Search and stochastic phenomena in physical and biological systems
Palma de Mallorca, 1 June 2012

Following the line: Marine birds fly on top of ocean coherent structures

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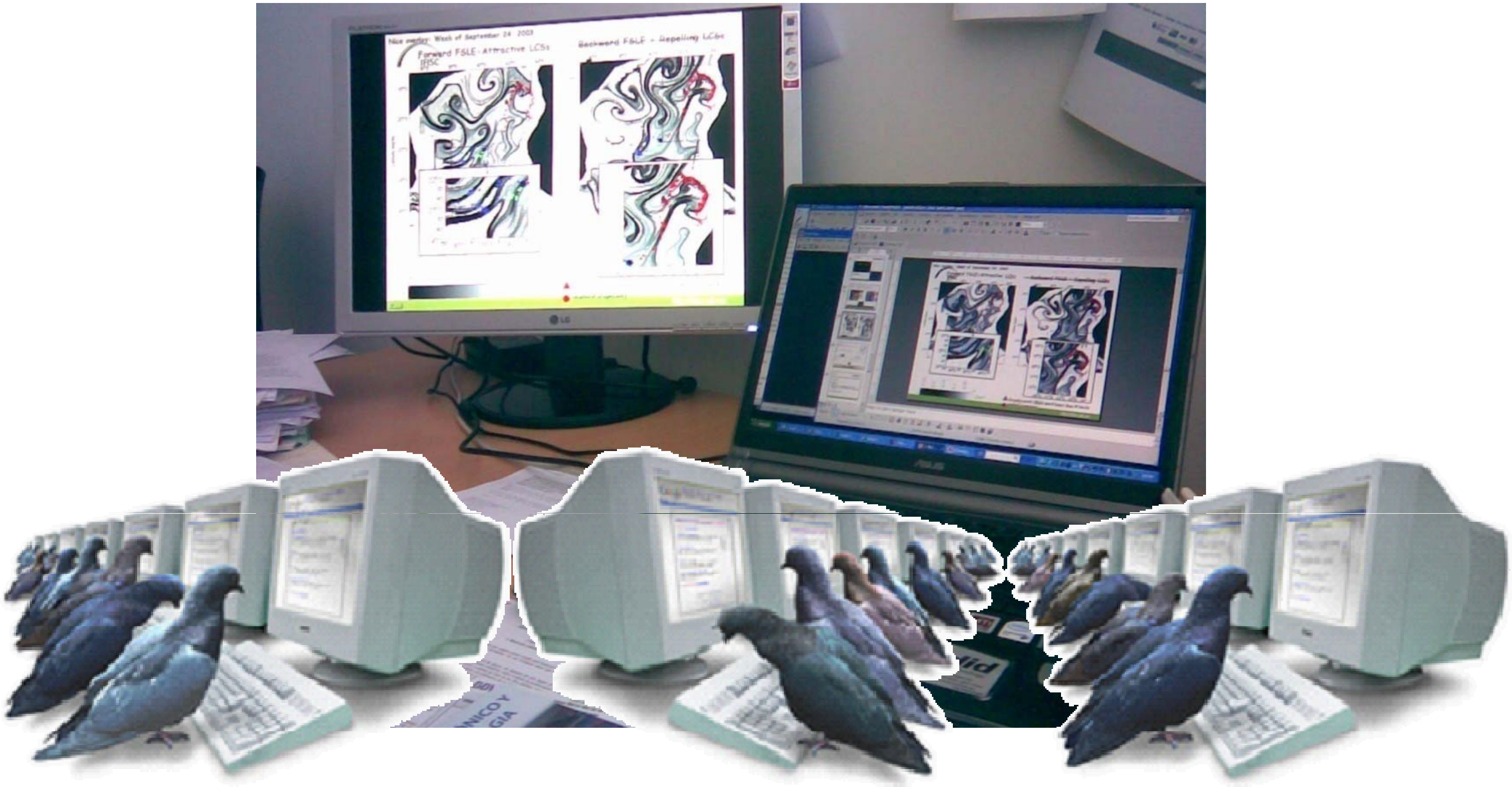
CSIC-UIB, Palma de Mallorca, Spain

with C. López, V. Rossi, V. Garçon, J. Sudre,
E. Tew Kai, H. Weimerskirch, F. Marsac …

IFISC

Do birds know about Lyapunov exponents?

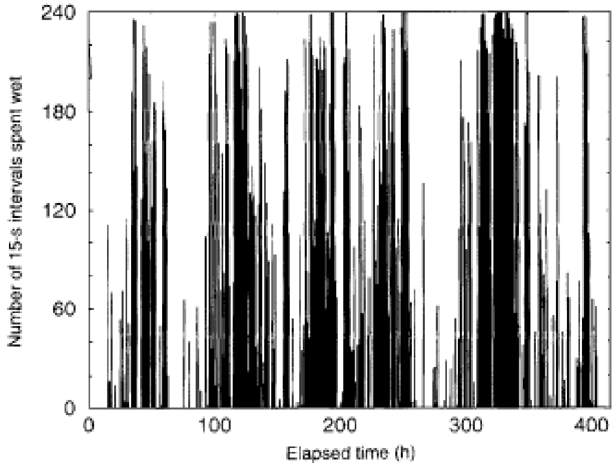


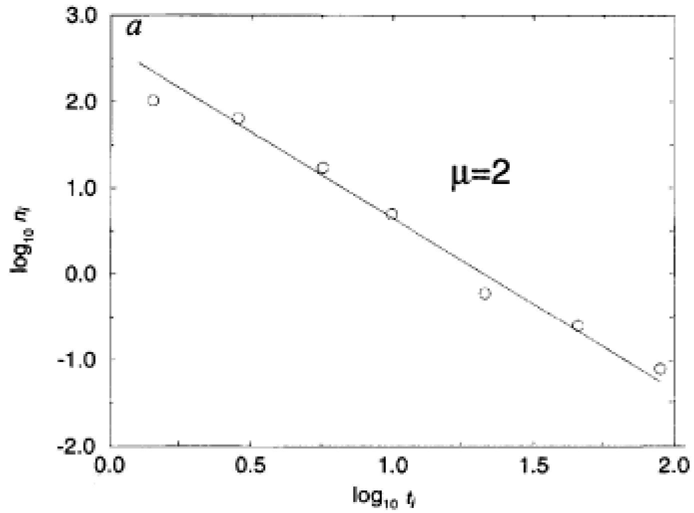
Tew Kai, Rossi, Sudre, Weimerskirch, Lopez, Hernandez-Garcia, Marsac, Garçon, PNAS 106, 8245 (2009)

Lévy flight search patterns of wandering albatrosses

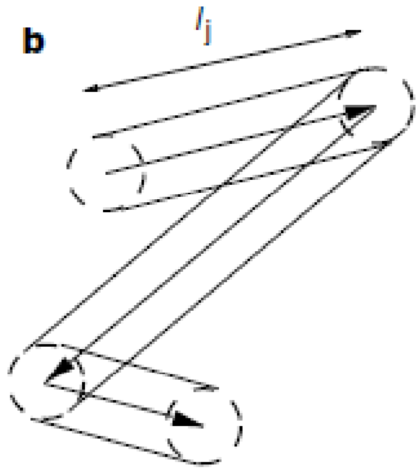
G. M. Viswanathan*, V. Afanasyev†, S. V. Buldyrev*,
E. J. Murphy†, P. A. Prince† & H. E. Stanley*

Nature 1996





Viswanathan et al., Nature 1999, *Optimizing the success of random searches*

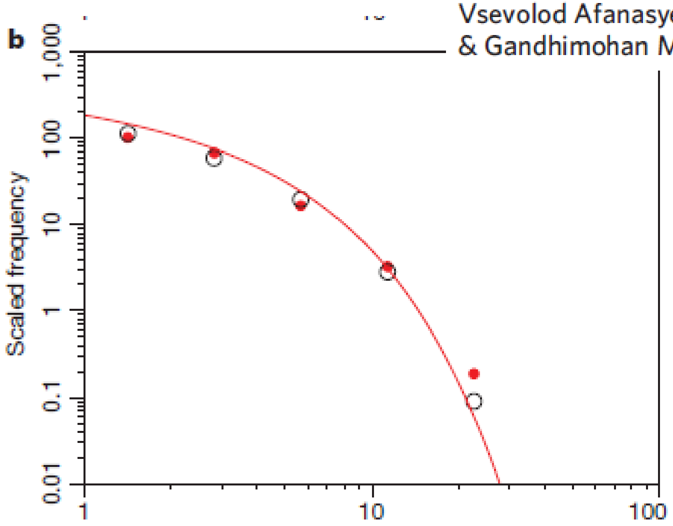


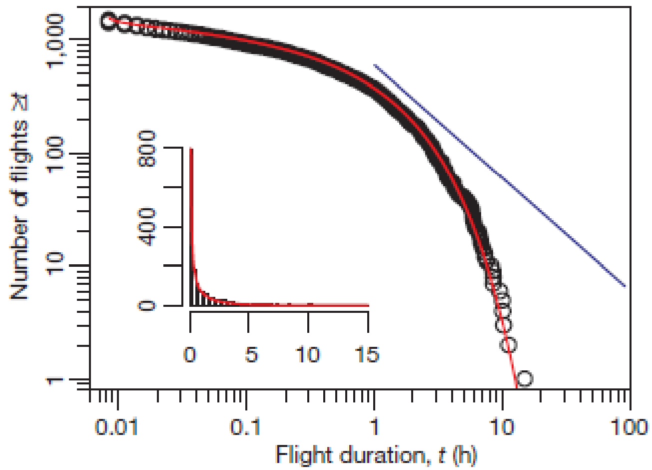
Lévy flights with exponent -2 is the search strategy optimizing encounters with homogeneously distributed prey
(non destructive mode)

Nature 2007

Revisiting Lévy flight search patterns of wandering albatrosses, bumblebees and deer

Andrew M. Edwards[1]†, Richard A. Phillips[1], Nicholas W. Watkins[1], Mervyn P. Freeman[1], Eugene J. Murphy[1], Vsevolod Afanasyev[1], Sergey V. Buldyrev[2,3], M. G. E. da Luz[4], E. P. Raposo[5], H. Eugene Stanley[2] & Gandhimohan M. Viswanathan[6]





Bees, deer, mussels, monkeys, humans, zooplankton, …

Bartumeus and Levin, PNAS 2008

Bénichou, O., Loverdo, C., Moreau, M., & Voituriez, R. (2011). **Intermittent search strategies**. *Review of Modern Physics*, *83*, 72.

Campos, Boyer, Larralde talks …

- Miramontes, O., Boyer, D., & Bartumeus, F. (PloS One 2012). Prey detection patterns are not directly related to predator movement patterns. Prey distribution is equally important

- Enviromental inhomogeneity is relevant to determine and to limit animal motion

Compared to terrestial animals, birds seem to be less restricted by geographic accidents

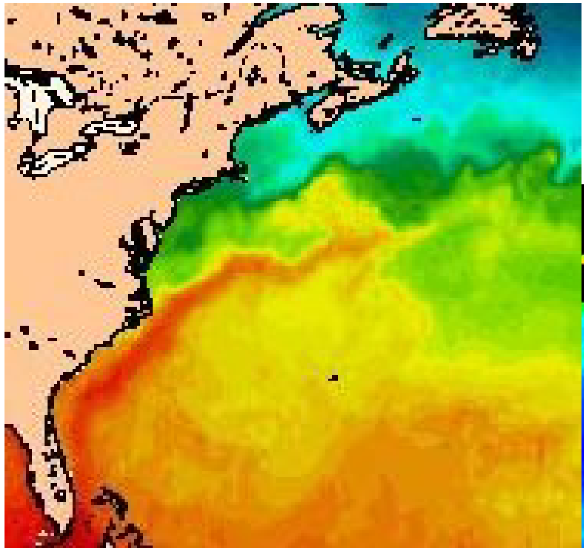
Specially marine birds look as good candidates to observe intrinsic search strategies rather than environment-induced ones

since the turbulent ocean seems a good random unstructured medium. Or not …?

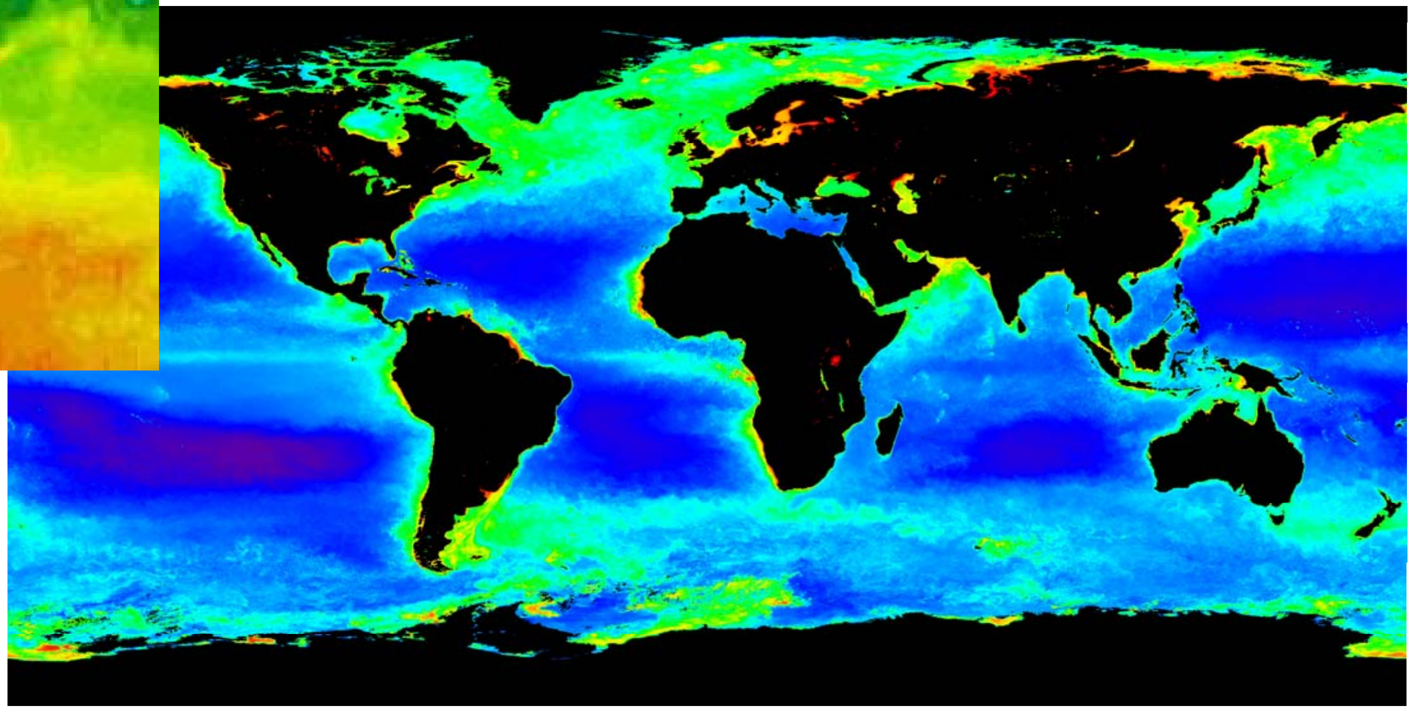
OUTLINE

- Ocean is populated with strong physical structures (in particular **Lagrangian Coherent Structures**)
- **Finite-size Lyapunov exponents** are good tools to observe them
- These structures have strong impact on **plankton**
- **Frigatebirds** fly on top of Lagrangian Coherent Structures

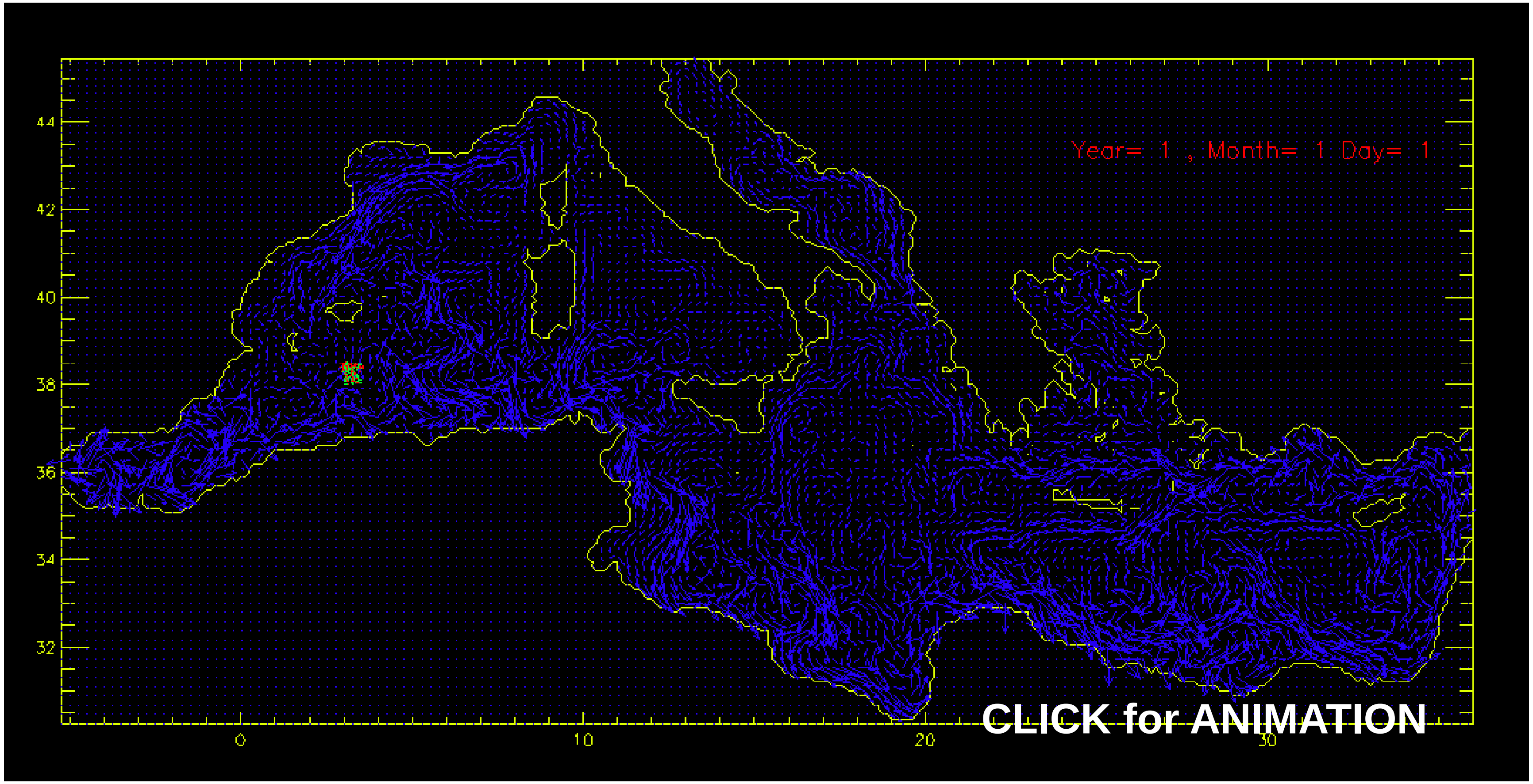
Chlorophyll-a (≈ phytoplankton) from space



Gulf stream
temperature



MODIS Image
1 month average



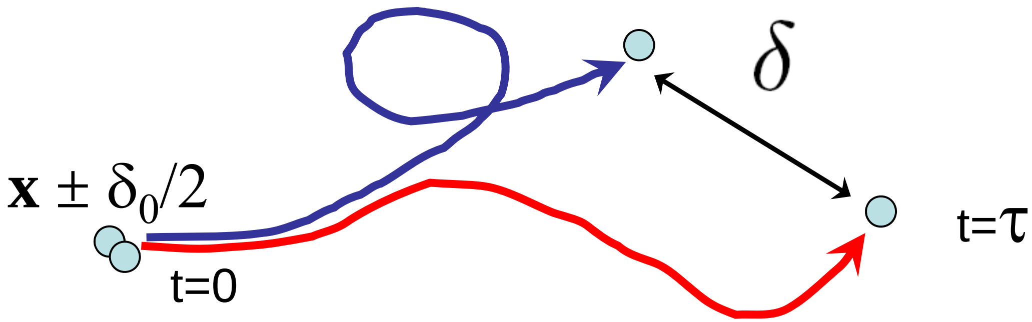
Drifters, tracer motion

$$\lambda(t) = \lim_{\|\delta(0)\| \to 0} \frac{1}{t} \ln \frac{\|\delta(t)\|}{\|\delta(0)\|}$$

Finite-**time** Lyapunov exponent

$$\lambda = \lim_{t \to \infty} \lambda(t)$$

Lyapunov exponent



$$\lambda(\delta_0, \delta_f) \equiv \frac{1}{\tau} \log \frac{\delta_f}{\delta_0}$$

Finite-size Lyapunov exponent

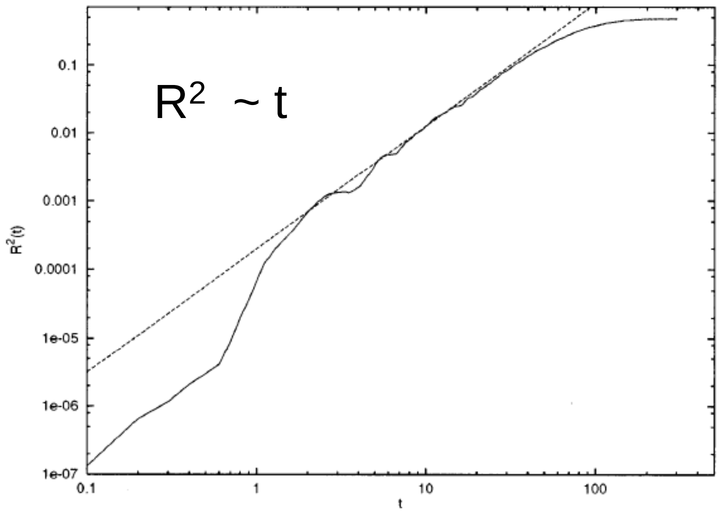
FSLE

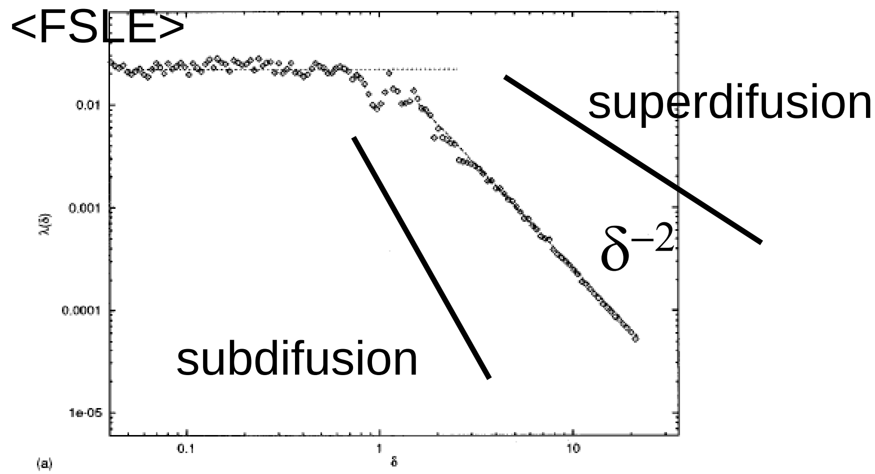
All the quantities are also functions of the initial position and time:

$$\lambda(\mathbf{x}, t, \delta_0, \delta_f)$$

Opening a parenthesis on FSLE

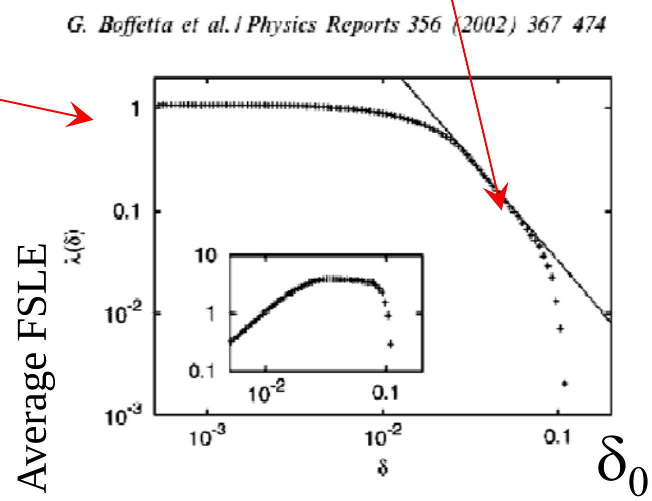
(





Subexponential growth (diffusion regime)

Exponential growth of separations (chaotic regime)

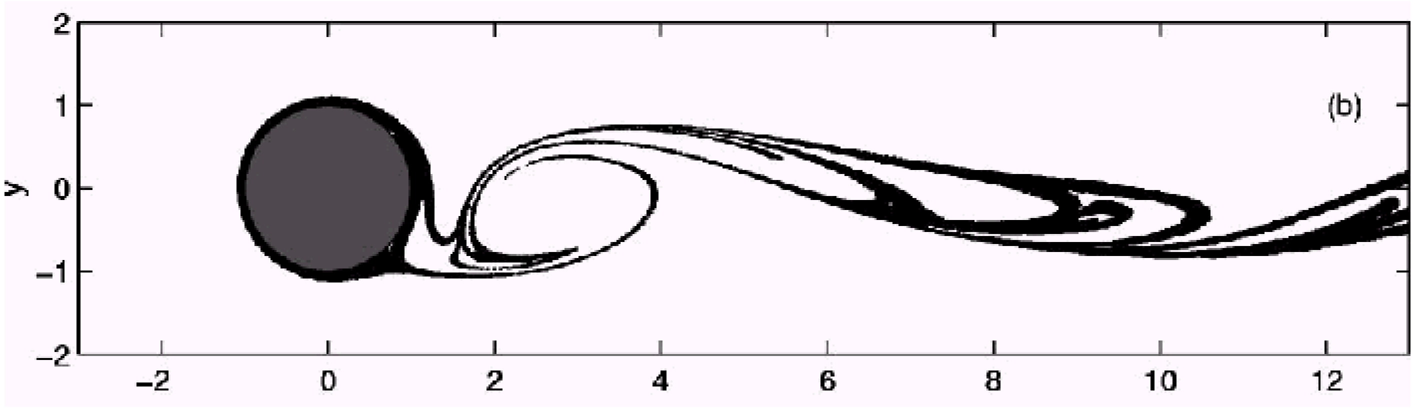


2D turbulence

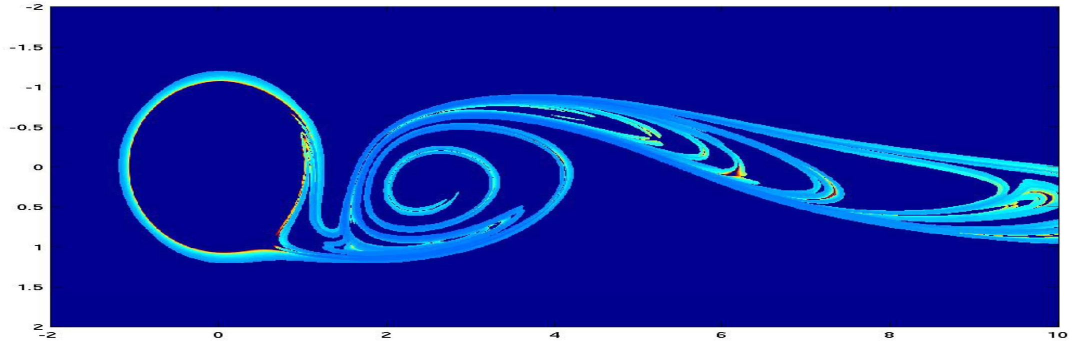
The FSLE was originally introduced to quantify dispersion from non-infinitesimal initial separations (Aurell et al. 1997). Very convenient in closed domains
Boffetta et al. Phys. Rep. 356 (2002).

)

The spatial dependence of the FSLE allows the detection of stable and unstable manifolds of hyperbolic objects

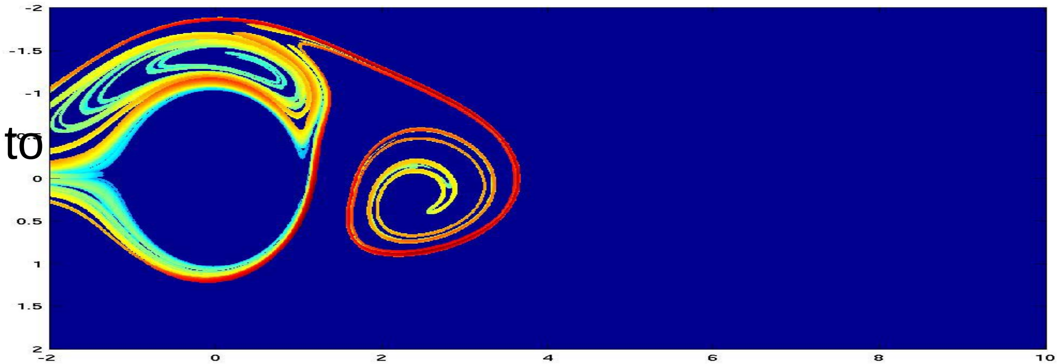


MAXIMA of FSLE: Lagrangian Coherent Structures (LCSs)



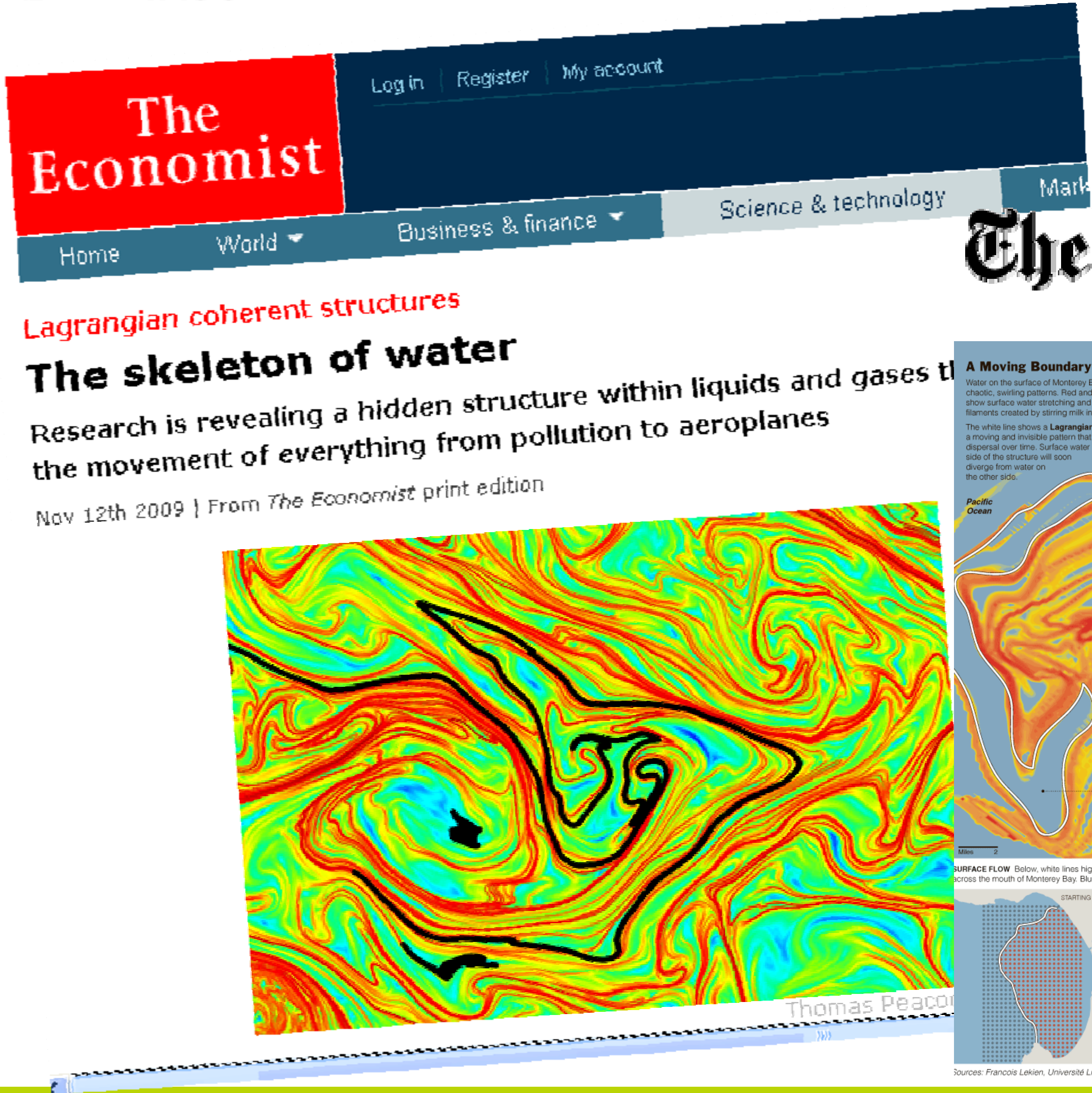
FSLE values from **time-backwards** trajectories

The lines organizing the flow seem to be the manifolds associated to strongest local Lyapunov exponents (backards and forward)



FSLE values from **time-forward** trajectories

Lagrangian Coherent Structures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Lagrangian coherent structures

The skeleton of water

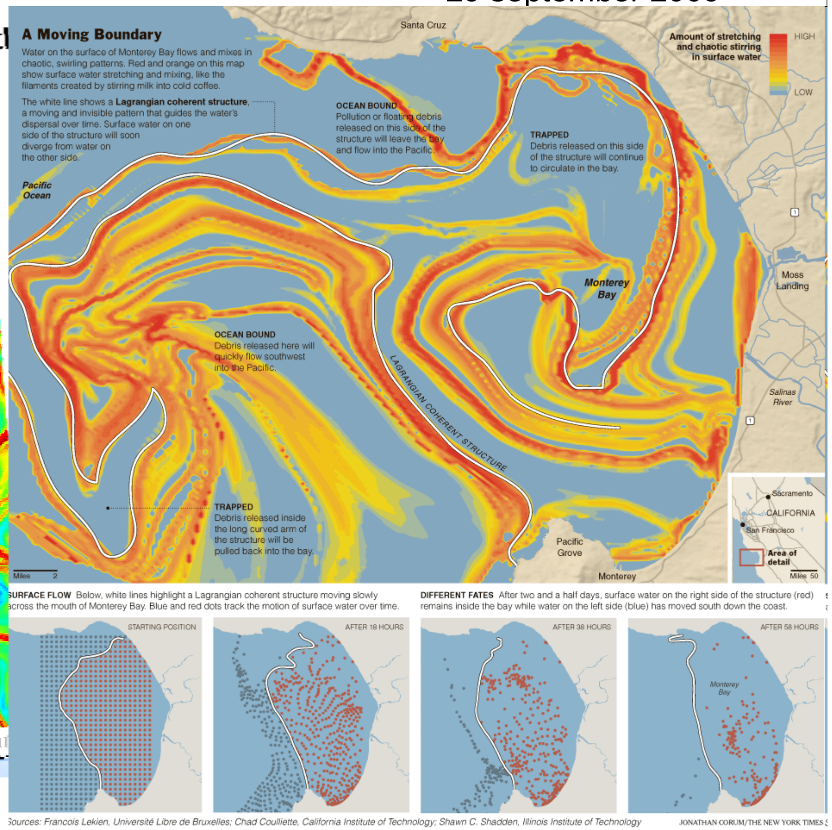
Research is revealing a hidden structure within liquids and gases tl
the movement of everything from pollution to aeroplanes

Nov 12th 2009 | From *The Economist* print edition

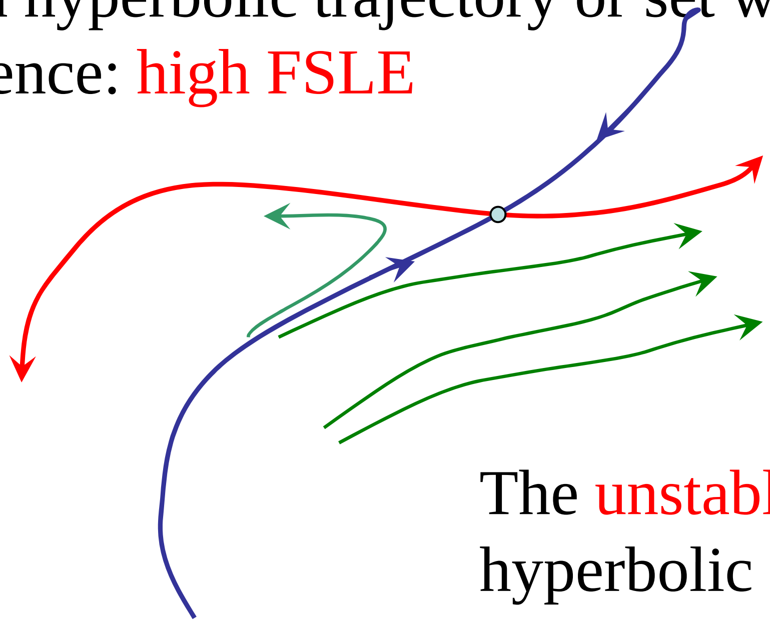
Thomas Peaco

The New York Times

29 september 2009



The idea is that initial conditions close to the stable manifold of a hyperbolic trajectory or set will show strong divergence: high FSLE

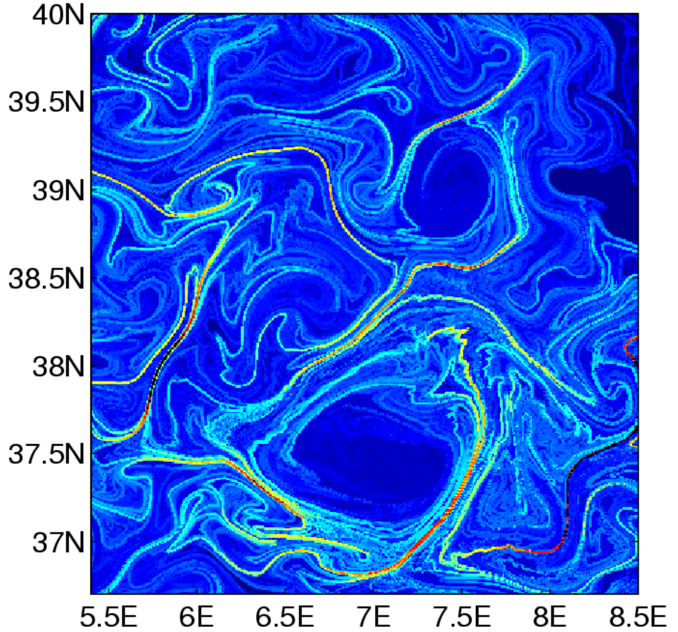


The unstable manifold of hyperbolic sets would be marked by high FSLE in the time backwards direction

Other types of Lyapunov exponents would display similar information, but FSLE is less afected by saturation

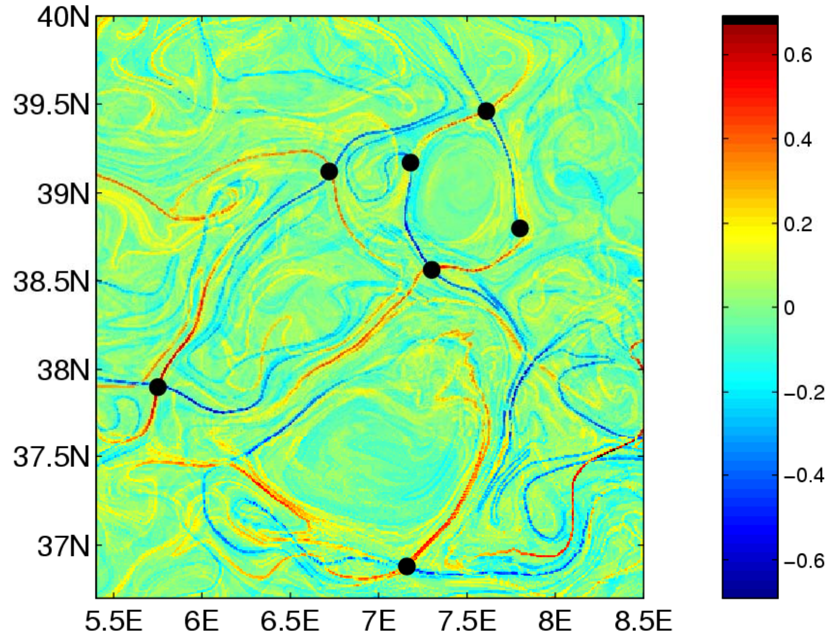
REMARK: these are heuristic consideration. Theorems needed (some available for FTLE)

CLICK ON THE FIGURES FOR MOVIES



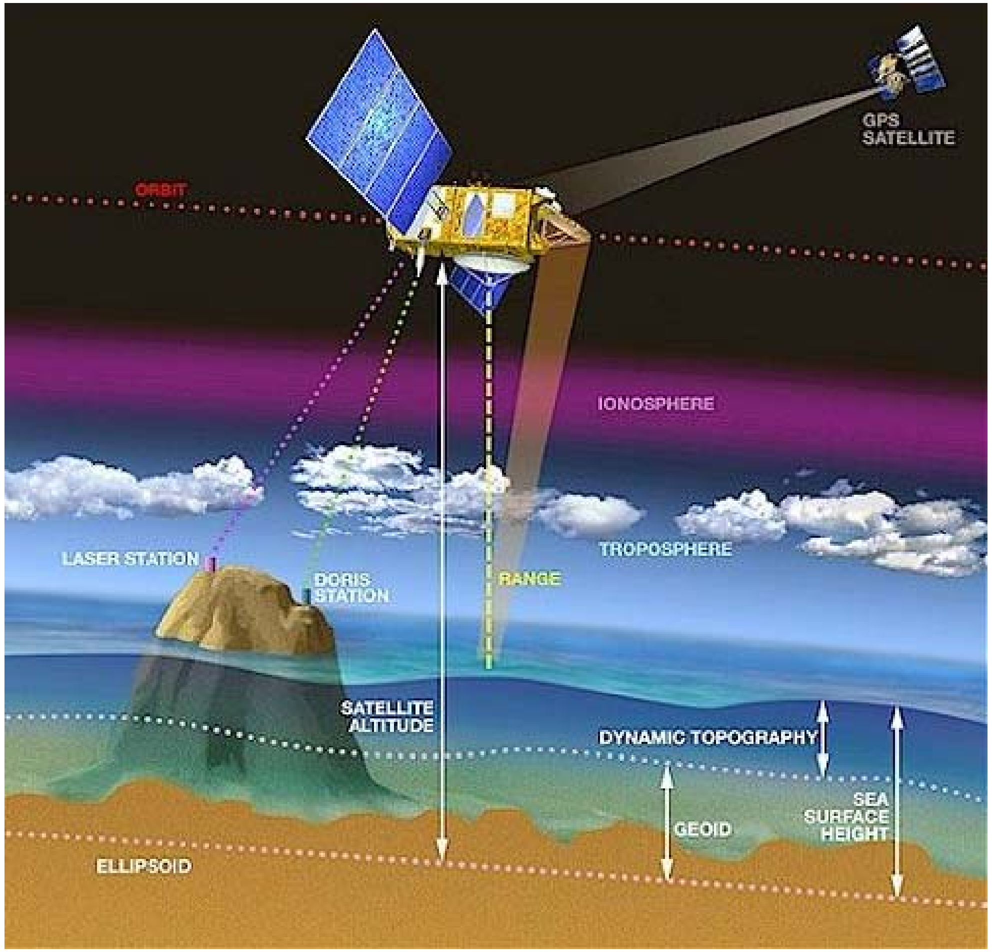
FSLE from time-backwards Integrations.
Are they really unstable manifolds of hyperbolic trajectories?

FSLE from forward and backwards integrations



The strongest lines are seen to organize tracer flow

SATELLITE ALTIMETRY FROM TOPEX/POSEIDON, ERS-2, JASON, ENVISAT, …



Dynamic Topography (DT)=
Sea Surface Heigh (SSH) – Geoid (G)

SSH ≈ 3 cm
G ≈ meters …

Sea Level Anomalies (SLA) =
$SSH - \langle SSH \rangle_t = DT - \langle DT \rangle_t$

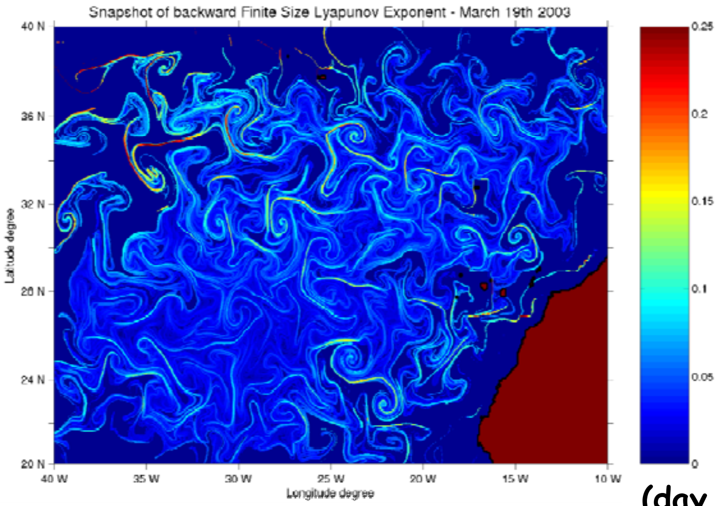
Dynamic topography determines, via the Colioris force, the velocity field (at large scales, geostrophic approximation)

Ageostrophic components Can be estimated from scatterometer data

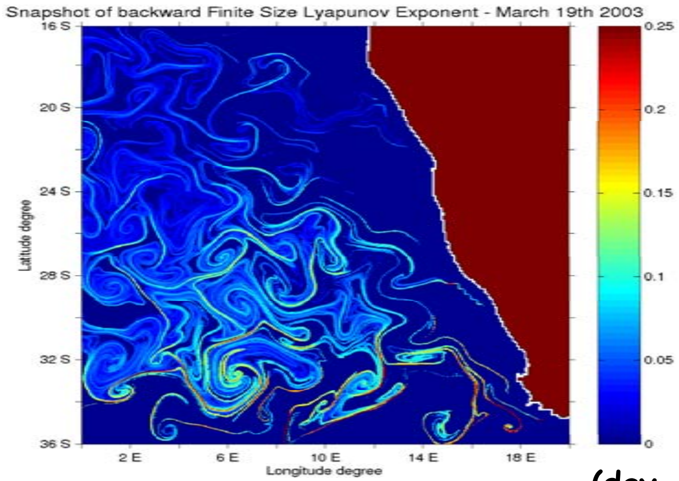
(Surface roughness → wind → Eckman component)

FROM ALTIMETRY DATA

BENGUELA

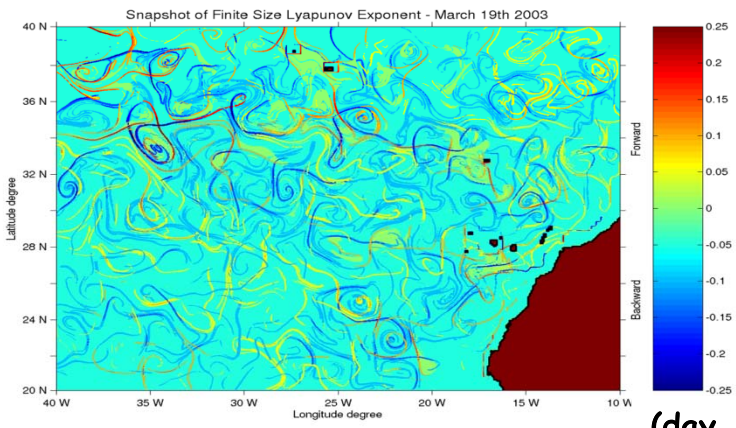


(day s^{-1})



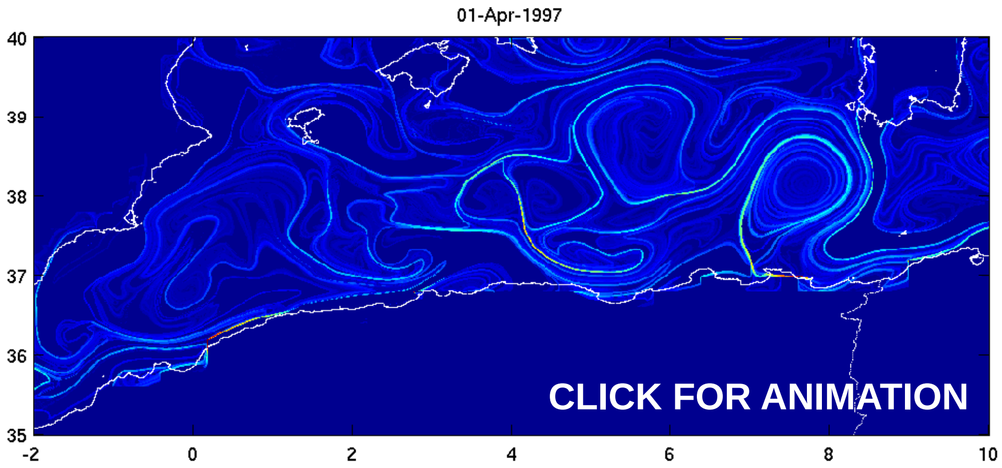
(day s^{-1})

March 19 2003 snapshots

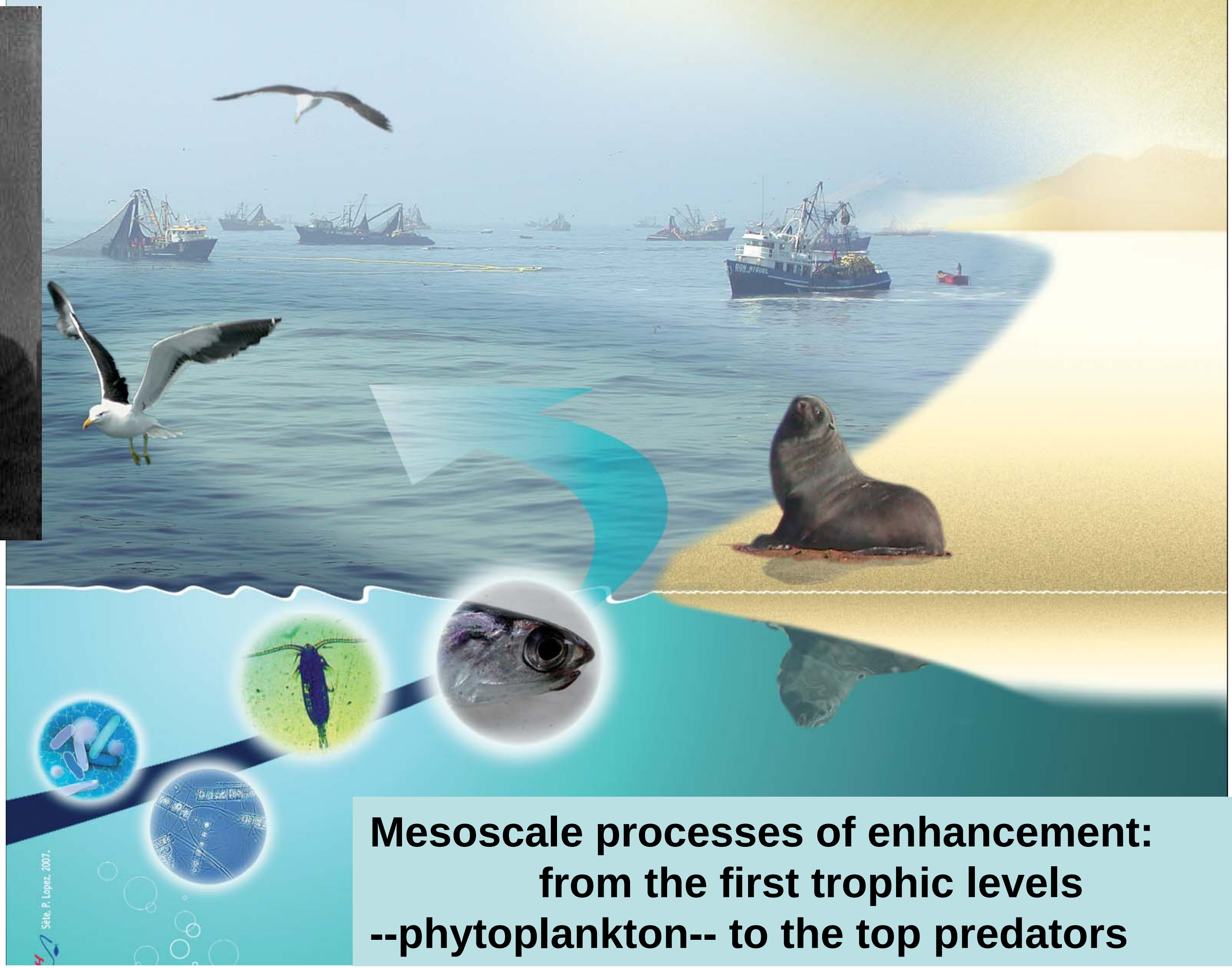


(day s^{-1})

CANARY

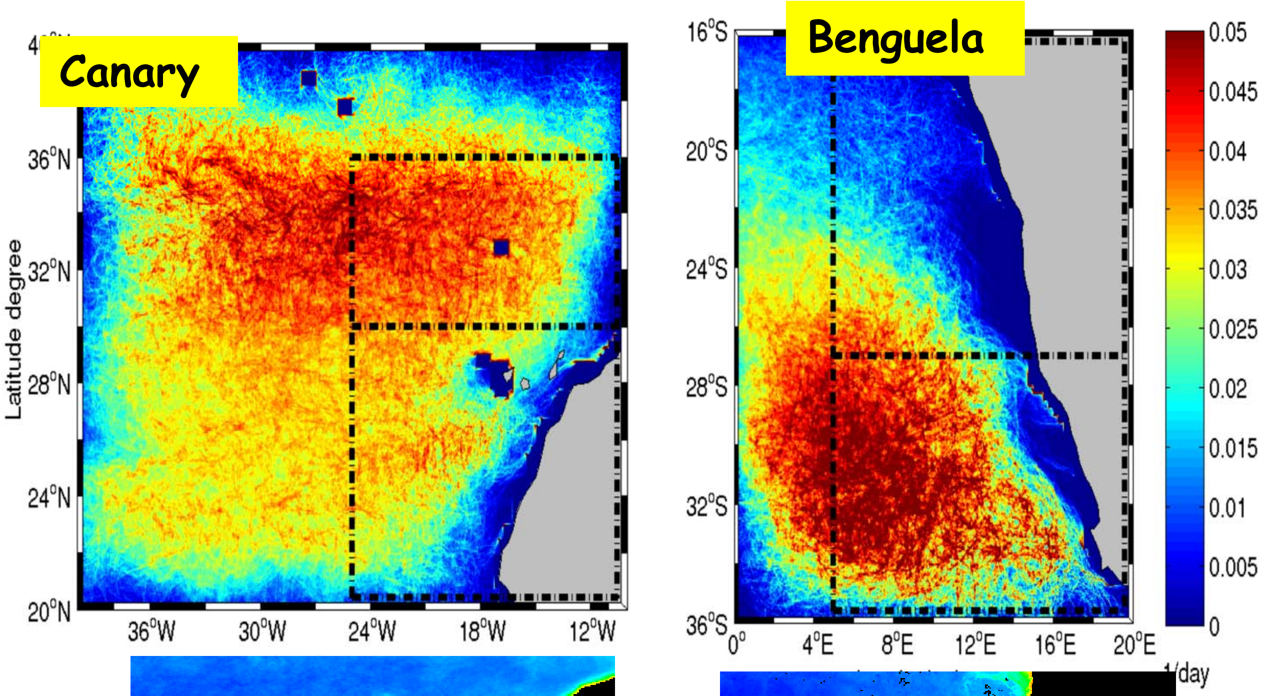


Describing biological process with Lyapunov eyes …

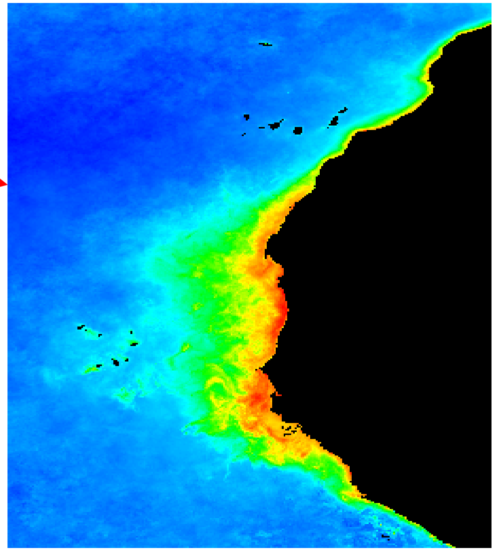


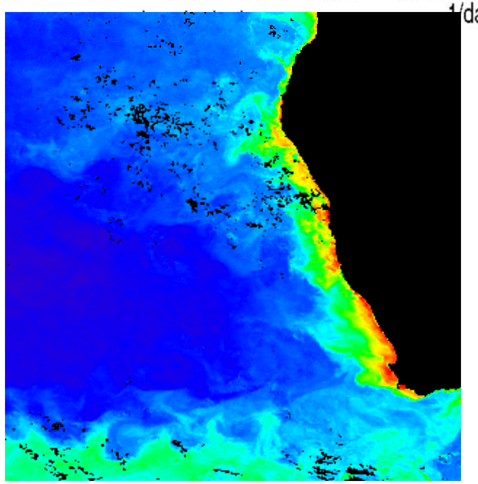
Mesoscale processes of enhancement:
from the first trophic levels
--phytoplankton-- to the top predators

Backward FSLE (λ-): Temporal average **(a measure of horizontal MIXING)** from June 2000 till June 2005



Phytoplankton and in the world major upwelling areas

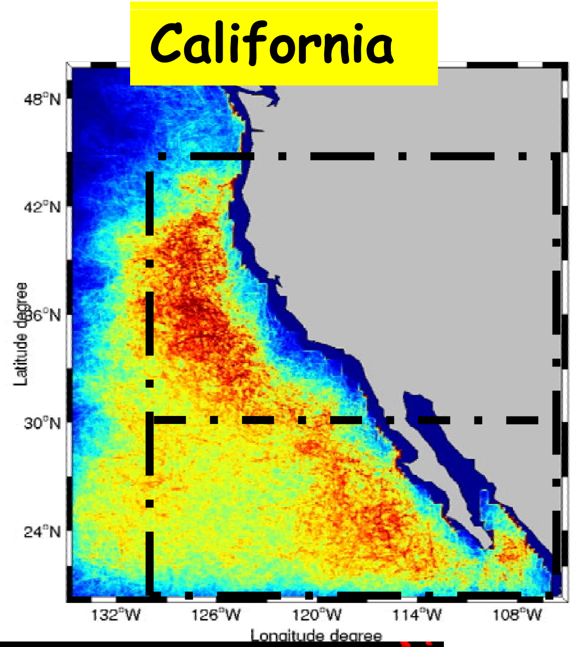


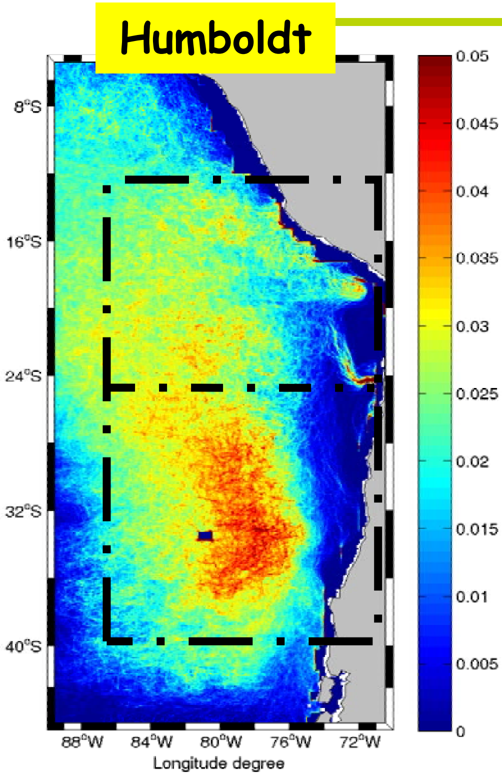


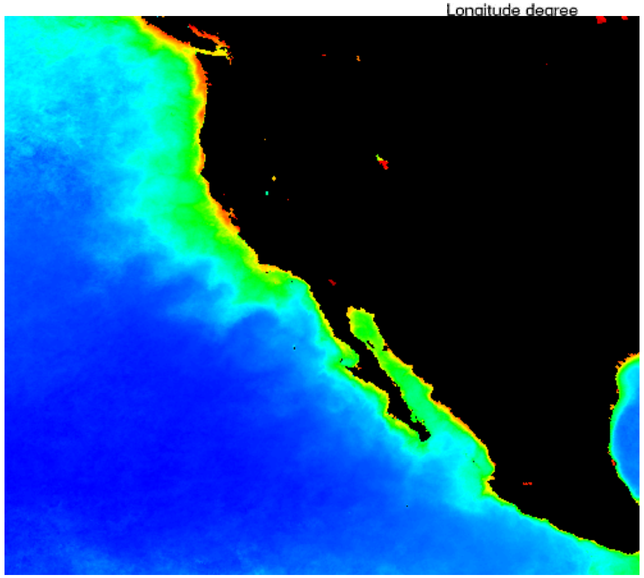
Rossi et al.,

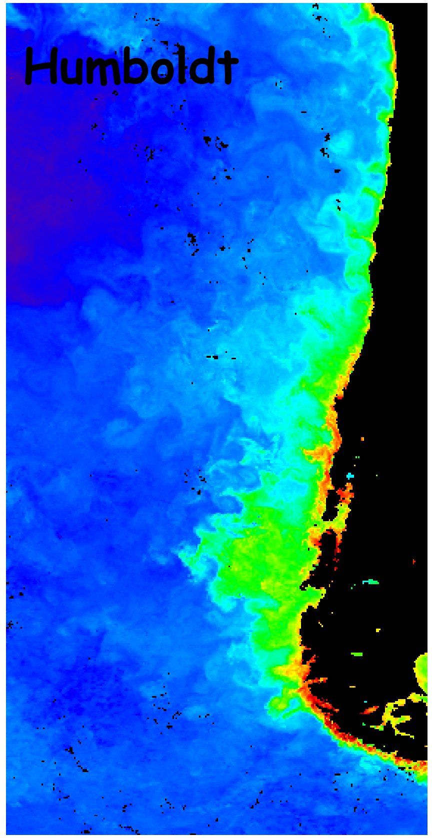
Geophys, Res. Lett. 2008

Nonlin. Proc. Geophys. 2009









Backward FSLE (λ-):
Temporal average
(a measure of horizontal MIXING)
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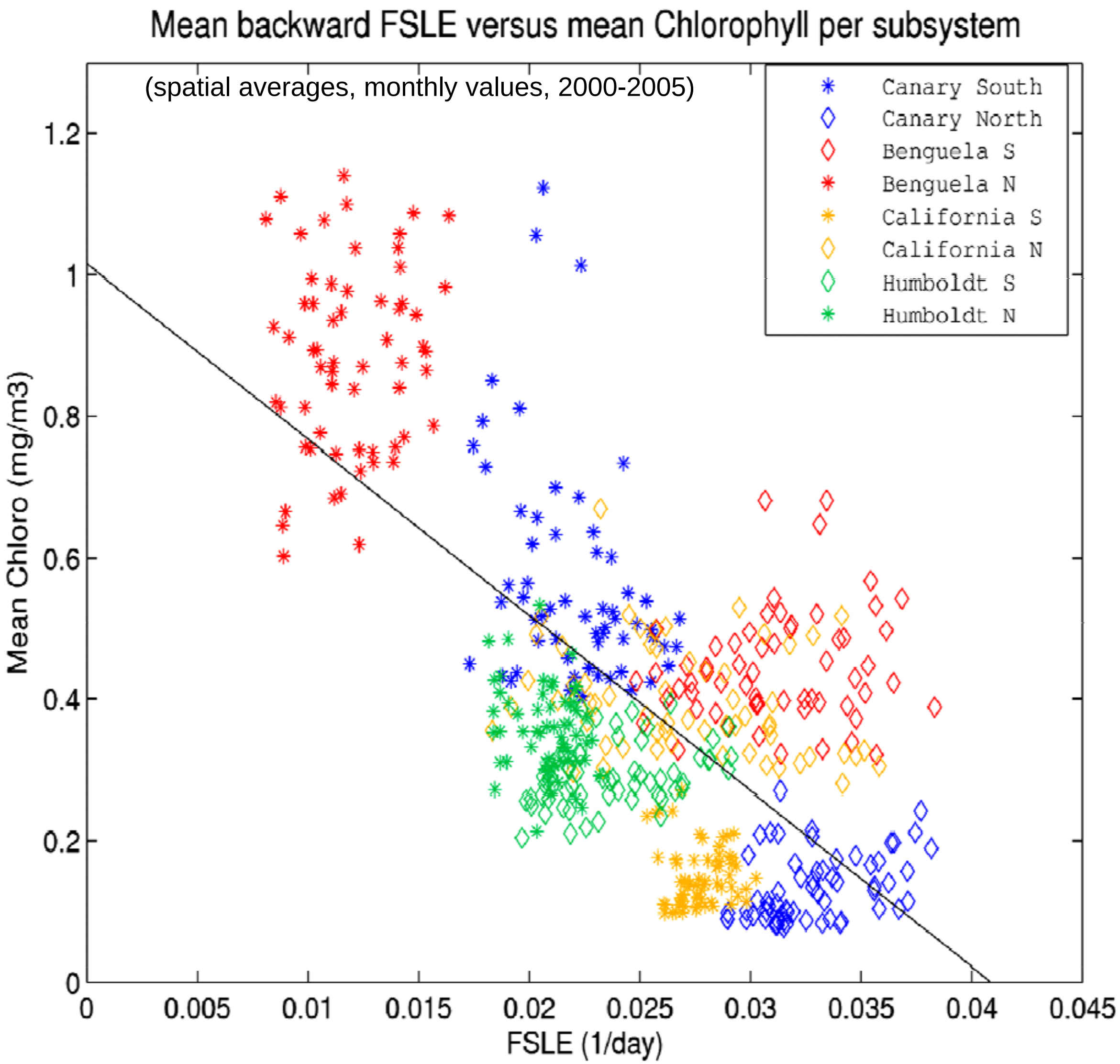
Rossi et al.,
Geophys, Res. Lett. 2008
Nonlin. Proc. Geophys. 2009



- Negative correlation
- Clustering
- Less turbulent systems are characterized by: LOW FSLE / HIGH CHLOROPHYLL.
- Most turbulent systems: HIGH FSLE / LOW CHLOROPHYLL.

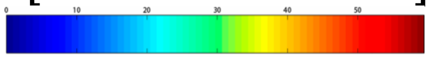
Opposite to behavior seen in less enriched systems

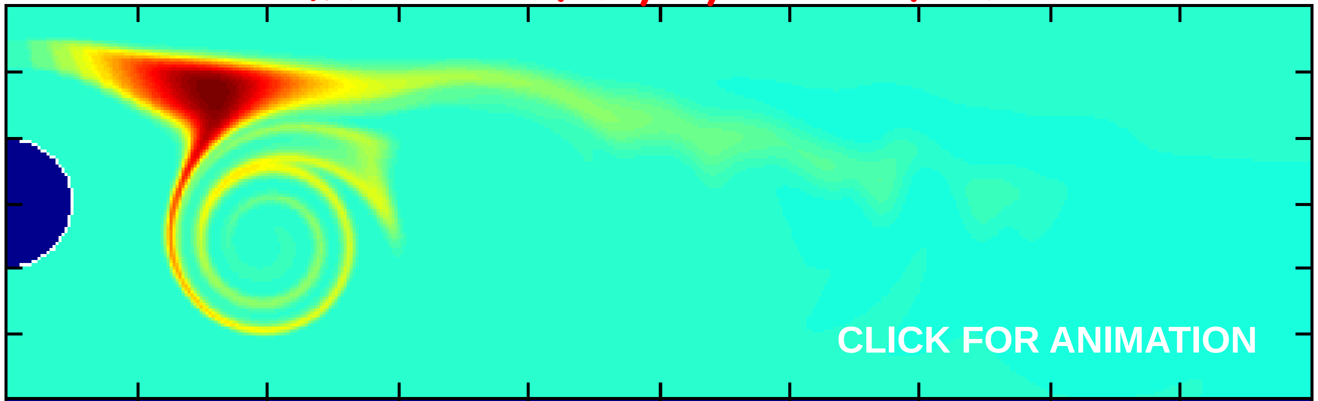
Simulations of N, P, Z in a flow

steady state inflow
concentrations (N, P, Z)

phytoplankton

[0 14]



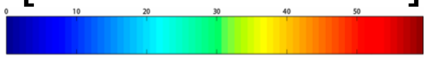


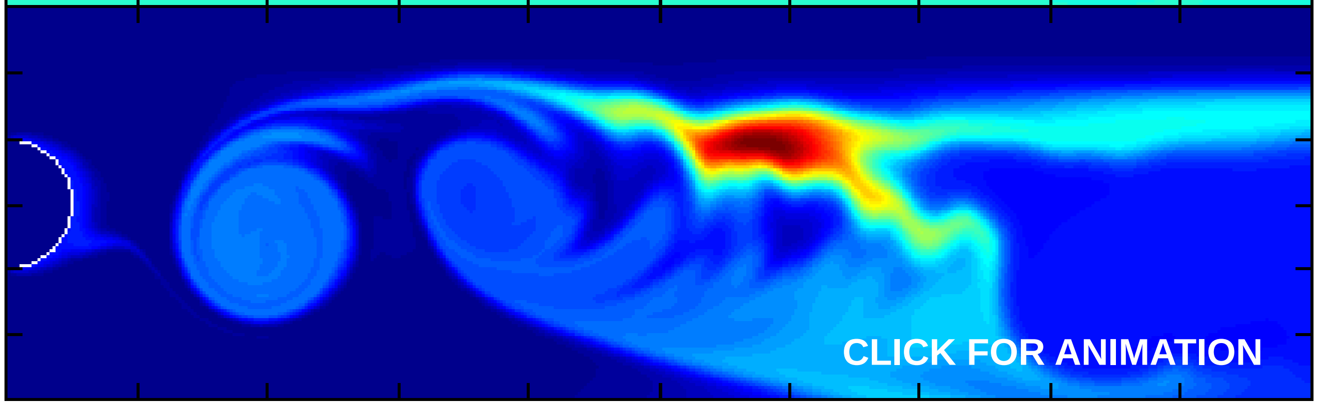
Y

low inflow
concentrations (N, P, Z)

phytoplankton

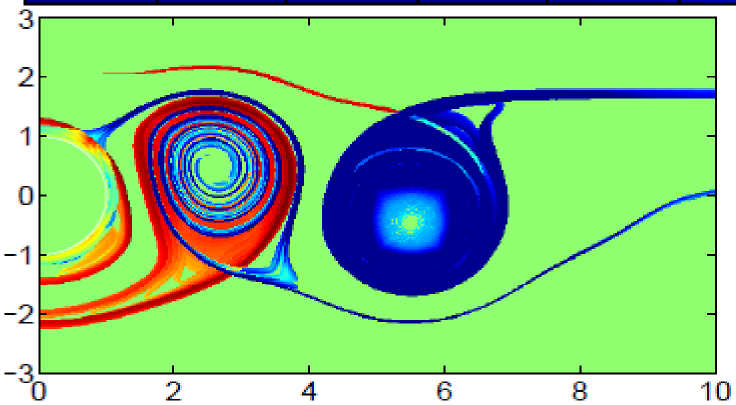
[0 45]





Y

FSLE field



Sandulescu et al. *Nonlinear Processes in Geophysics* **14**, 443-454 (2007)

Sandulescu et al. *Ecological Complexity* **5**, 228-237 (2008)

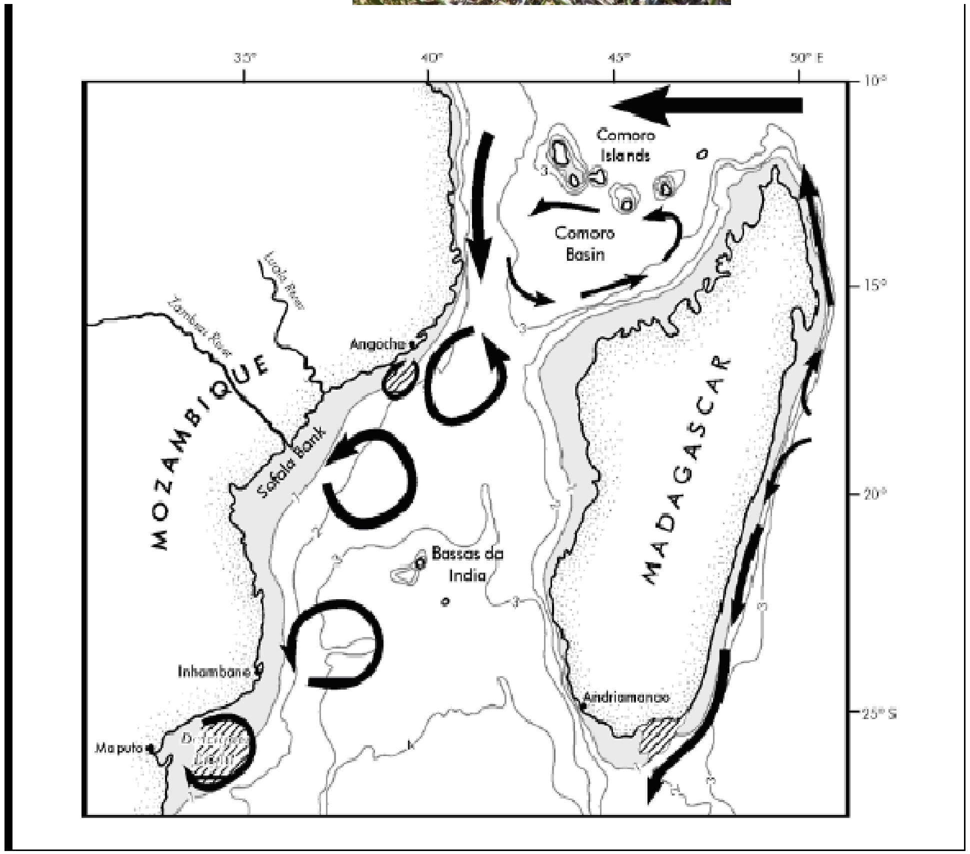
- Lagrangian Coherent Structures give the skeleton of horizontal transport
- This certainly influences abiotic quantities: temperature, nutrients, …
- This certainly influences plankton distribution
- From there, impact is expected in plankton consumers, their predators, … cascades up along the food chain …

FRIGATEBIRDS in the MOZAMBIQUE CHANNEL

Particular topography (channel/islands) linked with strong mesoscale activity:

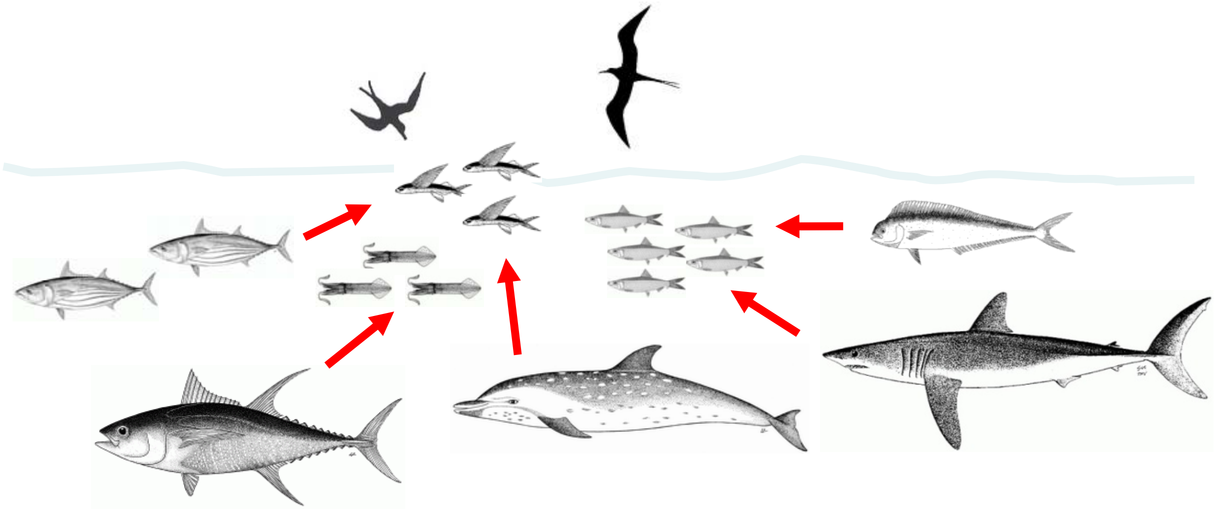
- Large anticyclonic cell at the north
- Local upwellings
- Anticyclonic and cyclonic mesoscale eddies moving southward permanently.

(De *Ruijter et al., 2004*)



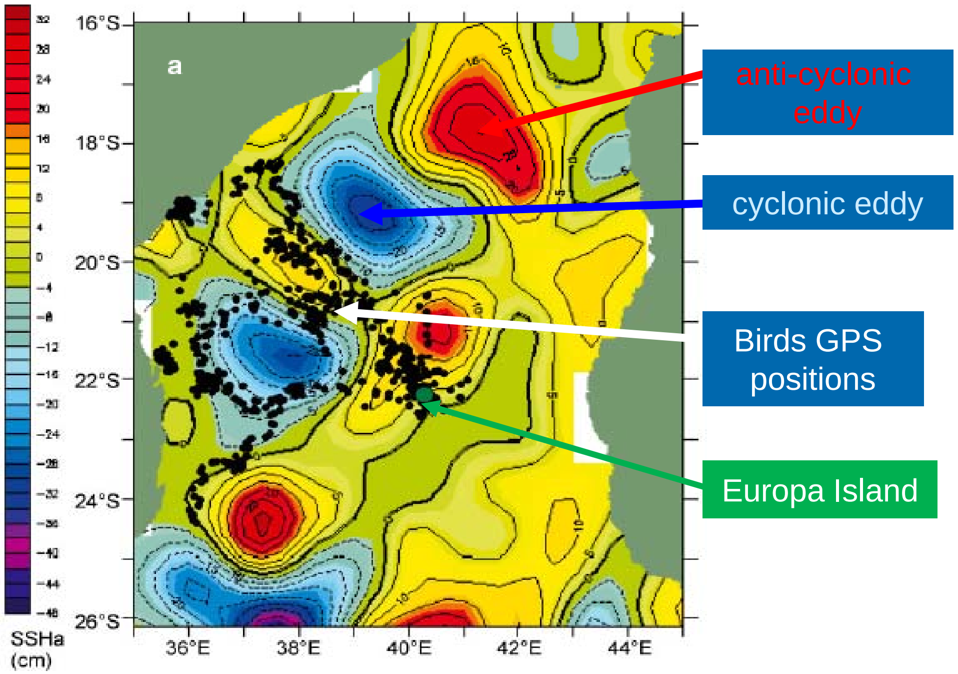
Great frigatebird (*fregata minor*):

- Large seabirds (light weight < 5 kg and large wings > 2m). Use thermals to soar before gliding over long distances and time (days/nights over weeks).
- Traveling at high altitudes to locate patches of prey and come close to surface to feed (reduced flight speed indicates foraging).
- Feeding occurs only during daytime (peaks in the morning and evening).
- Unable to dive or rest on the water surface (permeable plumage) → in association with subsurface predators (tuna, …): **fisheries indicators**



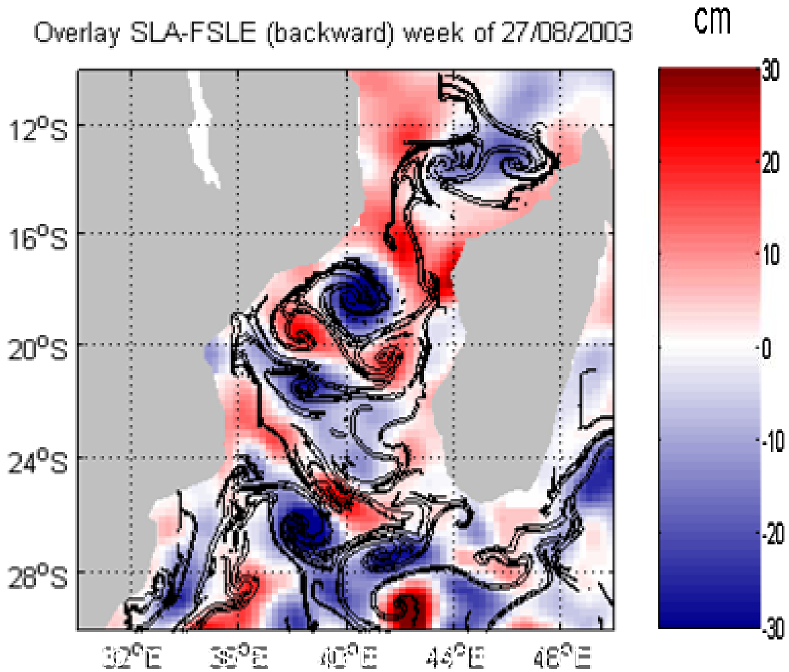
Weimerskirch et al. 2004; Jaquemet et al. 2005

SSH (cm): Eulerian view



Weimerskirch et al,2004

Lagrangian FSLEs versus SSH



The Lagrangian FSLE gives access to submesoscale structures

We identify Lagrangian Coherent Structures with |FSLE| > 0.1 day^{-1}

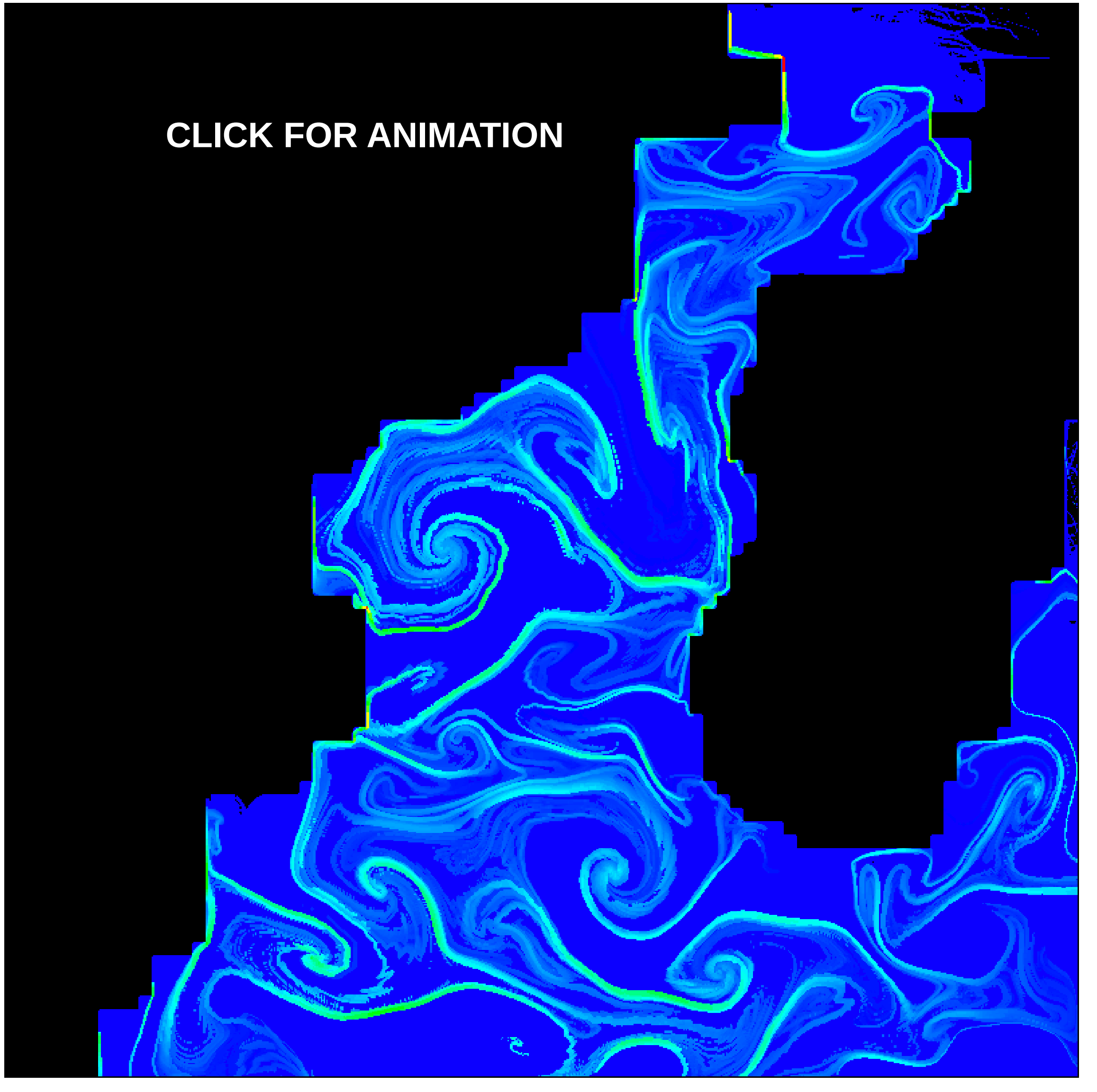
8 birds (from Europa Island community) fitted with satellite transmitter and altimeter.

Followed for their foraging trips from August 18 to September 30, 2003.

1600 Argos positions from 50 trips, distributed into 17 long trips (> 614 km) and 33 short trips.

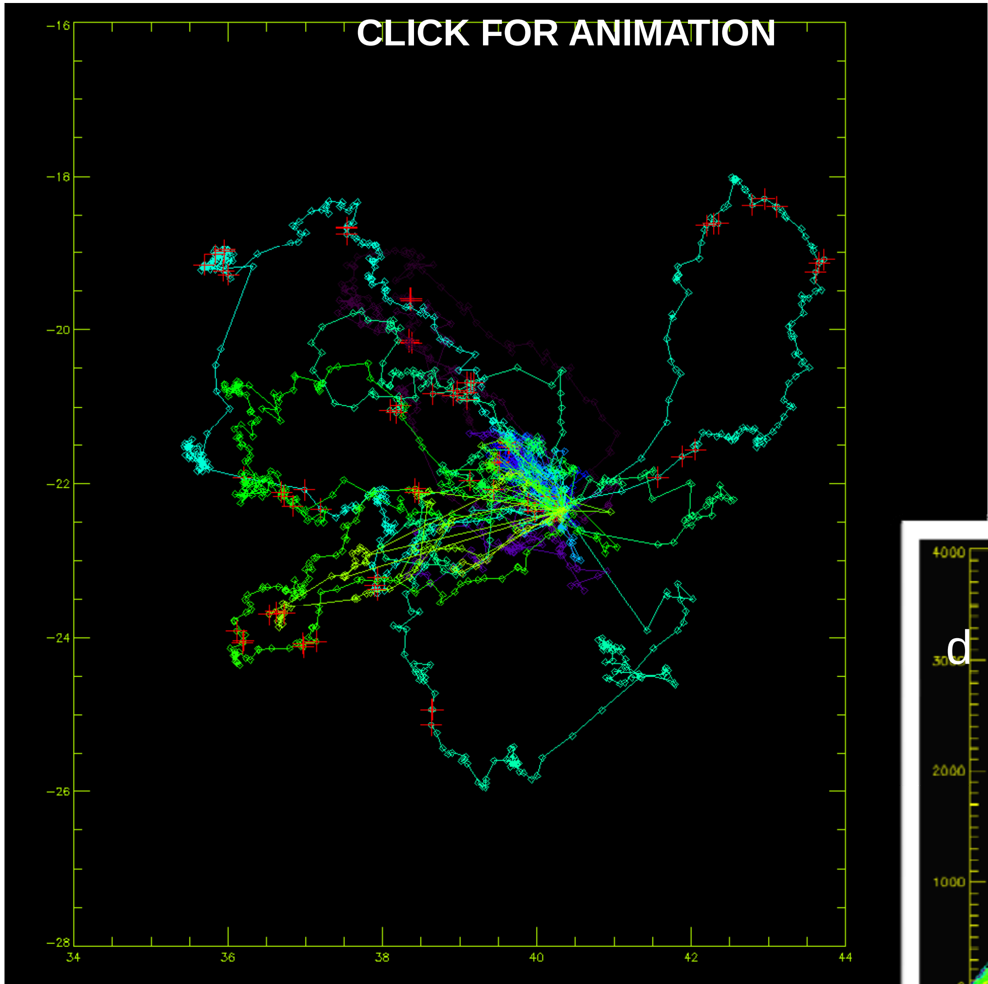
(Weimerskirch et al., 2004)

Satellite transmitter and altimeter
(total weight : 1 to 3% mass of adults, max 45g)



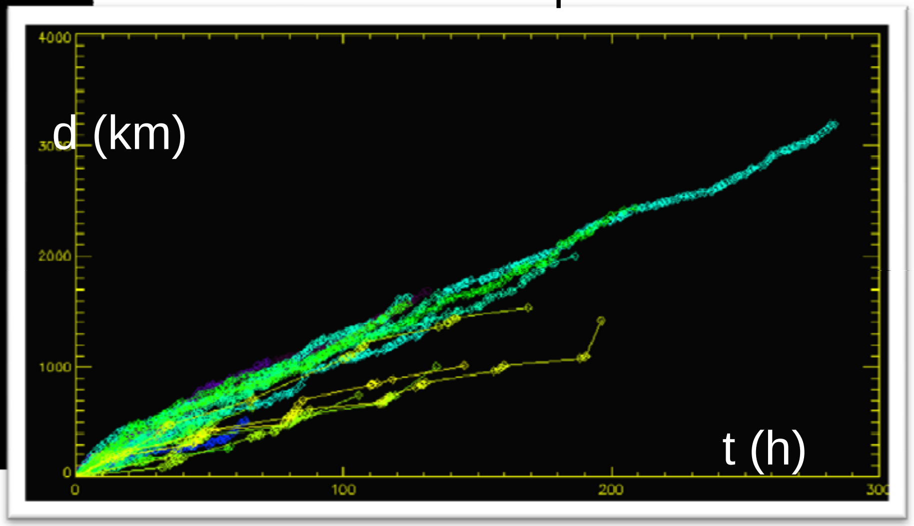
Backwards
FSLE

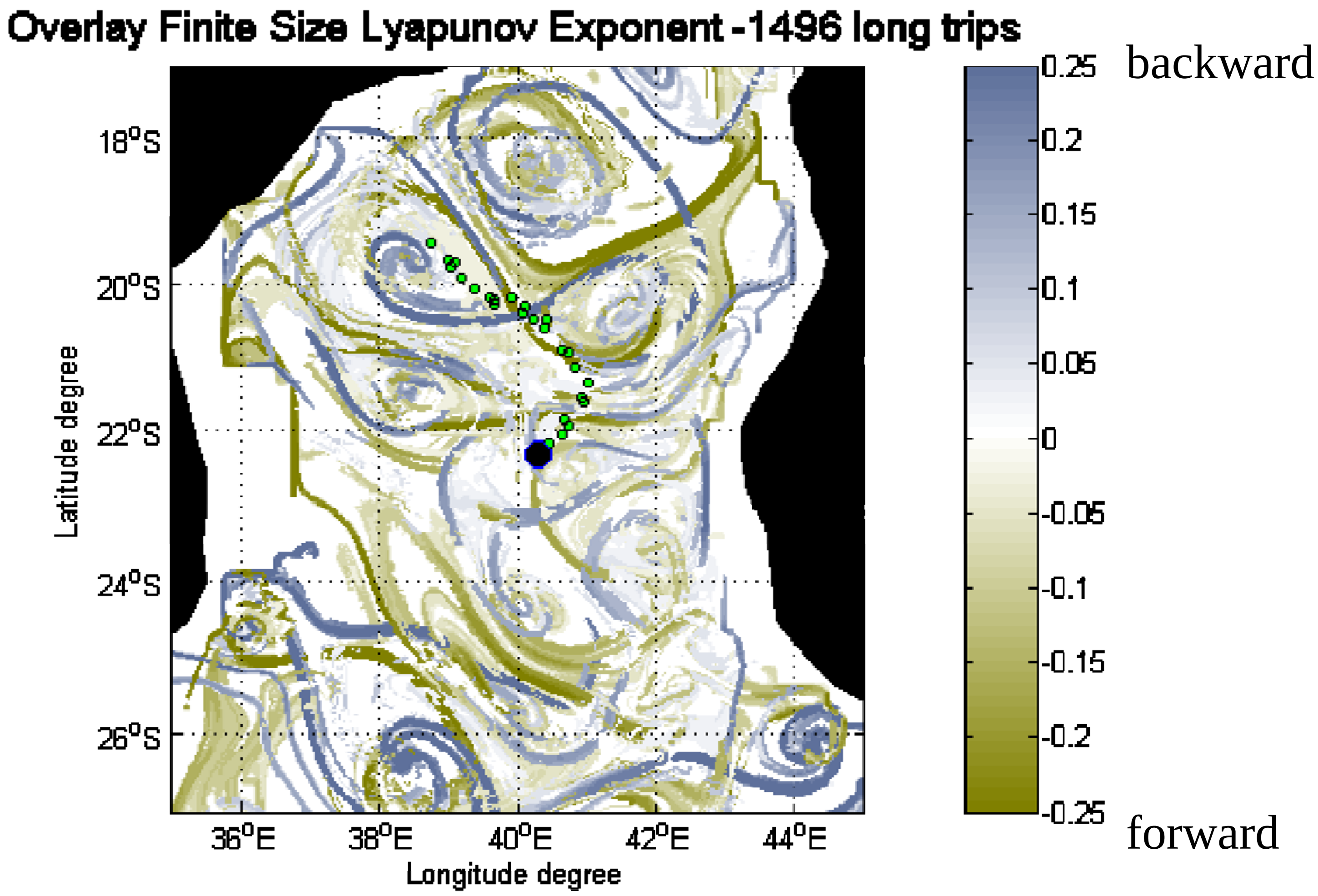
August 18 -
September 30,
2003.



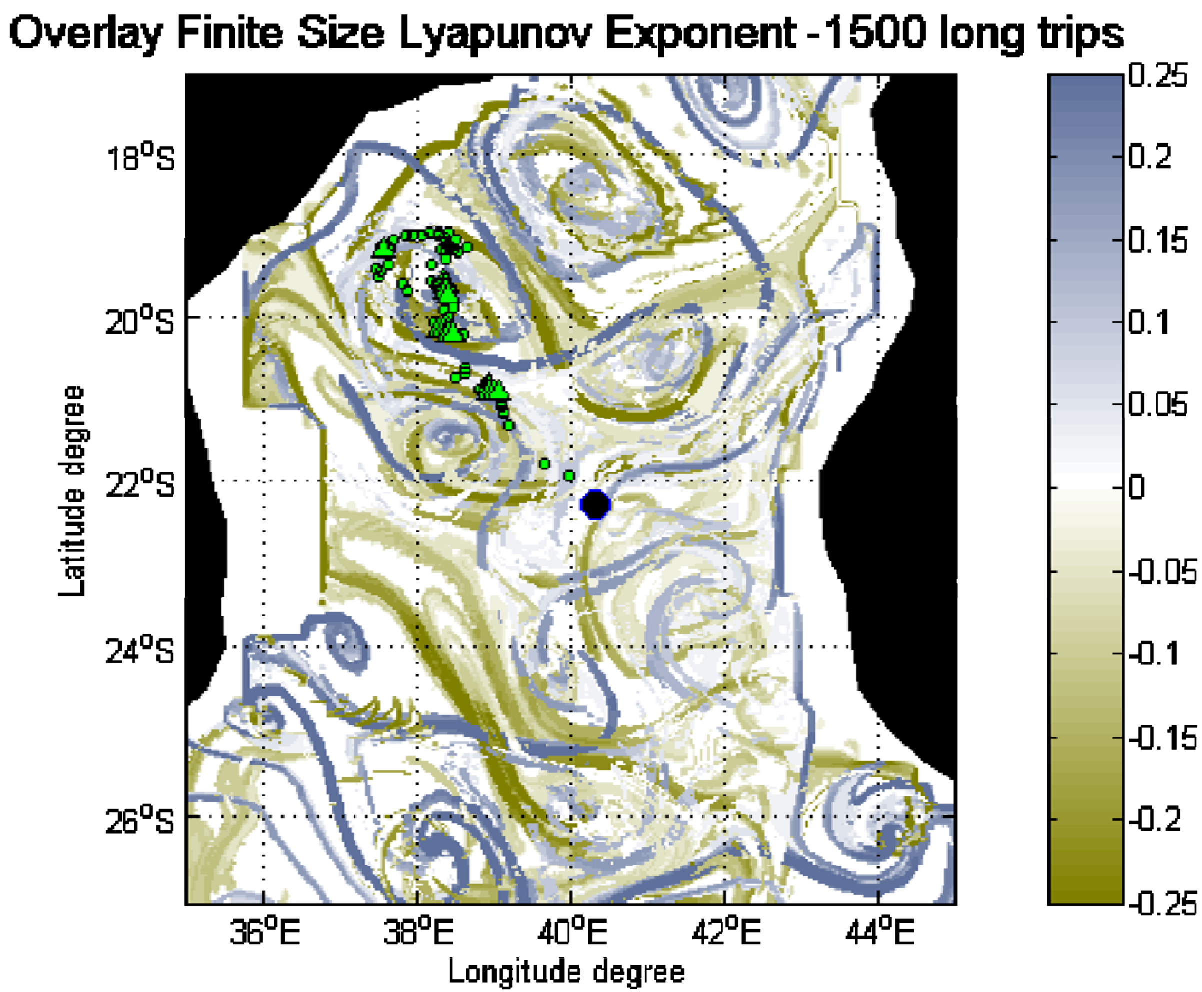
Birds flights

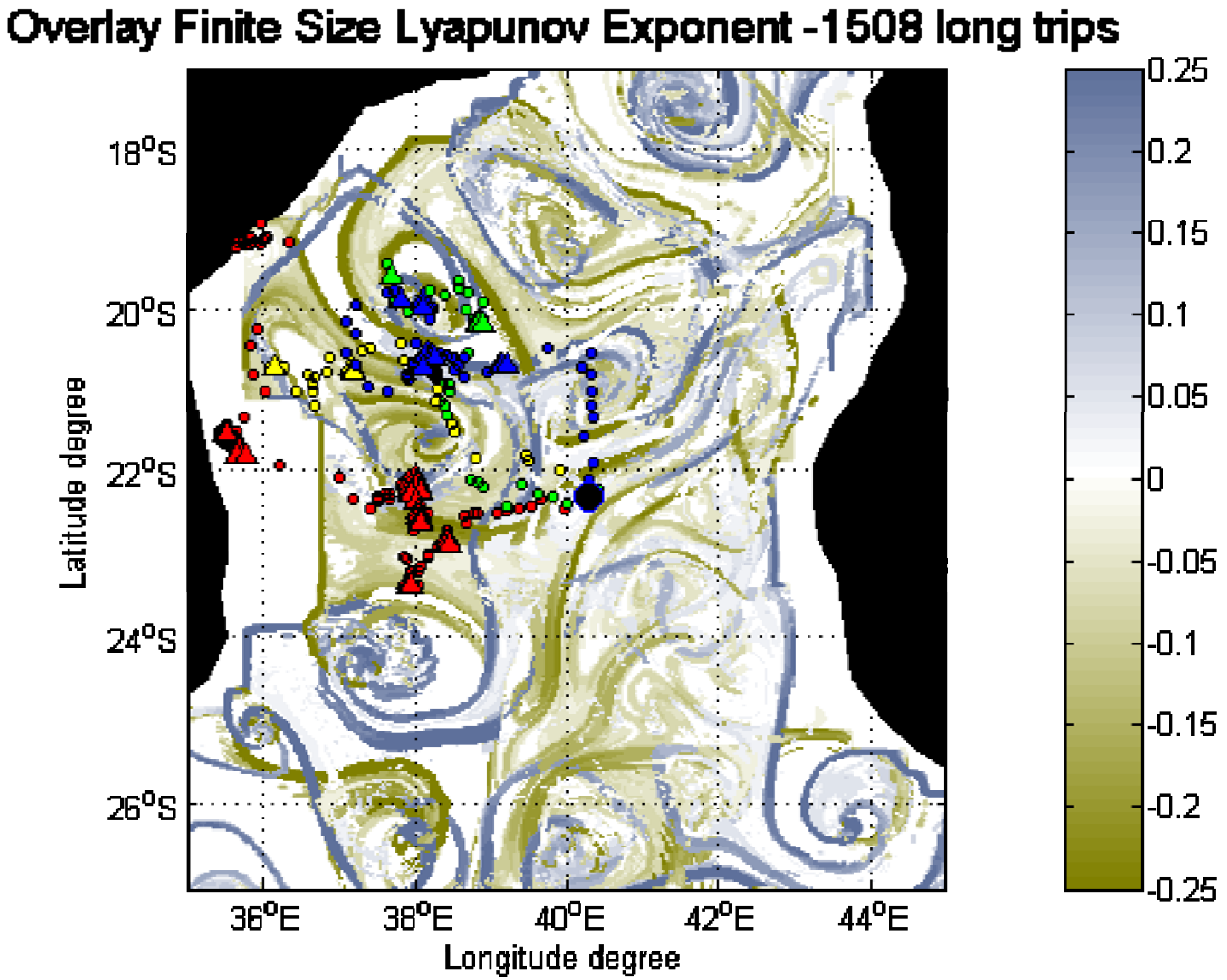
Birds displacement

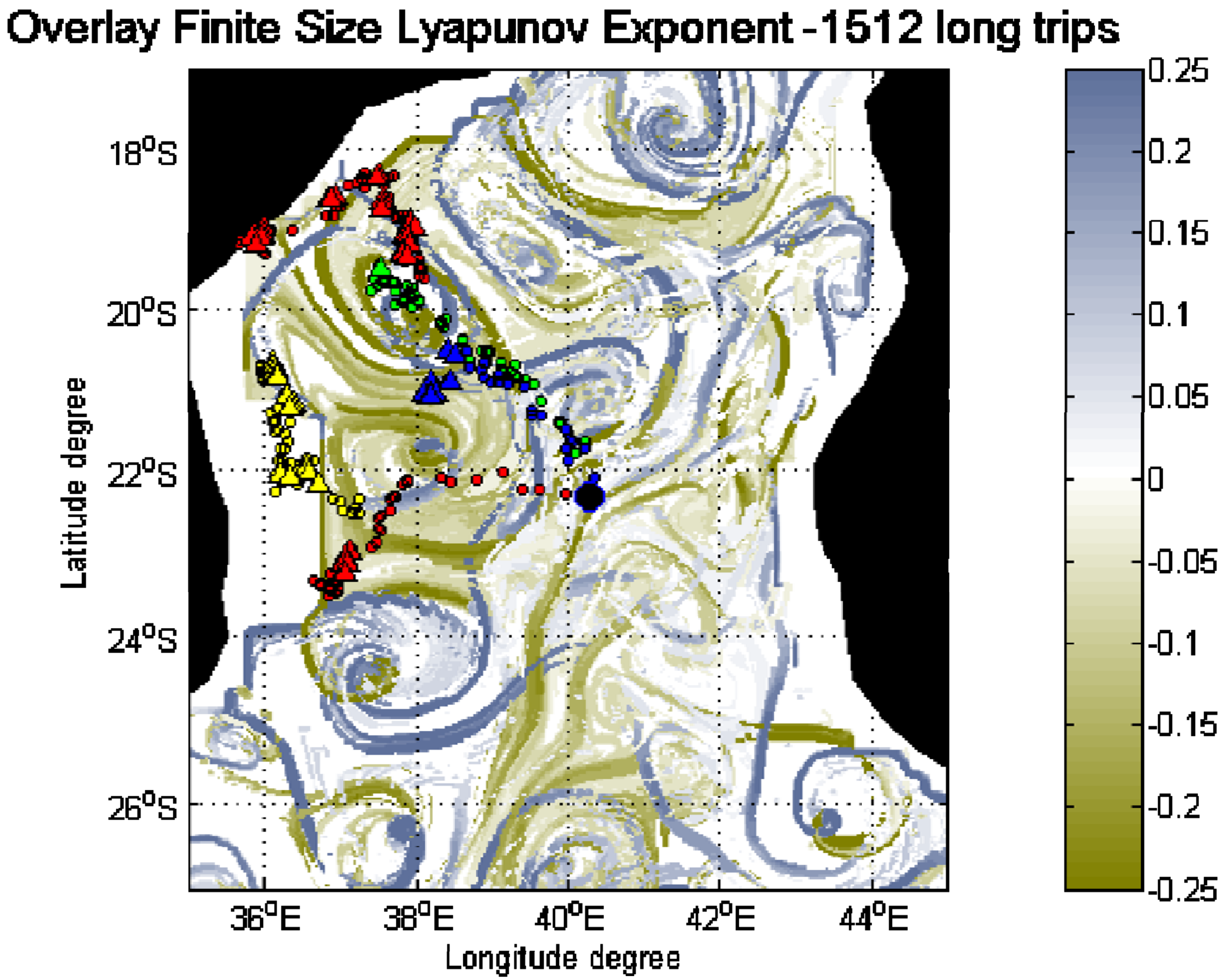


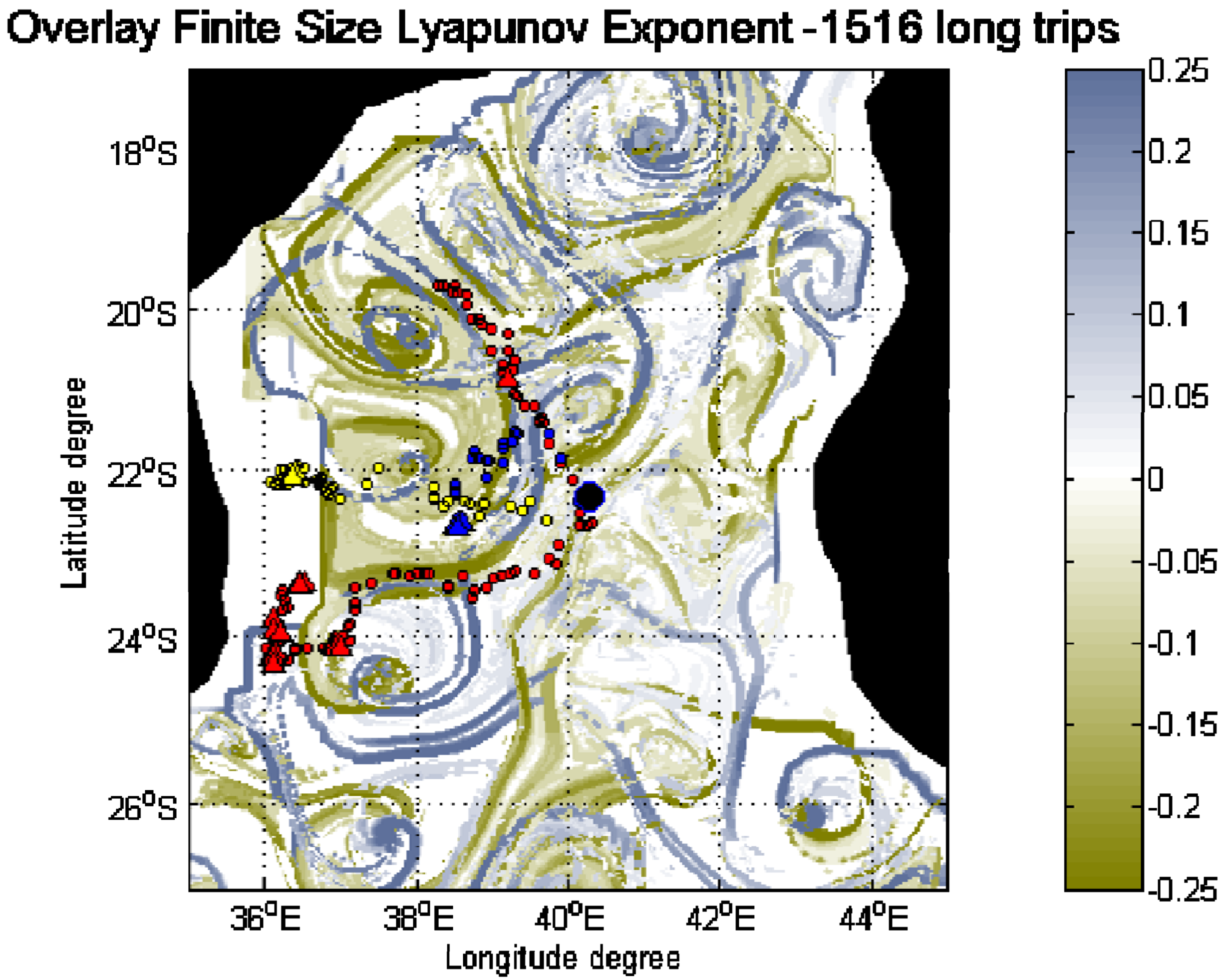


Overlay Finite Size Lyapunov Exponent -1496 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
backward
forward


Overlay Finite Size Lyapunov Exponent -1500 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25


Overlay Finite Size Lyapunov Exponent -1508 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25


Overlay Finite Size Lyapunov Exponent -1512 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25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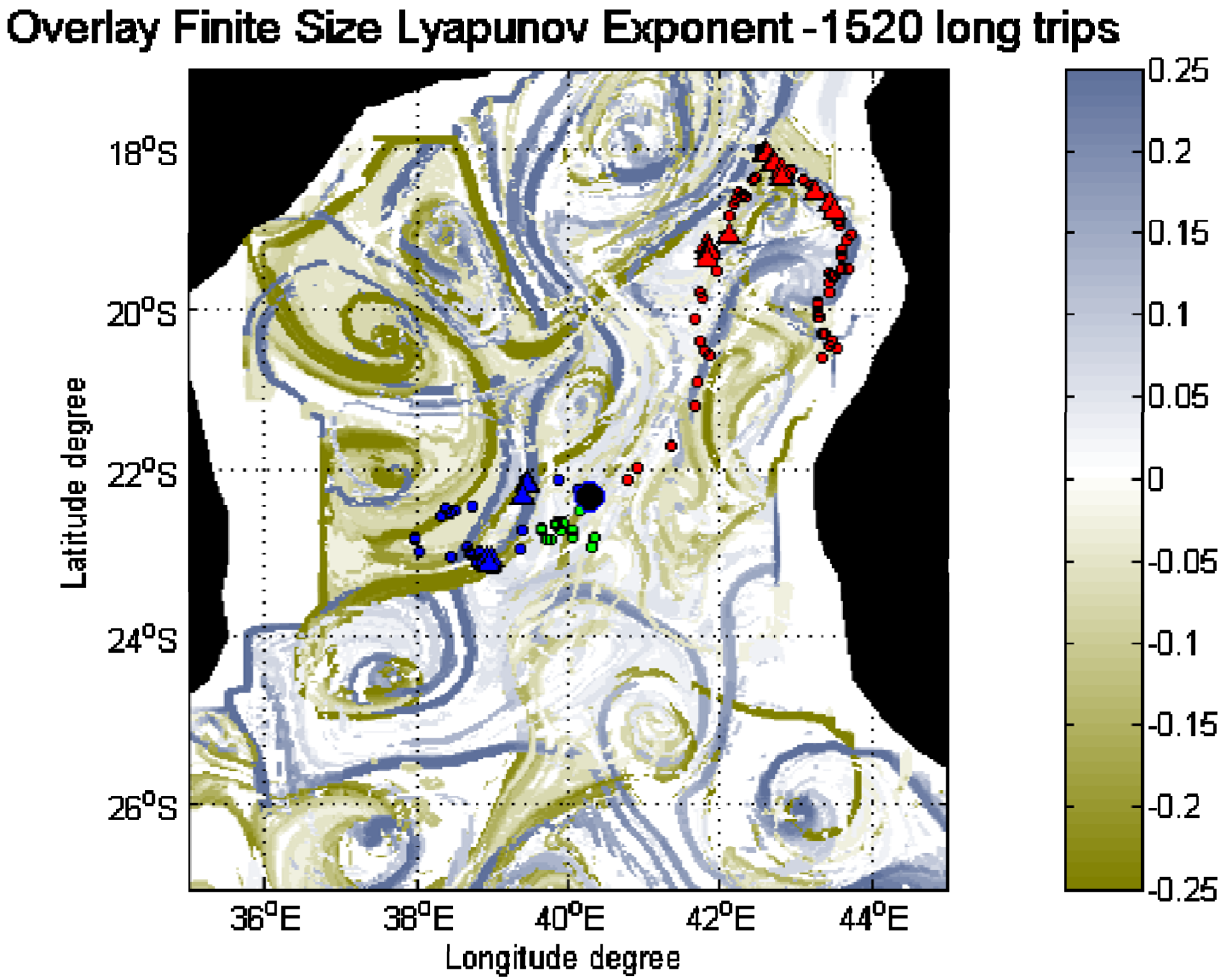
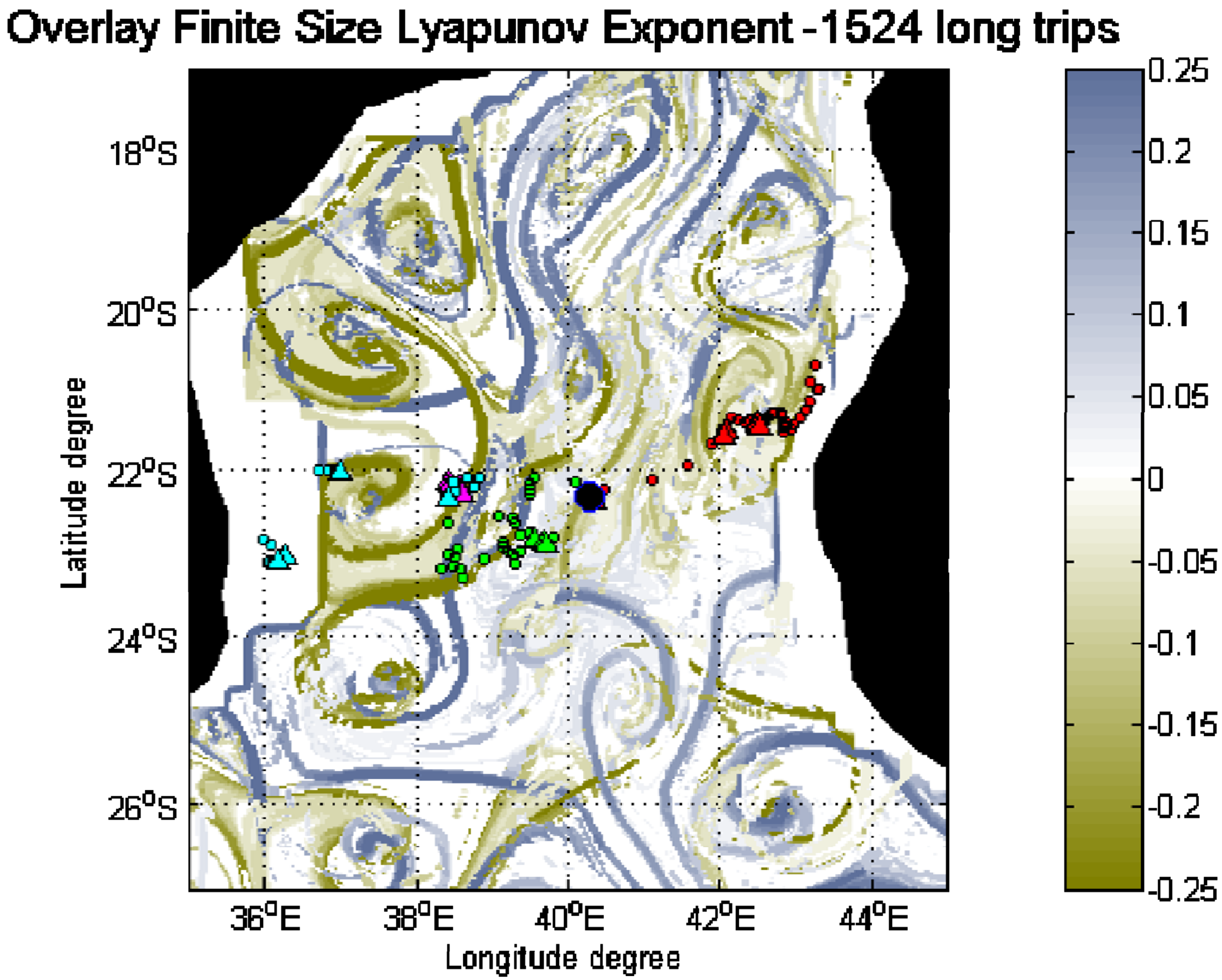
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25


Overlay Finite Size Lyapunov Exponent -1520 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25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Latitude degree
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22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Longitude degree
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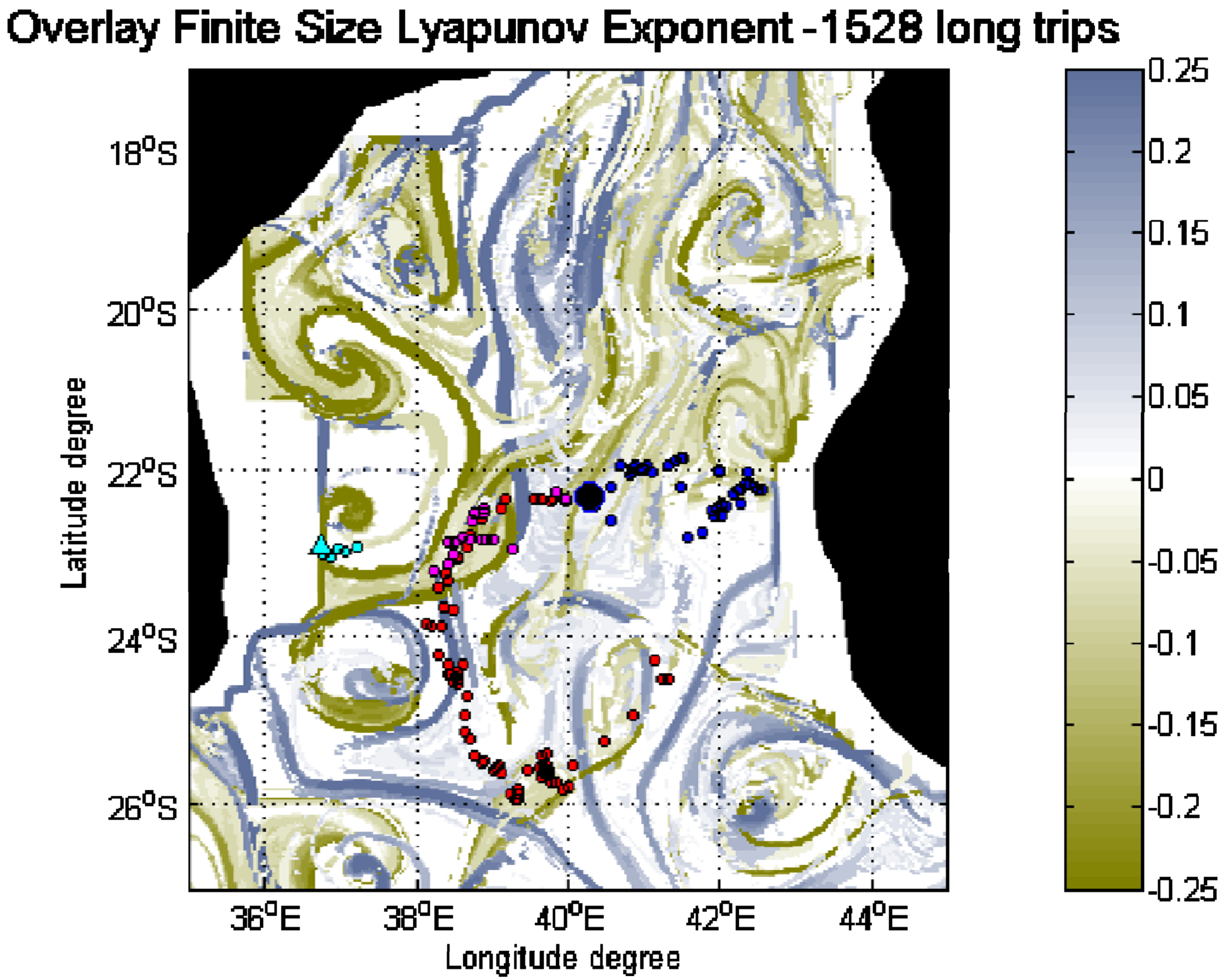
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25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20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
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0.2
0.15
0.1
0.05
0
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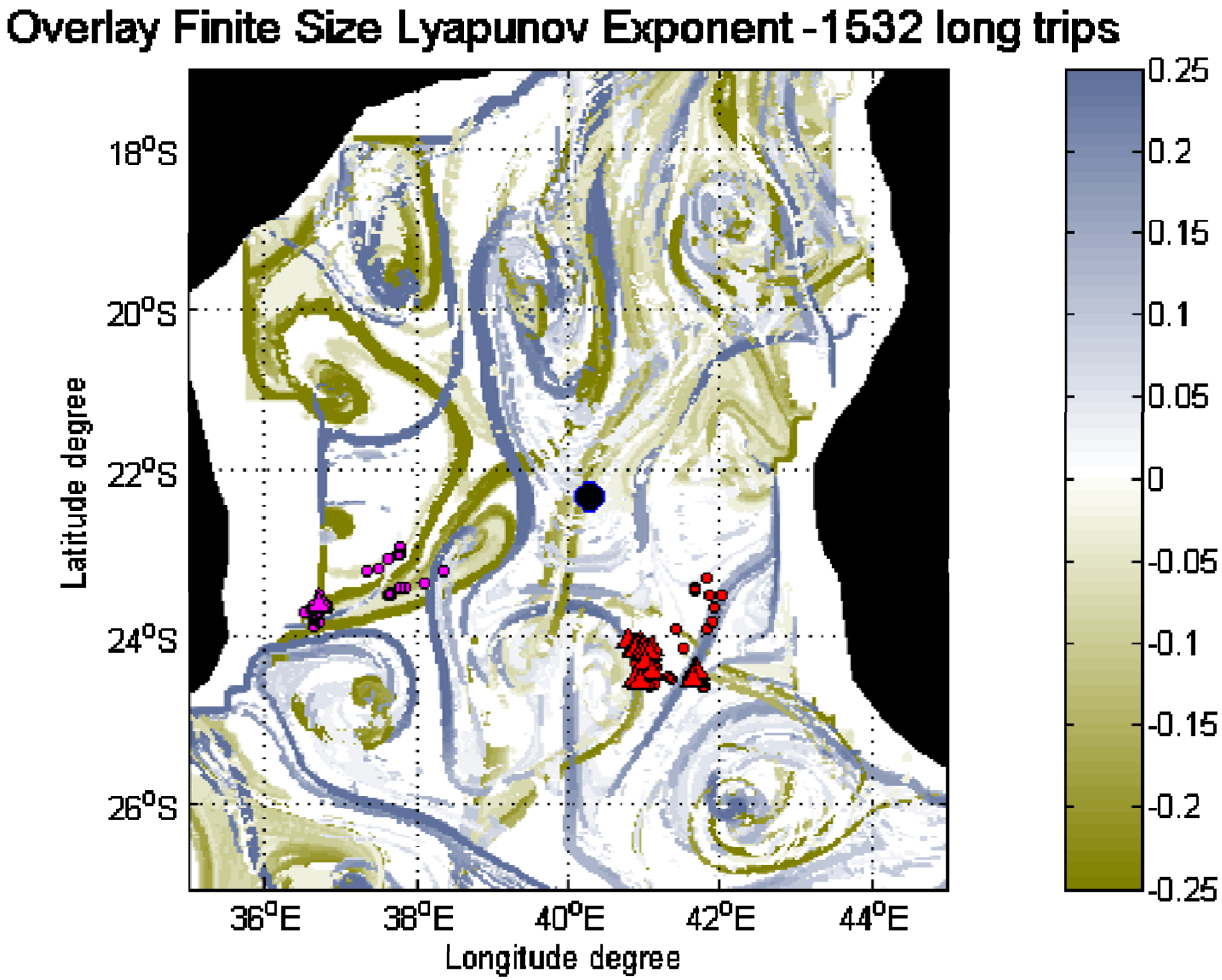
-0.1
-0.15
-0.2
-0.25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22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Longitude degree
Latitude degree
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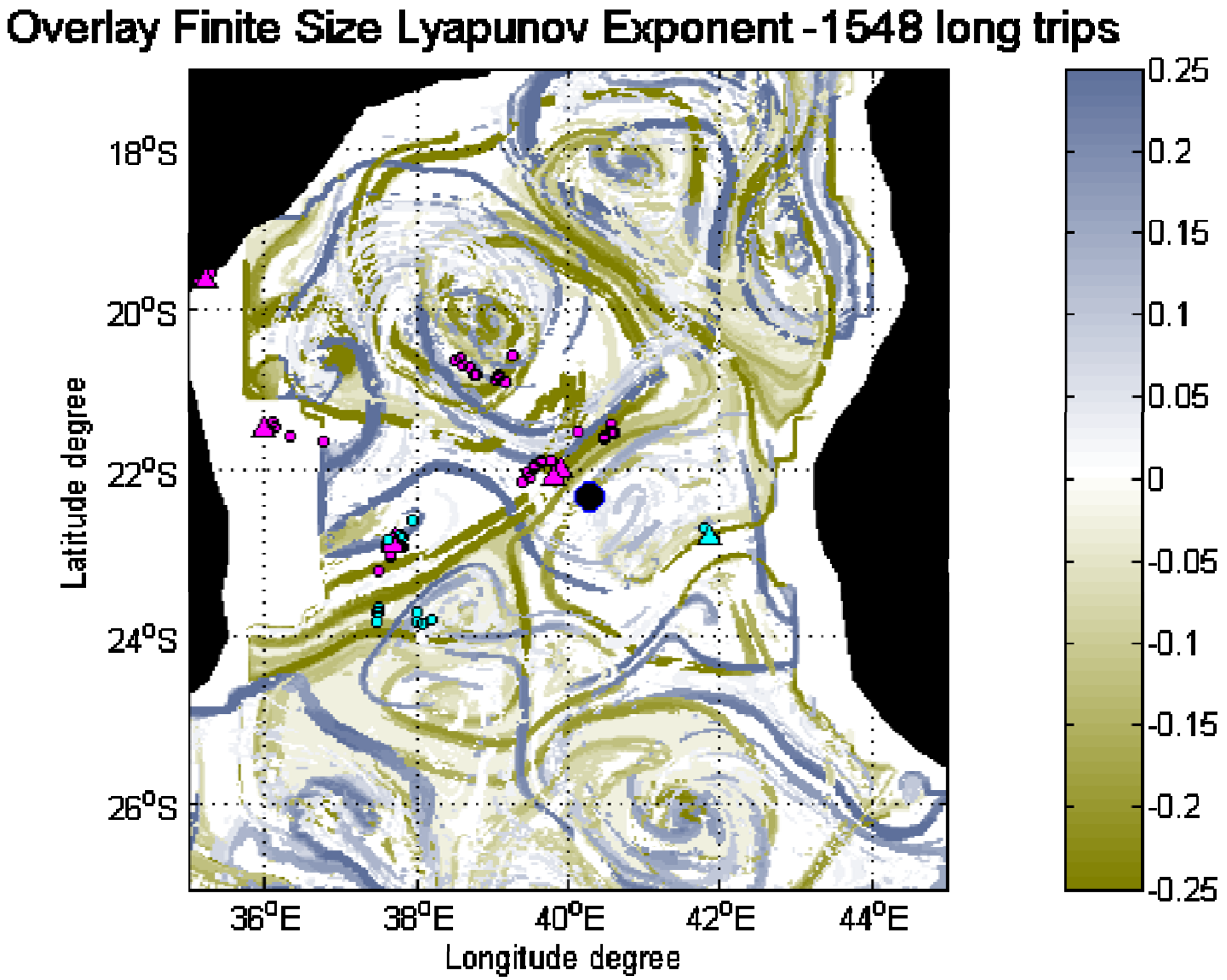
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25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24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
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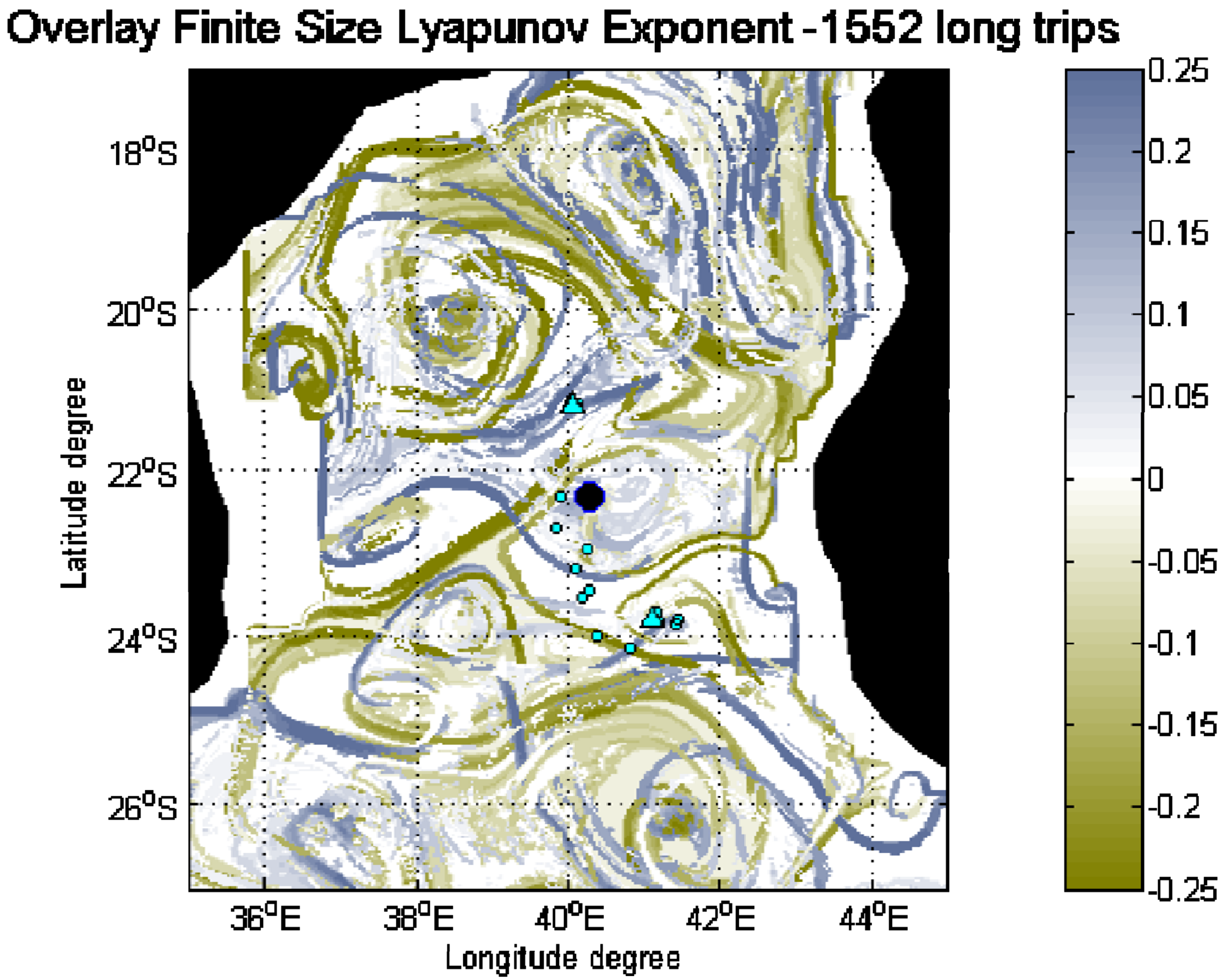
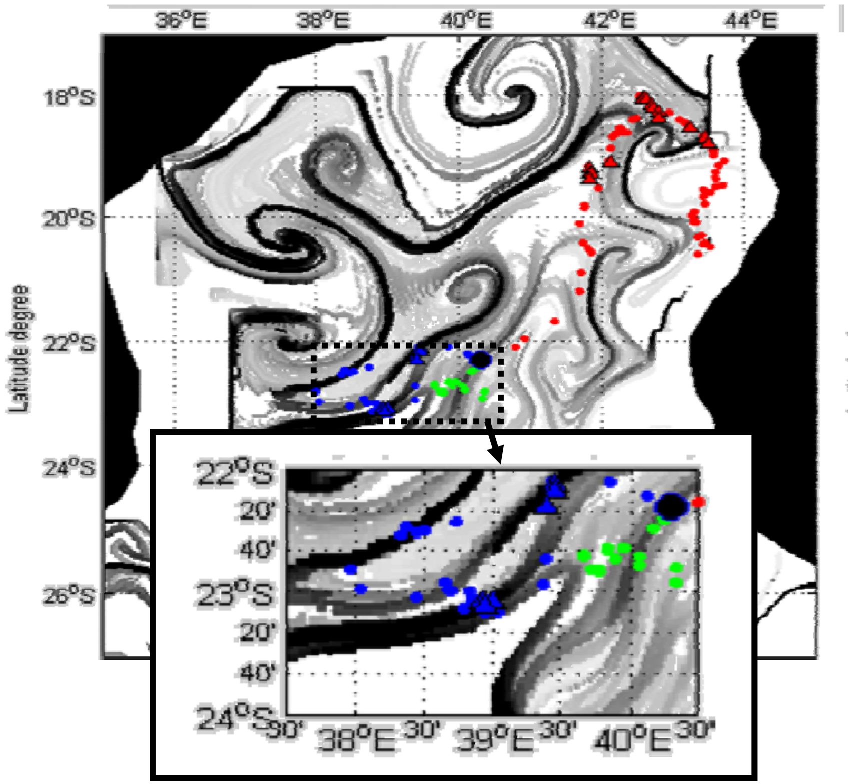
-0.25


Overlay Finite Size Lyapunov Exponent -1552 long trips
Latitude degree
18°S
20°S
22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25

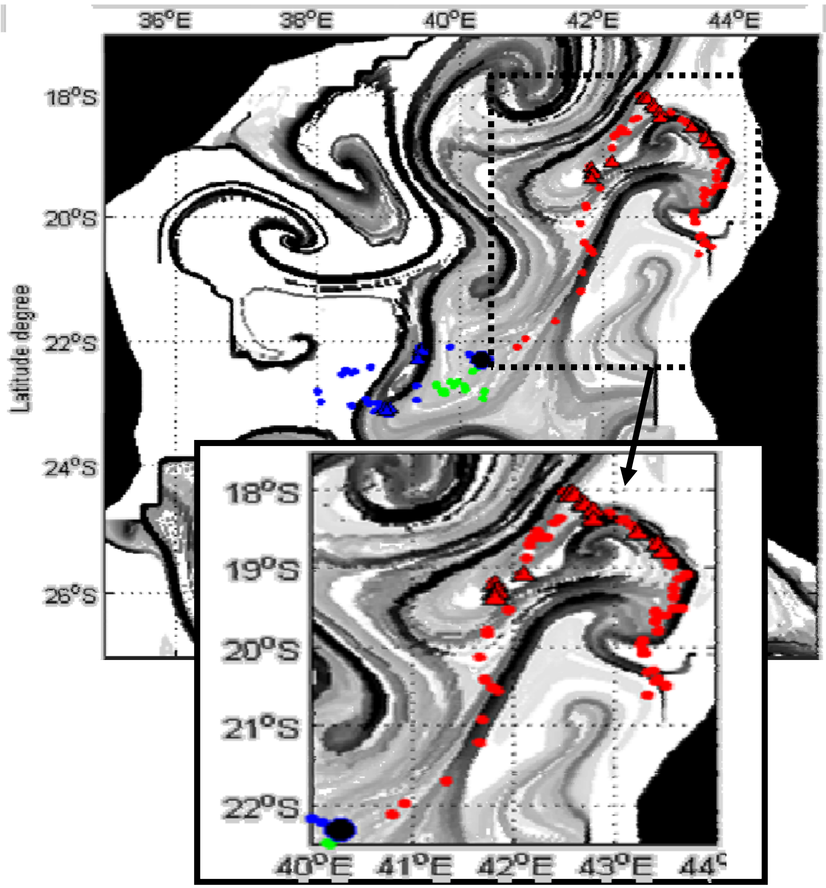
IFISC

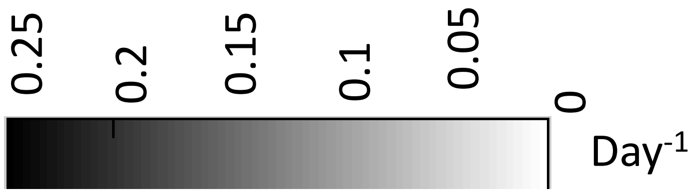
Week of September 24, 2003

Backward FSLE=Attractive LCSs



Forward FSLE = Repelling LCSs

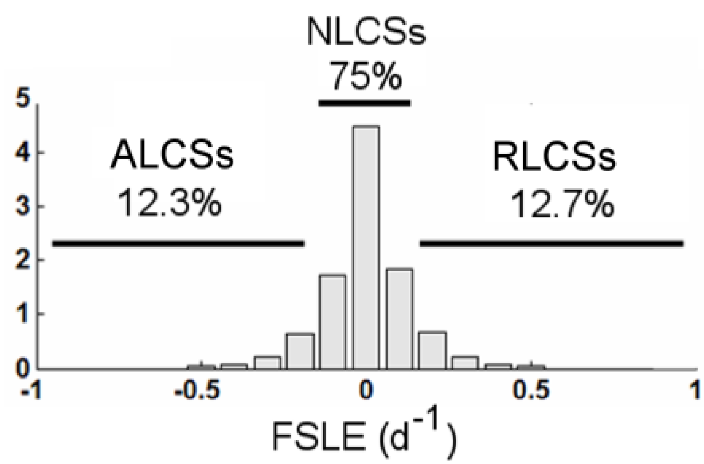


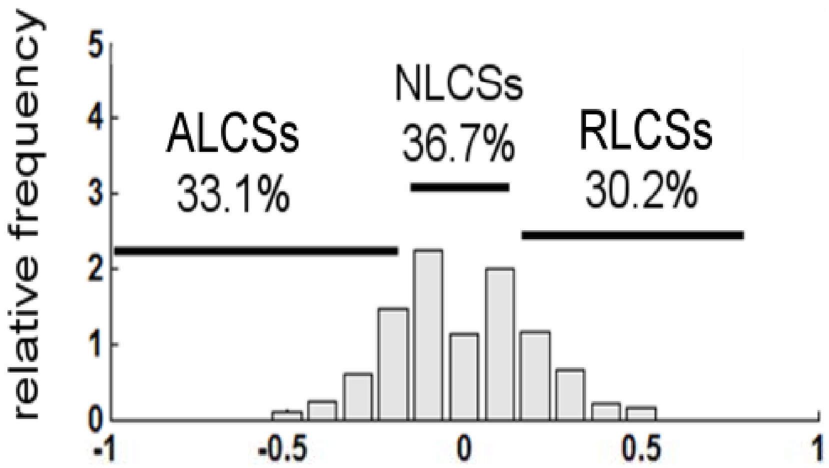


▲ **foraging patch (flight speed lower than 10 km/h)**

● **seabird trajectory**

Histograms of FSLE values





ALCS: attracting LCS, i.e. FSLE (backwards) < - 0.1 day^{-1}

RLCS: repelling LCS, i.e. FSLE (forwards) > 0.1 day^{-1}

NLCS: not LCS (small FSLE)

Despite LCS occupy only 25% of space, 63% of bird's positions are on them

STATISTICAL TESTS

Table 1. Absolute frequency of seabird positions on LCSs and on no Lagrangian structures for long and short trips per week and result of the G-test for goodness of fit

Week	All trips: LCSs: $\|FSLE\| > 0.1$ day^{-1}	All trips: $\|FSLE\| < 0.1$ day^{-1}	Long trips: LCSs: $\|FSLE\| > 0.1$ day^{-1}	Long trips: $\|FSLE\| < 0.1$ day^{-1}	Short trips: LCSs: $\|FSLE\| > 0.1$ day^{-1}	Short trips: $\|FSLE\| < 0.1$ day^{-1}
1	38	9	19	7	19	2
2	78	40	55	12	23	28
4	208	85	147	54	61	31
5	167	109	137	84	30	25
6	120	77	89	51	31	26
7	79	55	72	32	7	23
8	53	34	53	34	—	—
9	61	59	61	59	—	—
10	55	31	45	24	10	7
14	35	12	35	12	—	—
15	10	5	10	5	—	—
%	63.7	36.3	65.9	34.1	56.0	44.0
G-test (log-likelihood ratio)						
n	1420		1097		323	
k	11		11		7	
df	10		10		6	
G	28.119		30.613		32.057	
P	0.00173		0.001		0.000	

One-tailed tests. Null hypothesis Ho: Seabird positions share equally LCSs ($|FSLE| > 0.1$ day^{-1} and on no LCSs. α = 5%.

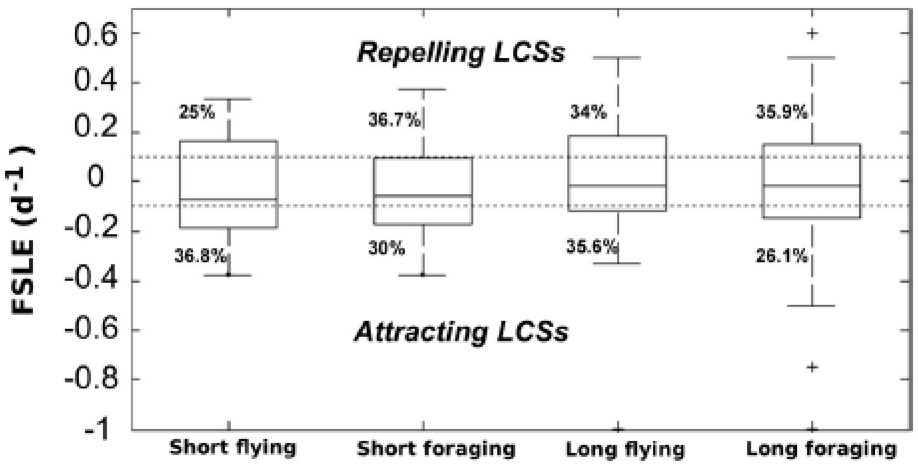


Table S2. Result of G-test statistics for comparison between frequency of bird positions on repelling or attracting LCS during flying and foraging and short and long trips

Variable	Flying	Foraging
Long trips		
Repelling LCS (FSLE > 0.1 day^{-1})	318	50
Attracting LCS (FSLE<-0.1 day^{-1})	333	37
n	738	
G	2.29	
P	0.13021	
Short trips		
Repelling LCS (FSLE > 0.1 day^{-1})	76	9
Attracting LCS (FSLE<-0.1 day^{-1})	112	10
n	207	
G	0.34	
P	0.55993	

Two-tailed tests. Null hypothesis Ho: seabirds share out equally on repelling and attracting structures when they fly or forage. α = 5%.

Results of statistical tests:

- Frigate birds fly on top of LCSs **both for travelling as for foraging**
- No significant difference between day and night positions
- No significant difference between come and return trip

Frigatebirds 'follow' LCSs not only to find there prey, but as biological corridors which bring them to foraging places

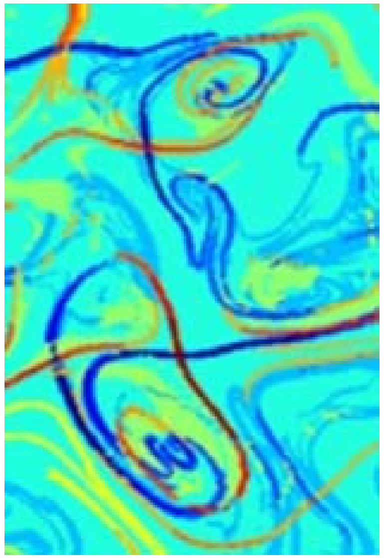
Aggregation of prey on LCSs? or aggregation of subsurface predators?

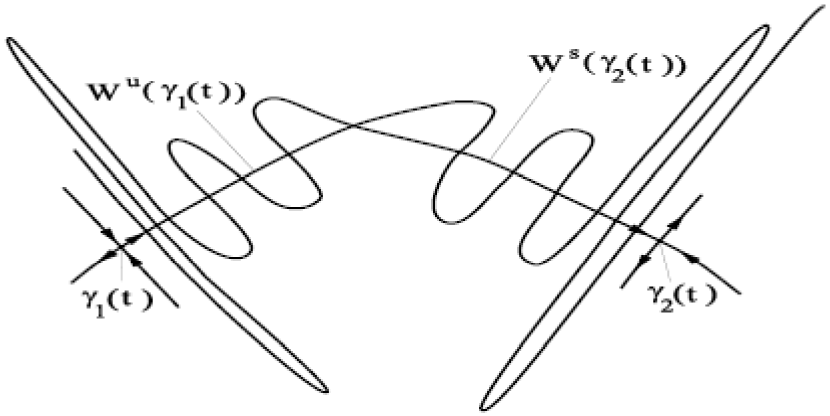
Olfatory clues (DMS produced by zooplankton) ? thermal air currents?

Tew Kai et al. PNAS (2009)

Puzzling issue: no significant difference between attracting and repelling LCSs

- Tangencies between manifolds?
- Interleaving between them?
- 3d dynamics associated both to ALCS and RLCS?
- Do they simply avoid low FSLE regions?





- Biological processes in oceans are impacted by fluid flow at all trophic levels, from primary producers to top predators. Marine environment is dynamic but structured, and Lagrangian Coherent Structures (via FSLEs) are a convenient way to analyze this structure and the physical-biological interactions
- The motion of Frigatebirds is impacted by this: they use Lagrangian Coherent Structures to navigate in this moving medium

Tew-Kai et al. PNAS 106, 8245 (2009)
http://ifisc.uib-csic.es/publications
http://ifisc.uib-csic.es/research/research_fluid.php