Frigatebirds follow Lagrangian Coherent Structures

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V. Rossi, V. Garçon, J. Sudre (LEGOS, Toulouse),
H. Weimerskirch (CEBC, Chizé), …

- Transport, stretching, swirling, …, by horizontal fluid motion certainly influences the distribution and the dynamics of abiotic quantities: temperature, nutrients, …
- This certainly influences plankton distribution

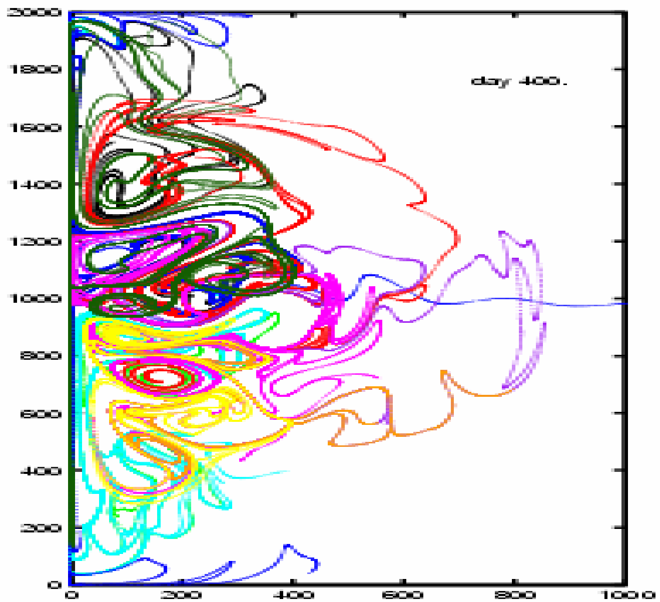
  V. Rossi et al. Geophysical Research Letters **35**, L11602 (2008)

  V. Rossi et al. Nonlin. Proc. Geophys. 16, 557 (2009)

- From there, impact is expected in plankton consumers, their predators, … cascades up along the food chain …

CHARACTERIZING THE SCHELETON OF LAGRANGIAN TRANSPORT

Or how to Identify the relevant trajectories and manifolds in time-aperiodic flows, out of this mess …



From Mancho, Small and Wiggins, 2005

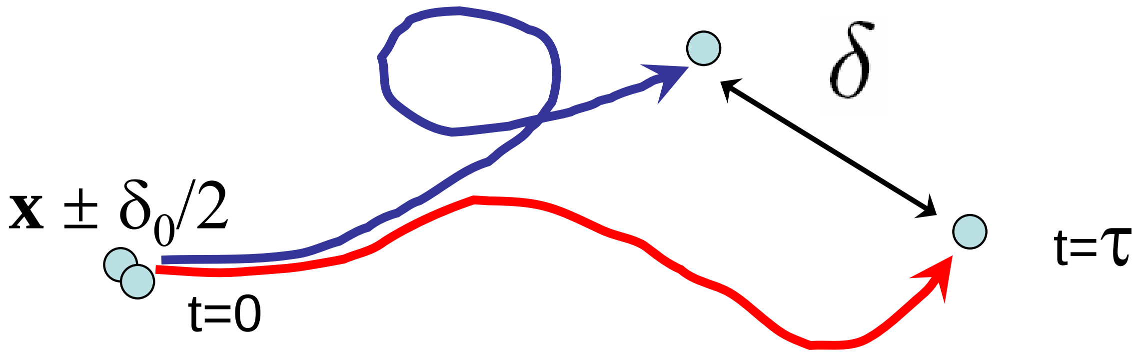
- Attracting or repelling material lines (Haller, Poje, …)
- Stretching-field methods: Finite-time Lyapunov exponents, Finite-size Lyapunov exponents, …(Vulpiani, Legras, Artale, Haller, …)
- Distinguished hyperbolic trajectories (Wiggins, Ide, Mancho, …)
- Leaking (Tél, Schneider…)
- …

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

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

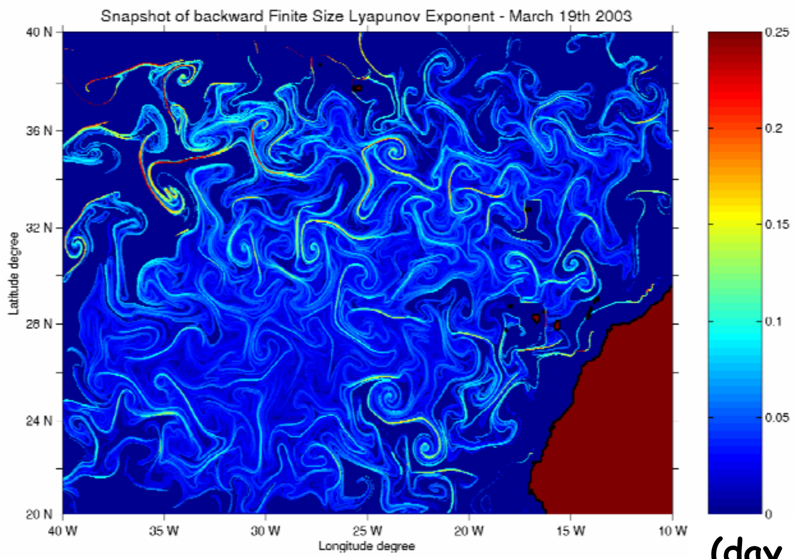
All the quantities are also functions of the initial position and time:

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

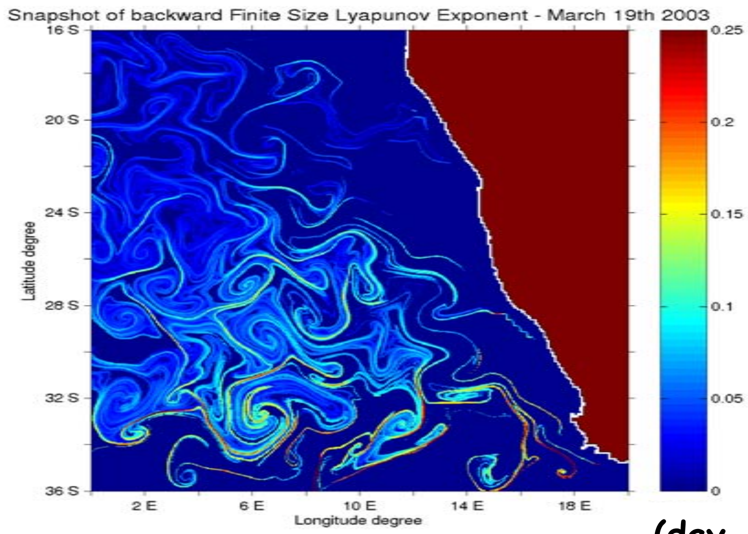
FROM ALTIMETRY DATA

BENGUELA

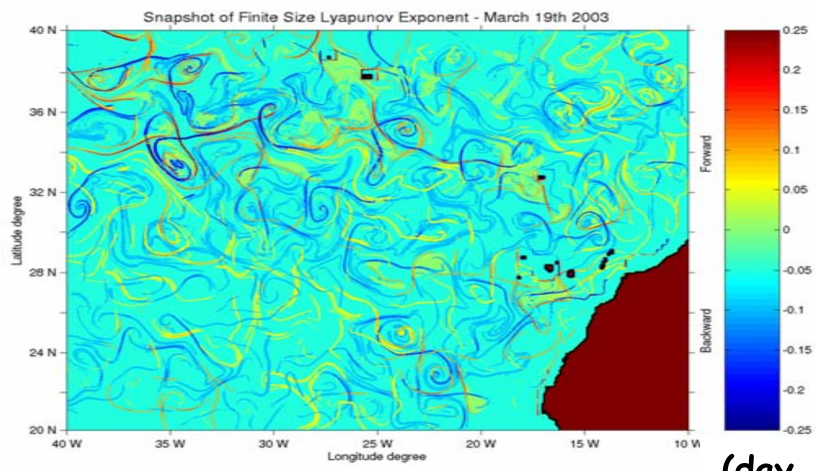
March 19 2003 snapshots



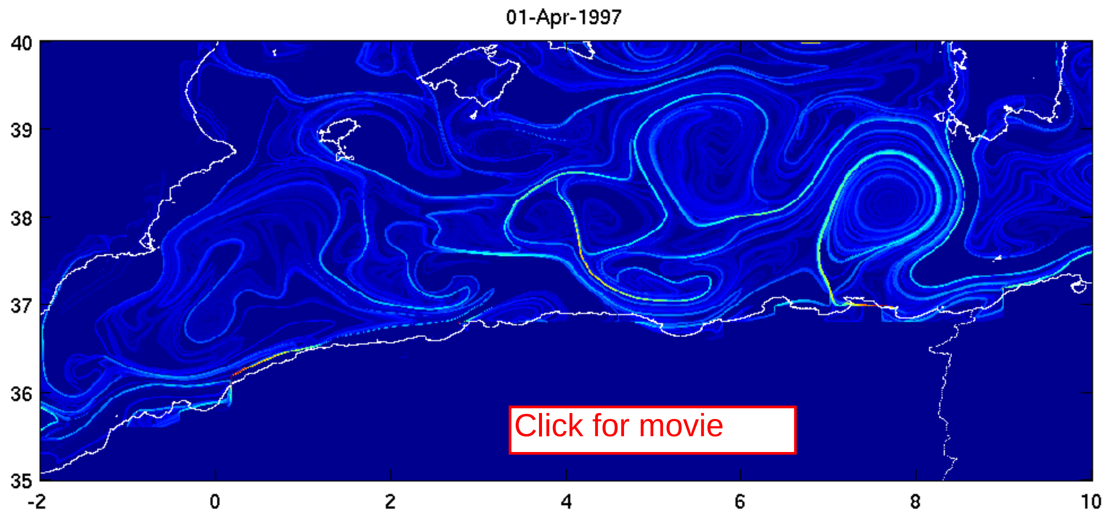
(day s^{-1})



(day s^{-1})



(day s^{-1})



CANARY

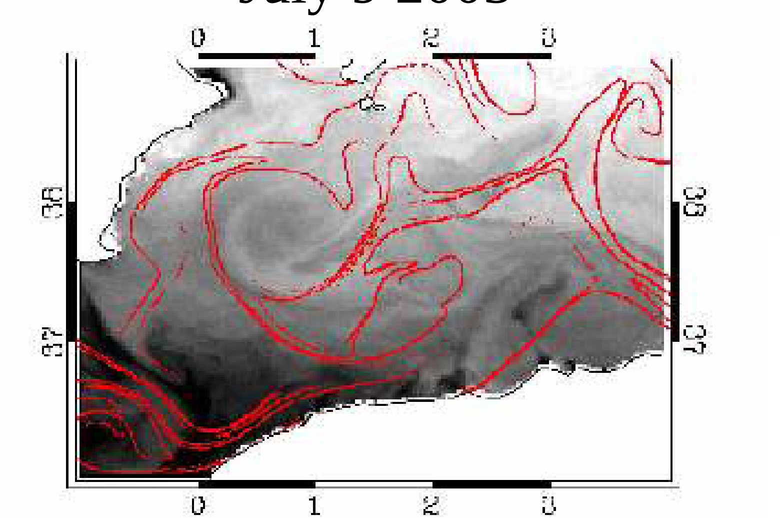
Note the presence of SUB-MESOSCALE detail

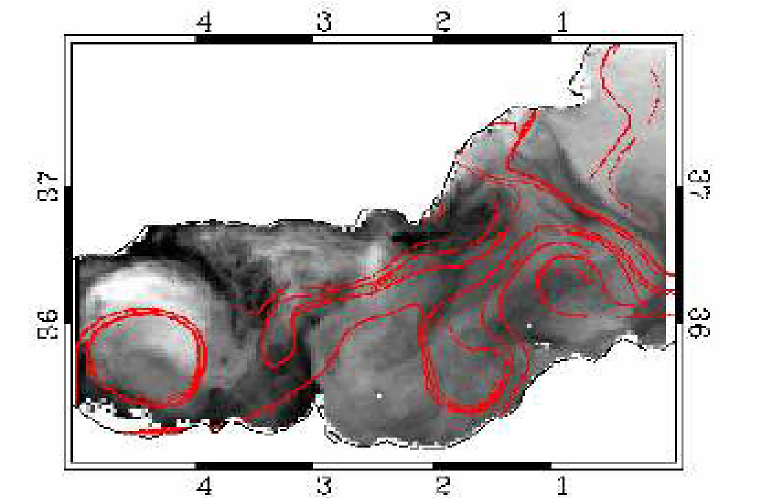
d'Ovidio et al. Deep-Sea Res. I 56, 15 (2009)
V. Rossi et al. Nonlin. Proc. Geophys. 16, 557 (2009)

Sea Surface Temperature vs lines of FSLE > 0.1 day^{-1} (LCSs)

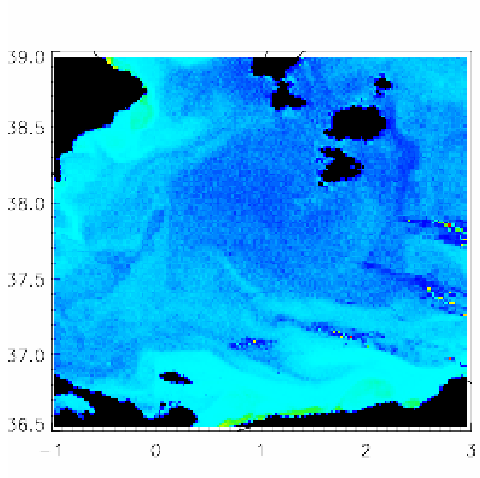
d'Ovidio et al.
Deep-Sea Res. I (2009)

July 9 2003



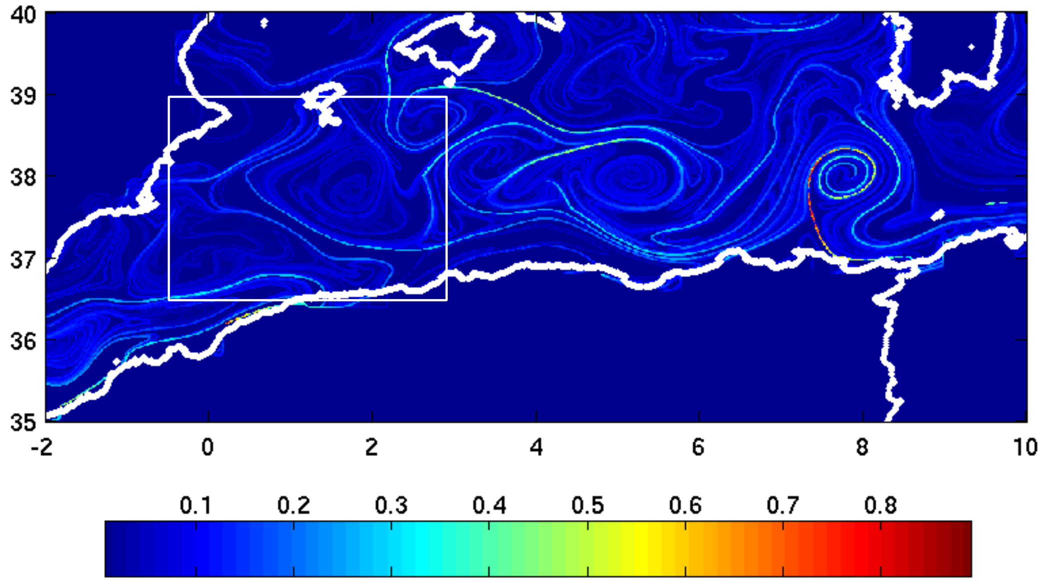


April 6 2004



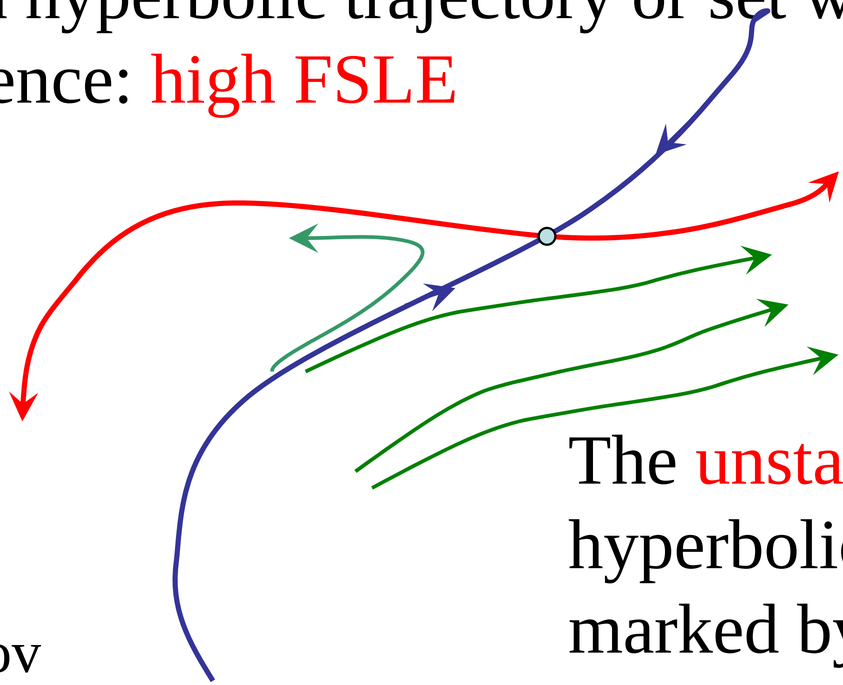
Chlorophyill

18 May 1998



days^{-1}

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



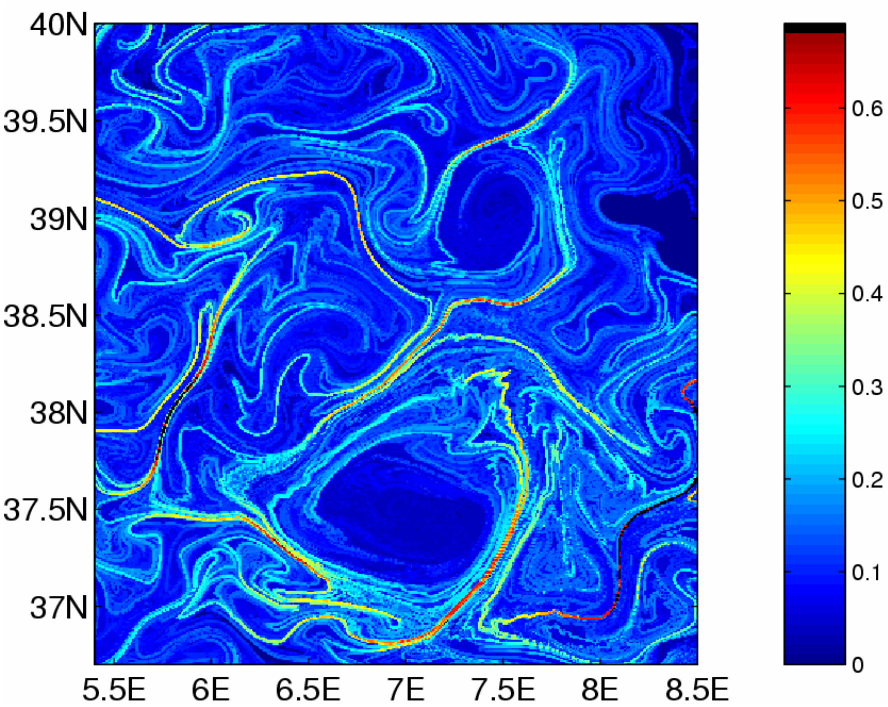
The unstable manifold of hyperbolic sets would be marked by high FSLE in the time backwards direction

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

RIDGES IN LYAPUNOV FIELDS:

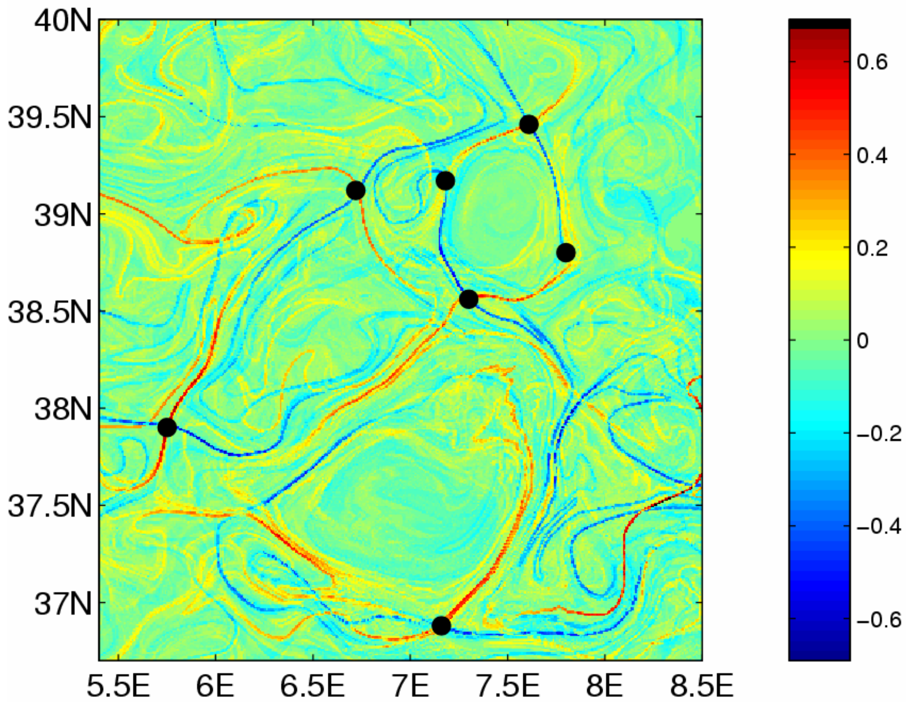
LAGRANGIAN COHERENT STRUCTURES(LCS)

REMARK: these are heuristic consideration. Theorems needed (some begin to be available for FTLEs)



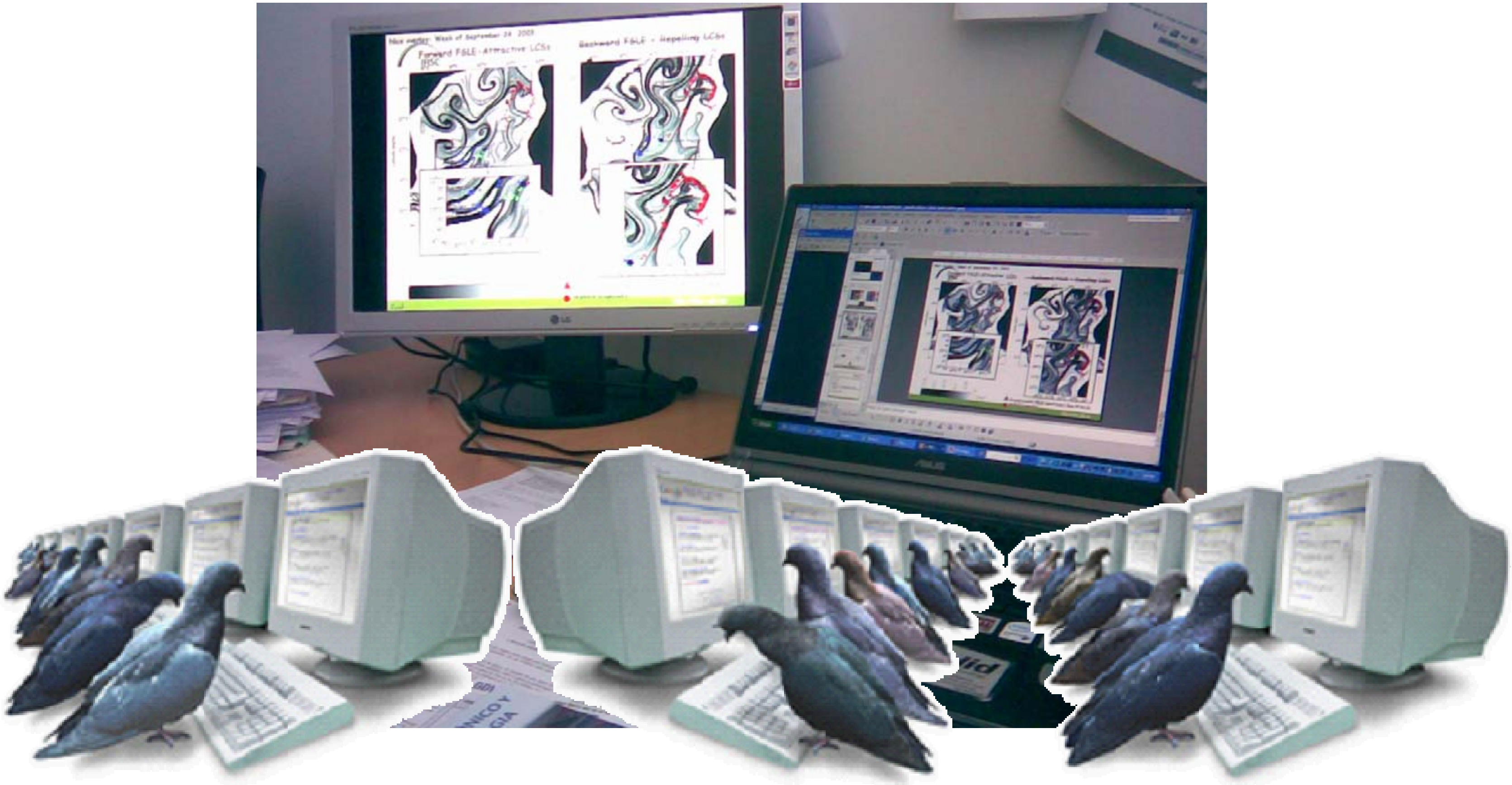
FSLE from time-backwards Integrations.
Are they really unstable manifolds of hyperbolic trajectories?

FSLE from forward and backwards integrations



Click figures for movies

Do birds know about FSLE calculations?

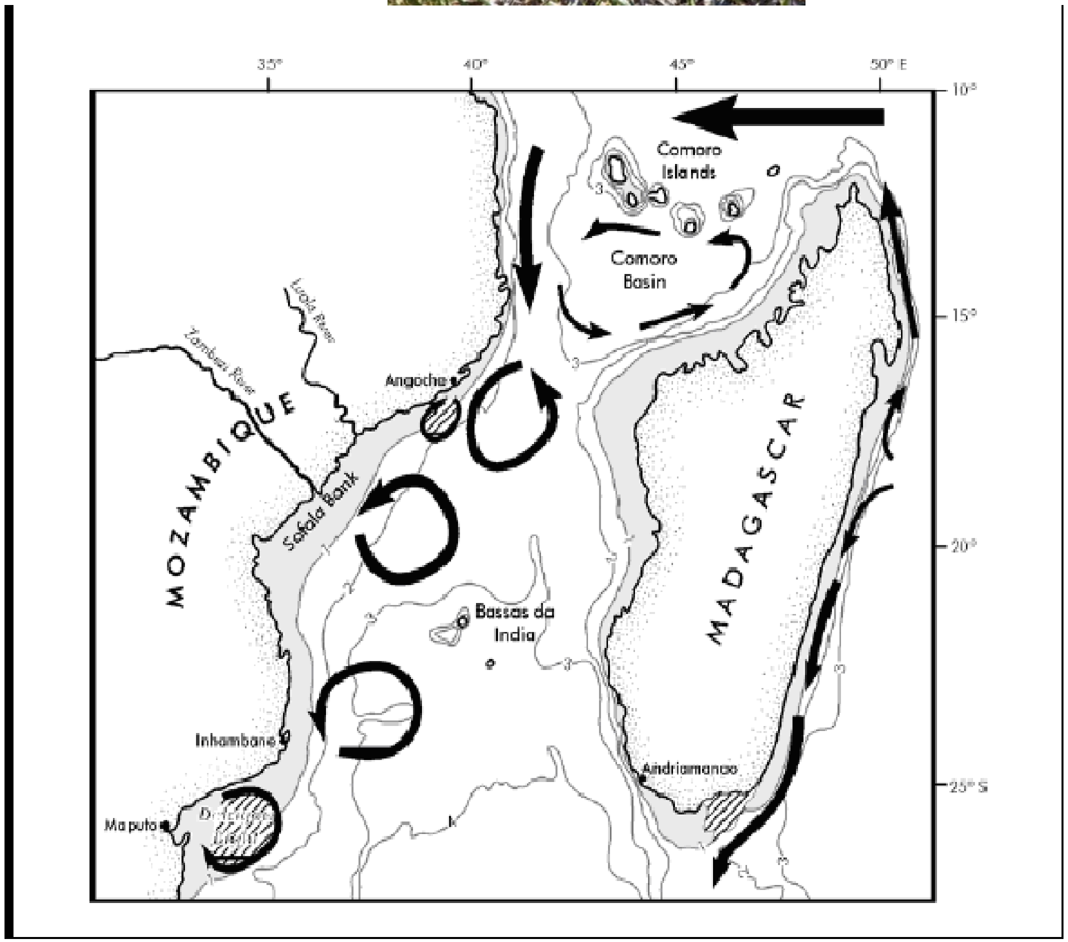


Tew Kai, Rossi, Sudre, Weimerskirch, Lopez, Hernandez-Garcia, Marsac, Garçon, PNAS 106, 8245 (2009)

FRIGATEBIRDS in the MOZAMBIQUE CHANNEL

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

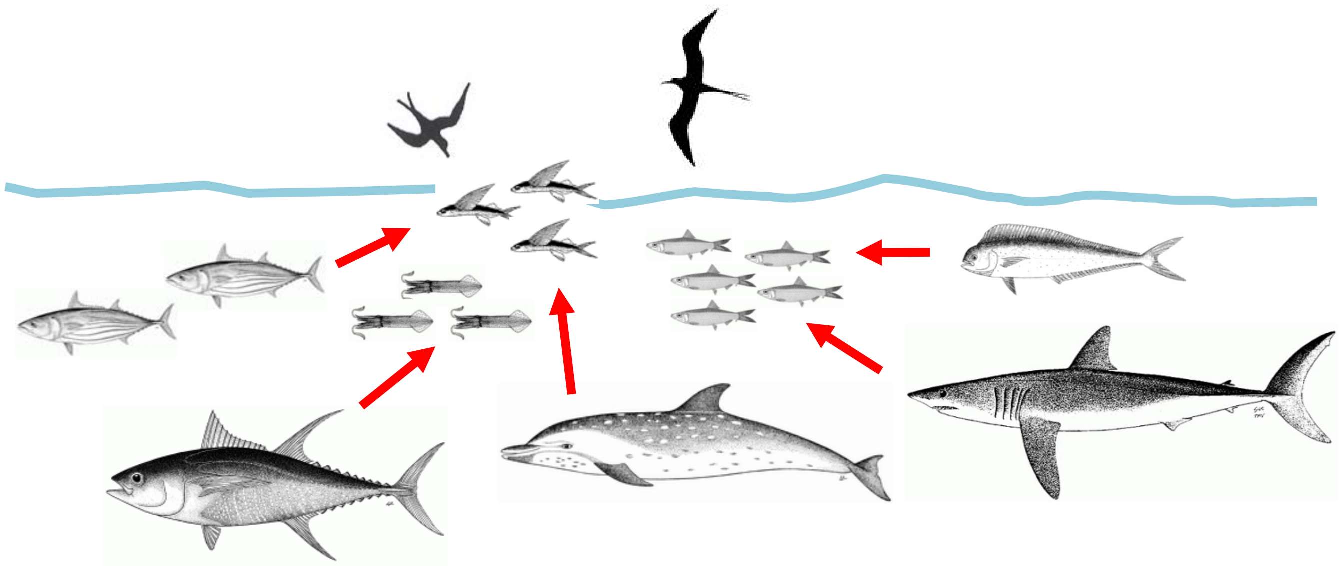
- Large anticyclonic cell at the north
- Local upwellings
- Anticyclonic and cyclonic mesoscale eddies moving southward permanently.



(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

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

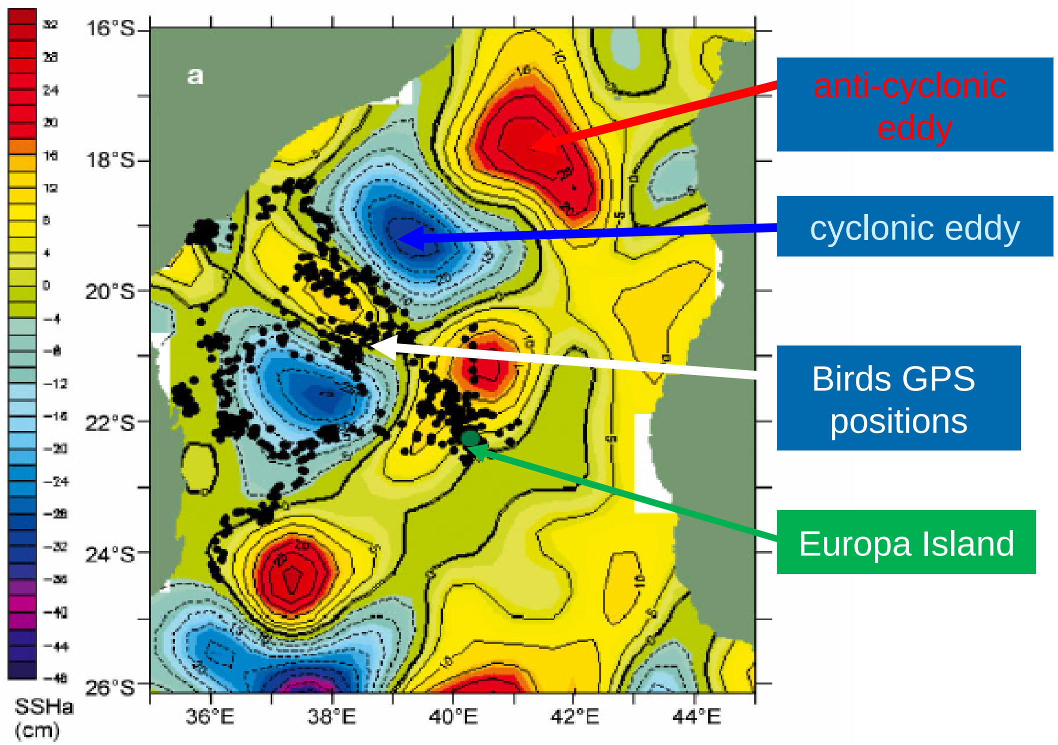
8 birds (from Europa Island community) fitted with satellite transmitter and altimeter.

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

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

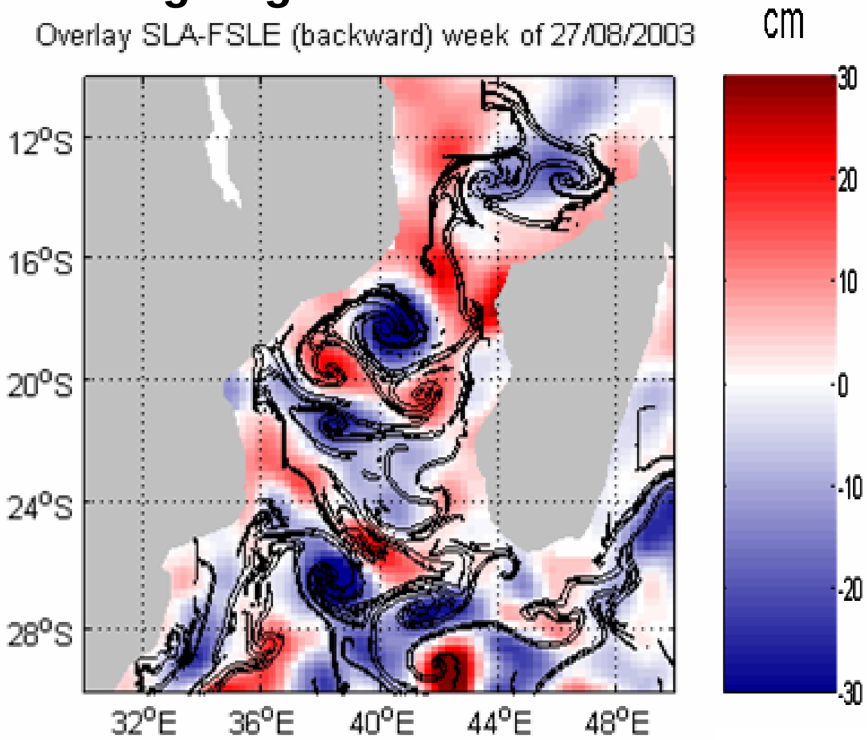
(Weimerskirch et al., 2004)

SSH (cm): Eulerian view



Weimerskirch et al,2004

Lagrangian FSLEs versus SSH

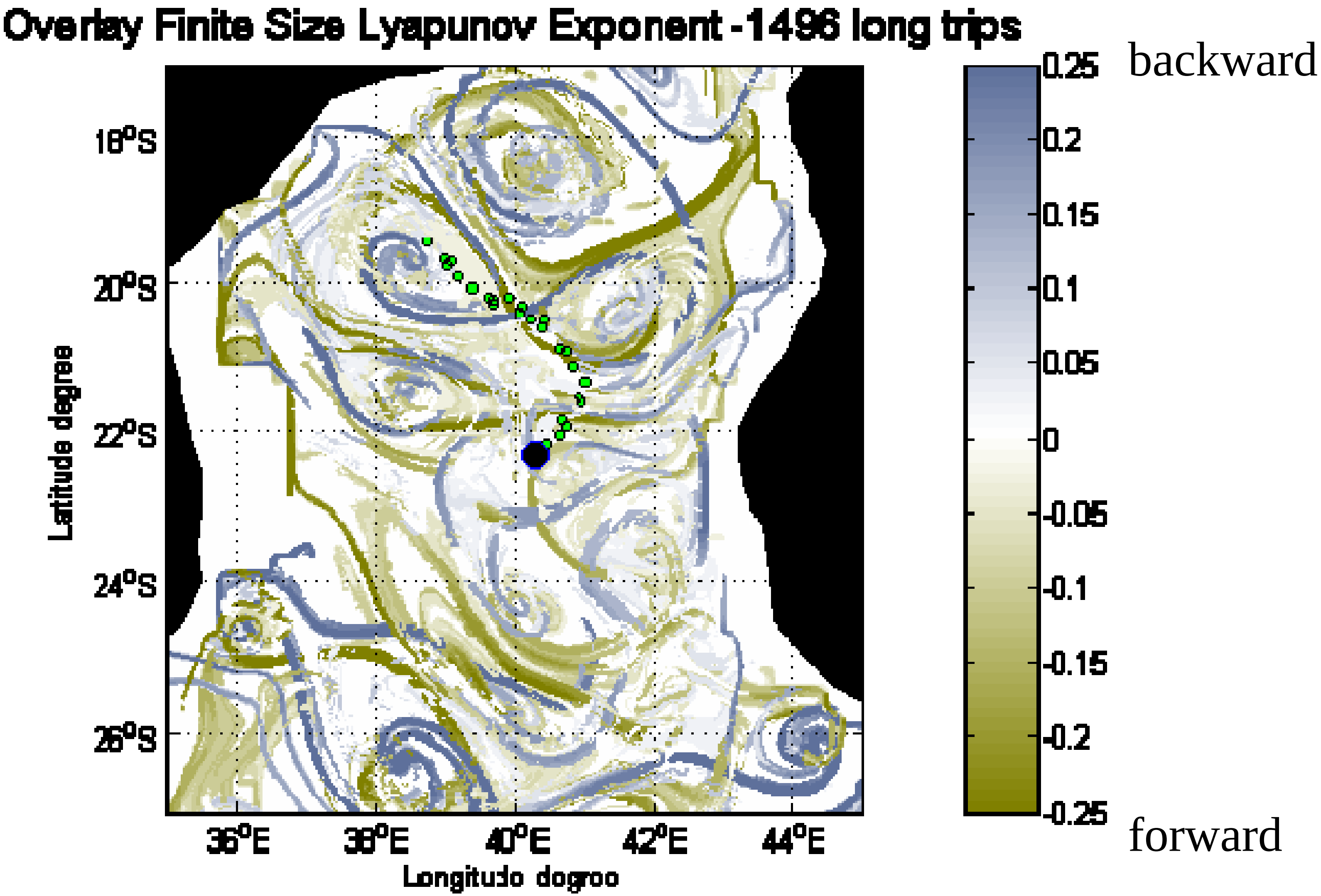


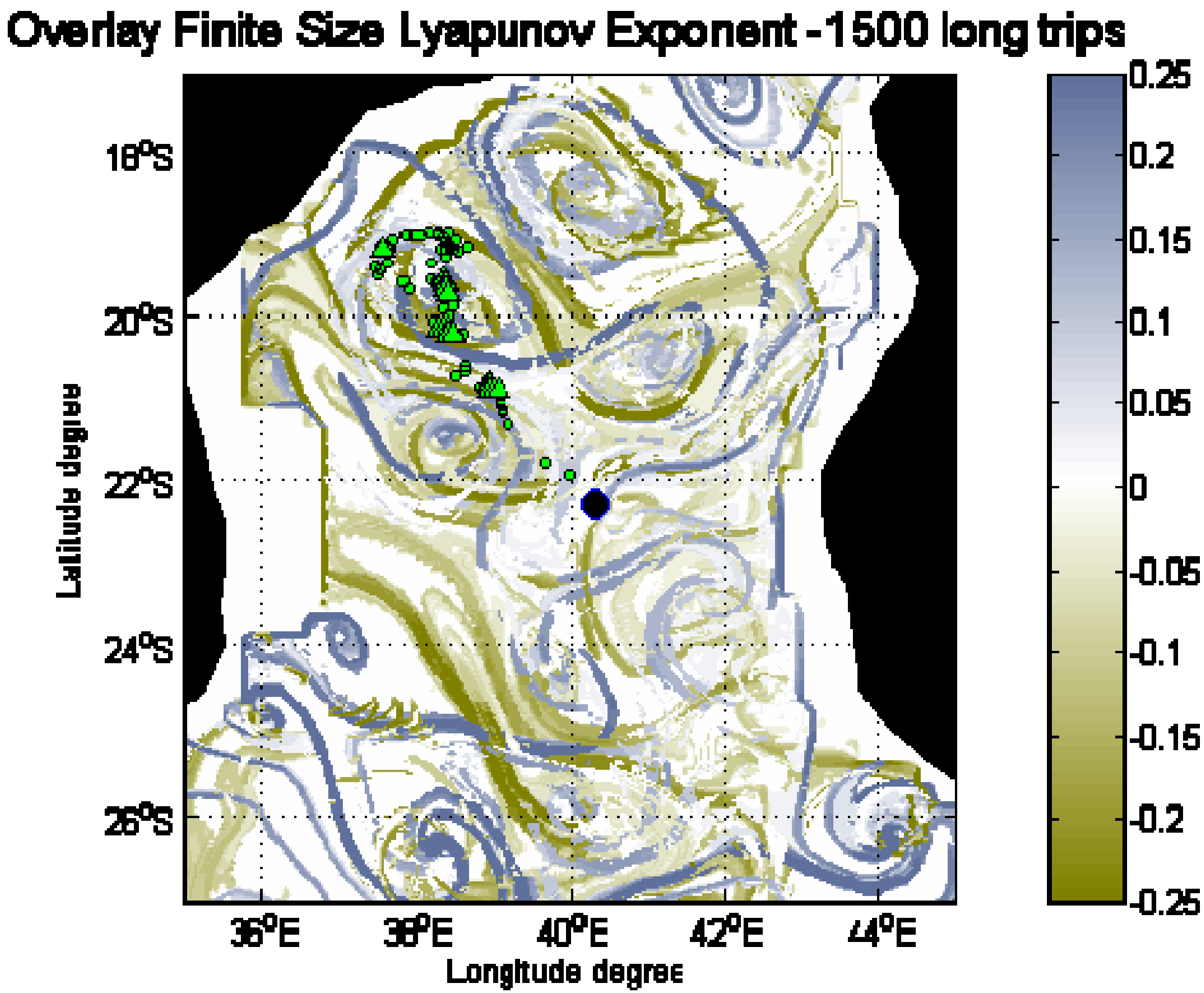
Sub-mesoscale: spatial resolution of FSLE: 2.5km

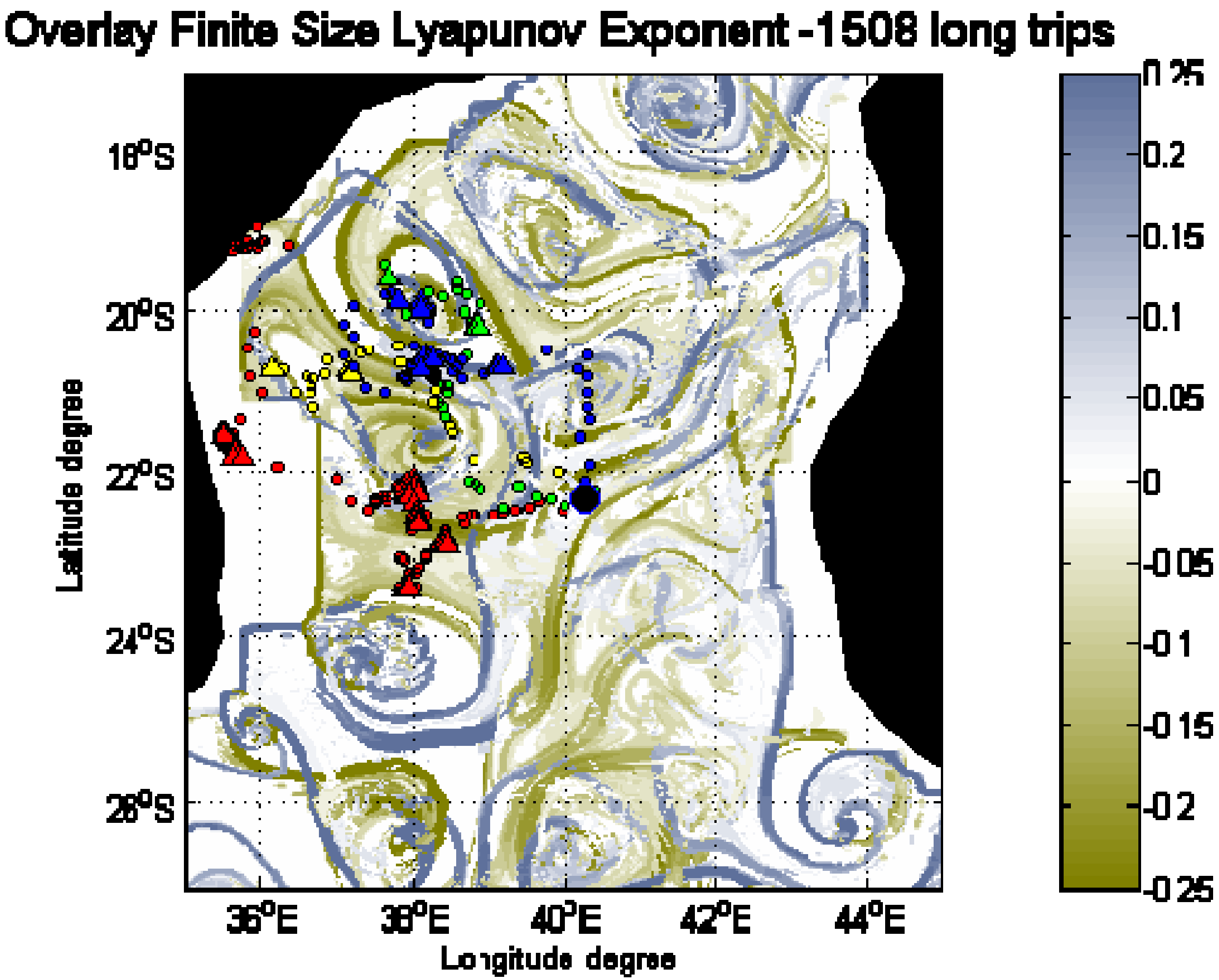
Dayly surface currents at ¼ degree resolution
from altimetry+scatterometter+mean topography

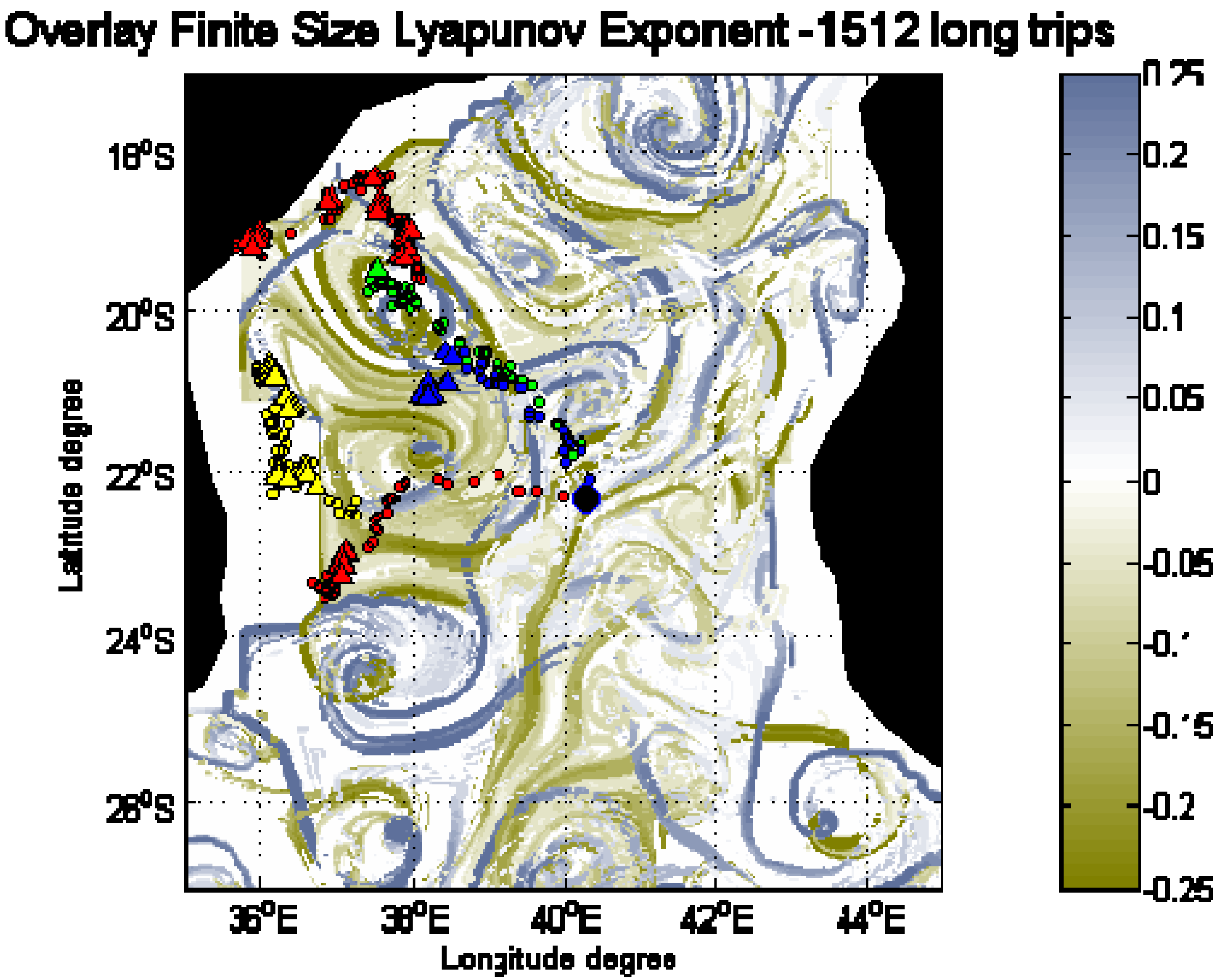
The Lagrangian FSLE gives access to submesoscale structures

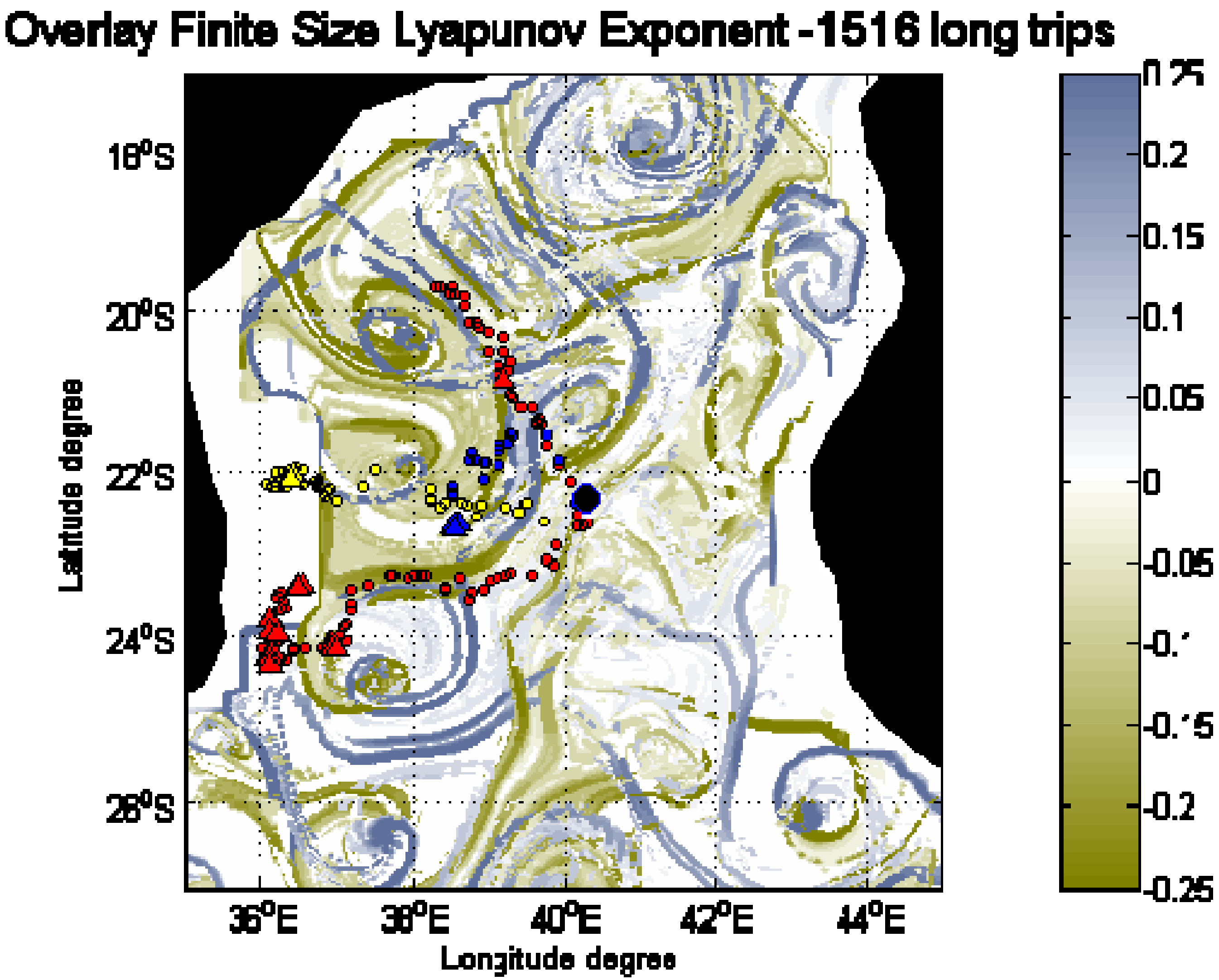
Lagrangian Coherent Structures: |FSLE| > 0.1 day^{-1}

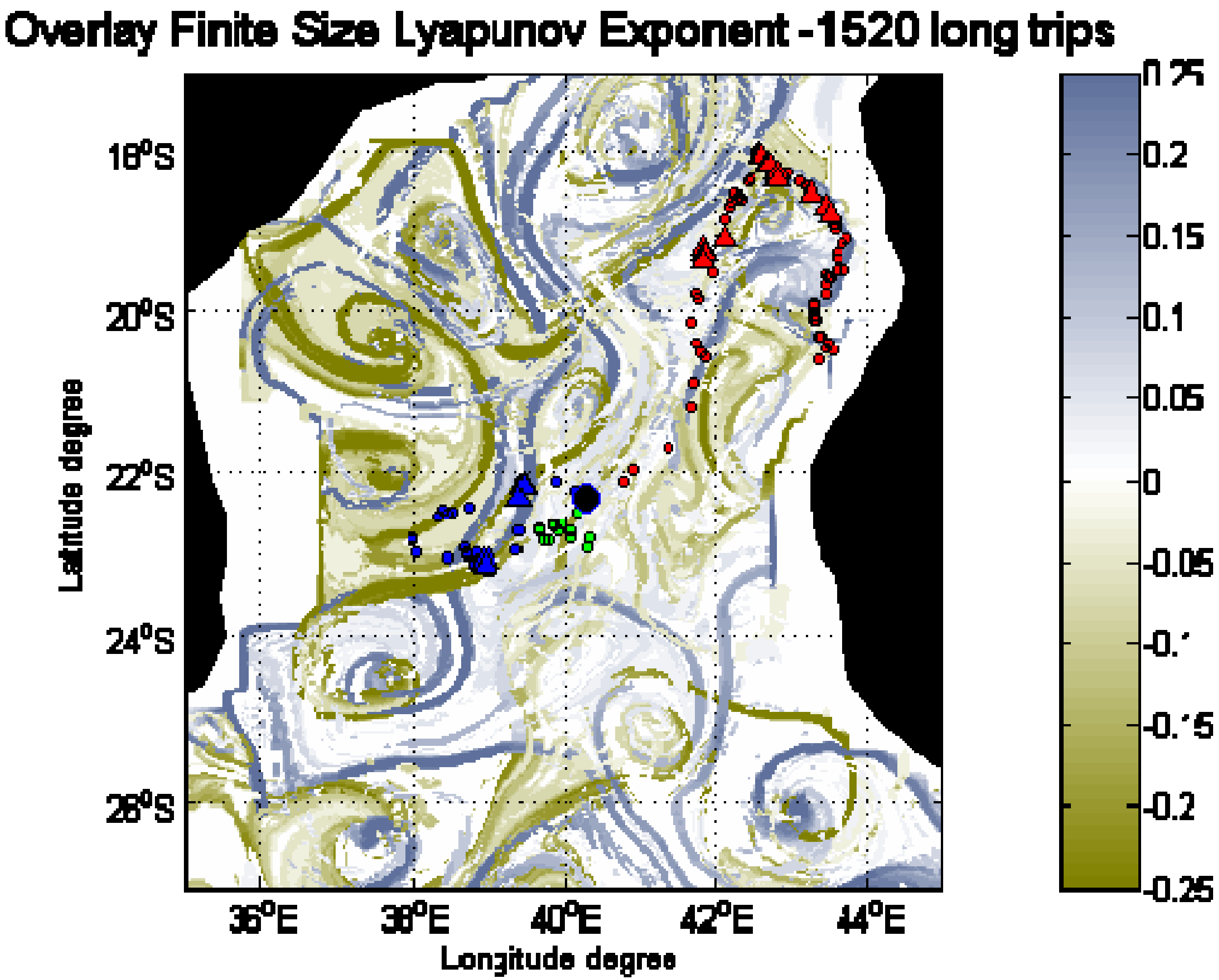

Overlay Finite Size Lyapunov Exponent -1496 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
backward
forward

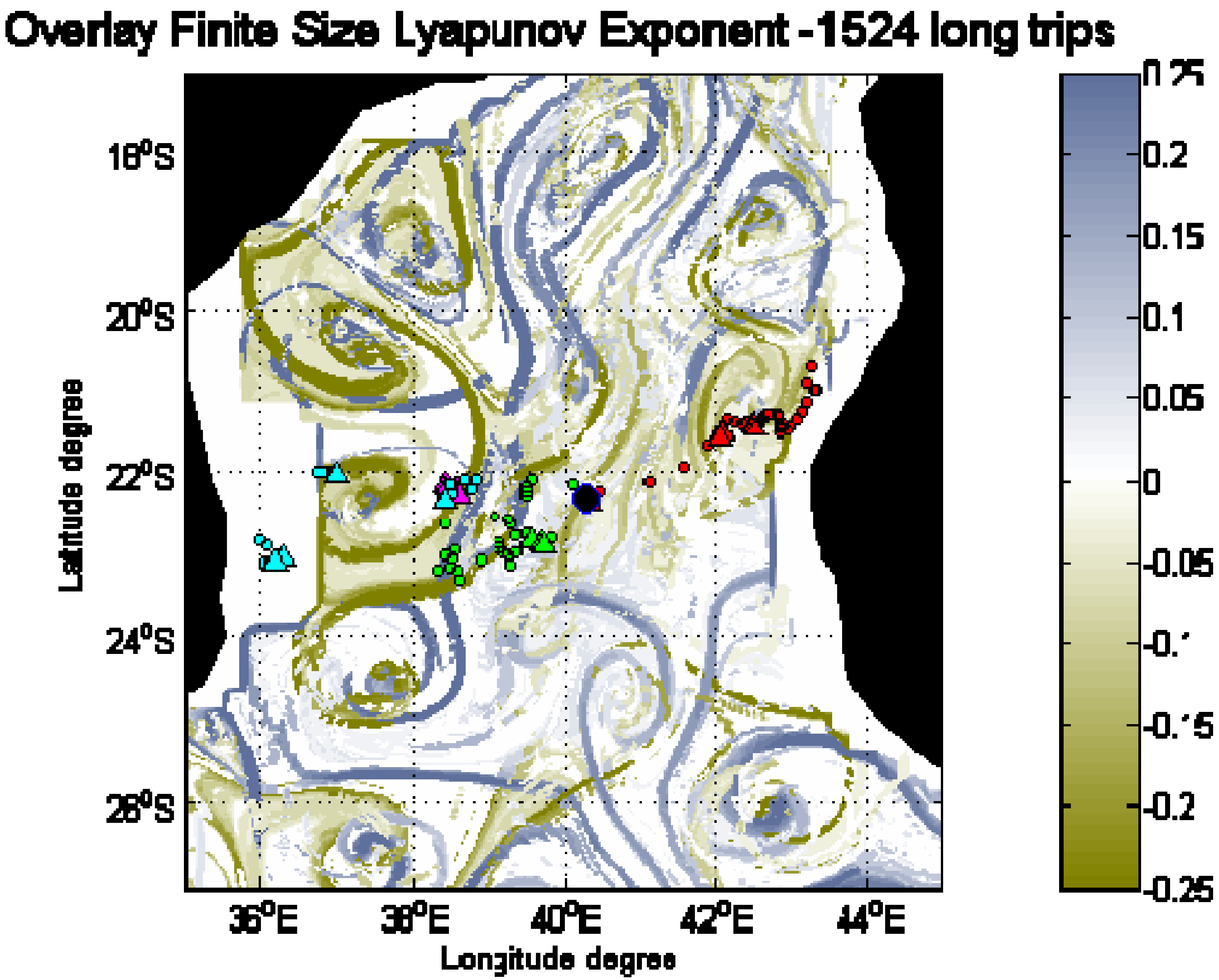

Overlay Finite Size Lyapunov Exponent -1500 long trips
18°S
20°S
22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Longitude degree
Latitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25

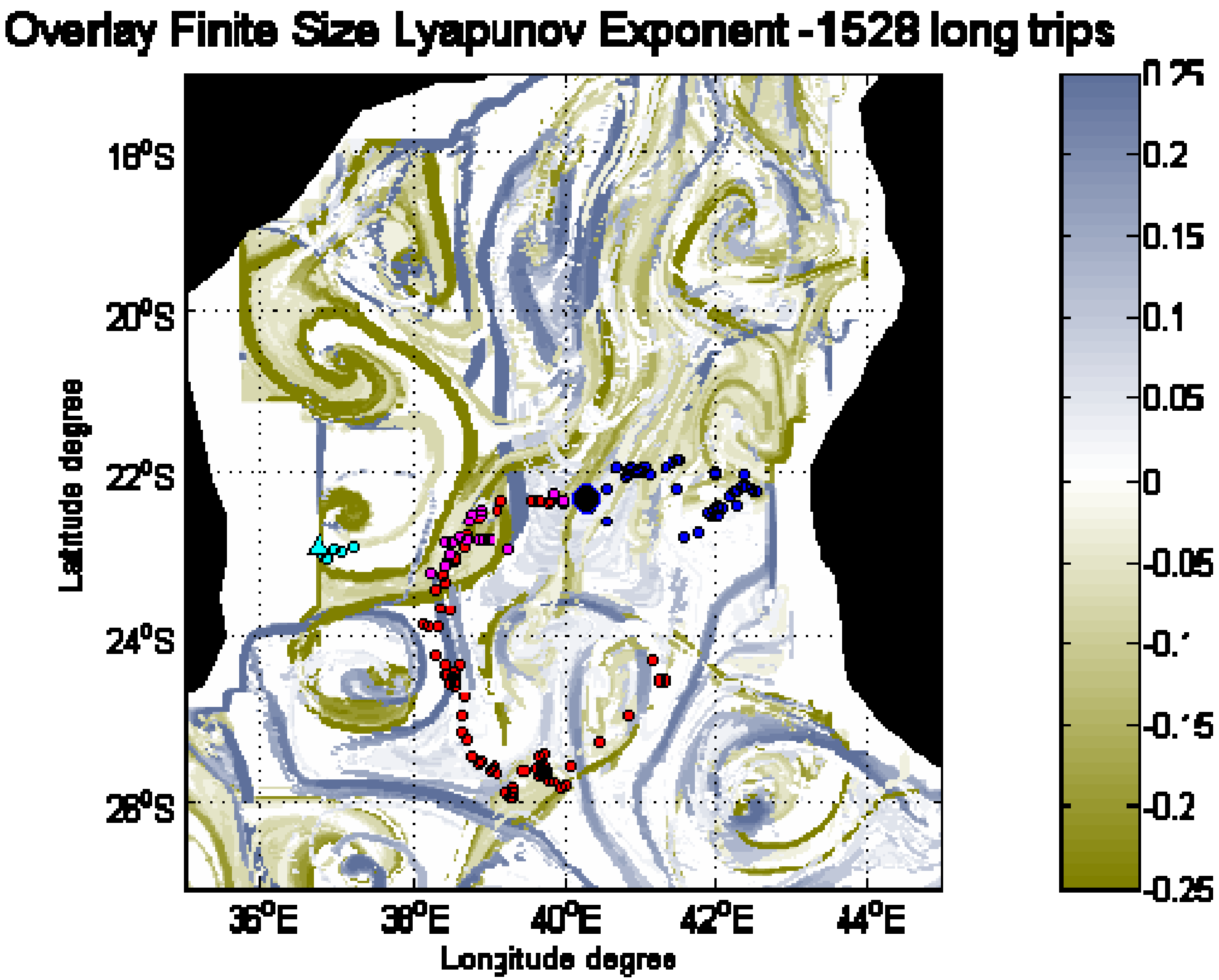

Overlay Finite Size Lyapunov Exponent -1508 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25


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

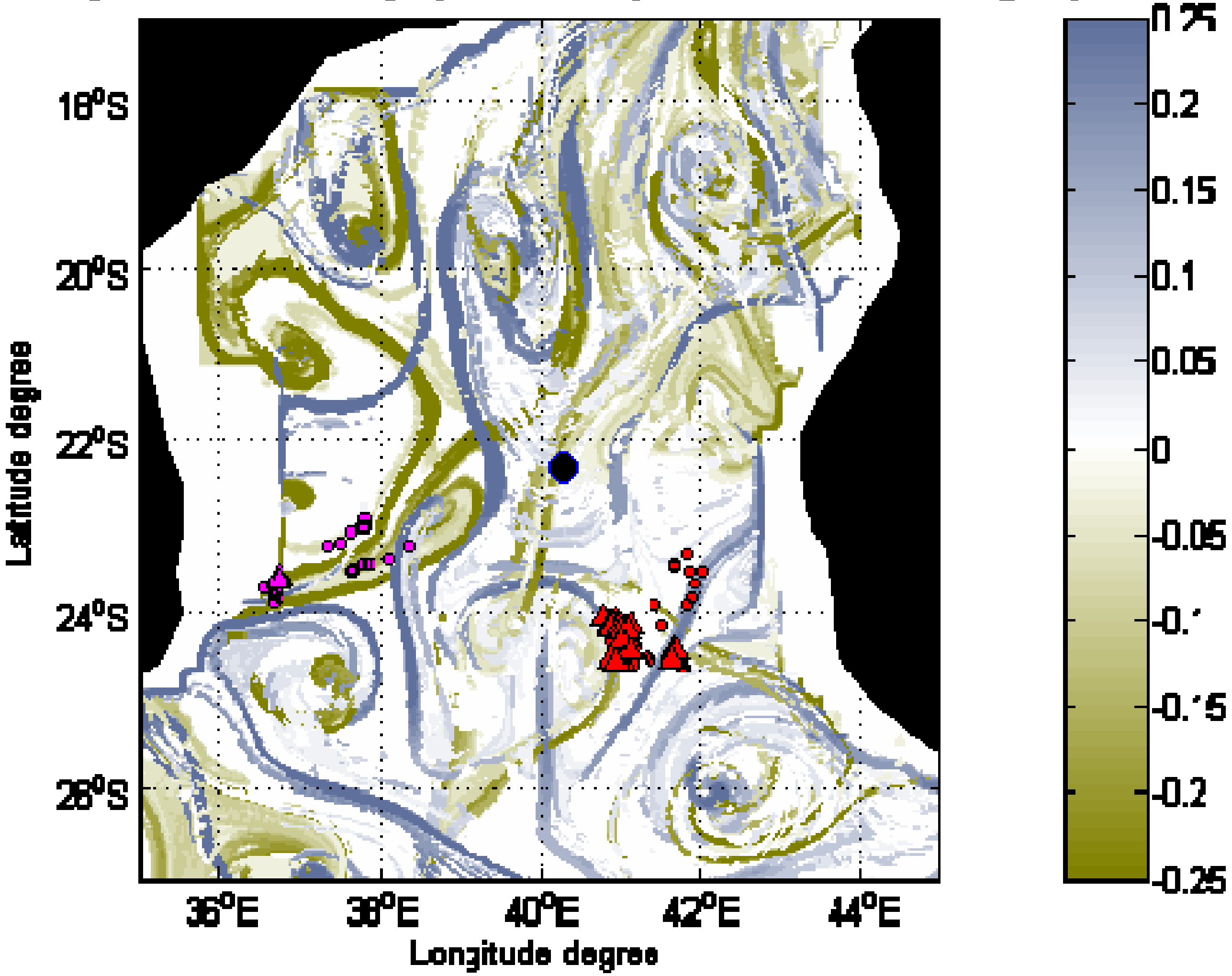

Overlay Finite Size Lyapunov Exponent -1516 long trips
18°S
20°S
22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Longitude degree
Latitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.2
-0.25

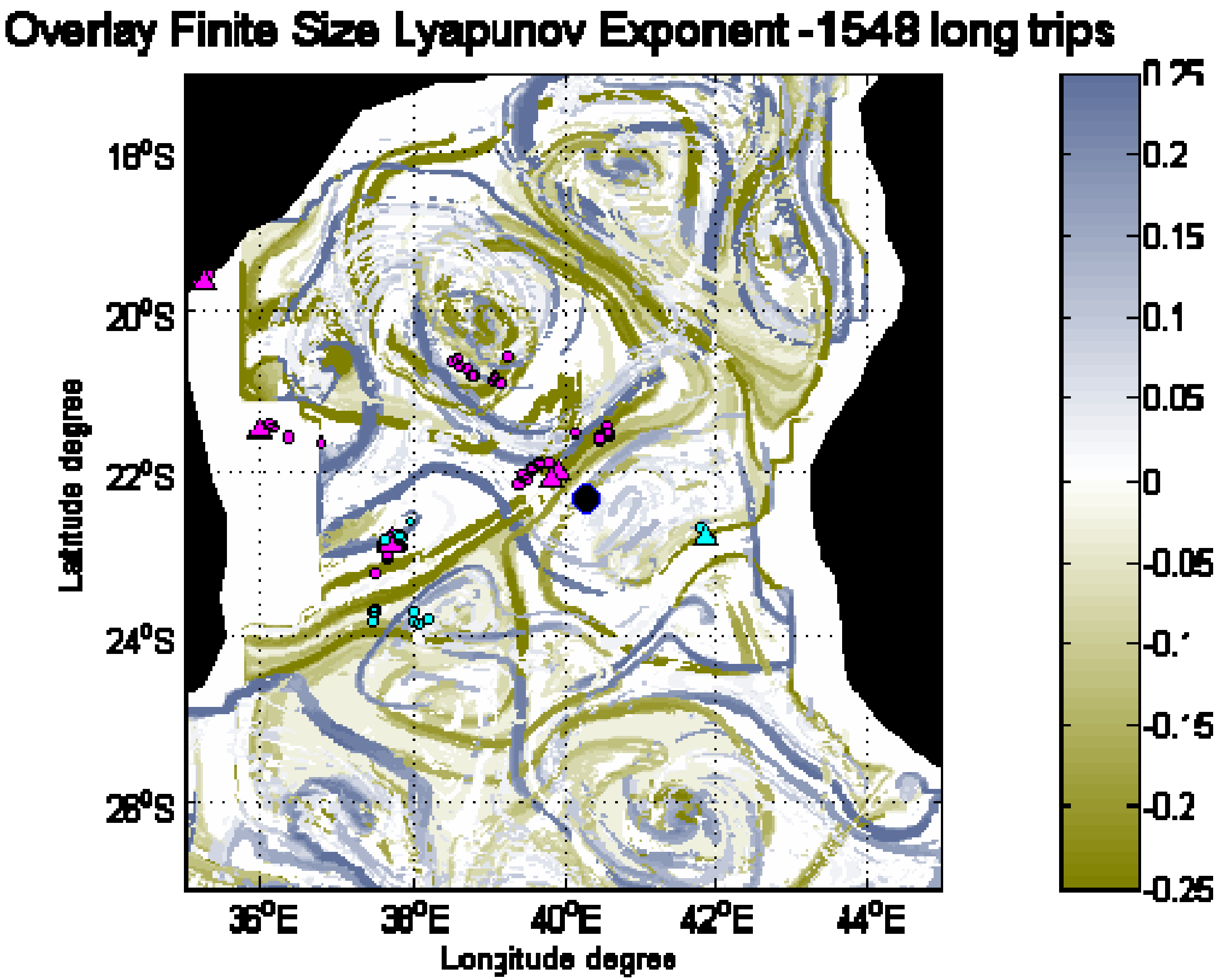

Overlay Finite Size Lyapunov Exponent -1520 long trips
18°S
20°S
22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Longitude degree
Latitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.2
-0.25


Overlay Finite Size Lyapunov Exponent -1524 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
0.2
0.15
0.1
0.05
0
-0.05
-0.2
-0.25

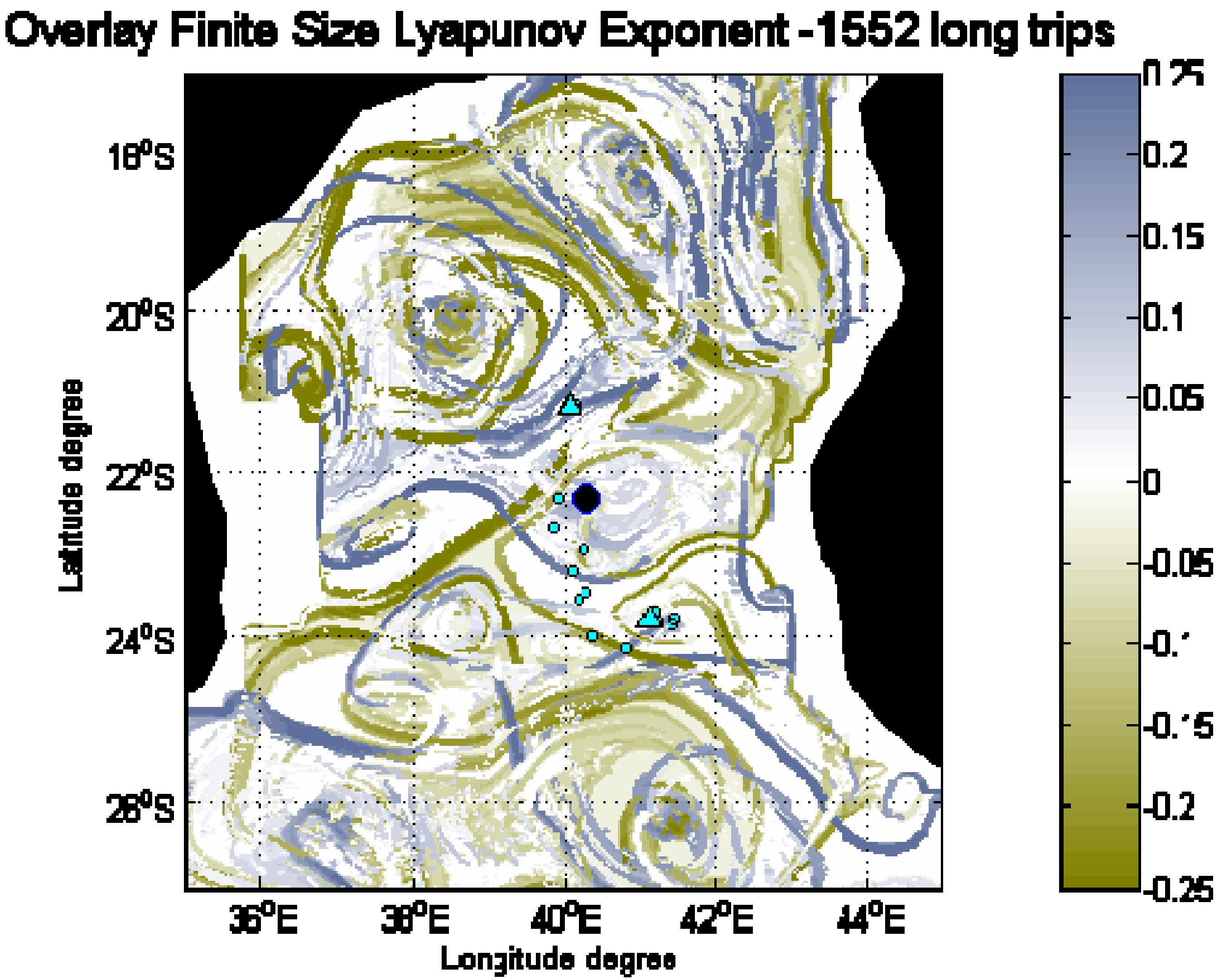

Overlay Finite Size Lyapunov Exponent -1528 long trips
18°S
20°S
22°S
24°S
26°S
36°E
38°E
40°E
42°E
44°E
Latitude degree
Longitude degree
0.2
0.15
0.1
0.05
0
-0.05
-0.2
-0.25

Overlay Finite Size Lyapunov Exponent -1532 long trips



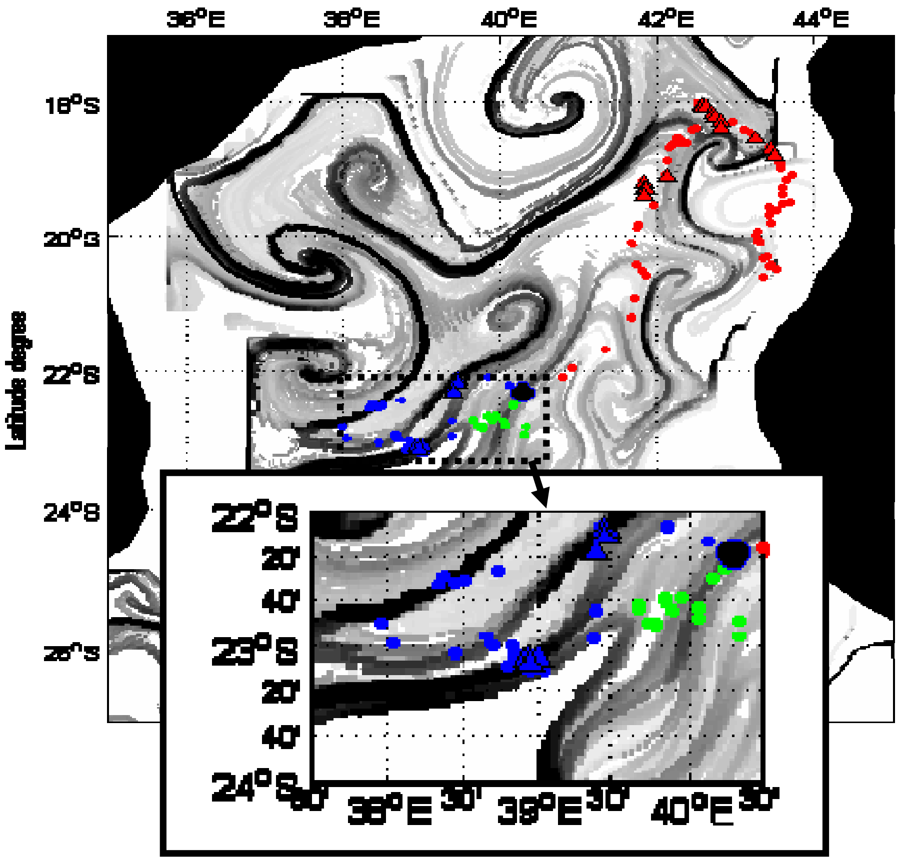


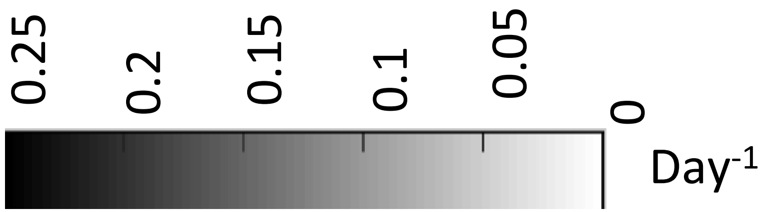
Overlay Finite Size Lyapunov Exponent -1548 long trips
18°S
20°S
22°S
24°S
26°S
Latitude degree
36°E
38°E
40°E
42°E
44°E
Longitude degree
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25


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

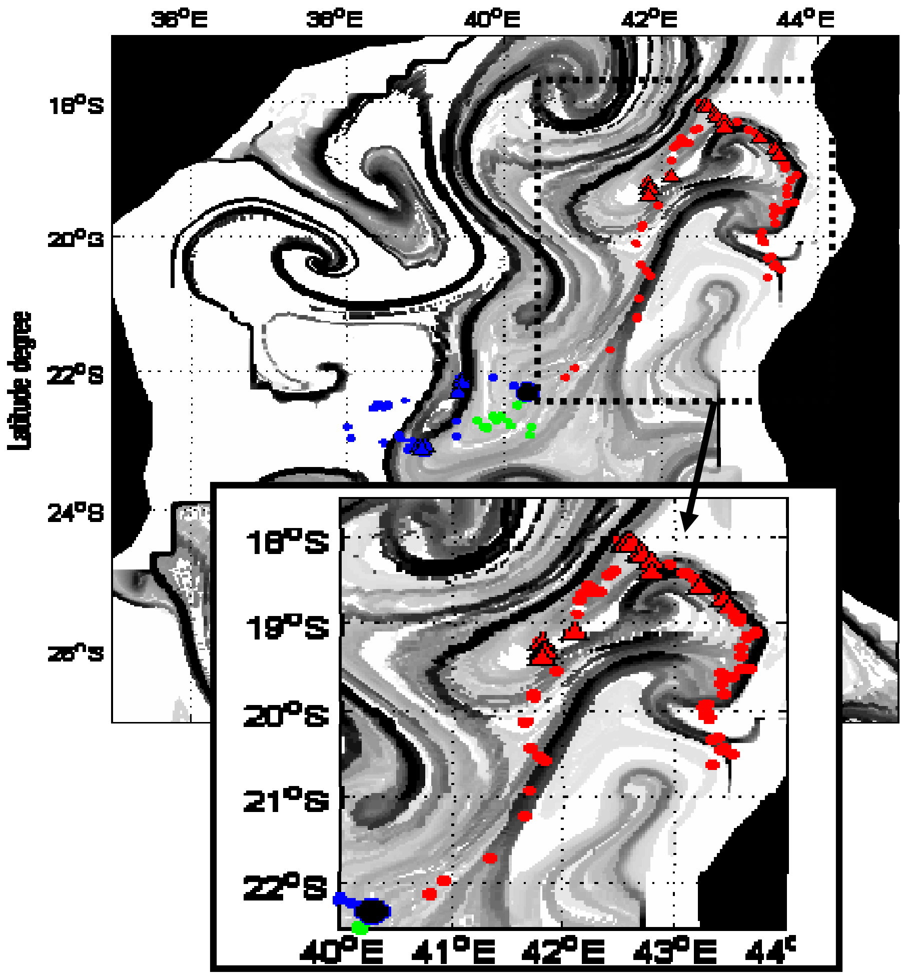
Week of September 24, 2003

Backward FSLE=Attractive LCSs





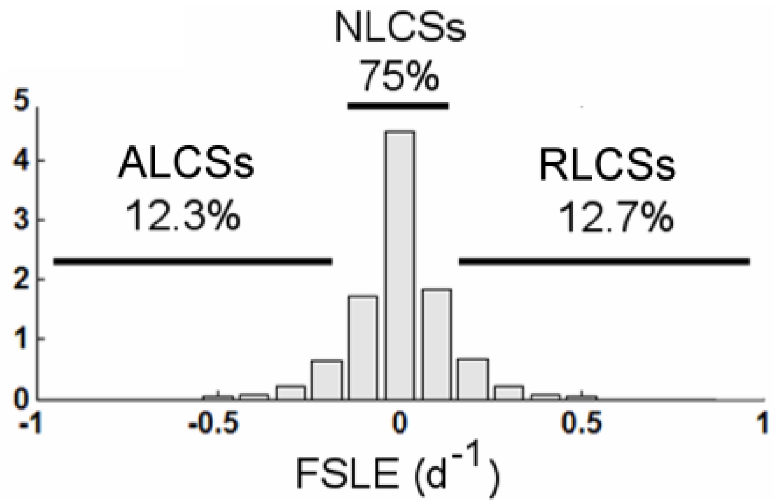
Forward FSLE = Repelling LCSs

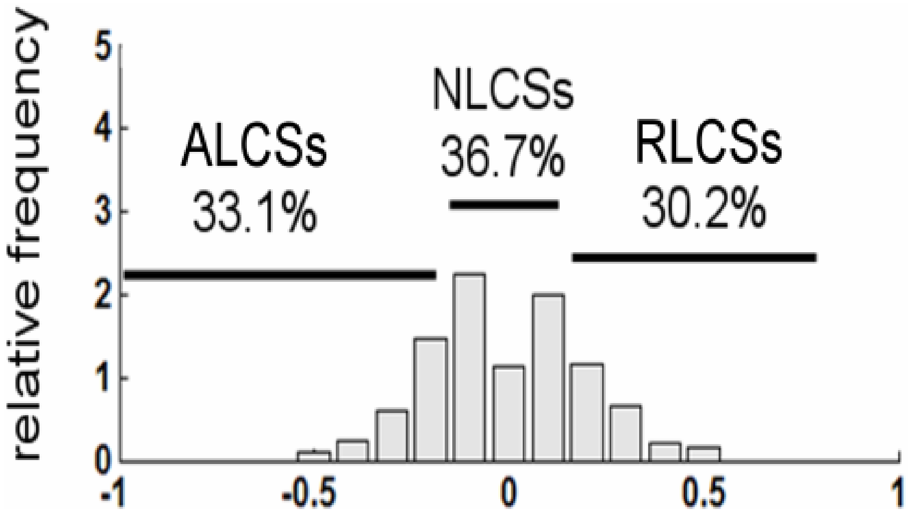


foraging patch (flight speed lower than 10 km/h)

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

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

	All trips		Long trips		Short trips	
Week	LCSs: $\lvert FSLE\rvert > 0.1\ day^{-1}$	$\lvert FSLE\rvert < 0.1\ day^{-1}$	LCSs: $\lvert FSLE\rvert > 0.1\ day^{-1}$	$\lvert FSLE\rvert < 0.1\ day^{-1}$	LCSs: $\lvert FSLE\rvert > 0.1\ day^{-1}$	$\lvert FSLE\rvert < 0.1\ day^{-1}$
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 ($\lvert FSLE\rvert > 0.1\ day^{-1}$ and on no LCSs. $\alpha = 5\%$.

STATISTICAL TESTS

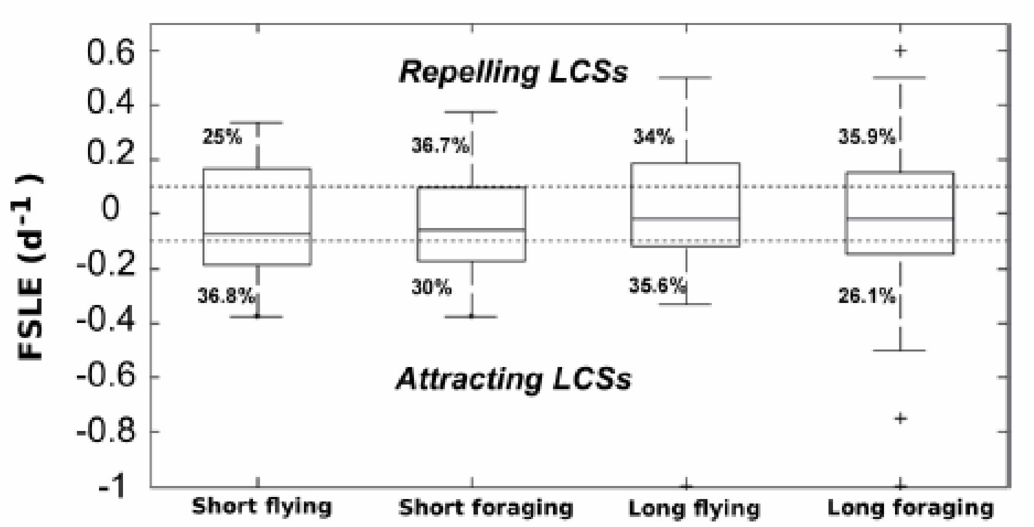


Table S2. Result of G-test statistics for comparison between frequency of bird positions on repelling or attracting LCS during flying and foraging and short and long trips

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. $\alpha = 5\%$.

Results of statistical tests:

- Frigate birds fly on top of LCCs 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?

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?

Tew Kai et al. PNAS (2009)

SUMMARY

- Lagrangian coherent structures, as revealed by FSLEs, influence whole marine ecosystems, from the abiotic component to top predators
- Frigatebirds follow LCSs as BIOLOGICAL CORRIDORS which allow them to find prey.
- Many open questions:
  - How do they detect the structures?
  - Why do they find both attracting and repelling?
  - …

http://ifisc.uib-csic.es/publications/