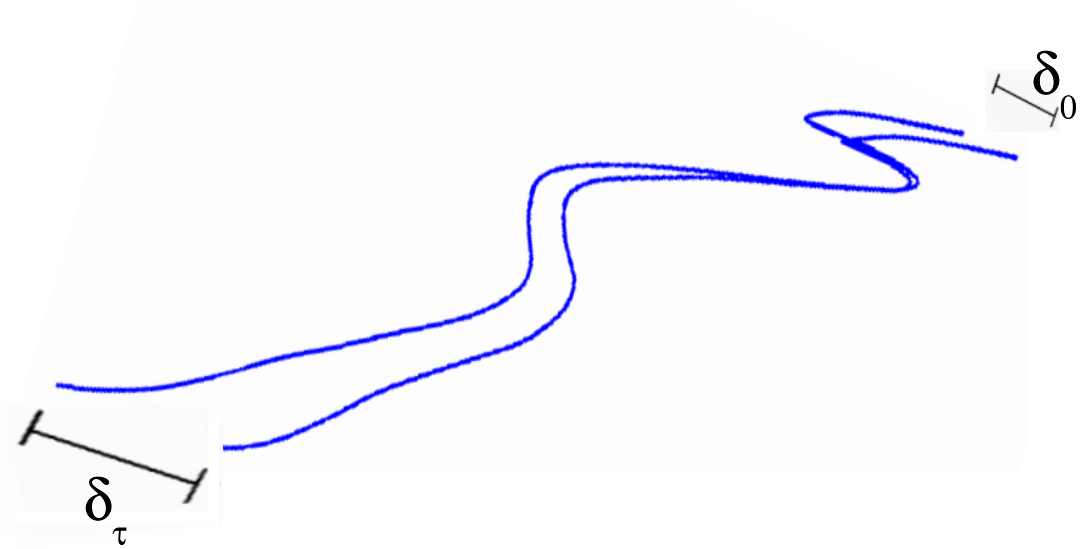
Finite Size Lyapunov Exponents (FSLEs)

$$\lambda = \frac{1}{\tau} \log (\delta_\tau/\delta_0)$$

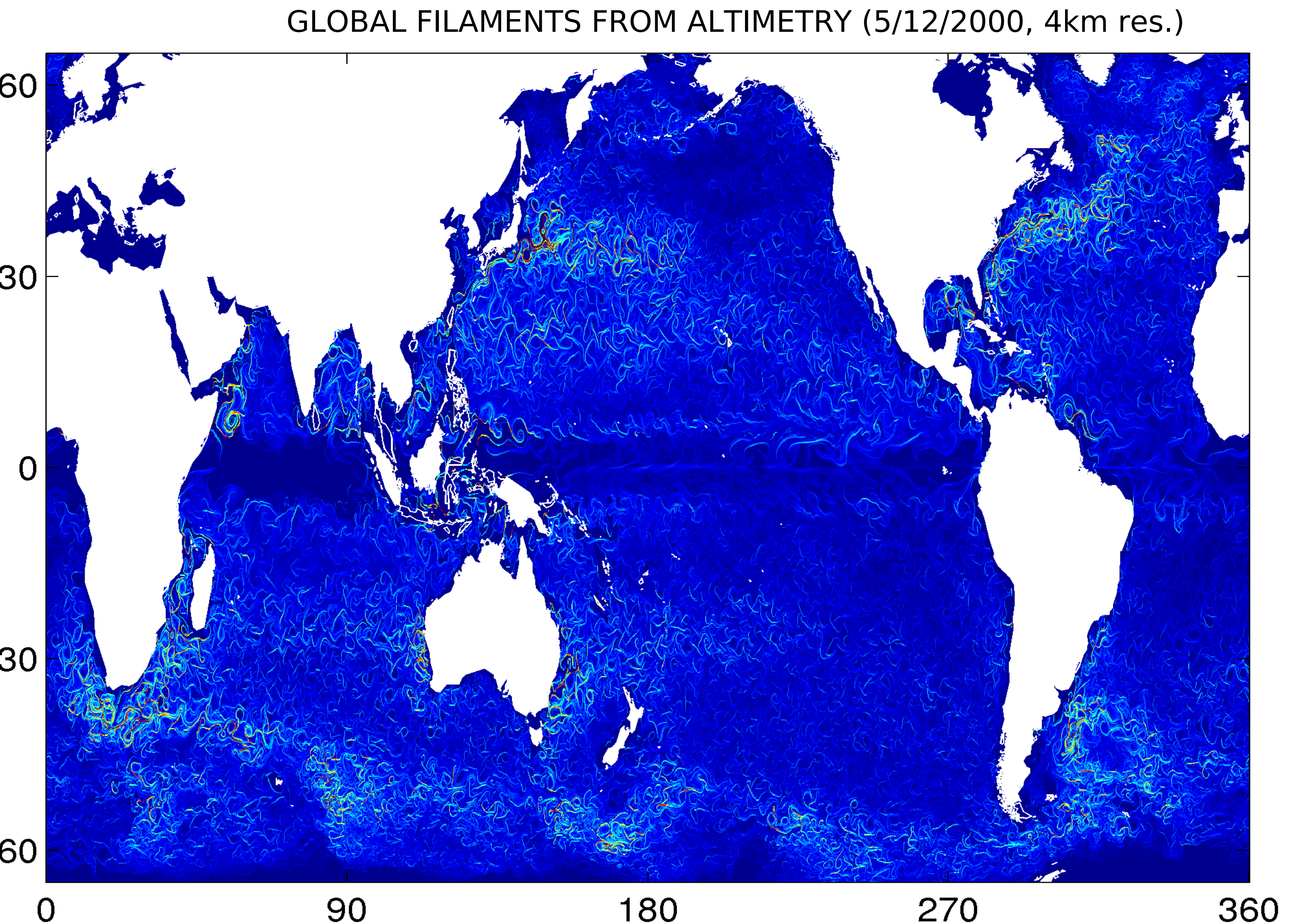
δ_0 - initial separation

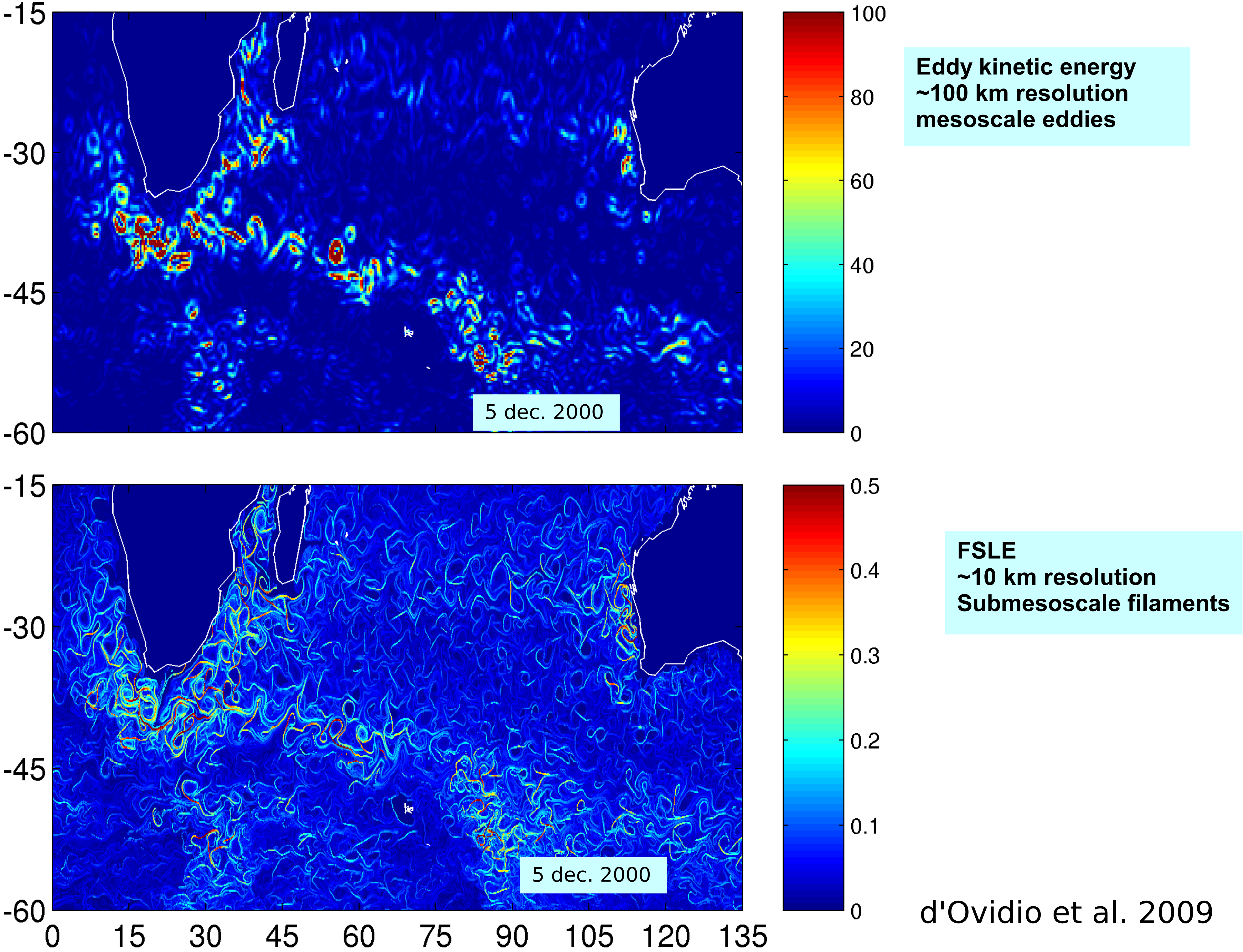
δ_τ - separation after time τ

τ - time needed for the separation to grow from δ_0 to δ_τ

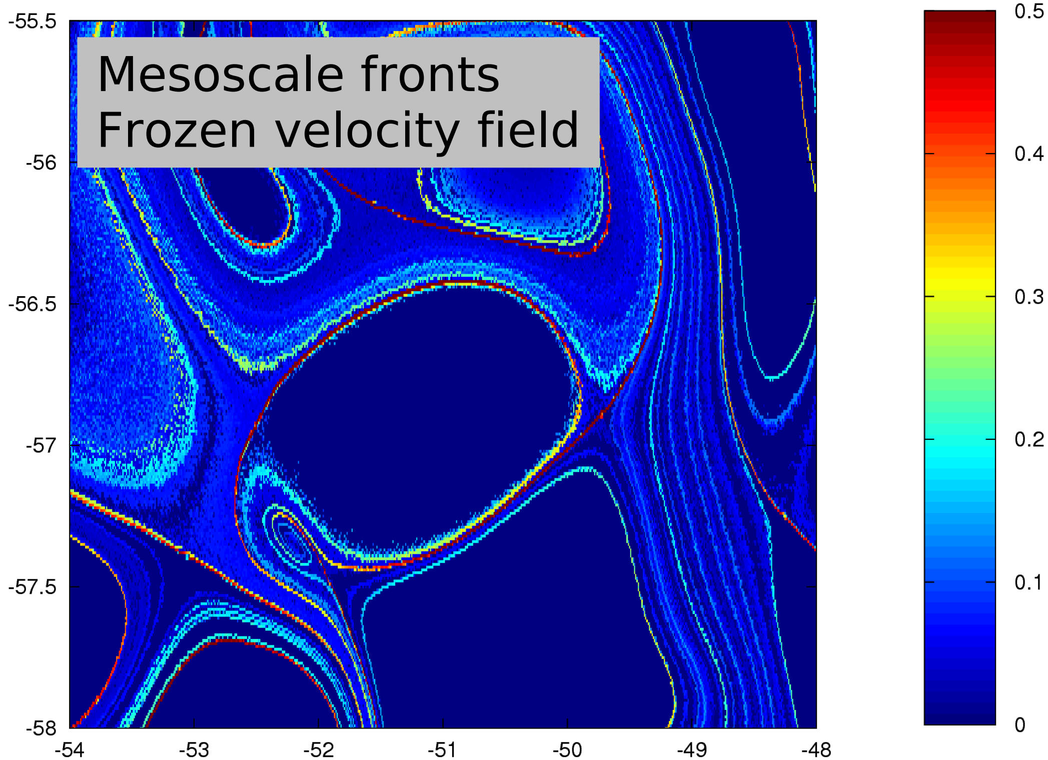


Aurell et al., Phys. Rev. Lett. **77**, 1262 (1996)
Boffetta et al., J. of Phys. A, **30**, 1 (1997) chao-dyn/9904049


GLOBAL FILAMENTS FROM ALTIMETRY (5/12/2000, 4km res.)
60
30
0
30
60
0
90
180
270
360



d'Ovidio et al. 2009

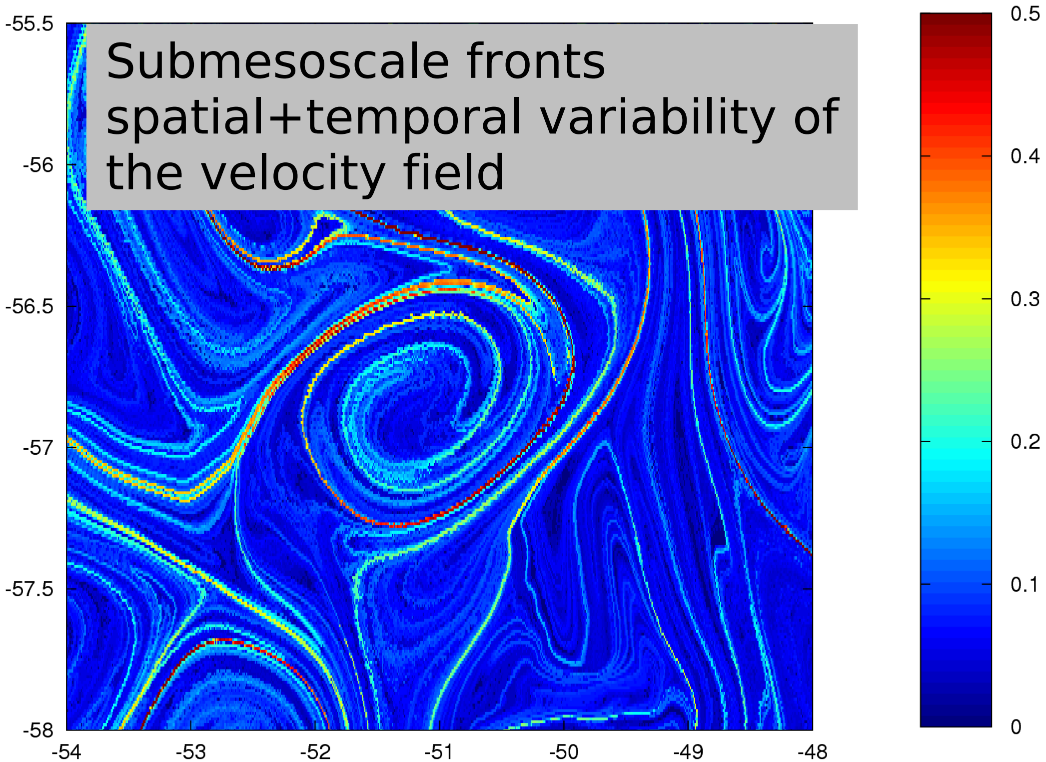


THE ROLE OF THE MESOSCALE TEMPORAL VARIABILITY

A two dimensional velocity field **without temporal** variability does not create filaments:

- eddy cores are perfectly isolated

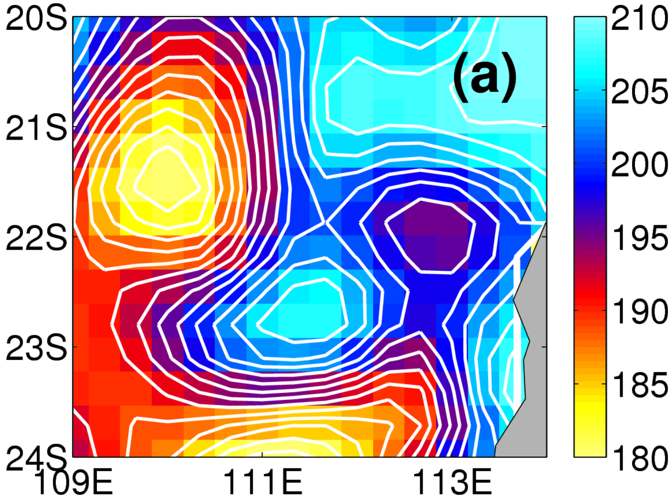
- tracer fronts and Lyapunov ridges become aligned to SSH isolines



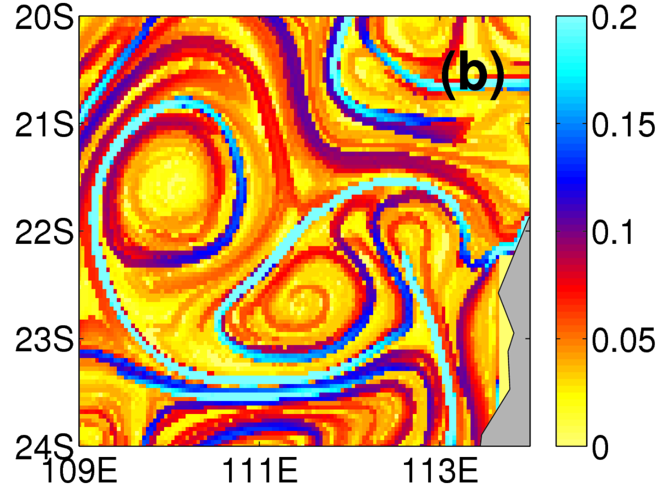
Lehahn et al. JGR 2007

FRONT ORIENTATION

SSH

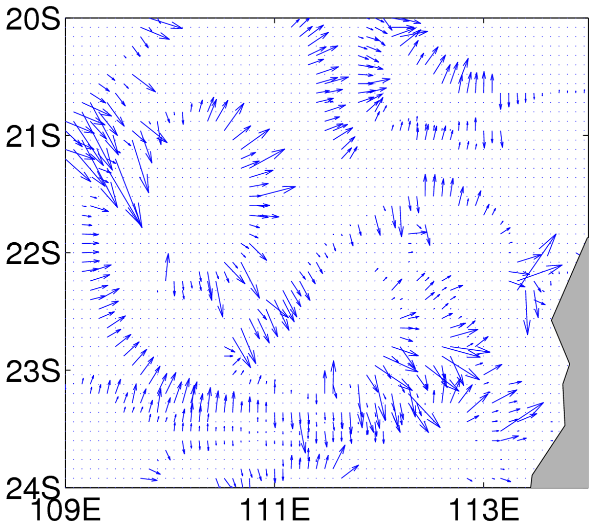


Lyapunov exponents

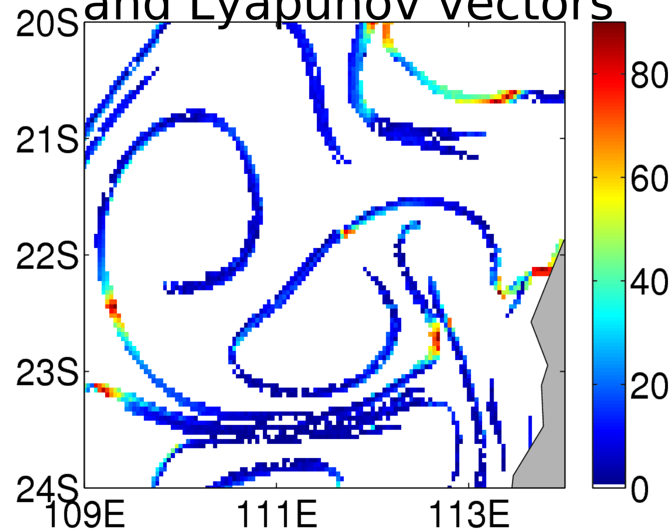


The Lyapunov exp. detects cross-streamline fronts connecting different eddies.

Lyapunov vectors

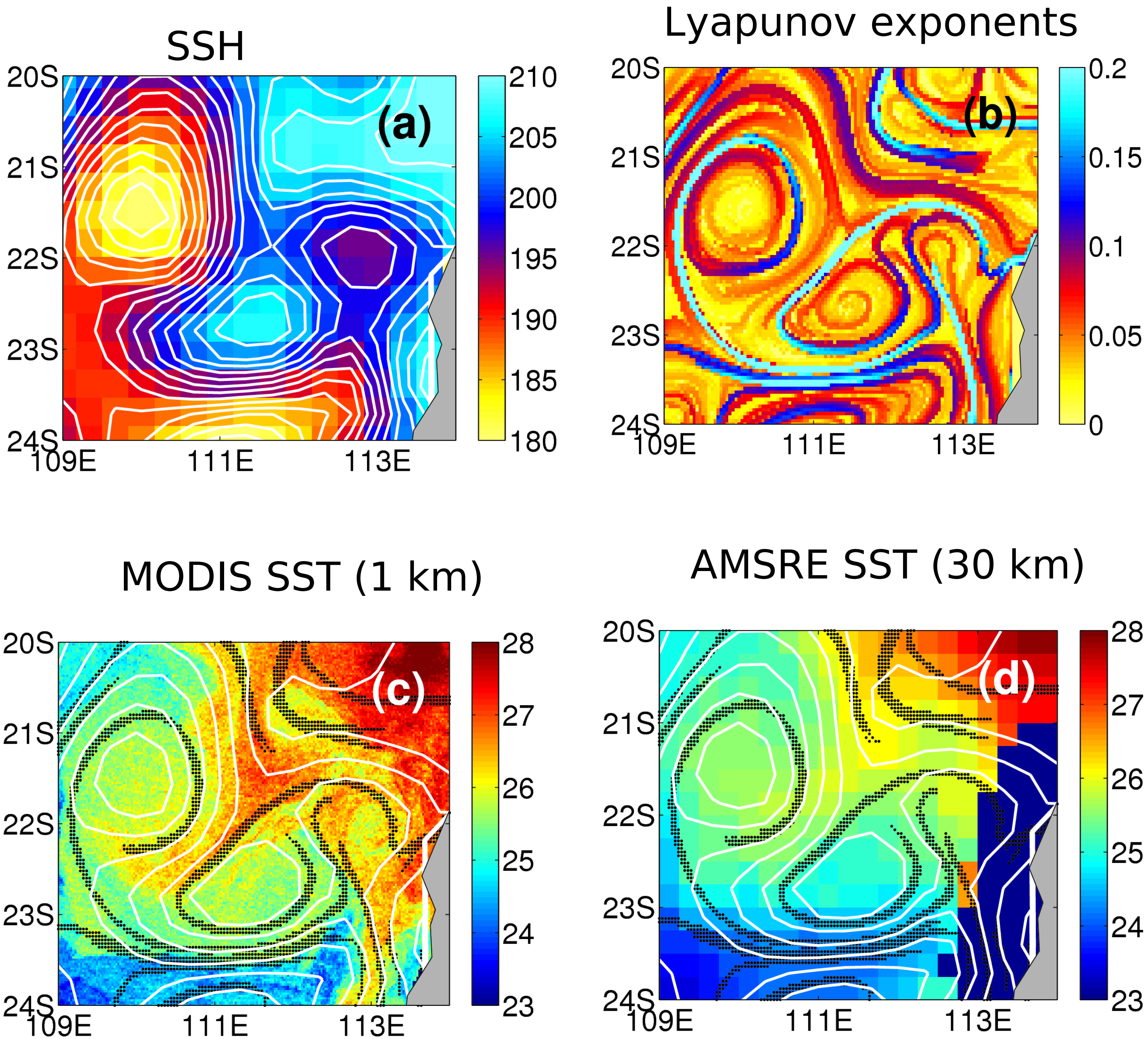


Angle between streamlines and Lyapunov vectors



The cross-streamline points can be found with Lyapunov vectors

FRONT ORIENTATION



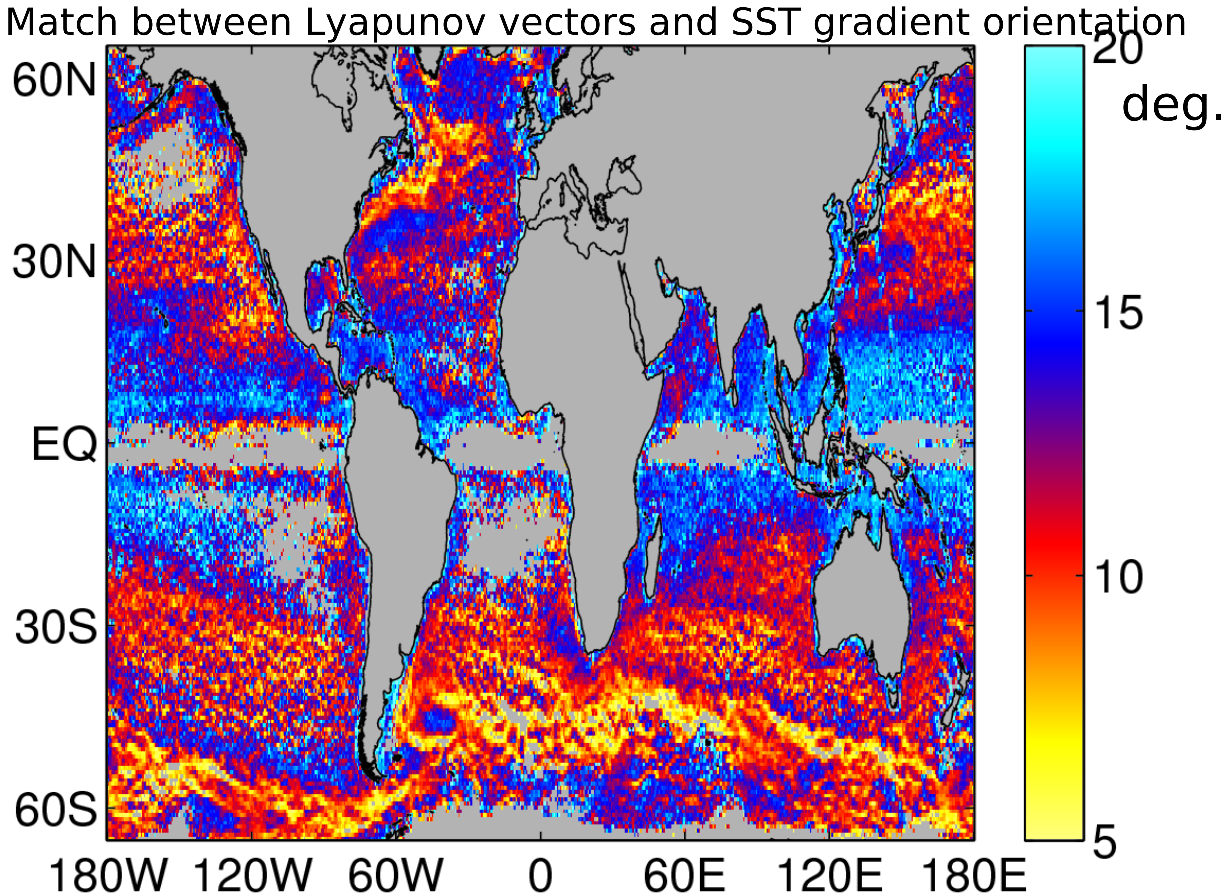
The Lyapunov exp. detects cross-streamline fronts connecting different eddies.

SST patterns seems to agree more with LE lines (black) than with streamlines (white)

-> global comparison

GLOBAL VALIDATION OF LYAPUNOV FRONT ORIENTATION

altimetry-derived Lyapunov exp. and vectors
res: 4 km resolution, 6 day
Compared with AMSRE SST gradient orientation



Good overall agreement (< 20 deg. on the average)
Best agreement over high EKE regions

Are Lyapunov vectors better than streamlines?

GLOBAL VALIDATION OF LYAPUNOV FRONT ORIENTATION

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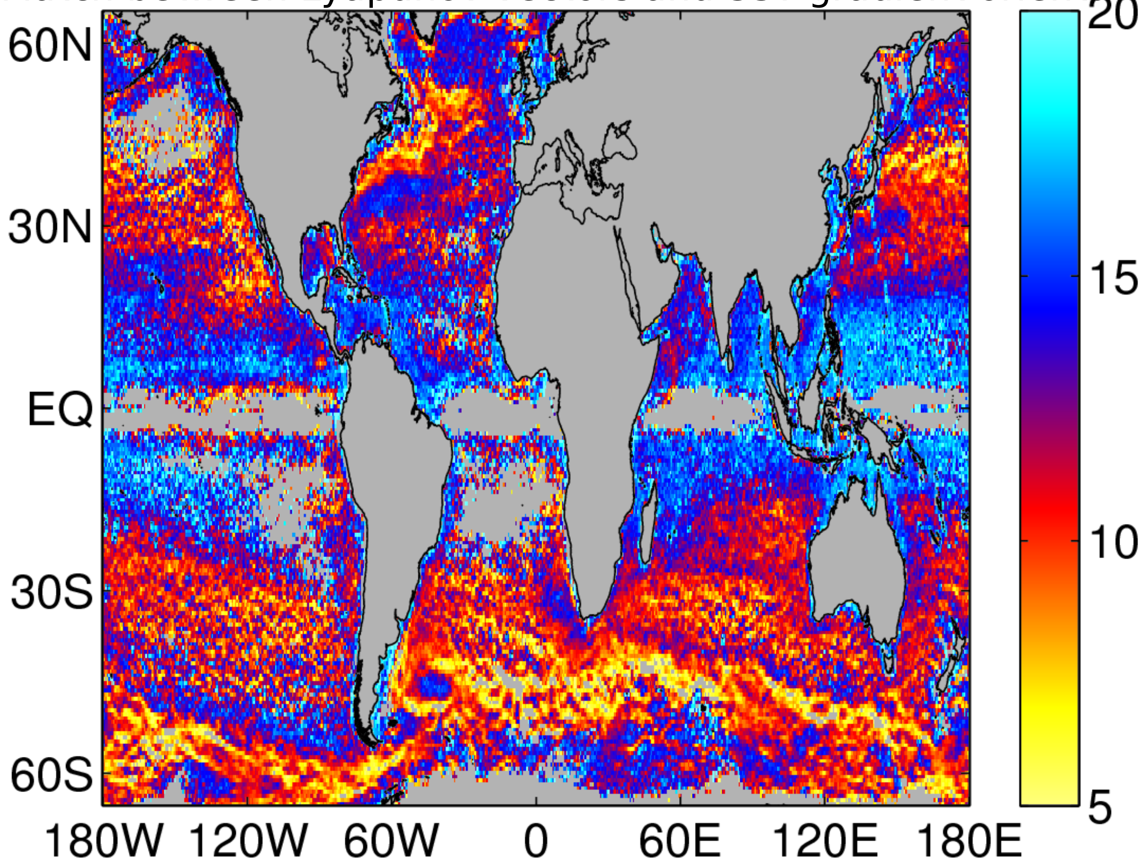
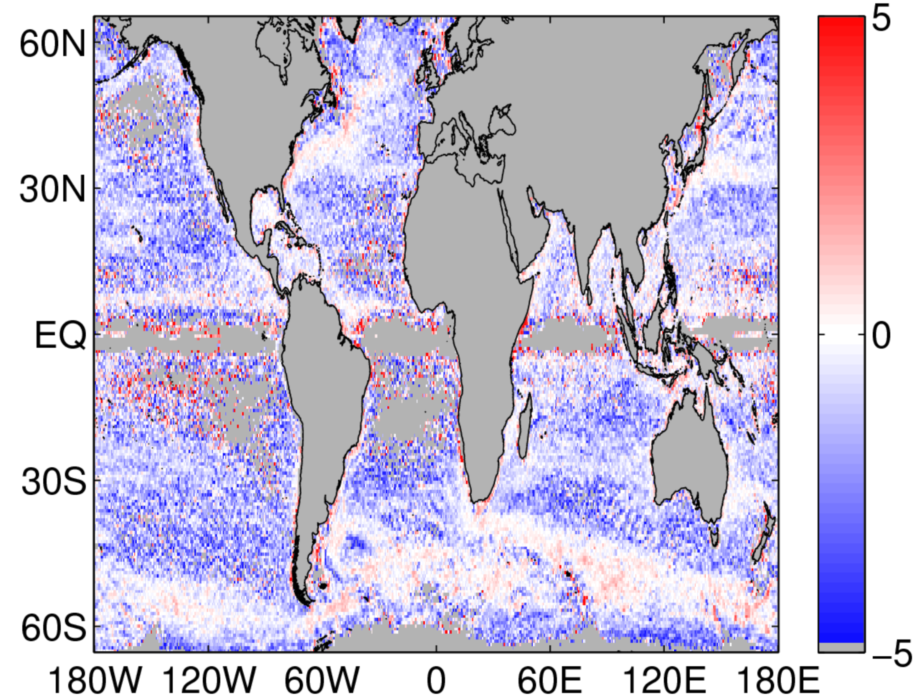
Match between Lyapunov vectors and SST gradient orientation



SSH/SST match - Lyapunov/SST match



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Are Lyapunov vectors better than streamlines?
Yes! Gain up to 5 deg.

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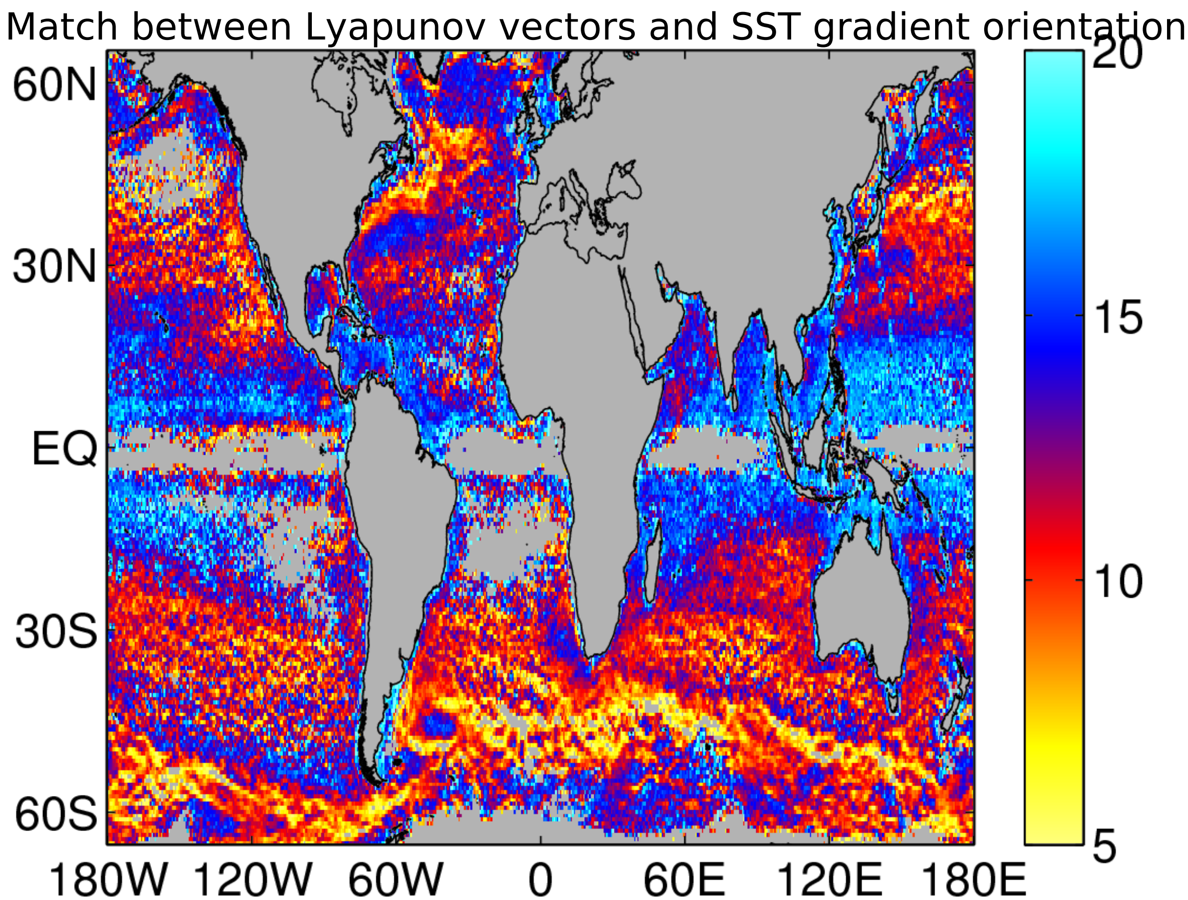

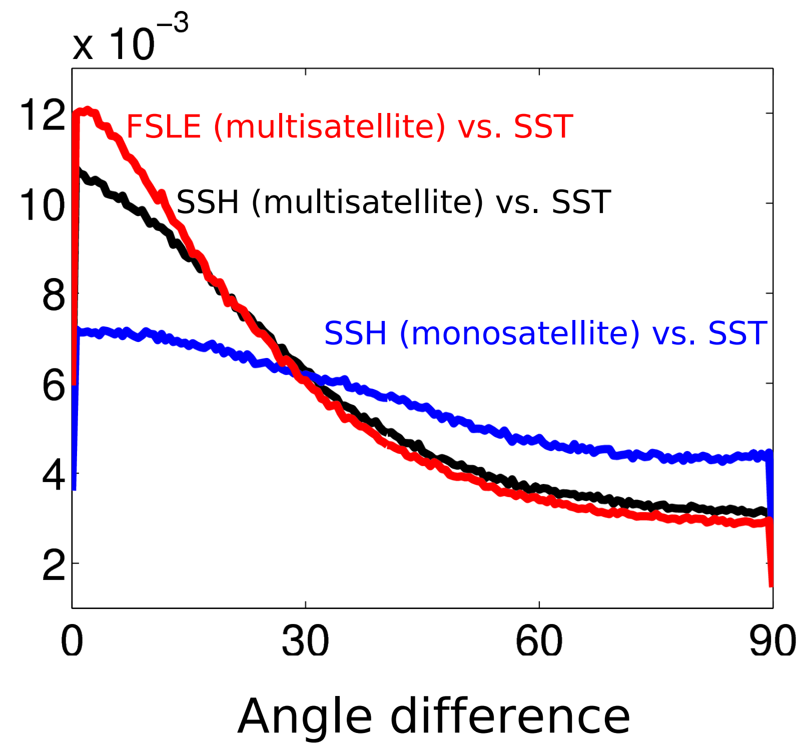

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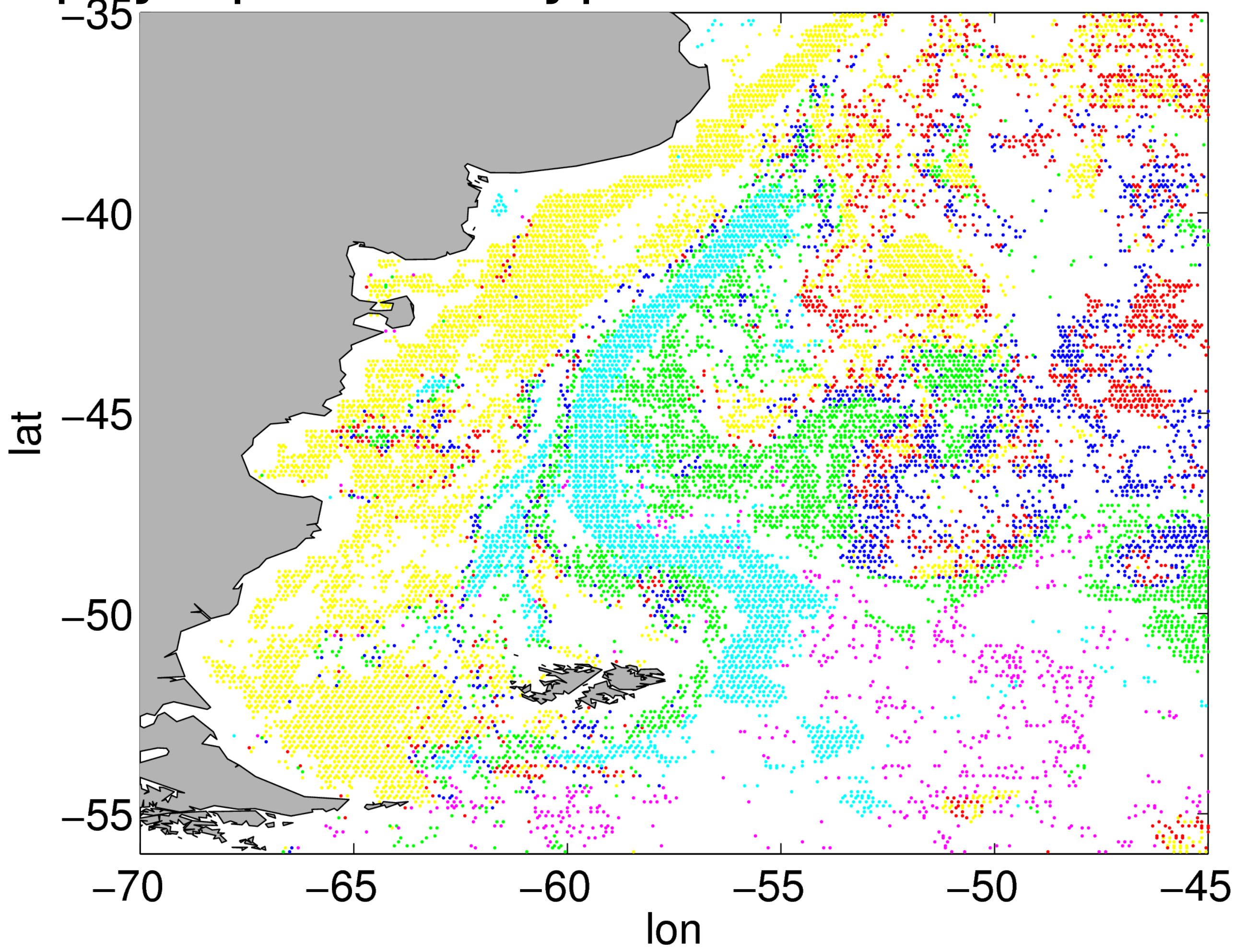
Yes! Gain up to 5 deg.

2. Example of application: fluid dynamical niches

Phytoplankton biogeography

Repartition of phytoplankton types in the oceans

Novel satellite products allow to map plankton communities



d'Ovidio et al. PNAS to appear.

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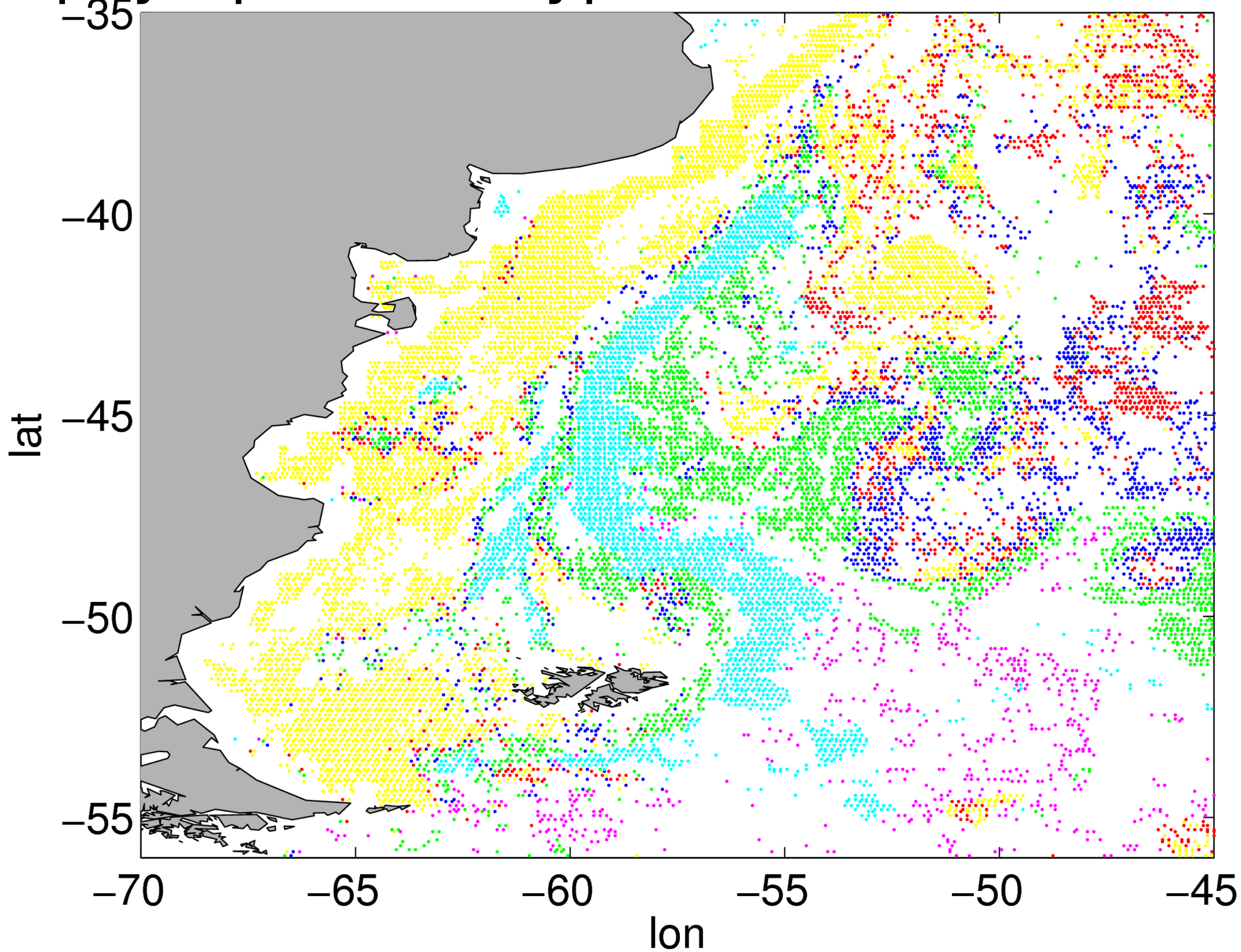
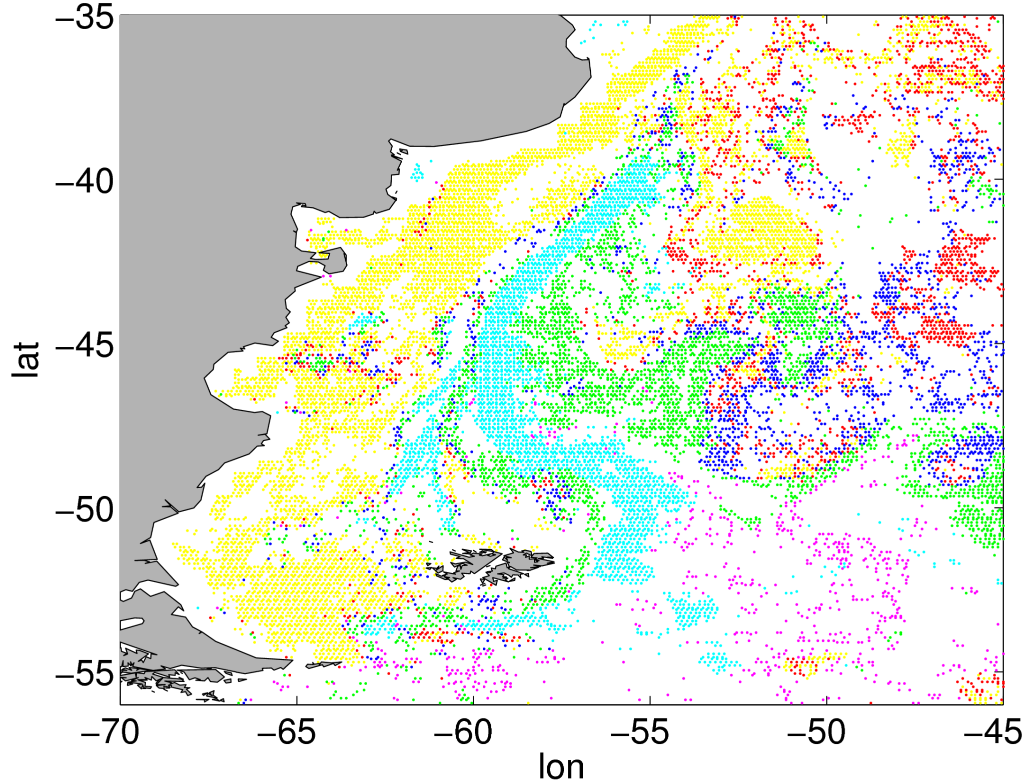


The specific dominant type affects biogeochemical properties and web chains

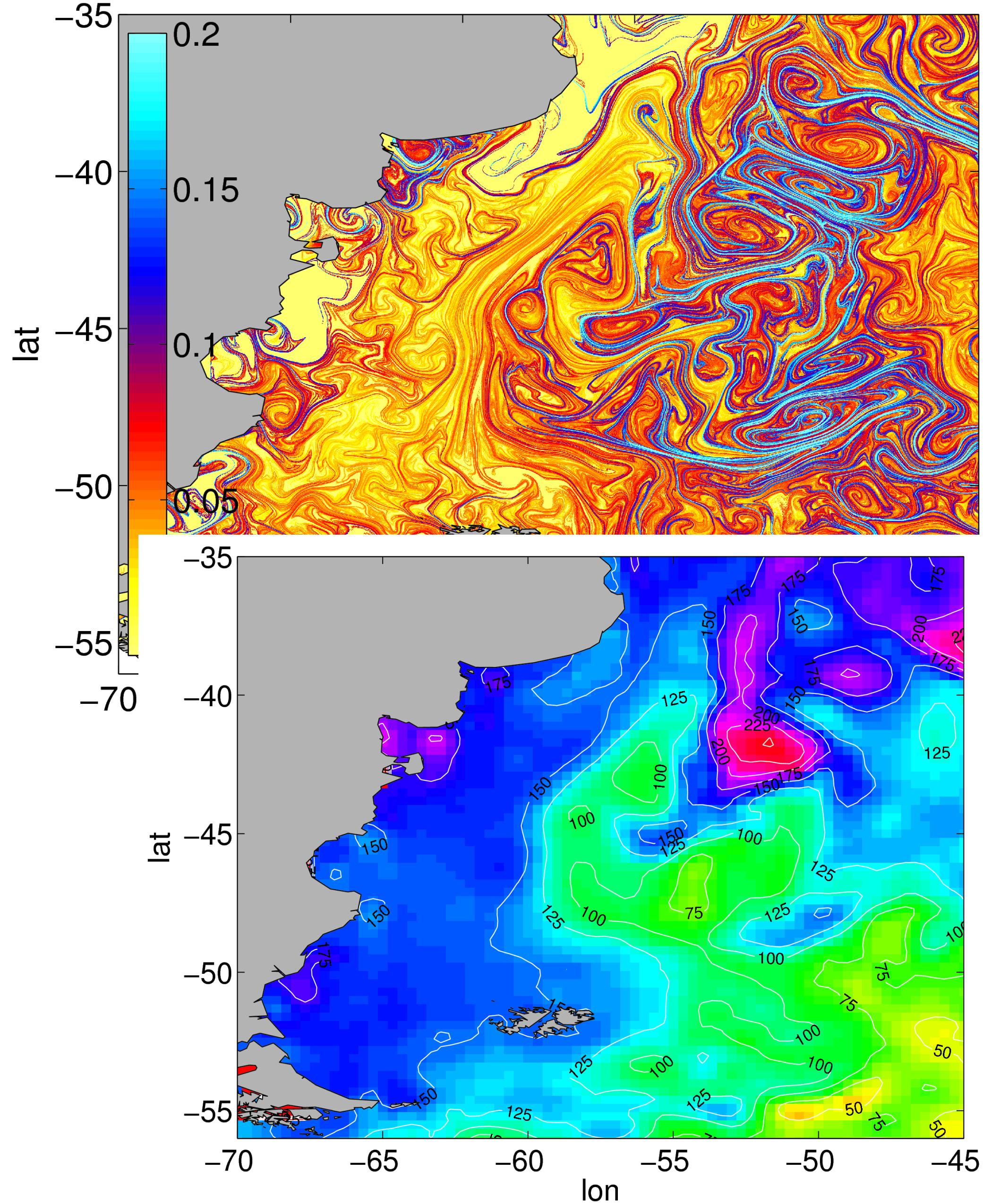
Diatoms -> good CO2 export, grazed by large zooplakton
Nanoeukariotes -> grazed by small zooplakton
Phaeocystis -> produce DMS (atmosphere interaction)
Coccolithophorides -> biocalcification, vulnerable to acidification

Comparison between PHYSAT types and Lyapunov exponents

PHYSAT types (SeaWiFS)



Lyapunov exponents (altimetry)



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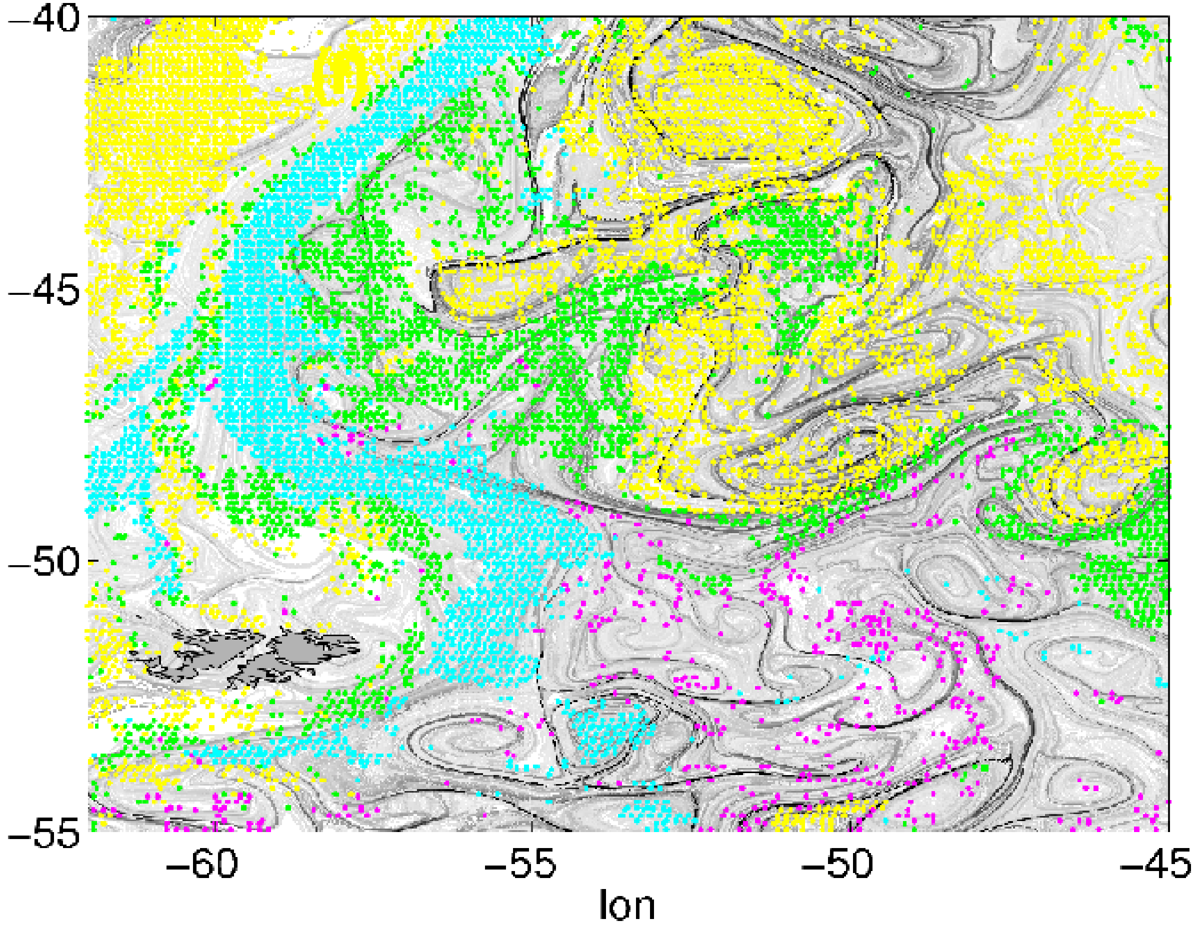
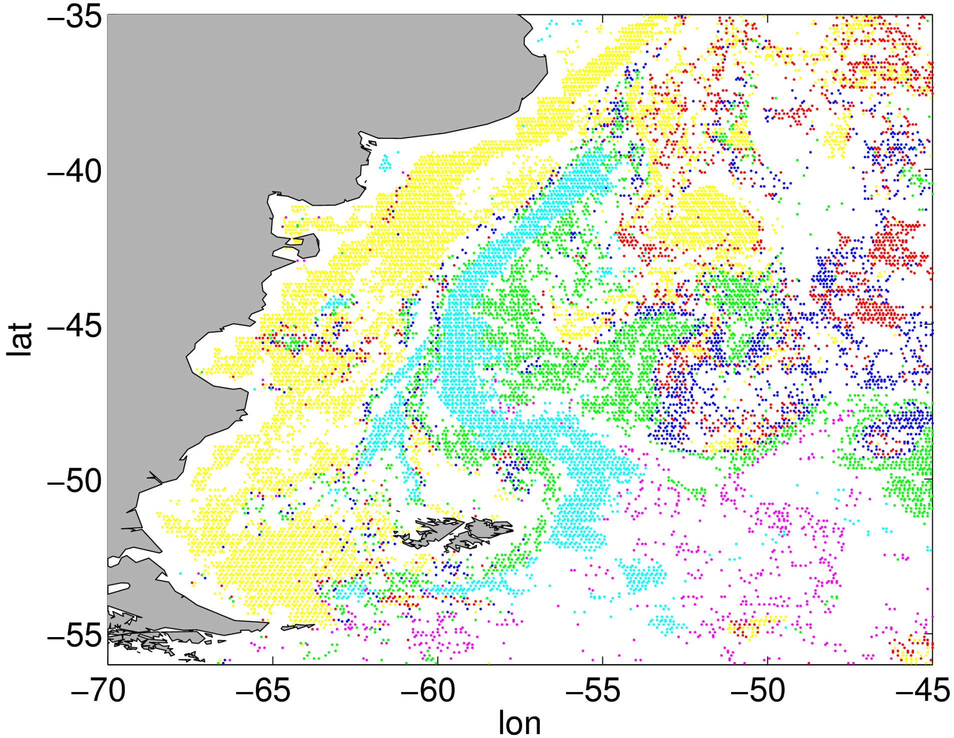
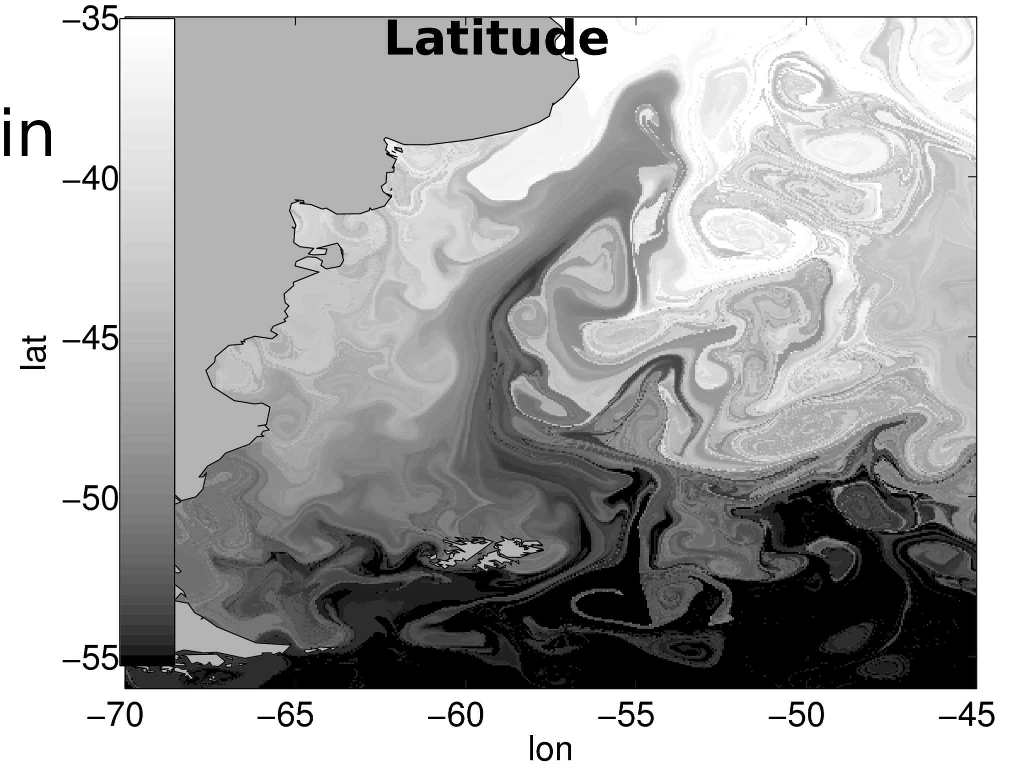
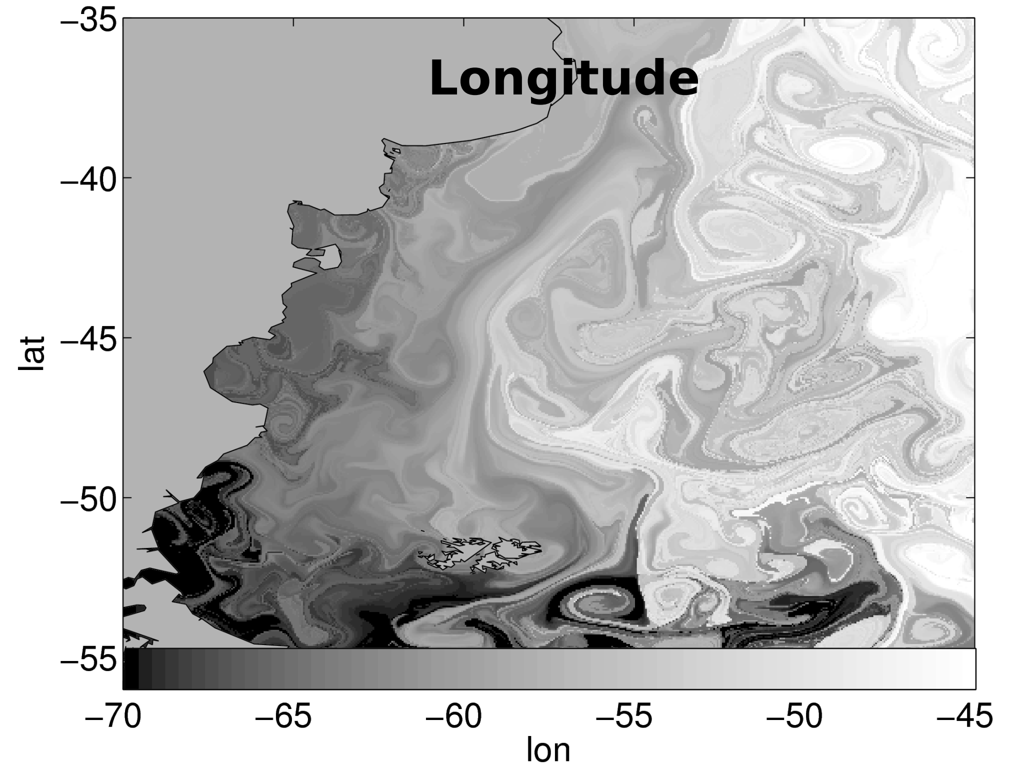


Dominant type community structure has submesoscale structure
Ecological frontiers are fronts induced by horizontal stirring

Estimation of water mass origin 3 months before the bloom

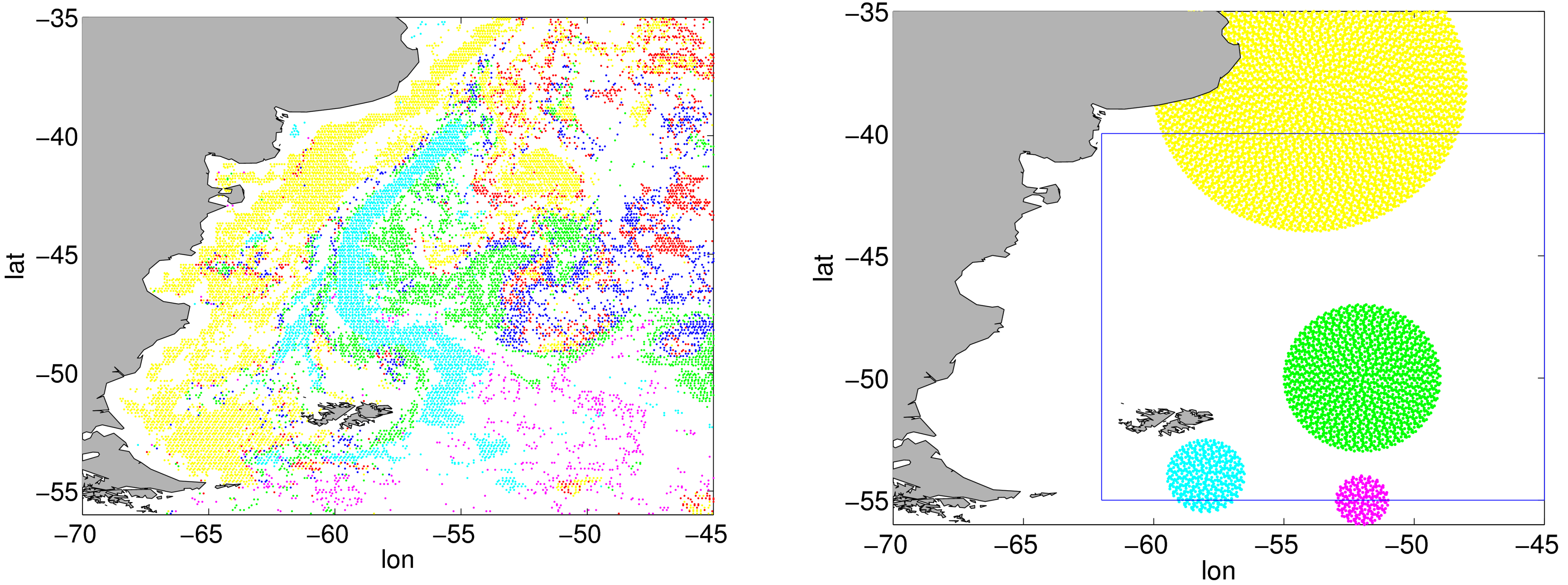




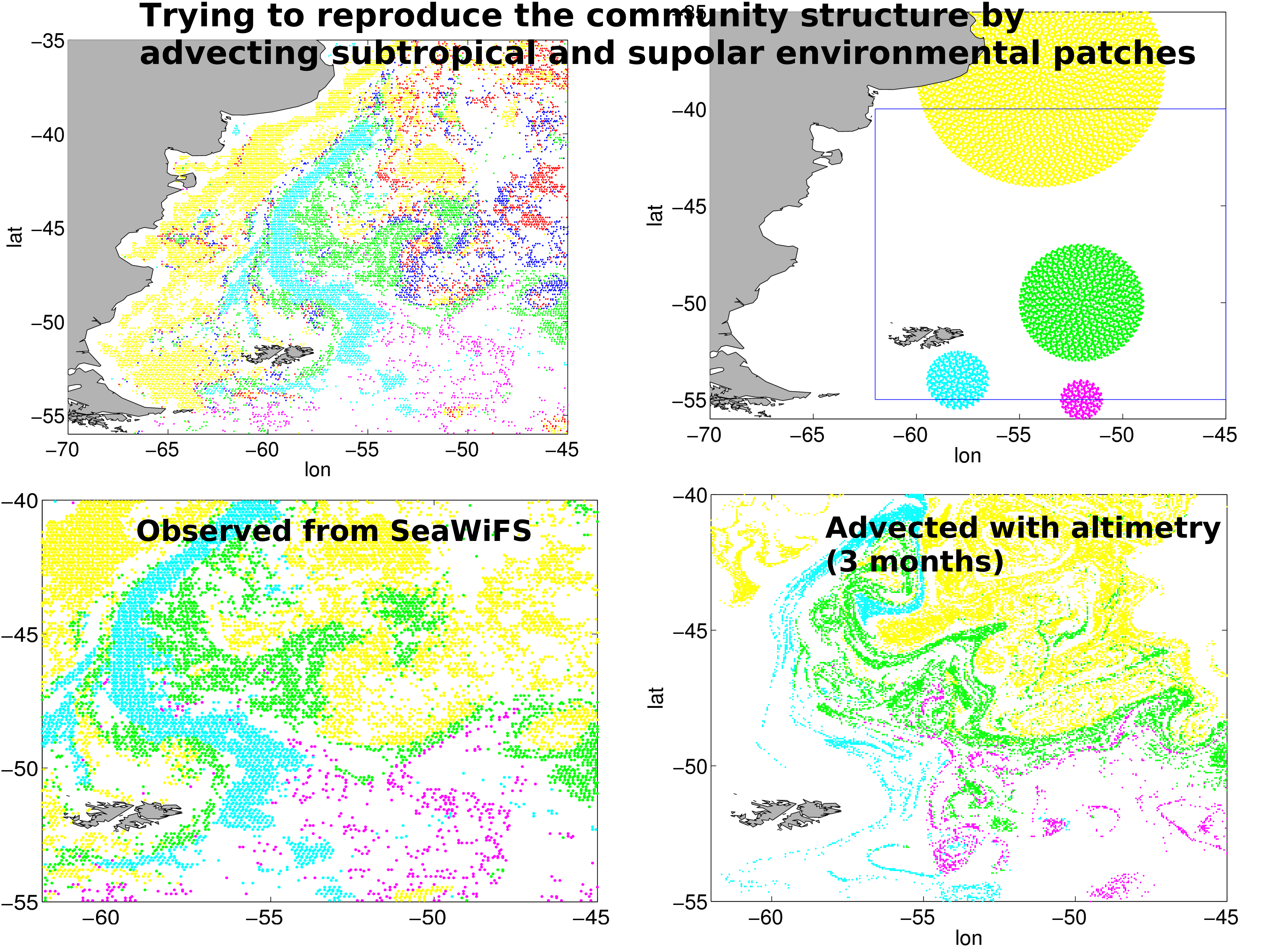


Borders of bioprovinces are fronts among water masses of different origin

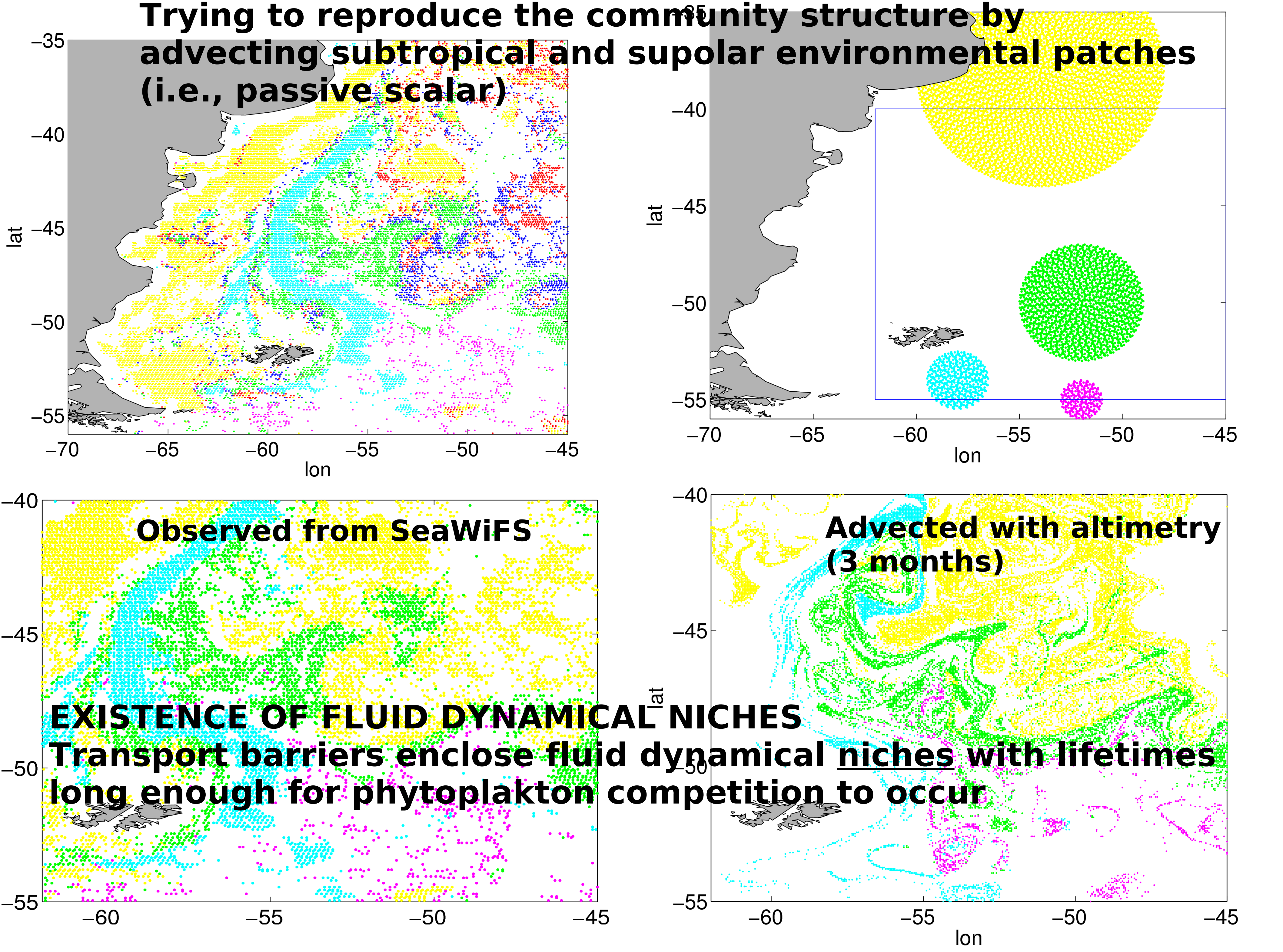
Trying to reproduce the community structure by advecting subtropical and supolar environmental patches



Trying to reproduce the community structure by advecting subtropical and supolar environmental patches



Trying to reproduce the community structure by advecting subtropical and supolar environmental patches (i.e., passive scalar)



EXISTENCE OF FLUID DYNAMICAL NICHES

Transport barriers enclose fluid dynamical <u>niches</u> with lifetimes long enough for phytoplakton competition to occur

Fluid dynamical niches as biophysical megacosms

The possibility of tracking fluid dynamical niches from surface velocities suggest the use of segregated water patches (~100 km wide) for megacosm experiments

LOHAFEX
An Indo-German ocean experiment to test the effect of iron fertilization on the ecology and carbon cycle in the Southern Ocean.

Why a megacosm experiment
- Link between lab mesocosms and large-scale dynamics
- Full inclusion of natural processes at the temporal scale of the bloom

See www.lohafex.com

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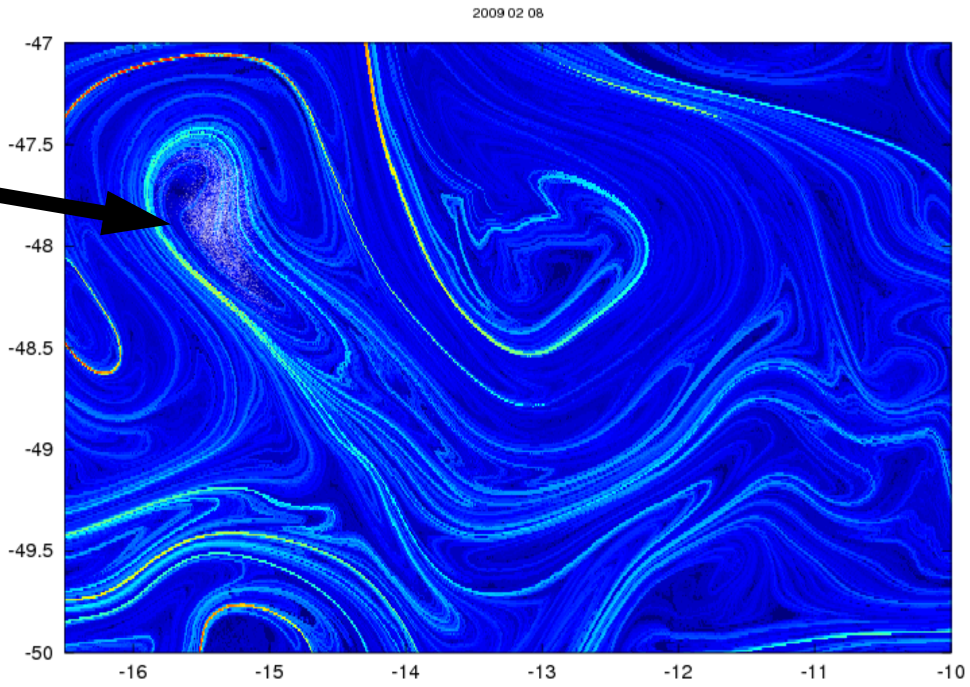

The identification of a megacosm with real-time Lyapunov calculation allowed to isolate and track a phytoplankton community for several weeks (February-March 2009).

Data currently analyzed

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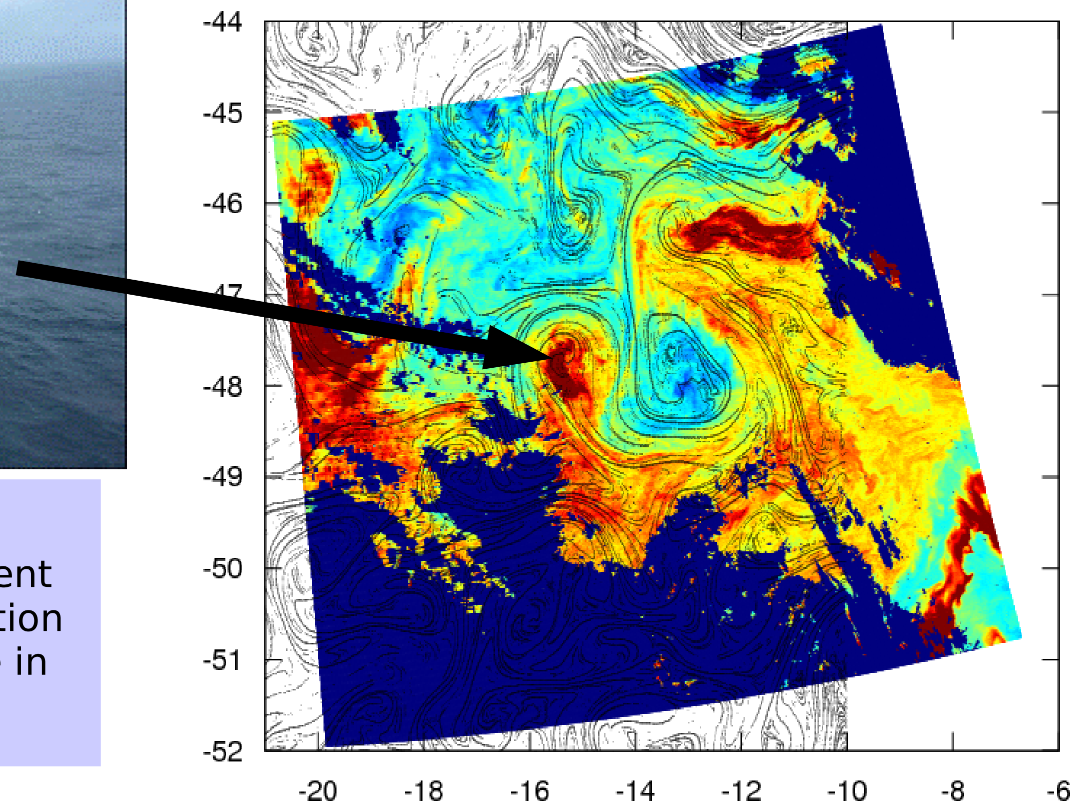

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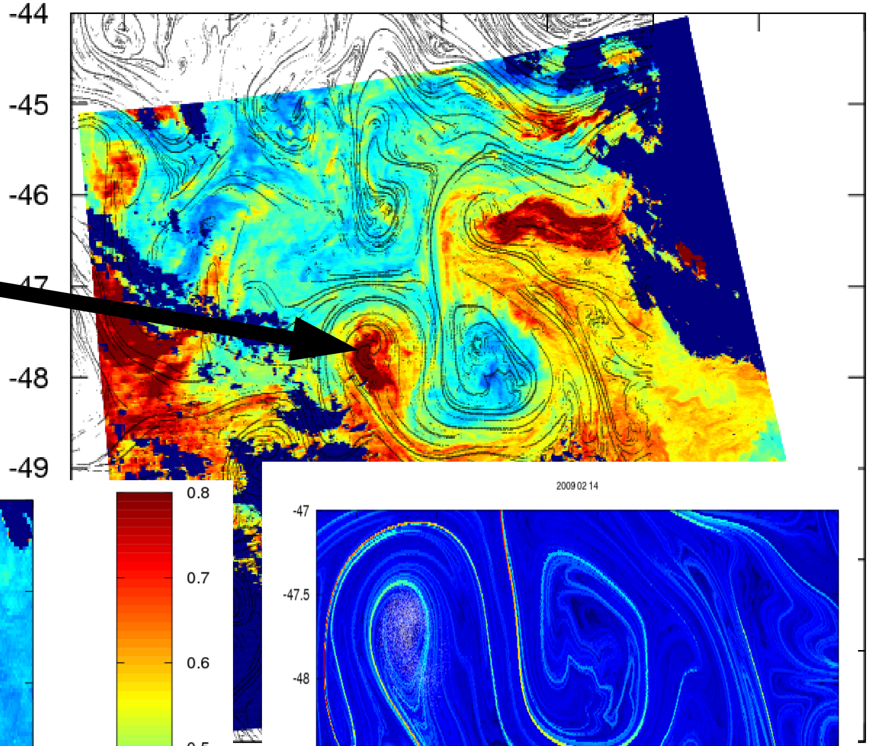

LOHAFE
An Indo-G
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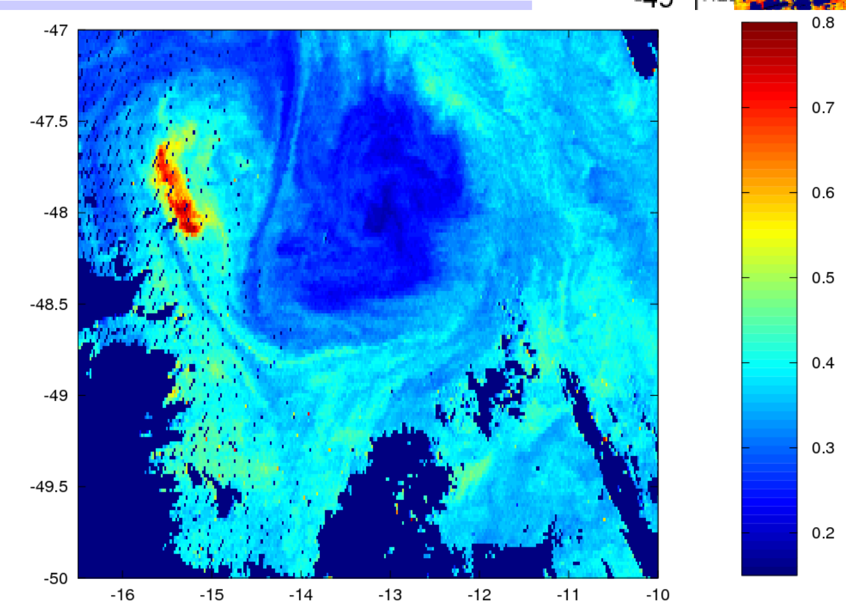
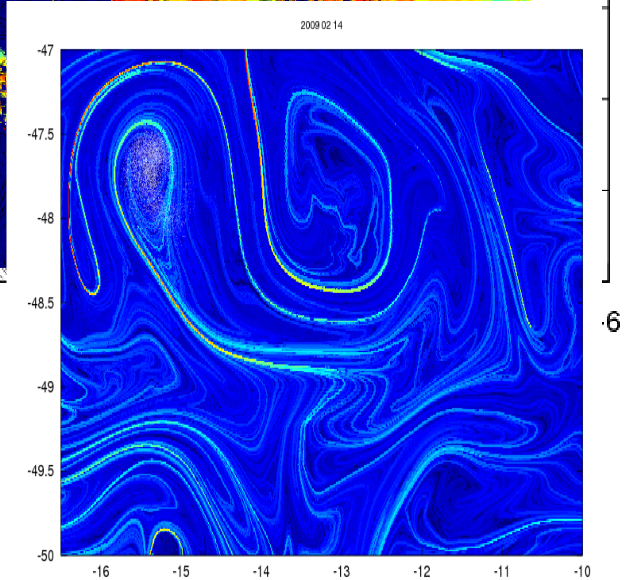
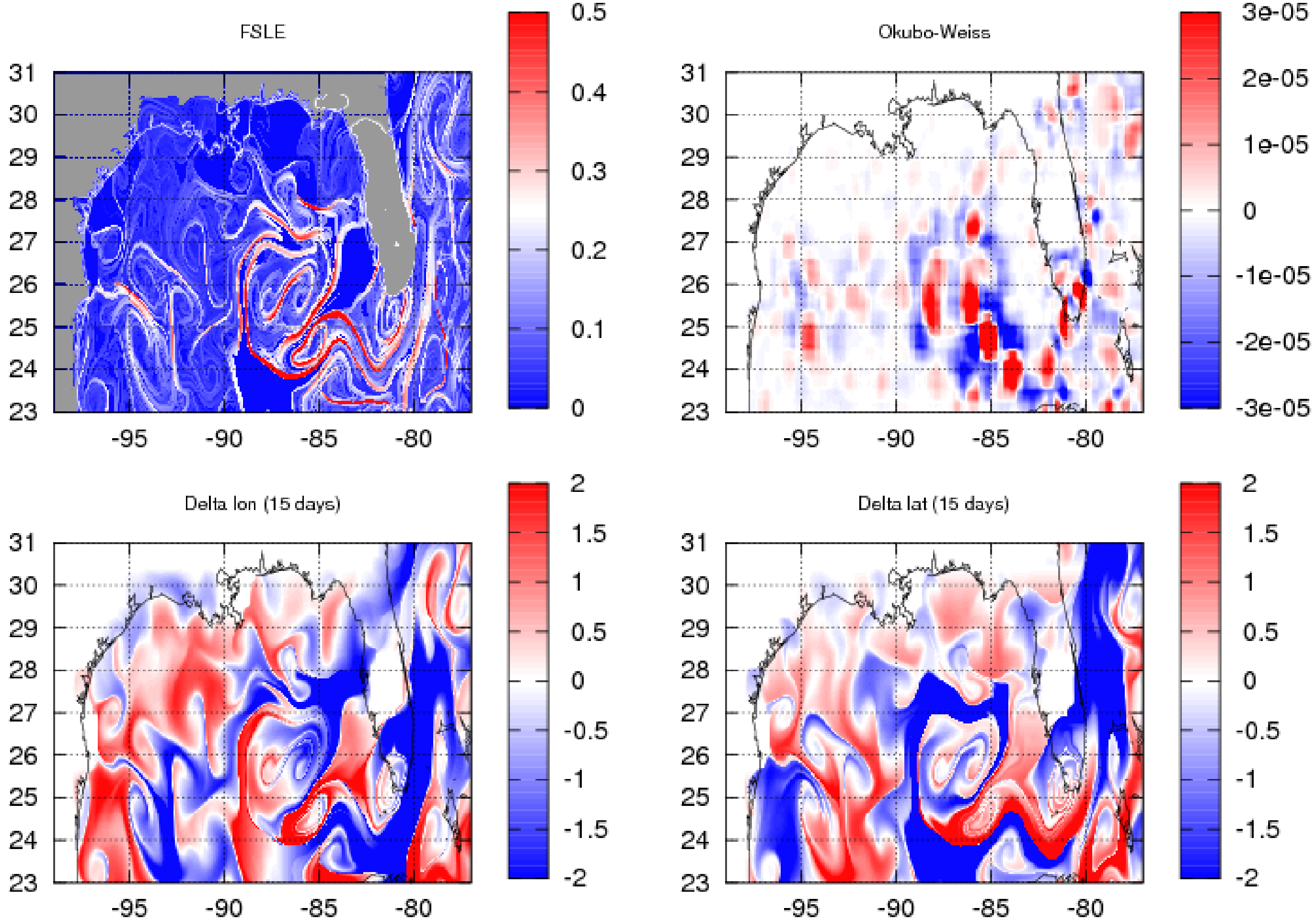




Lyapunov maps soon distributed through CTOH (Toulouse)

- Historical dataset
- Real time on request



In collaboration with R. Morrow

CONCLUSIONS - 1

Lot of tracer variability at the submesoscale: we need altimetry to understand how transport create/dissipate this variability

This issue is especially relevant for:

- **marine ecosystems** whose biotic processes resonate in time with (sub-)mesoscale temporal scales

- **in situ biogeochemical surveys** whose observations are affected by asynopticity

Current altimetry products shed some light on how advection can structure submesoscale tracer variability (niches) if Lagrangian tools are used with a precision of ~10s of km

High resolution altimetry may push this approach much further, in terms of spatial scales and in terms of precision

A possible issue to be addressed: temporal resolution

CONCLUSIONS - 2

SWOT and marine ecosystems

1. Understanding the repartition of marine biota in the oceans is instrumental to:

- understand how biodiversity reacts to environmental changes (natural and anthropic)
- decide conservation policies
- manage marine resources (fisheries)
- quantify the biogeochemical cycles (top-down controls, biogeochemical services)

2. Altimetry is a fundamental tool for understanding the structuring effect of ocean turbulence on the timescales of planktonic blooms

- provides spatial structure of the physical landscape (“niches”)
- allows adaptive in situ sampling (“megacosm” experiments)

3. Some ecological issues that can be addressed only with SWOT

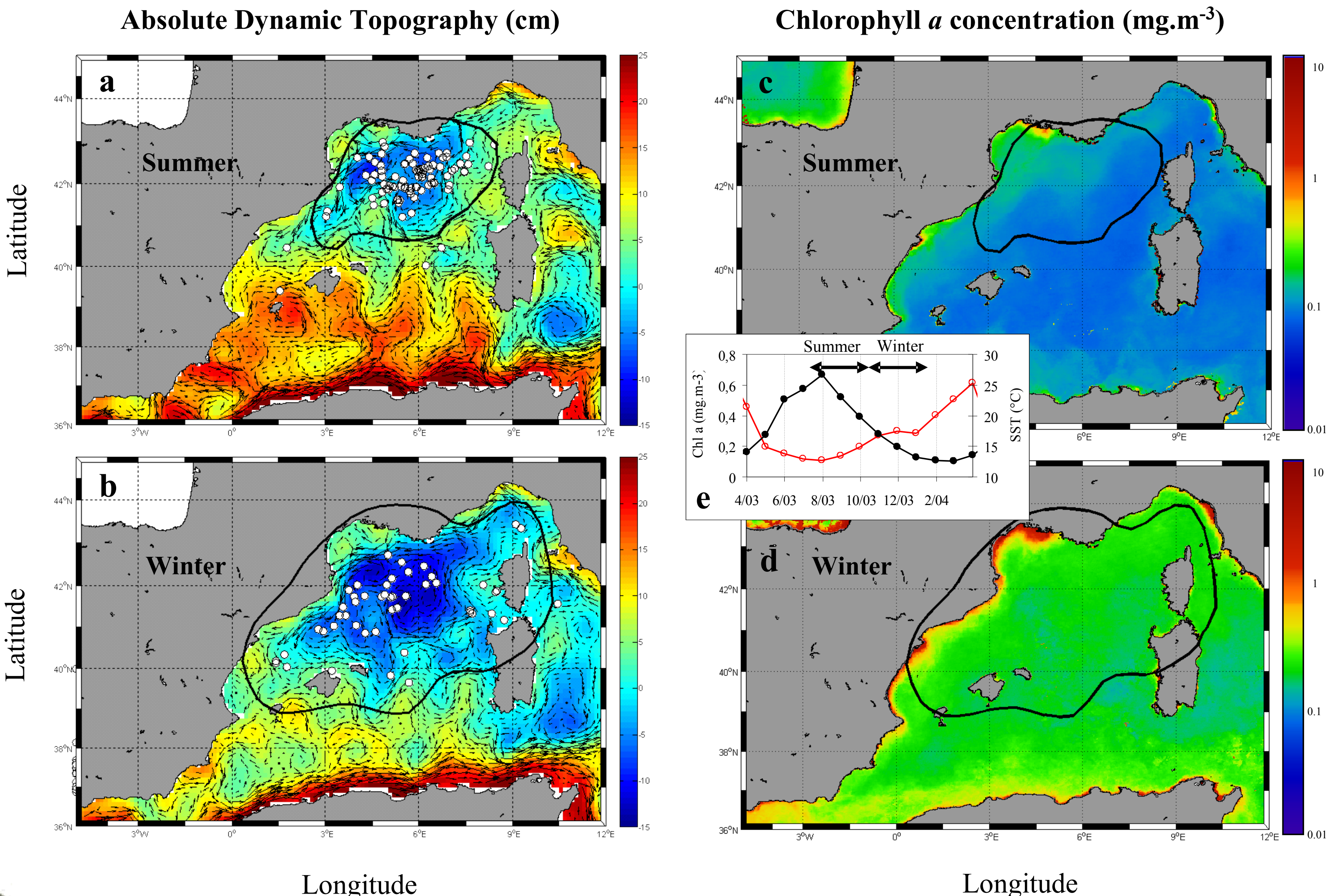
- Fluid dynamical niches:

How niches are organized below ~100 km? Do they exists? What are the merging/dissipation processes?

What is the dynamics of niches close to the coast? How are they connected to the open sea? What are they lifetimes?

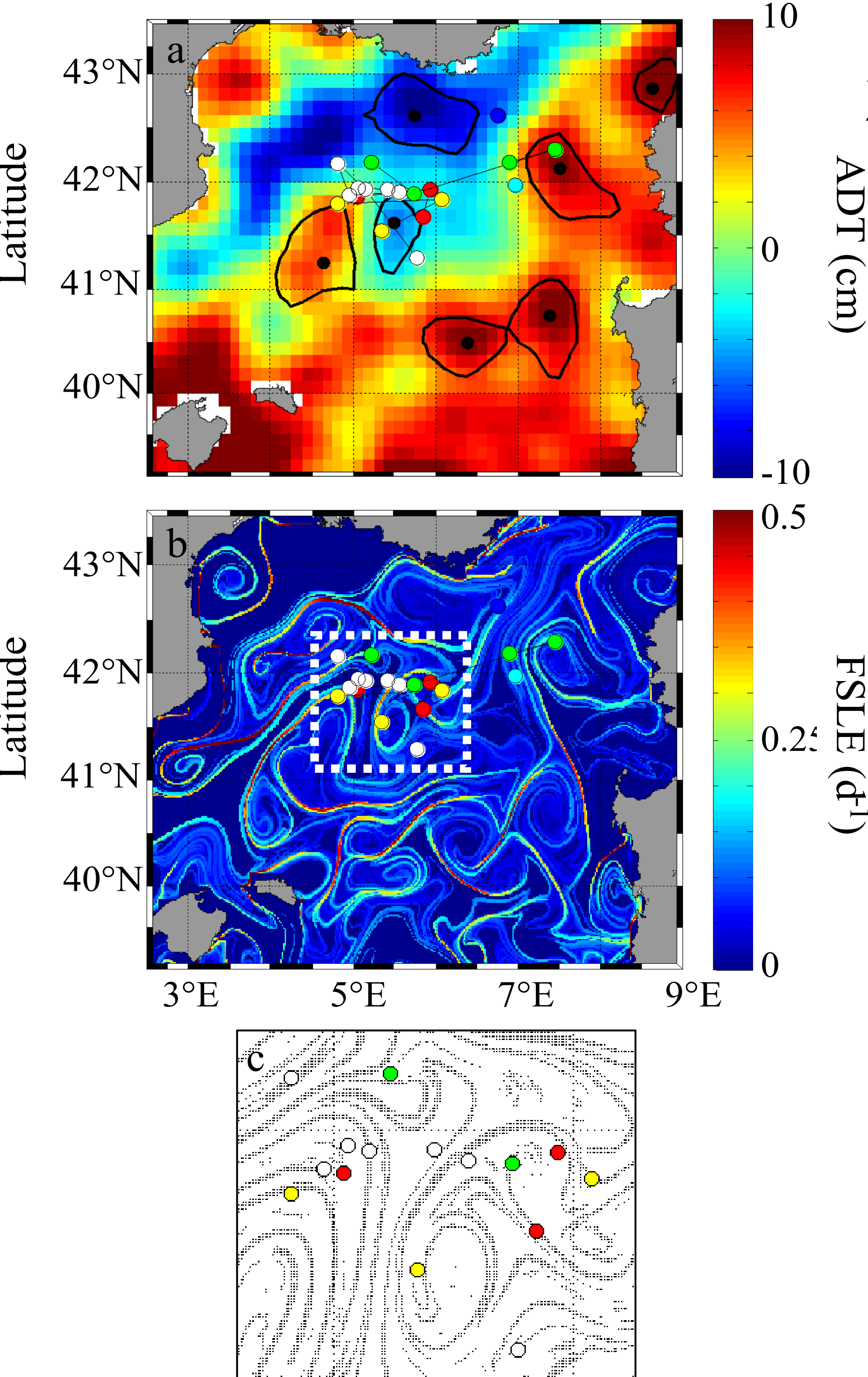
- in situ adaptive sampling

Reduce time of initial surveys (currently a sustantial part of total ship time!)
Improve success



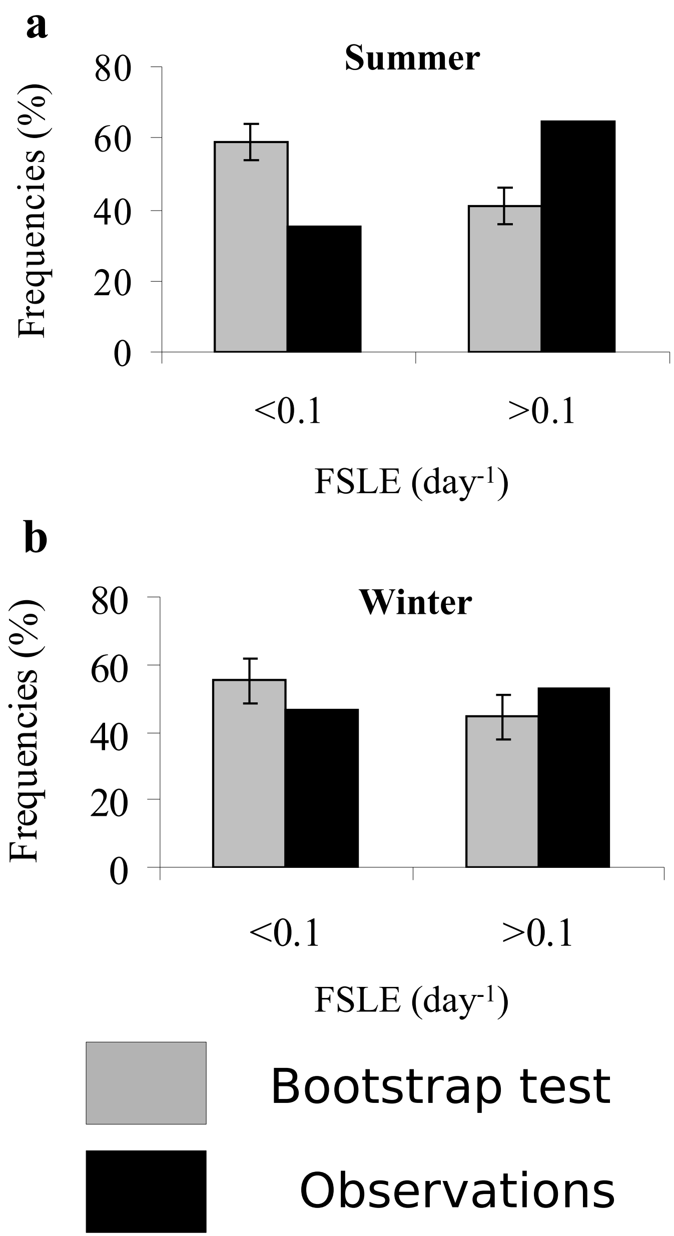
8 fin whales equipped with GPS tags (2003-2004)

XAMPLE



Whale positions on surface currents (top) and Lyapunov exponents (bottom)

RESULT

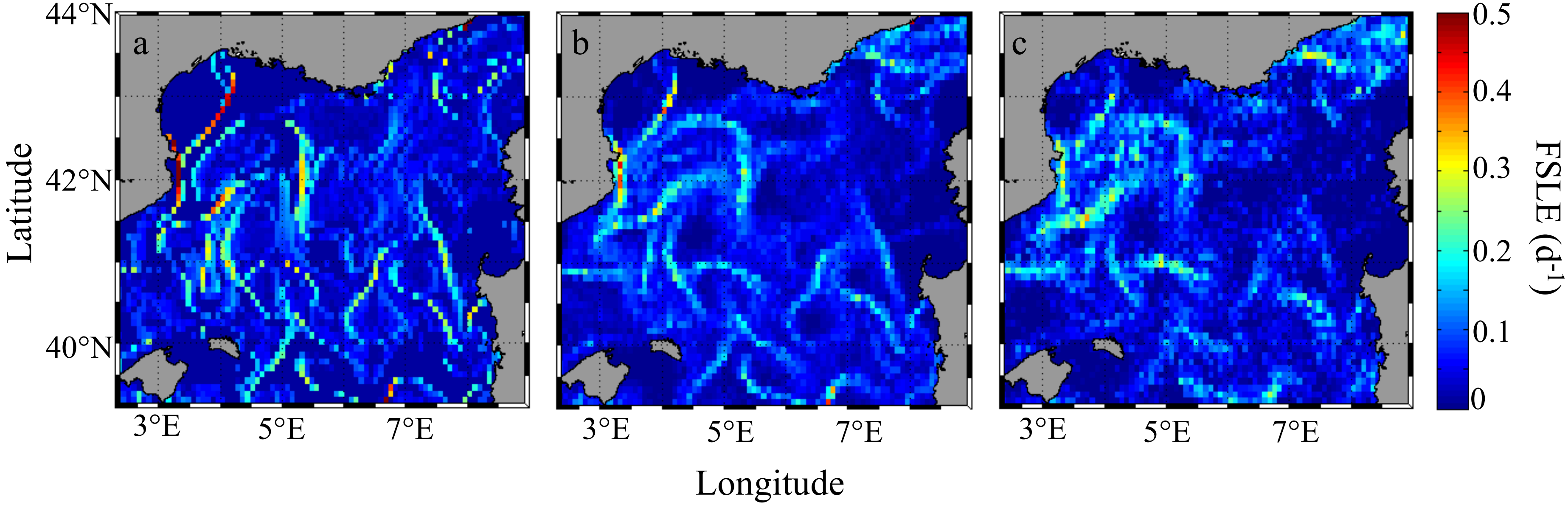


Whales prefer to forage along fronts induced by horizontal stirring

These are also the regions where commercial fishing activity is concentrated

Open question: how do whales detect fronts?
“Chemo/info-taxis”?
“Run and tumble?”

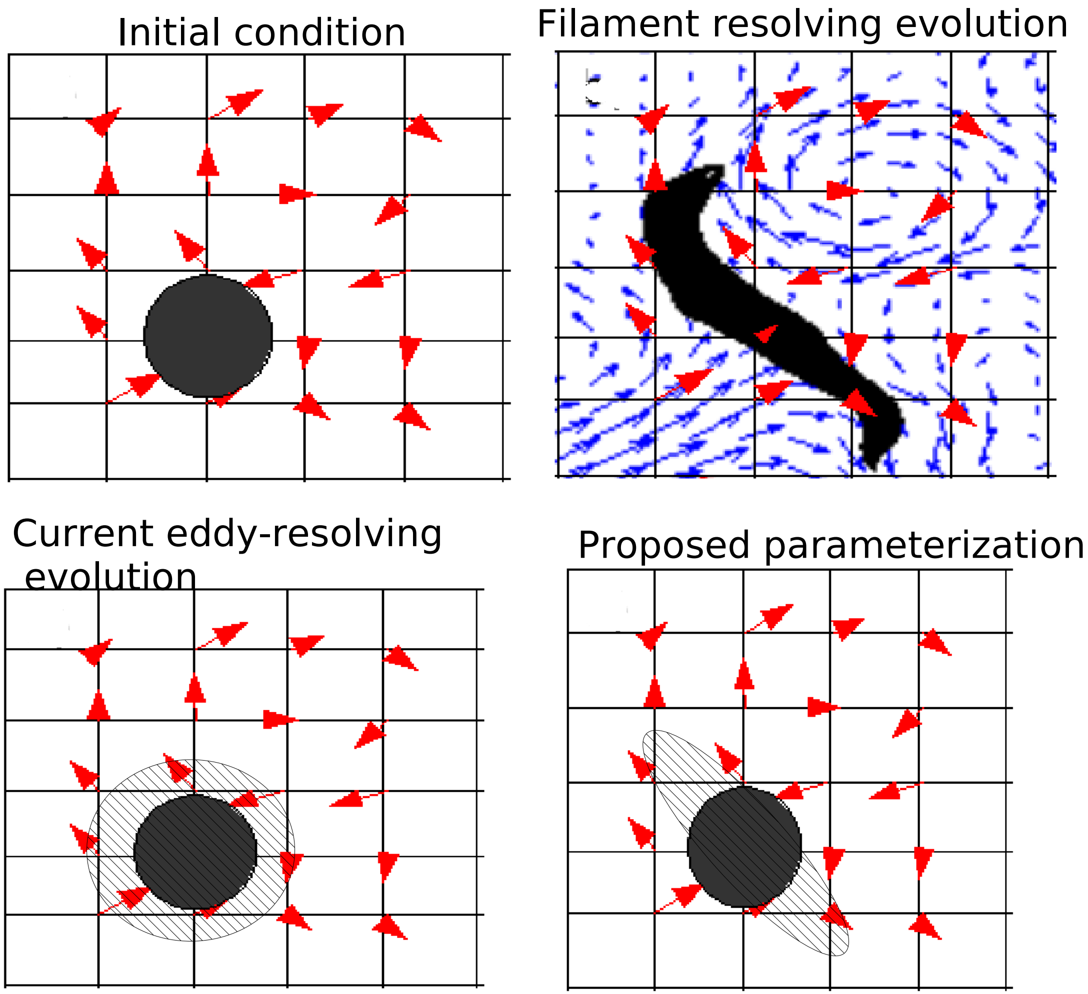
Robustness analysis



Lyapunov analysis robust to noise (random walk on particle trajectories equivalent to horizontal diffusivity of 0, 50, 200 m2/s resp.)

PARAMETERIZATION OF FILAMENTS INDUCED BY LATERAL STIRRING

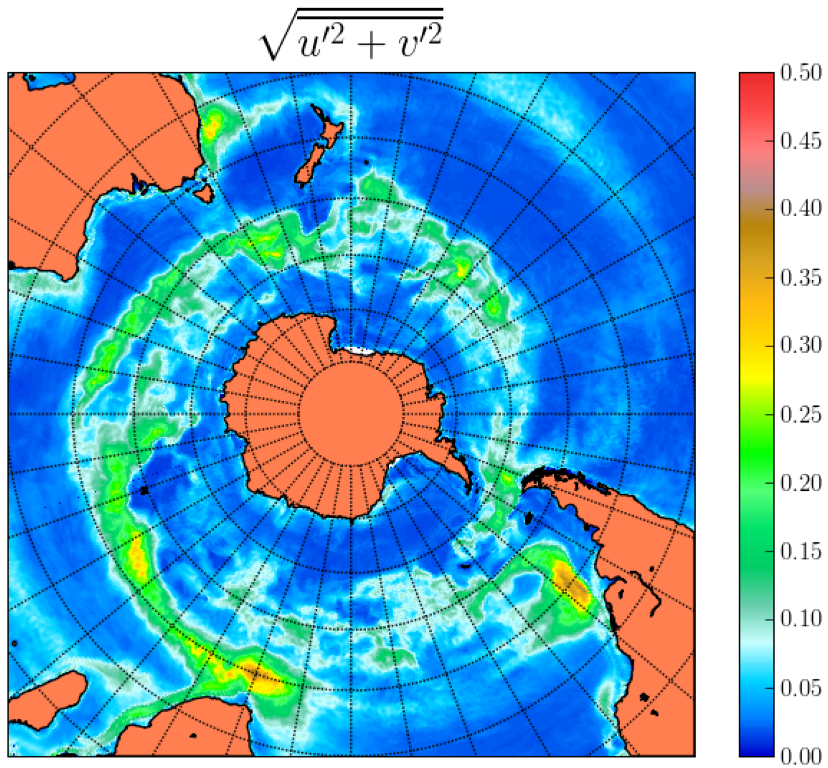
PROBLEM and PARAMETERIZATION PRINCIPLE

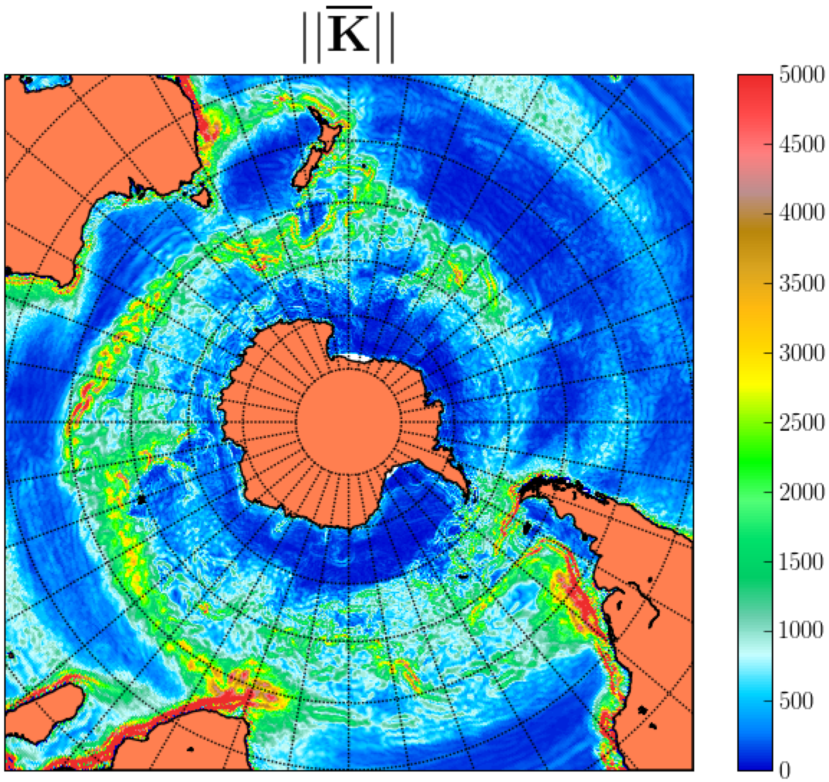


We propose to model the subgrid filamentation as an anisotropic diffusion operator.
The **direction** is given by the eigenvector of the deformation matrix.
The diffusion intensity is such that diffusion equals stretching.
Scale dependent diffusivity (L^2).
Currently working in diagnostic on NEMO (1/4 deg.)

Le Sommer, d'Ovidio, Madec, Oc. Mod., subm.

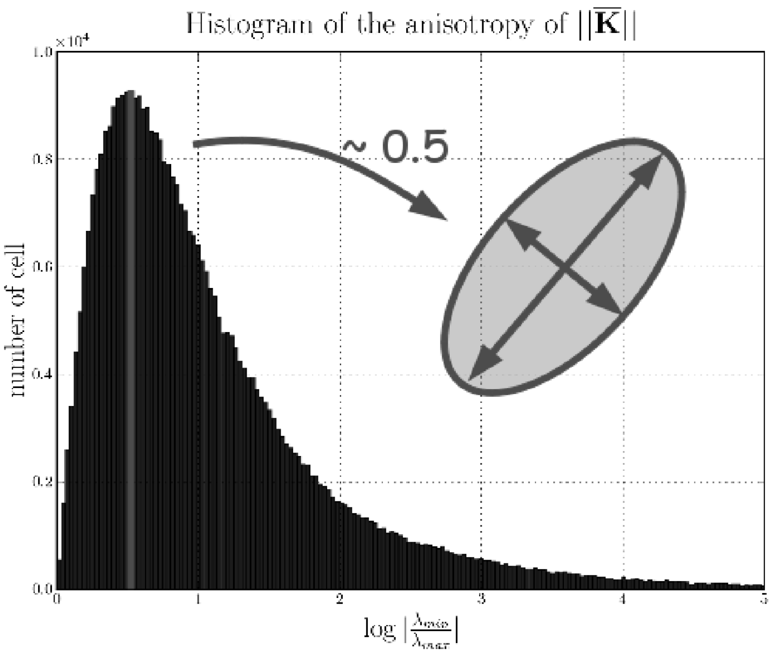
Diffusivity strongly variable in space

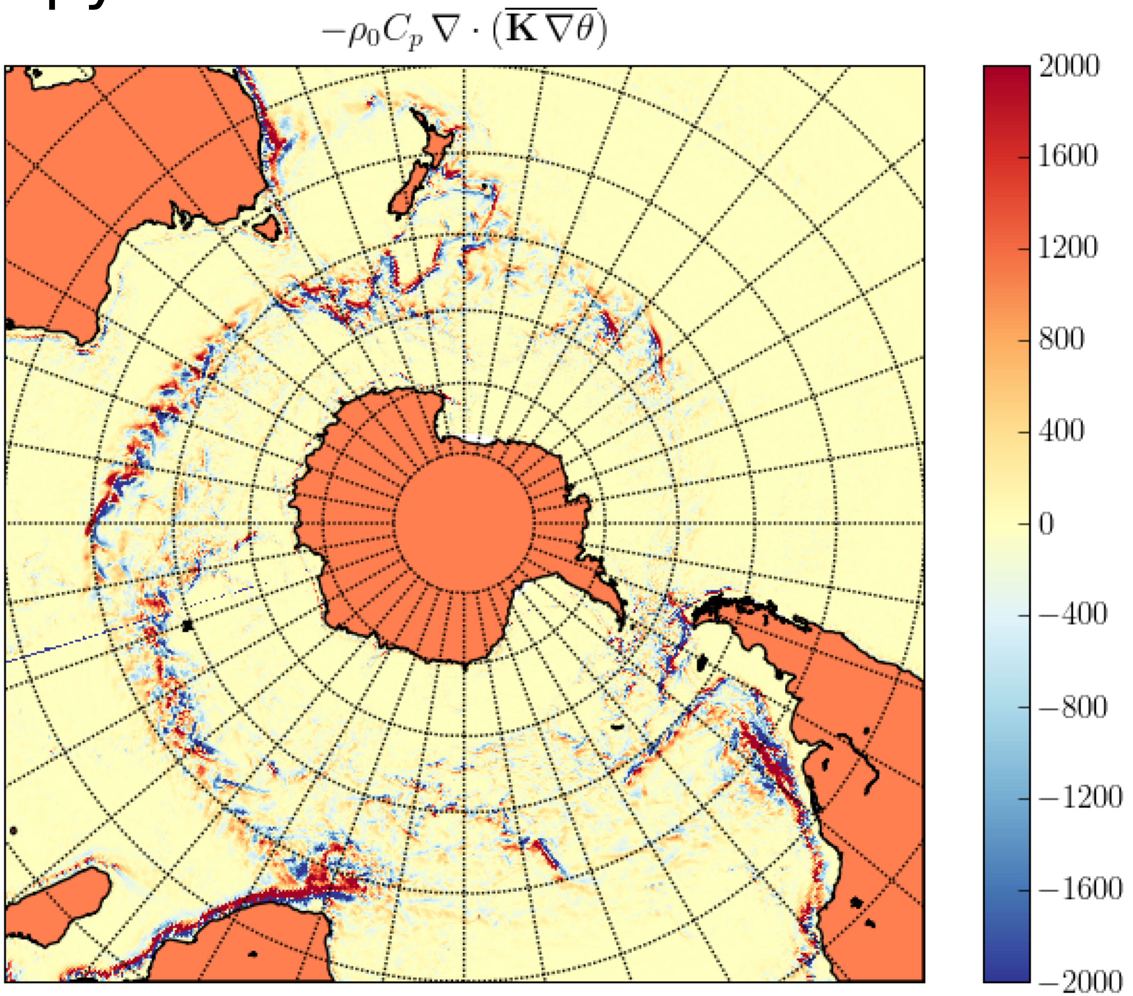




The anisotropic diffusivity is scale dependent ($\sim L^2$).
Tracer variance is decreased (numerically stable)
For 1/4 deg. resolution has peak values up to 5000 m2/s, but the average value corresponds to typical eddy-permitting isotropic diffusivities of 400 m2/sec.

Anisotropy





The diffusivity is strongly anisotropic.

Correlation with tracer gradients: heat flux due to anistropic diffusivity same order of magnitude as heat flux due to eddies

Use in prognostic under way.

CONCLUSIONS

Horizontal stirring generates submesoscale tracer variability from mesoscale velocities

- recipe for kinematic front: mesoscale turbulence (spatial+temporal variability)
- recipe for tracer front: mesoscale turbulence + large-scale gradient (+ tracer dynamics)

Process well captured by Lagrangian diagnostics (Lyapunov analysis)

- Subgrid filament detection from observations (front position, orientation, frontogenesis timescale)
- Parameterization for GCMs
- Adaptive in situ sampling

What are the large impacts of the submesoscale (stirring contribution)?

- precondition for submesoscale (3D) instabilities
- segregation/mixing of tracers
- structuring of marine ecosystems

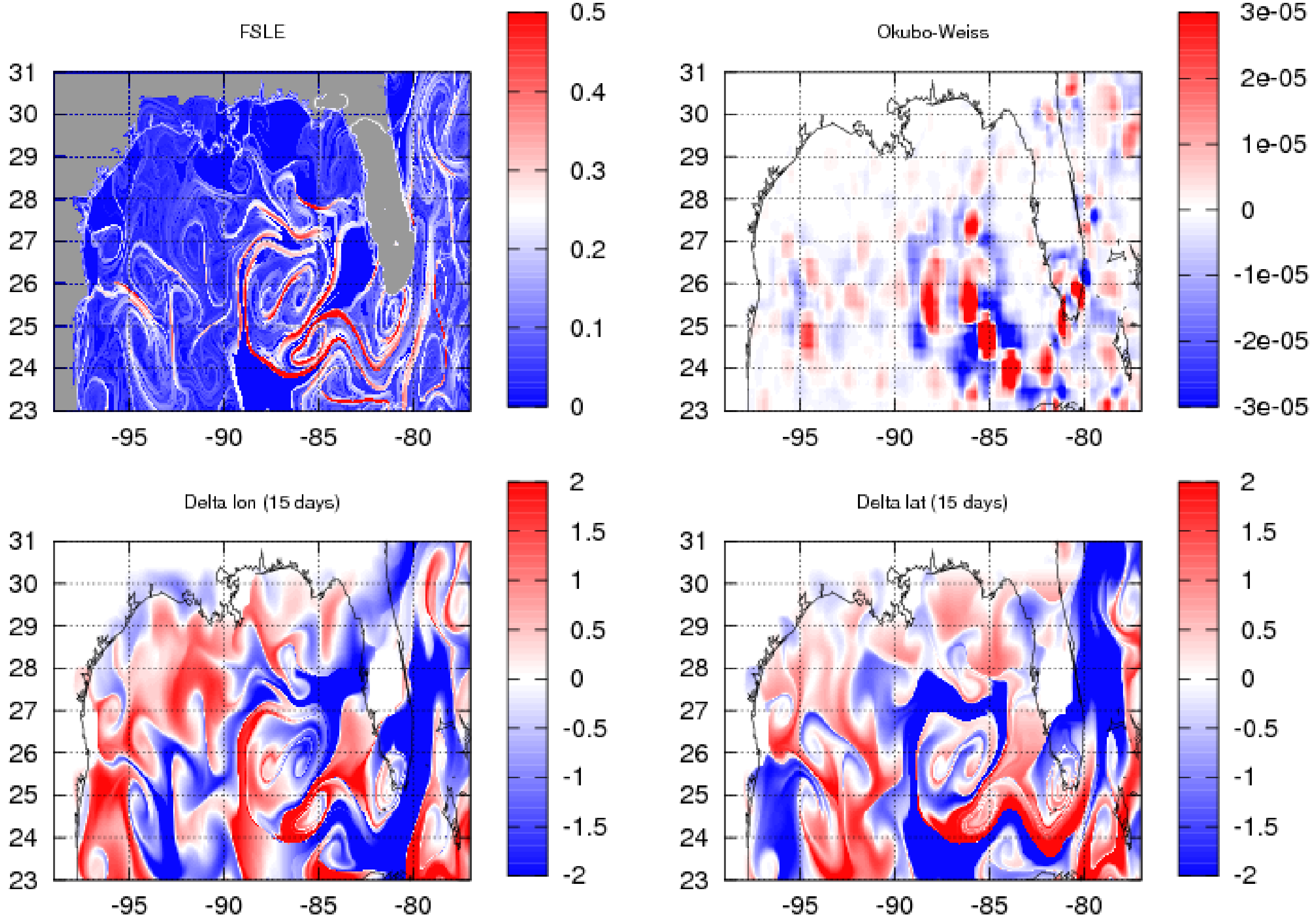
Some challenges

- large margin on improvements for velocity fields (SWOT!)
- lack of synoptic, submesoscale tracer observations (more adaptive sampling needed)
- the big missing ecological player: zooplankton

Lyapunov maps soon distributed through CTOH (Toulouse)

- Historical dataset 1990-2010
- Real time on request

E. g.: Gulf of Mexico, yesterday



Importance of the submesoscale (for others than us):

1 not resolved by global circulation models and global observation networks

What processes are we neglecting in global budgets? (when/where?)

2 Resonant biophysical regime (same **temporal** scale than plankton blooms)

Relevant for regional issues (fisheries, conservation ecology) and for global ones (niches for biogeography)

Missing link between mesocosms and global biogeochemical budgets

What we know

1. Rich variety of physical phenomena, with potential biological interactions

- Horizontal redistribution (local and far field effects)

- Vertical

2. Impact strongly variable (e.g., submeso vertical velocities for PP;)

Conclusions

There is the need in geophysics for linking transport properties to biogeochemical processes.

LCS detection is a very robust technique, adapt to real and model data for extracting transport and mixing information.

Segregation and mixing are usually the same phenomenon, on different timescale.

OCEAN
These transport barriers enclose **fluid dynamical niches**, with lifetimes comparable to phytoplankton ecology processes

Fluid dynamical niches can be targeted by campaign studies, for performing **megacosm experiments**

ATMOSPHERE
Mixing can be derived by LCS analysis if the geometrical information is exploited

Open theoretical issues (from a user perspective):
- Rigorous results on manifold detection and LEs
- Robustness analysis
- Relation with other diagnostics (e.g. effective diffusivity)