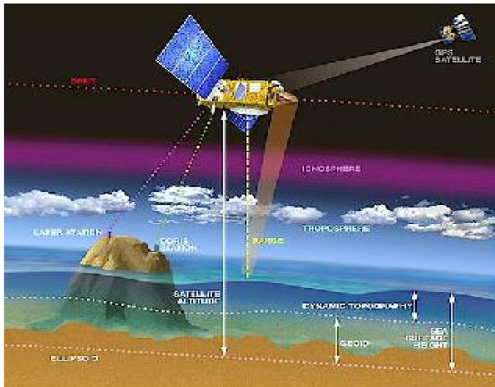
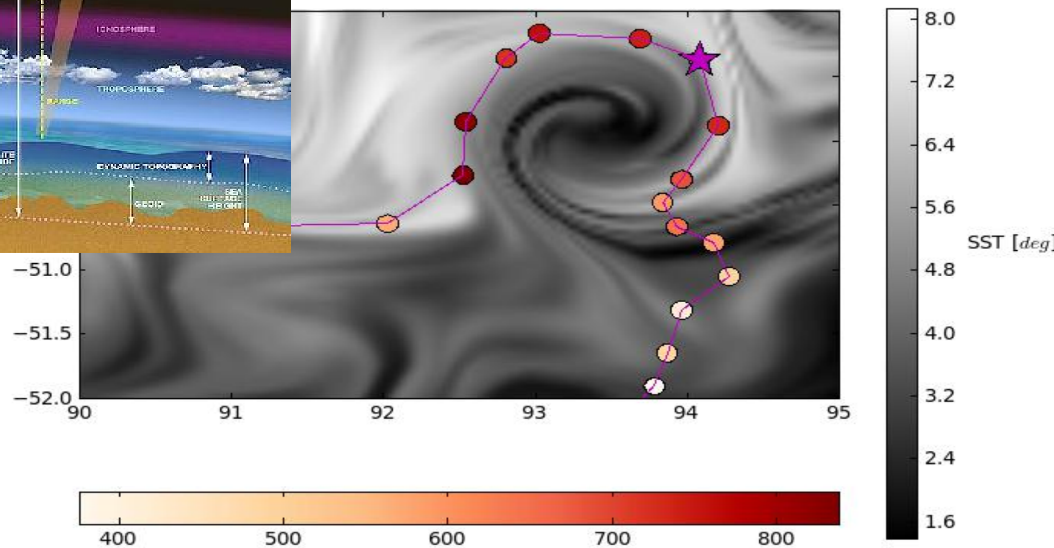
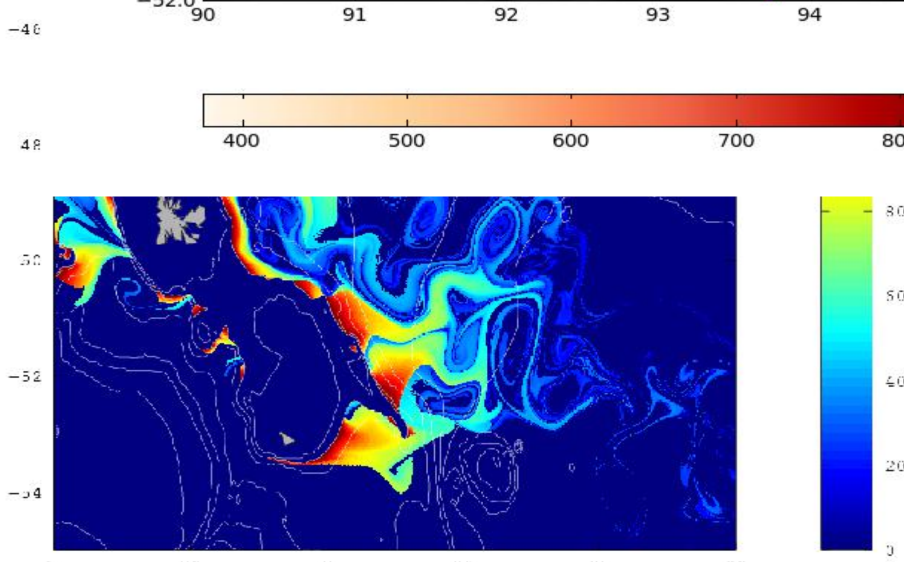
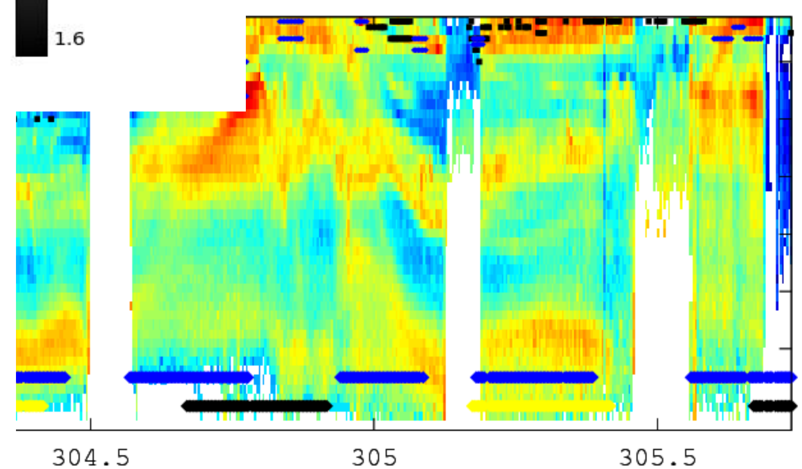
Stirring of ecological landscapes: from 2D to 3D dynamics

F. d'Ovidio
LOCEAN-IPSL, Paris









Work in collaboration with: A. Soccodato, A. Della Penna, C. Cotté, S. De Monte, S. Alvain, C. Guinet, S. Blain

Objectives of this presentation

- Examples of multisatellite data analysis for eco-biogeochemical applications

- Emergence of 3D dynamics: noise or signal?

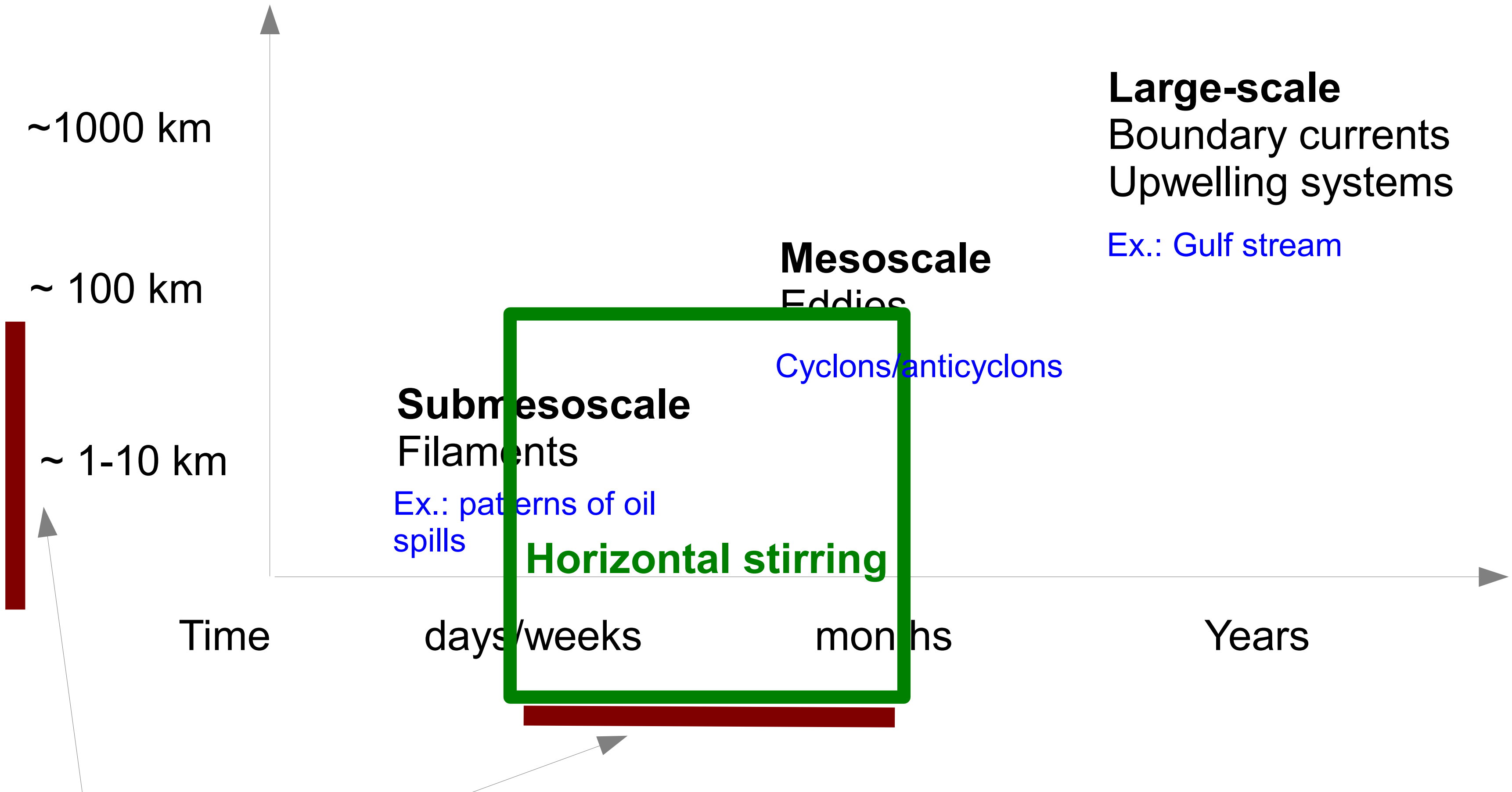
Outline

- Estimation of biogeochemical budgets by merging multisatellite data

- Hotspots of trophic interactions

- hotspots of biodiversity

A scale-dependent classification of the ocean circulation



Phytoplankton ecological timescales (doubling times, bloom,..) are **days/weeks**
Resonance between physics and biology at the submesoscale

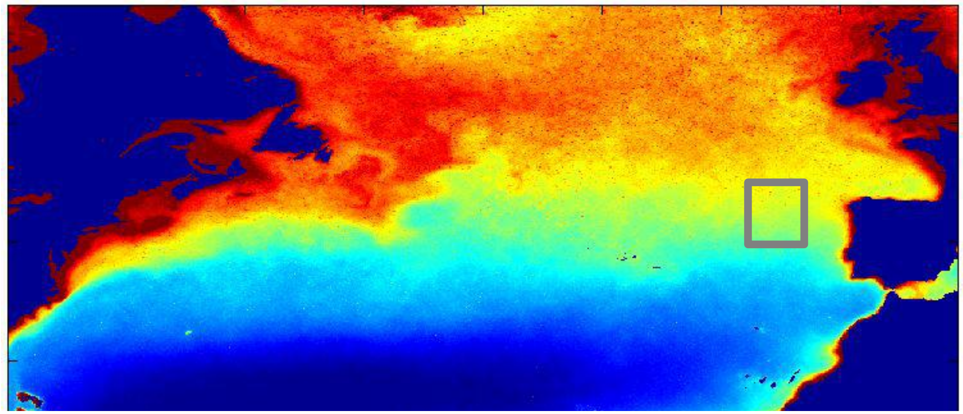
Key spatial scale: **limit of current global circulation models and global observational data**
Link between the surface and the ocean interior

Ecological patchiness

Dataset 1: **SeaWiFS**

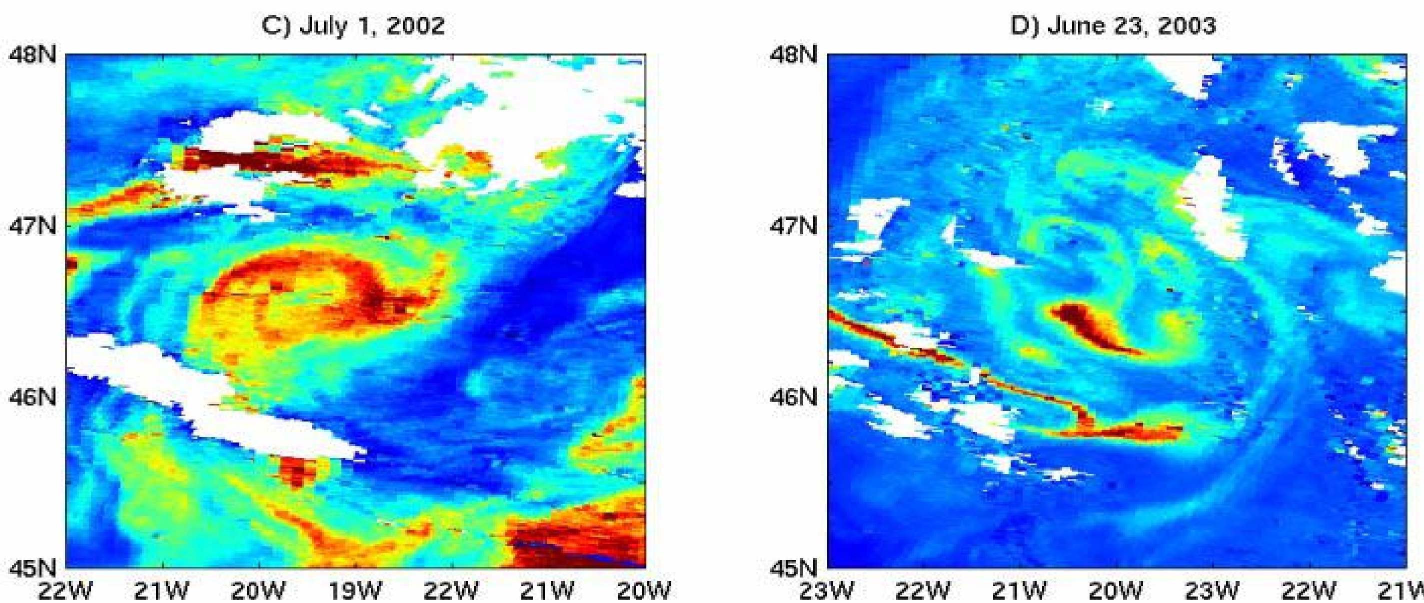
SeaWiFS chlorophyll

1000 km



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

100 km



Meso/submeso
scale patterns
Northeast Atlantic
(daily images)

(Sub-)mesoscale variability (~10 km, days/weeks) has the same tracer contrasts as the large scale (~1000 km, months/years) variability!

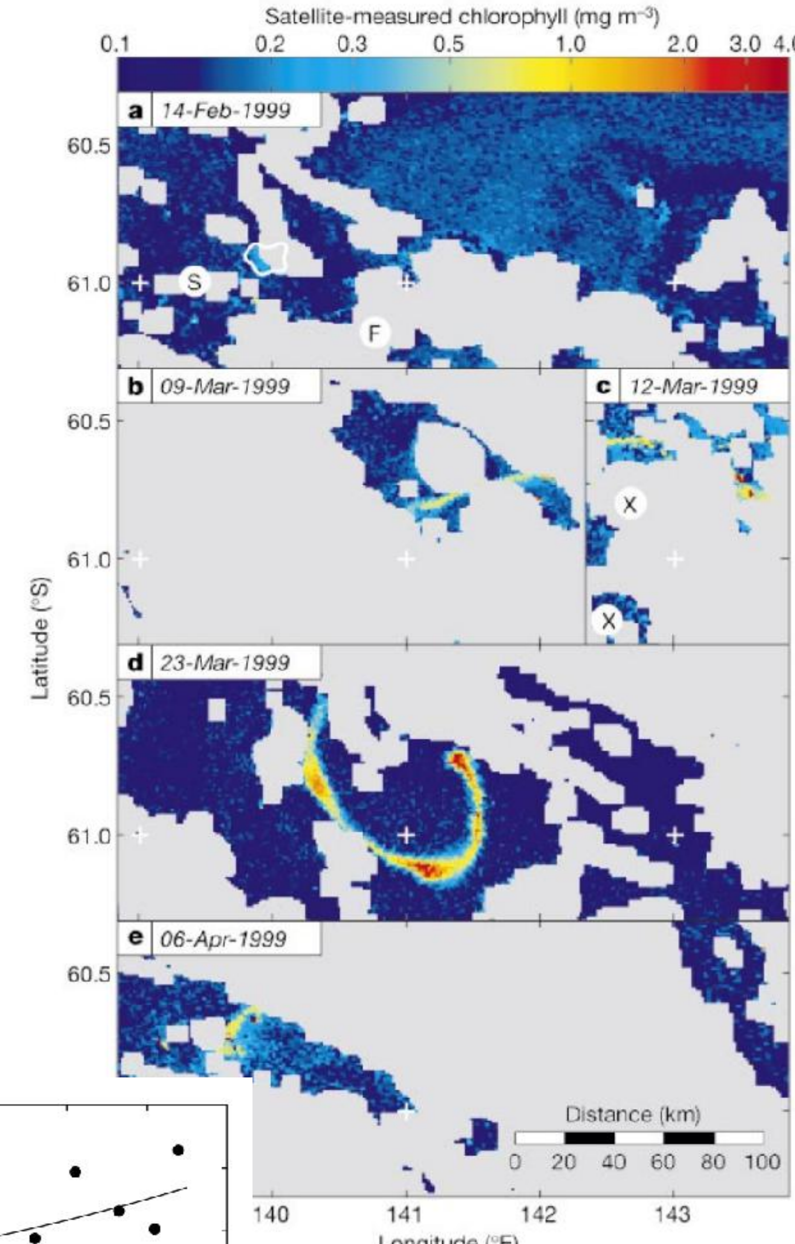
Results of both horizontal and vertical dynamics

Part I: Stirring and biogeochemistry

The SOIREE experiment (1999)

Importance of stirring in the development of an iron-fertilized phytoplankton bloom

Edward R. Abraham*, Cliff S. Law†, Philip W. Boyd‡, Samantha J. Lavender†§, Maria T. Maldonado‖§ & Andrew R. Bowie#†



Iron was released in nutrient-rich, low-Chlorophyll waters:

Main results

- Adding iron stimulated a planktonic bloom

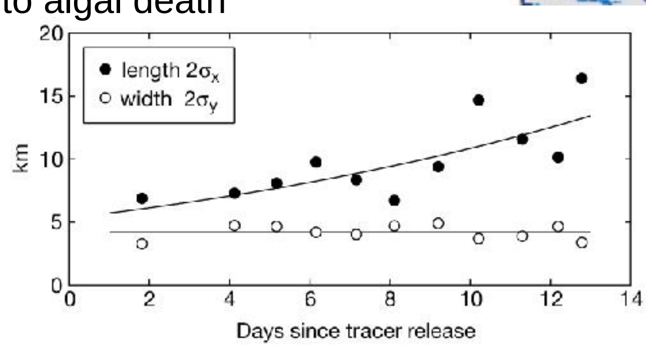
- The bloom was strongly affected by stirring

Open question:

- Does the bloom result in carbon export?

→ follow the phytoplanktonic patch from bloom to algal death

→ Estimate stirring contribution



Abraham et al., Nature, 2000

The EIFEX experiment (February 2004)

ARTICLE

doi:10.1038/nature11229

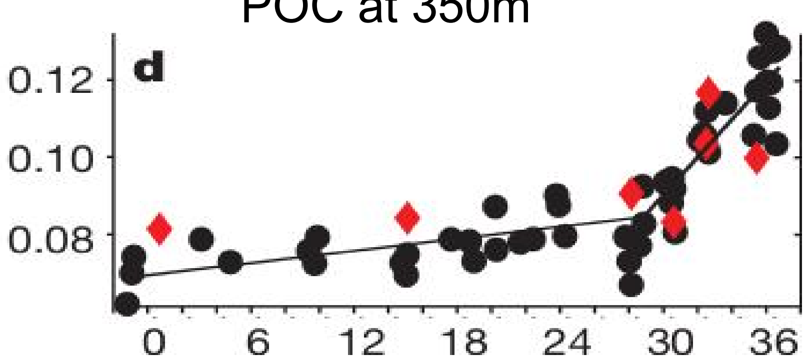
Deep carbon export from a Southern Ocean iron-fertilized diatom bloom

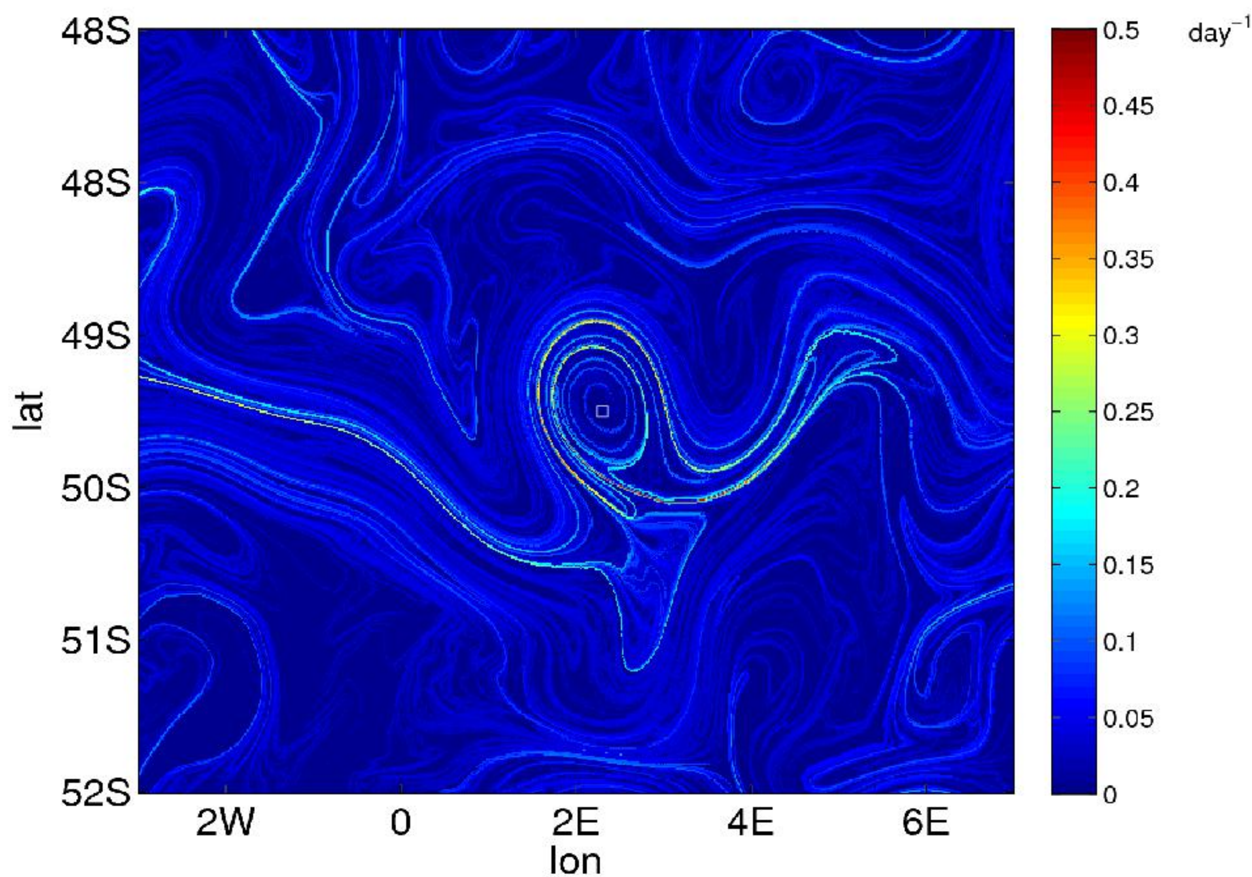
Victor Smetacek[1,2]*, Christine Klaas[1]*, Volker H. Strass[1], Philipp Assmy[1,3], Marina Montresor[4], Boris Cisewski[1,5], Nicolas Savoye[6,7], Adrian Webb[8], Francesco d'Ovidio[9], Jesús M. Arrieta[10,11], Ulrich Bathmann[1,12], Richard Bellerby[13,14], Gry Mine Berg[15], Peter Croot[16,17], Santiago Gonzalez[10], Joachim Henjes[1,18], Gerhard J. Herndl[10,19], Linn J. Hoffmann[16], Harry Leach[20], Martin Losch[1]

→ follow the phytoplanktonic patch from bloom to algal death: **40-day experiment**

→ Estimate stirring contribution: **relied on altimetry-derived diagnostics**

POC at 350m





Smetacek et al., Nature 2012

The EIFEX experiment (February 2004)


ARTICLE

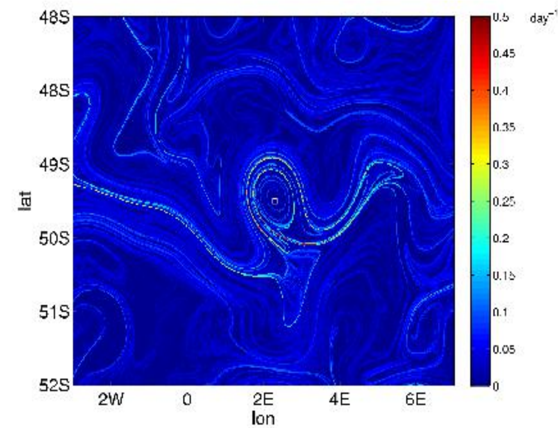
doi:10.1038/nature11229

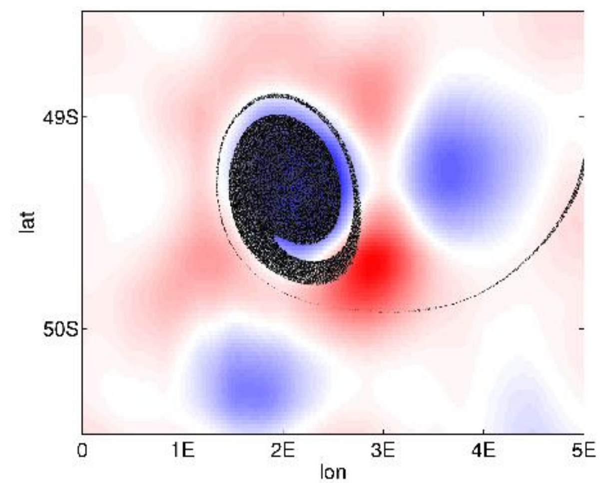
Deep carbon export from a Southern Ocean iron-fertilized diatom bloom

Victor Smetacek[1,2]*, Christine Klaas[1]*, Volker H. Strass[1], Philipp Assmy[1,3], Marina Montresor[4], Boris Cisewski[1,5], Nicolas Savoye[6,7], Adrian Webb[8], Francesco d'Ovidio[9], Jesús M. Arrieta[10,11], Ulrich Bathmann[1,12], Richard Bellerby[13,14], Gry Mine Berg[15], Peter Croot[16,17], Santiago Gonzalez[10], Joachim Henjes[1,18], Gerhard J. Herndl[10,19], Linn J. Hoffmann[16], Harry Leach[20], Martin Losch[1]

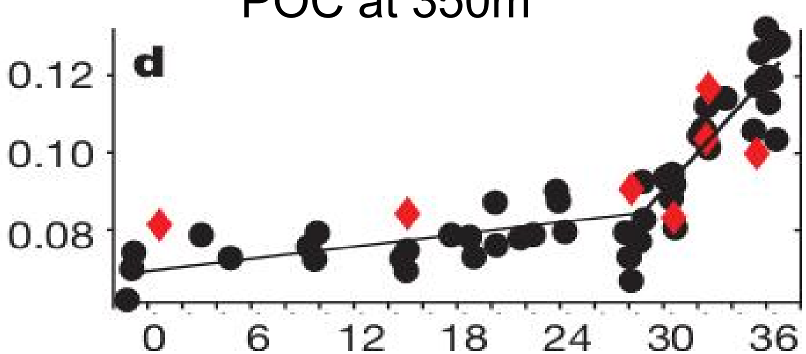
→ follow the phytoplanktonic patch from bloom to algal death: **40-day experiment**

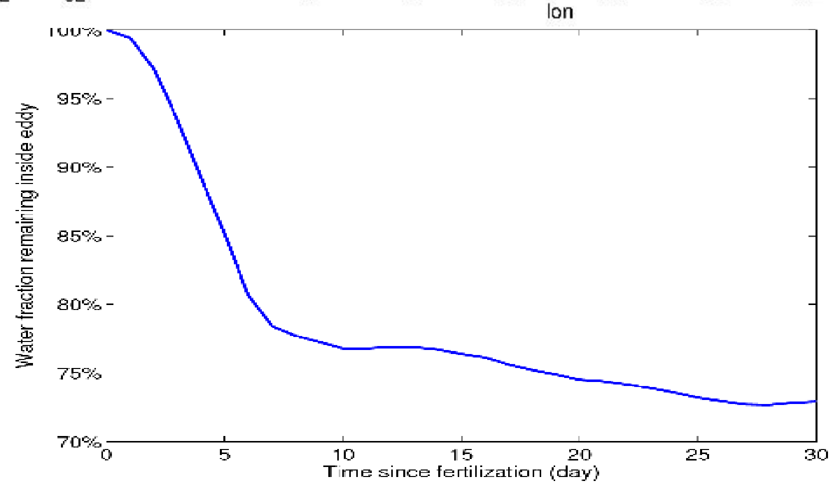
→ Estimate stirring contribution: **relied on altimetry-derived diagnostics**





POC at 350m





Smetacek et al., Nature 2012

The EIFEX experiment (February 2004)

ARTICLE

doi:10.1038/nature11229

Deep carbon export from a Southern Ocean iron-fertilized diatom bloom

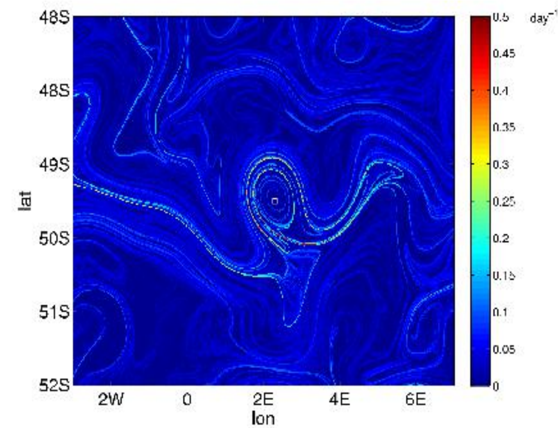
Victor Smetacek[1,2]*, Christine Klaas[1]*, Volker H. Strass[1], Philipp Assmy[1,3], Marina Montresor[4], Boris Cisewski[1,5], Nicolas Savoye[6,7], Adrian Webb[8], Francesco d'Ovidio[9], Jesús M. Arrieta[10,11], Ulrich Bathmann[1,12], Richard Bellerby[13,14], Gry Mine Berg[15], Peter Croot[16,17], Santiago Gonzalez[10], Joachim Henjes[1,18], Gerhard J. Herndl[10,19], Linn J. Hoffmann[16], Harry Leach[20], Martin Losch[1]

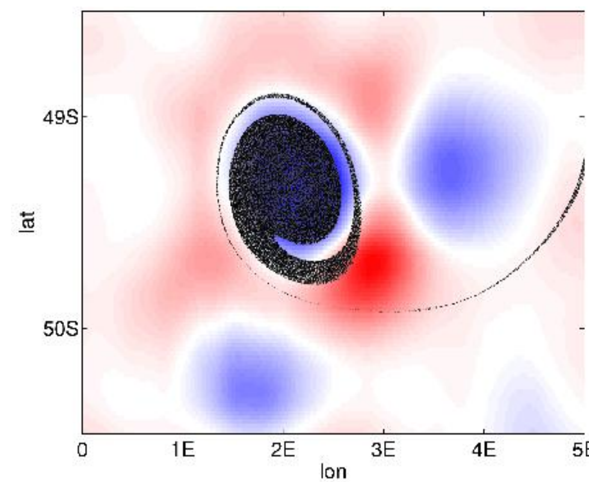
→ follow the phytoplanktonic patch from bloom to algal death: **40-day experiment**

→ Estimate stirring contribution: **relied on altimetry-derived diagnostics**

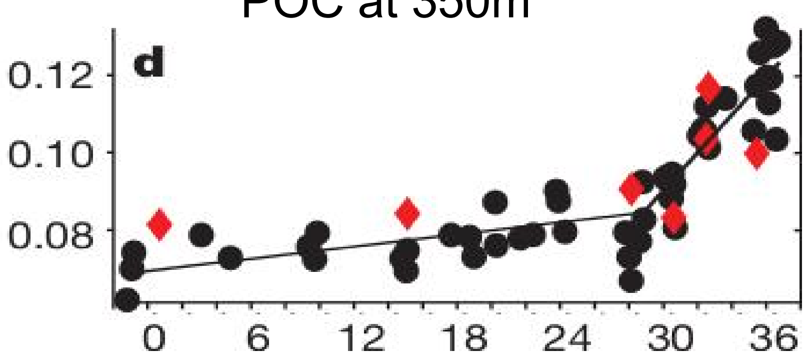
Open question:

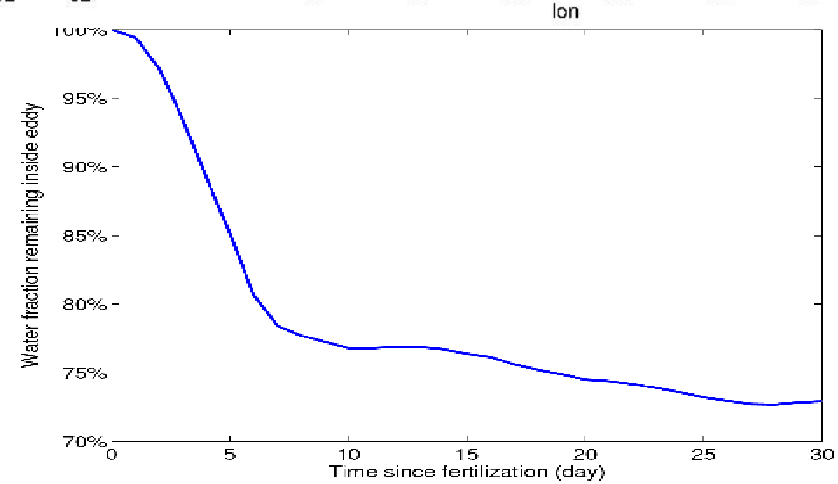
What happens in natural fertilization?





POC at 350m



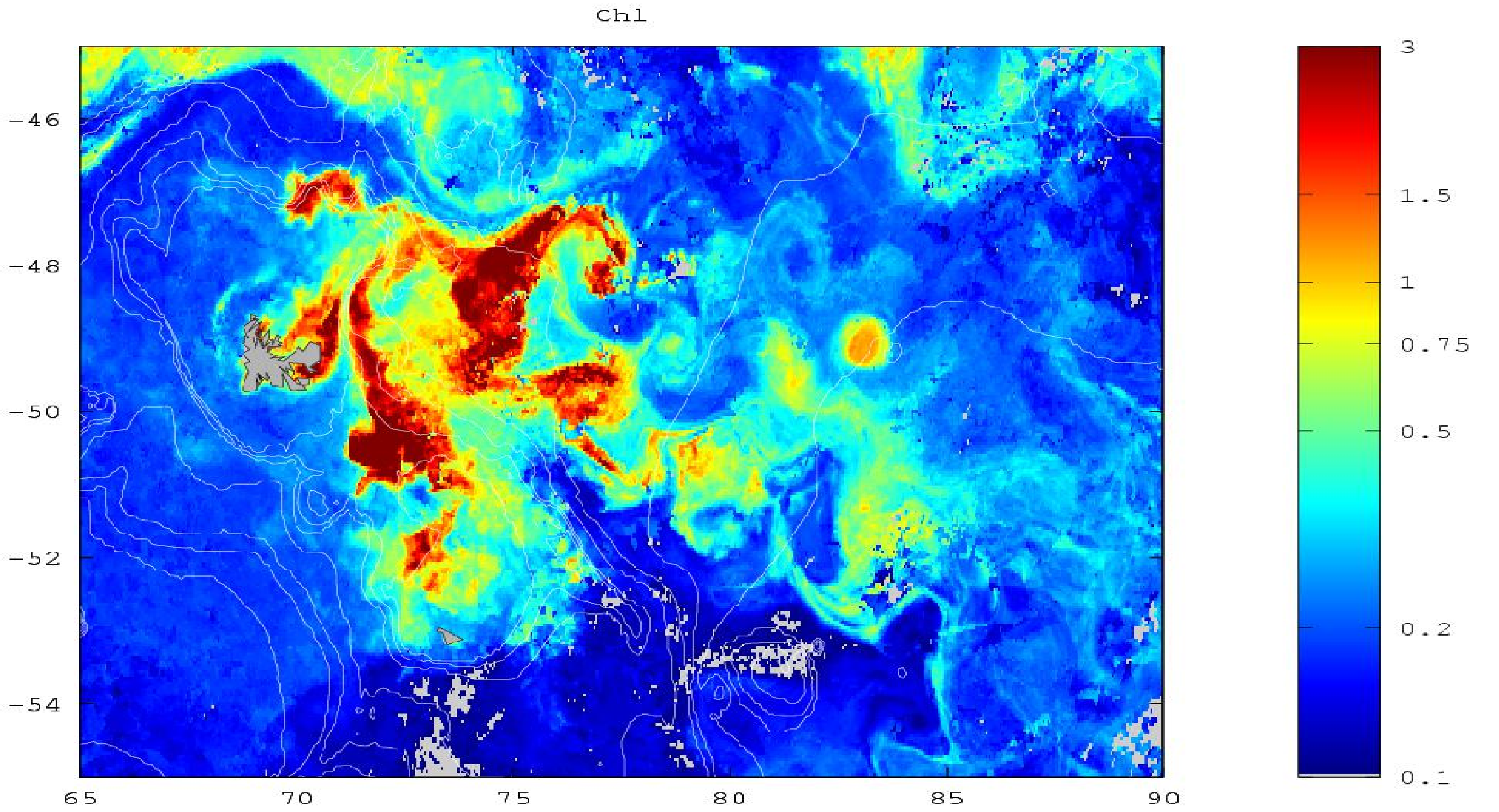


Smetacek et al., Nature 2012

The KEOPS2 experiment (end 2011)

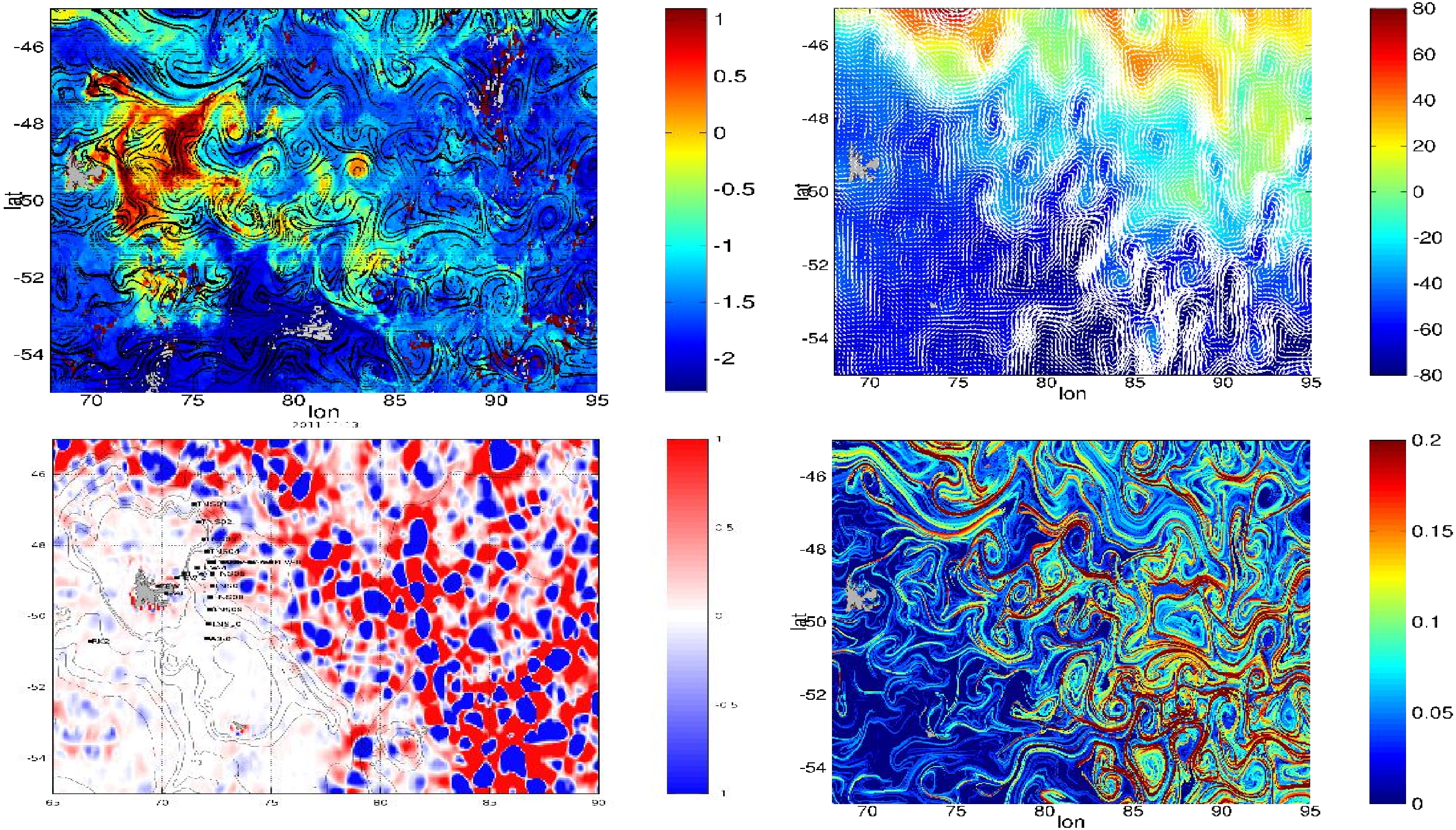
→ follow a naturally fertilized patch

→ Estimate stirring contribution and sources of iron



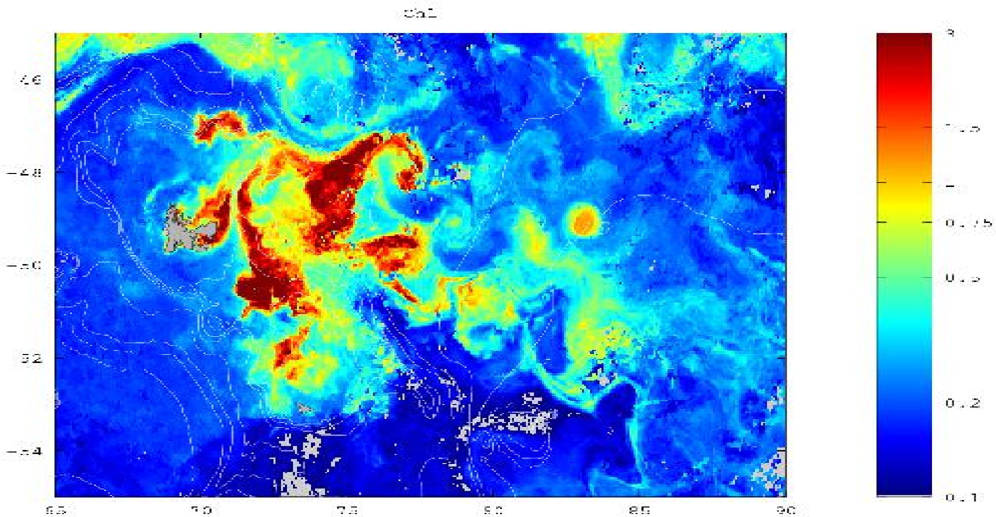
The KEOPS2 experiment (end 2011)

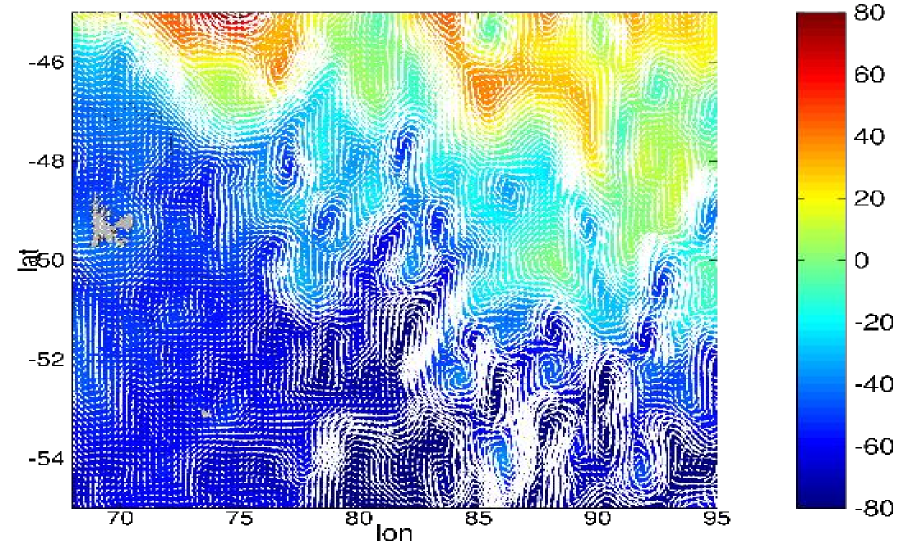
Disentangling iron sources and circulation patterns with altimetry

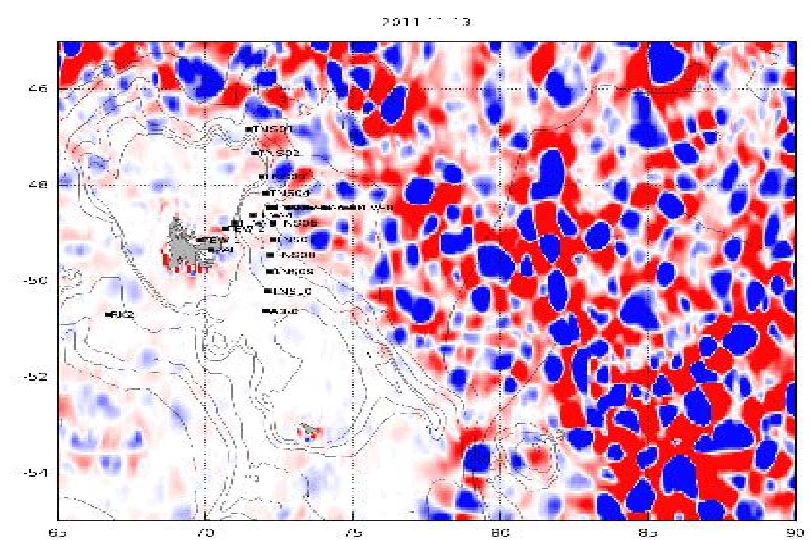


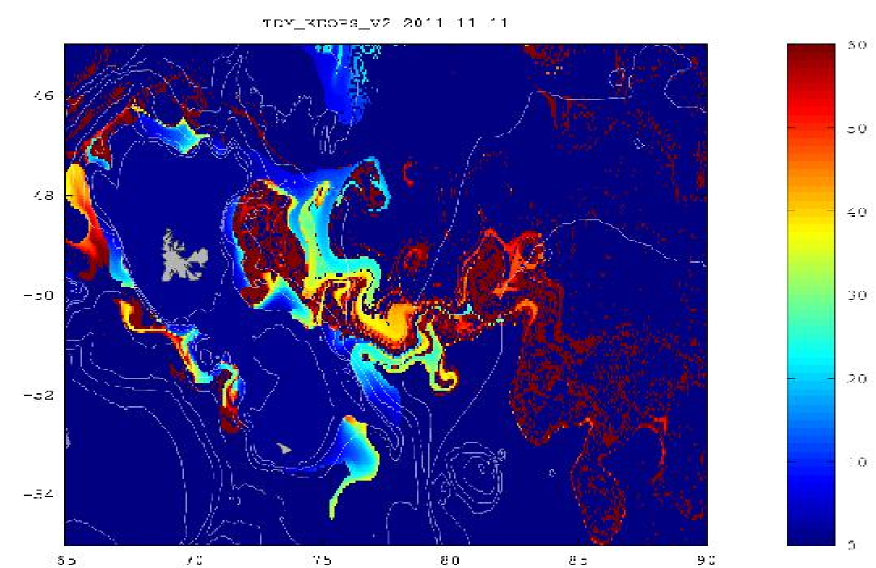
The KEOPS2 experiment (end 2011)

Disentangling iron sources and circulation patterns with altimetry

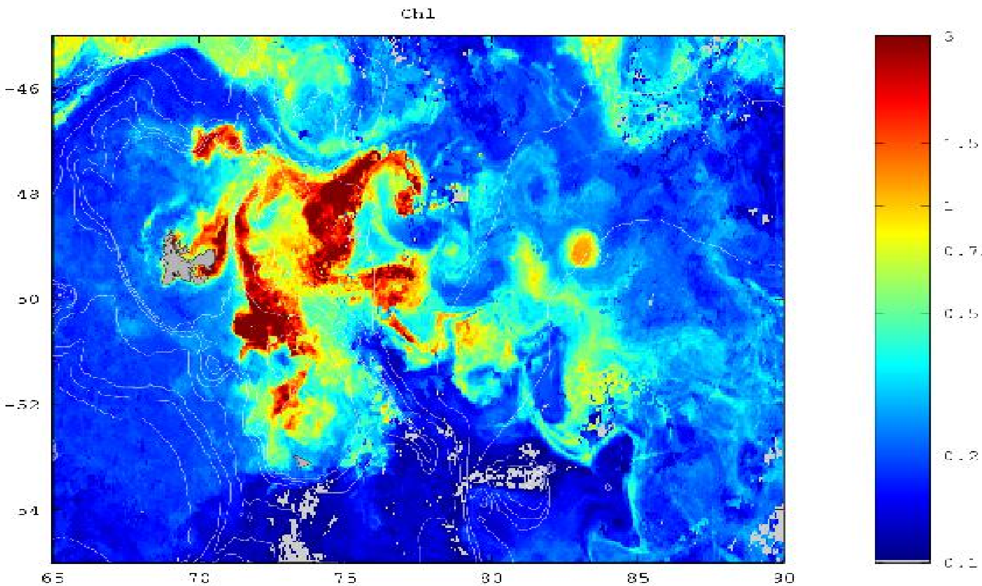






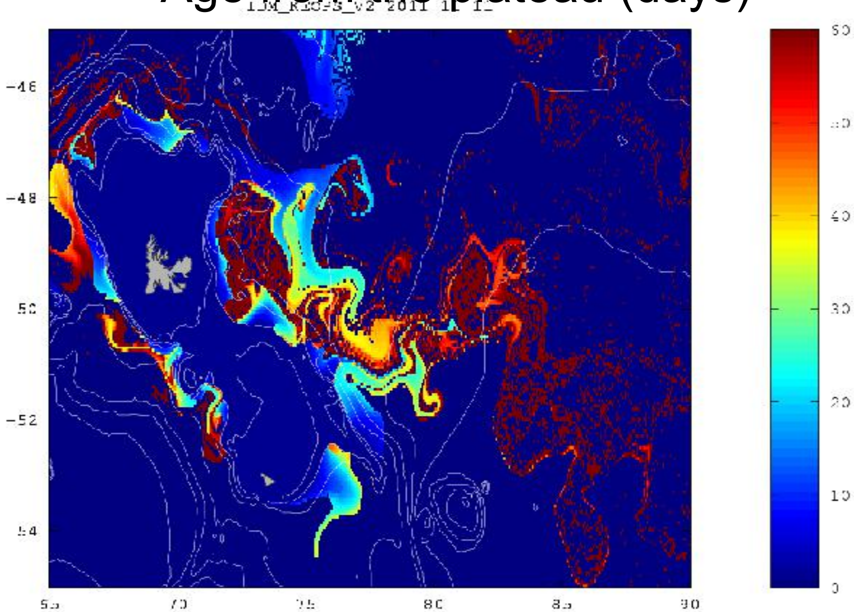


Iron concentration from altimetry data



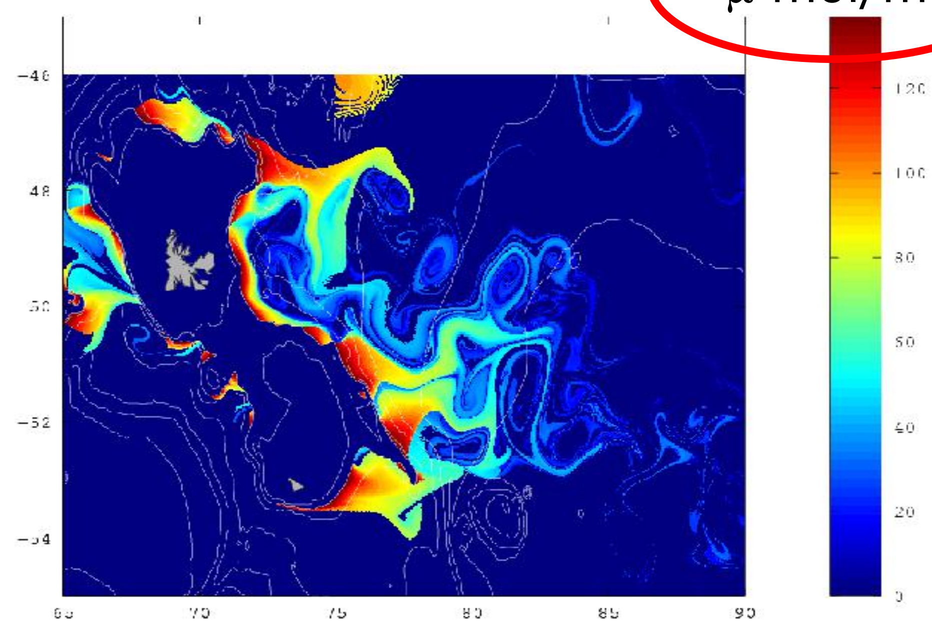
The age of water parcels can be converted in iron concentration by assuming a constant iron concentration over the plateau, an exponential scavenging dynamics and geostrophic dynamics for the mixed layer. KEOPS2 iron measurements are coherent with this approach.

Age from the plateau (days)



Iron concentration

μ mol/m²



Some conclusions (Satellite-derived stirring and biogeochemistry)

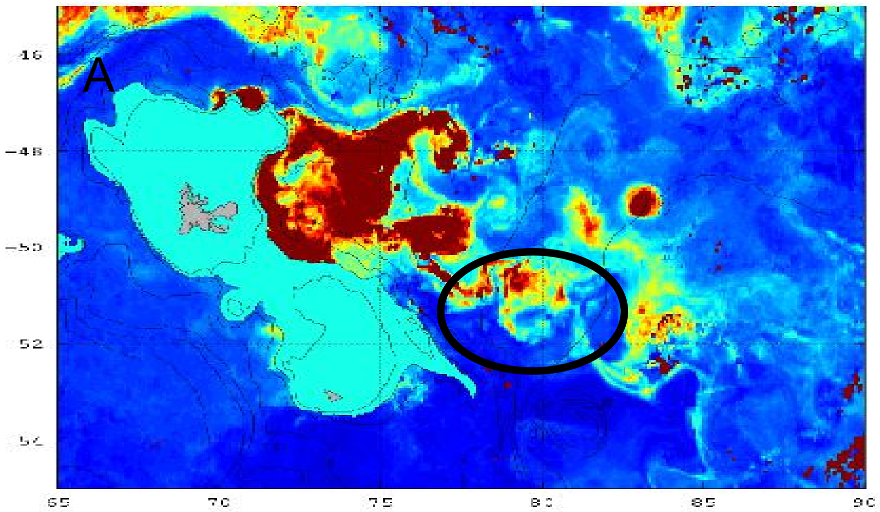
- Stirring patterns can be reconstructed accurately from altimetry

- “Virtual sensors” (e.g., Kerguelen iron concentration) can be constructed by gluing multisatellite data with theoretical tools

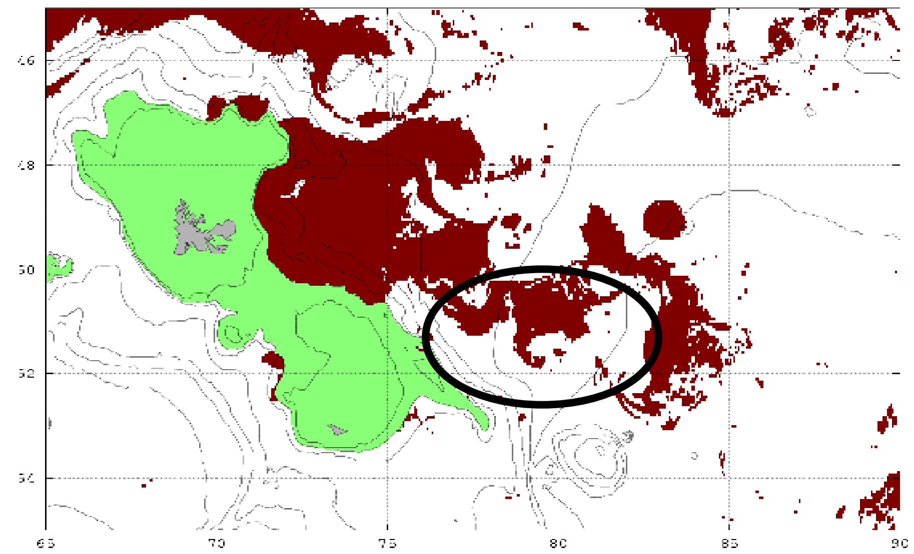
- Can we really neglect the 3D dynamics?

The KEOPS2 experiment (end 2011)

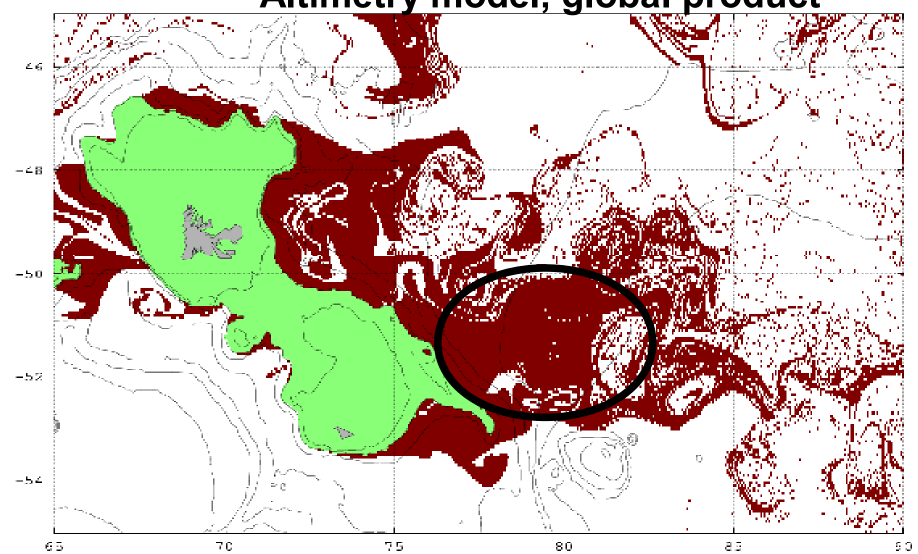
Ocean color



Ocean color, threshold

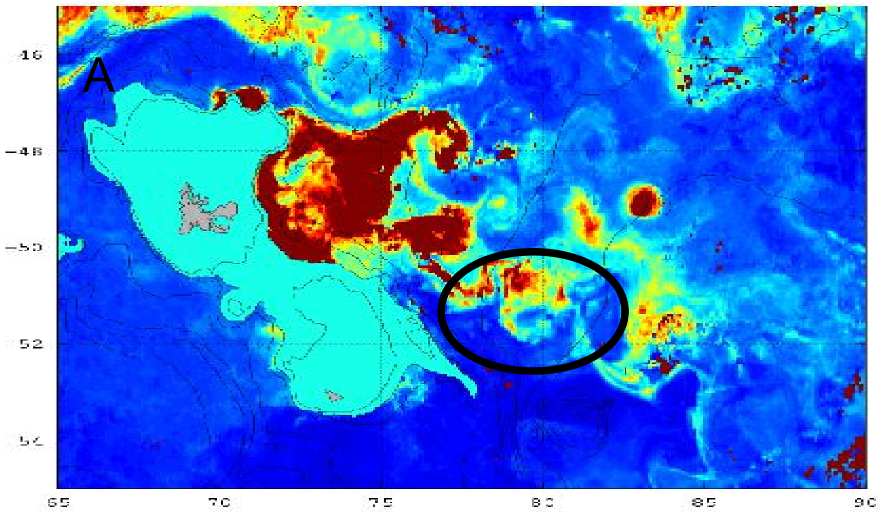


Altimetry model, global product

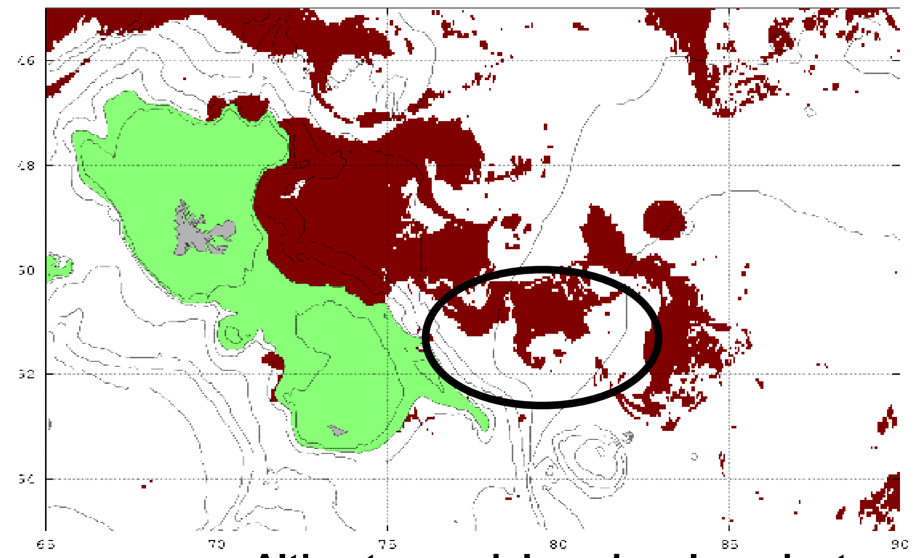


The KEOPS2 experiment (end 2011)

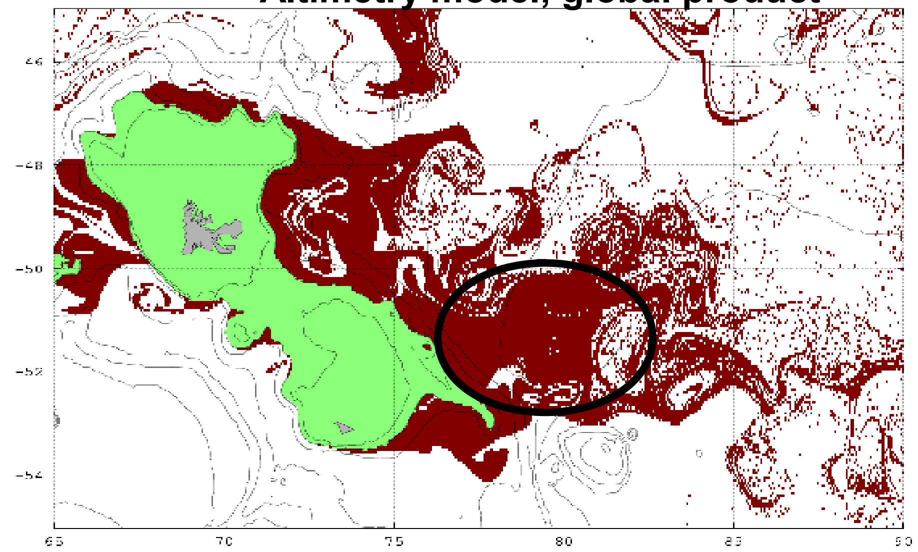
Ocean color



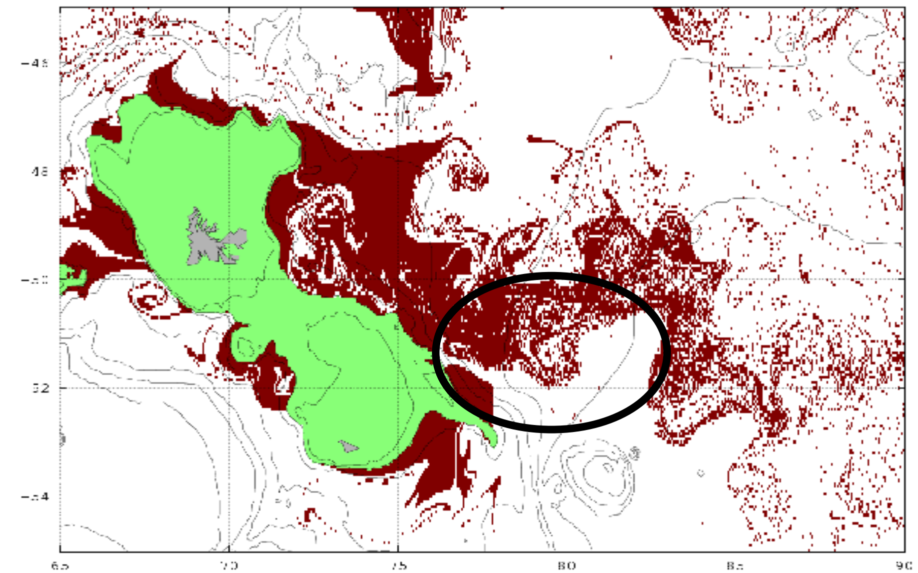
Ocean color, threshold



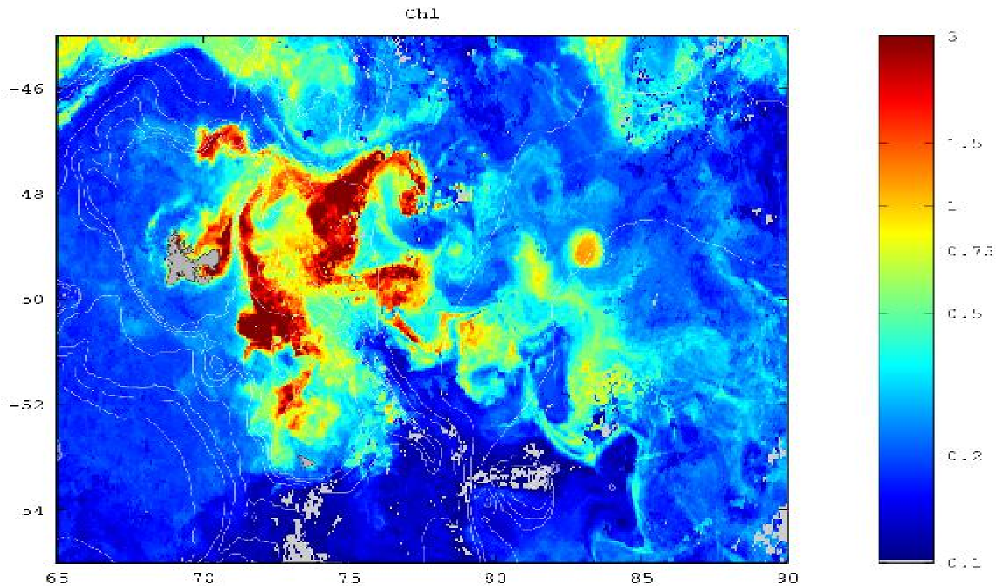
Altimetry model, global product



Altimetry model, regional product



Stirring patterns and Chl plume

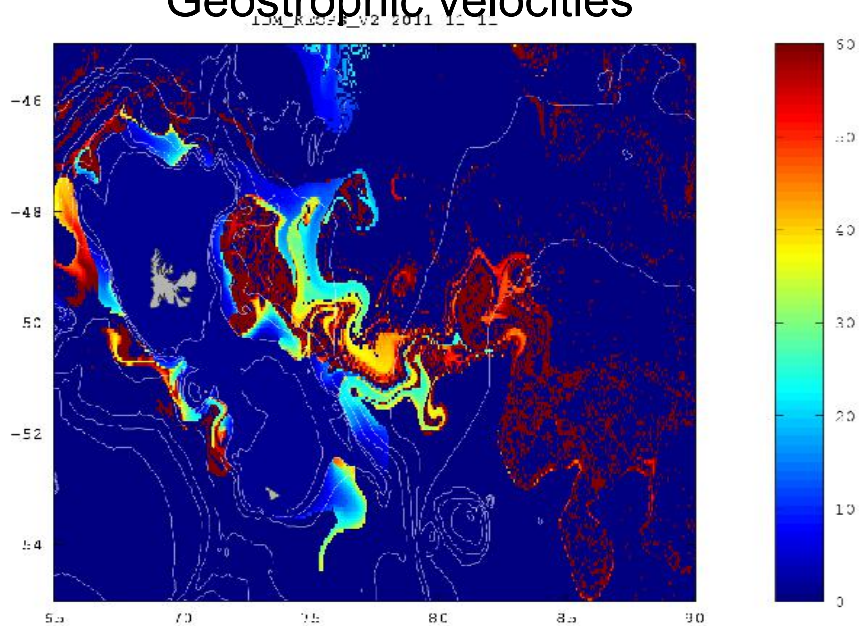


In Spring (11/nov/2011):

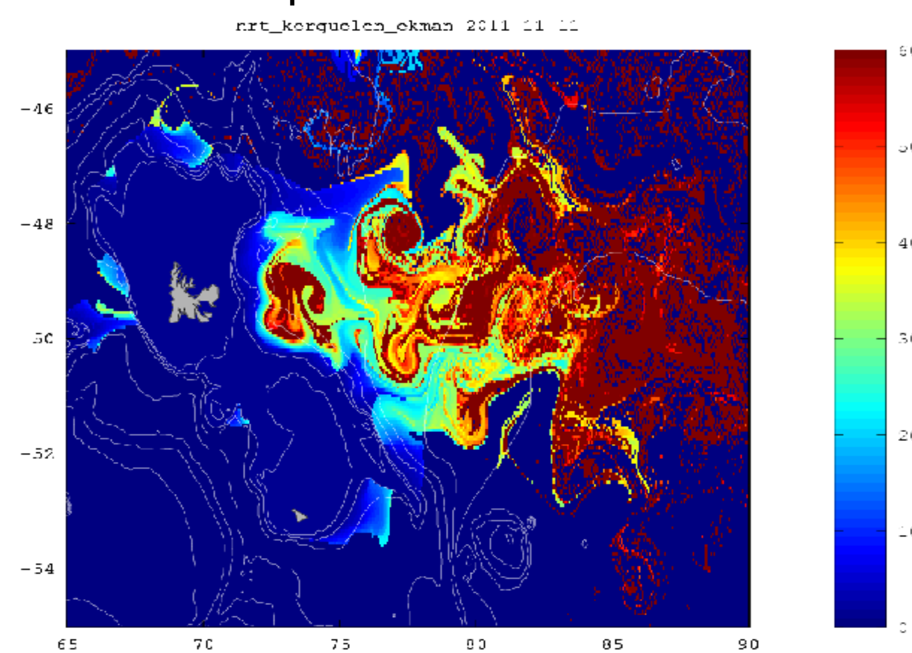
- Geostrophic (altimetry) velocities are very consistent with the hypothesis that blooming waters are water coming from the plateau.

- Adding Ekman velocities leads to largely overestimate the plume extension.

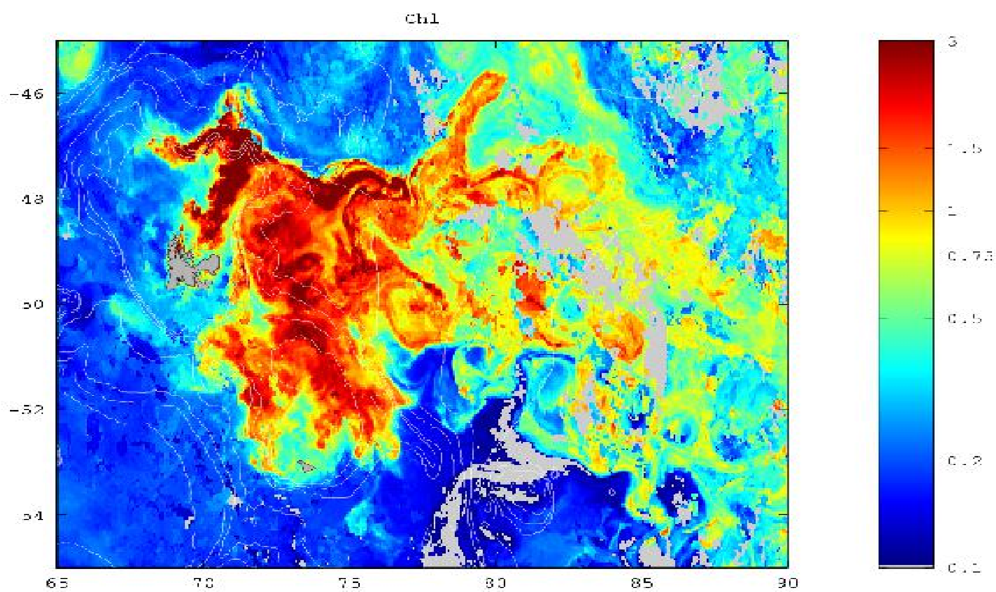
Geostrophic velocities



Geostrophic+Ekman velocities



I. Stirring patterns and Chl plume

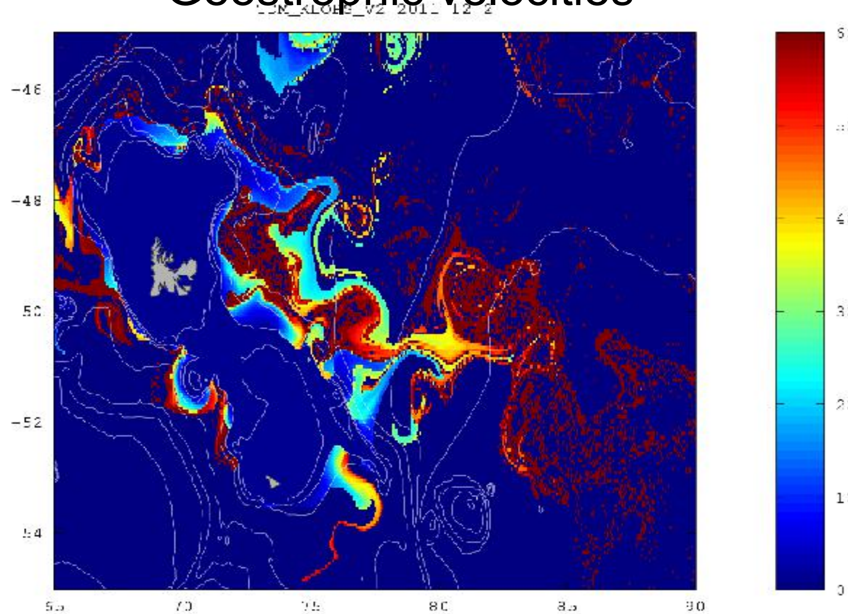


In summer (11/dec/2011):

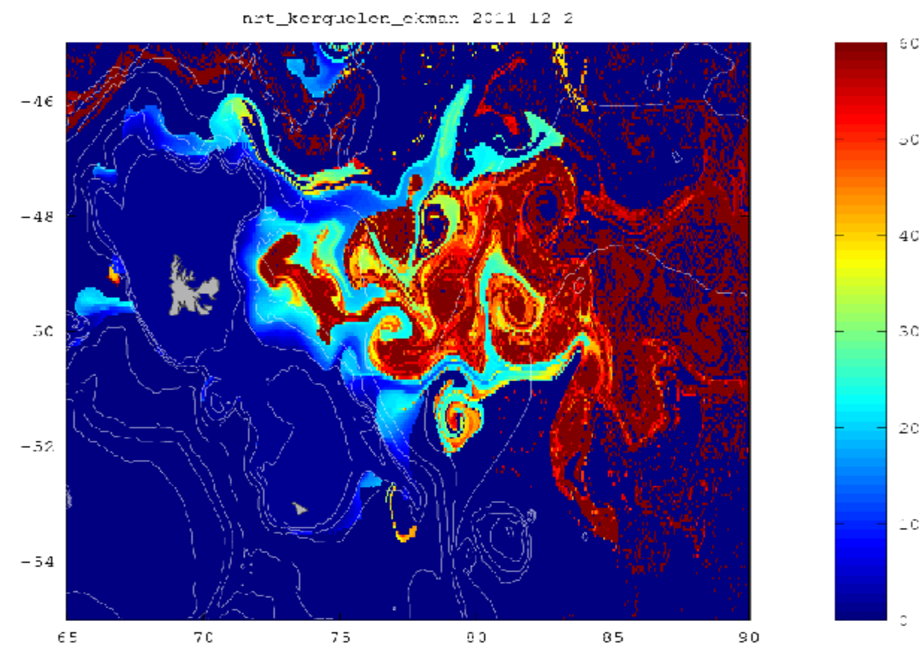
- Geostrophic (altimetry) velocities undersetimate the plume extension!

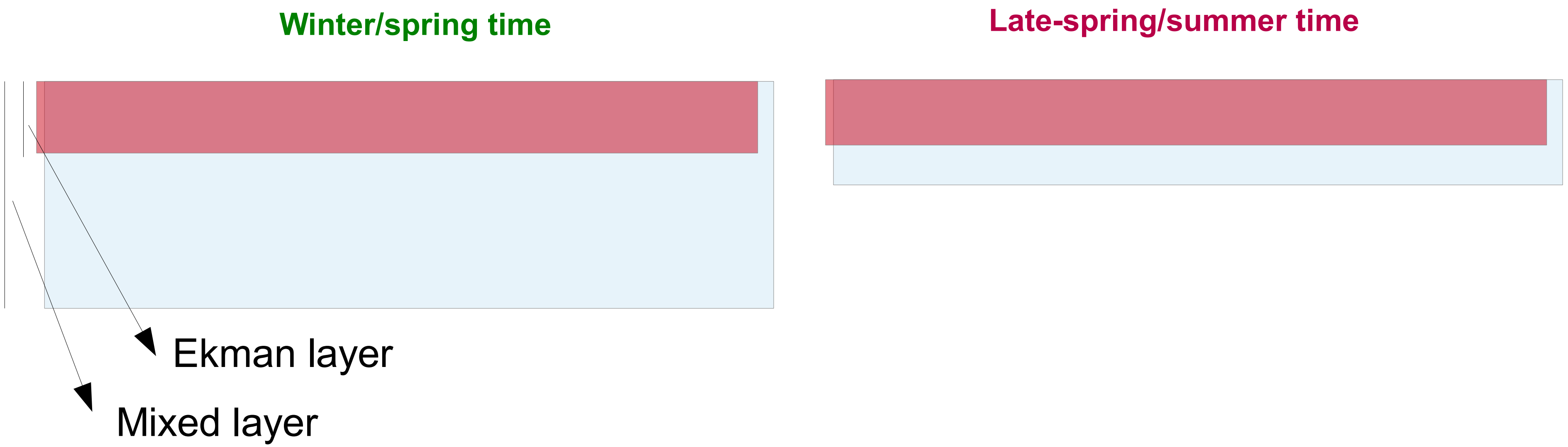
- Adding Ekman velocities agrees with Chl maps.

Geostrophic velocities



Geostrophic+Ekman velocities





Possible scenario:

1. There is an Ekman layer with a NE strong component.

2. **Winter/spring time**: the mixed layer is deeper than the Ekman layer: tracers diluted in the mixed layer have a geostrophic circulation, close-to-surface buoys at fixed depth have a geostrophic+Ekman trajectories.

3. **late-spring/summer time:** the mixed layer approaches the Ekman layer, and tracers also are structured by geostrophy+Ekman

Supporting observations:

1. Chl map consistent with geostrophy in early spring, with geostrophy+Ekman in late spring

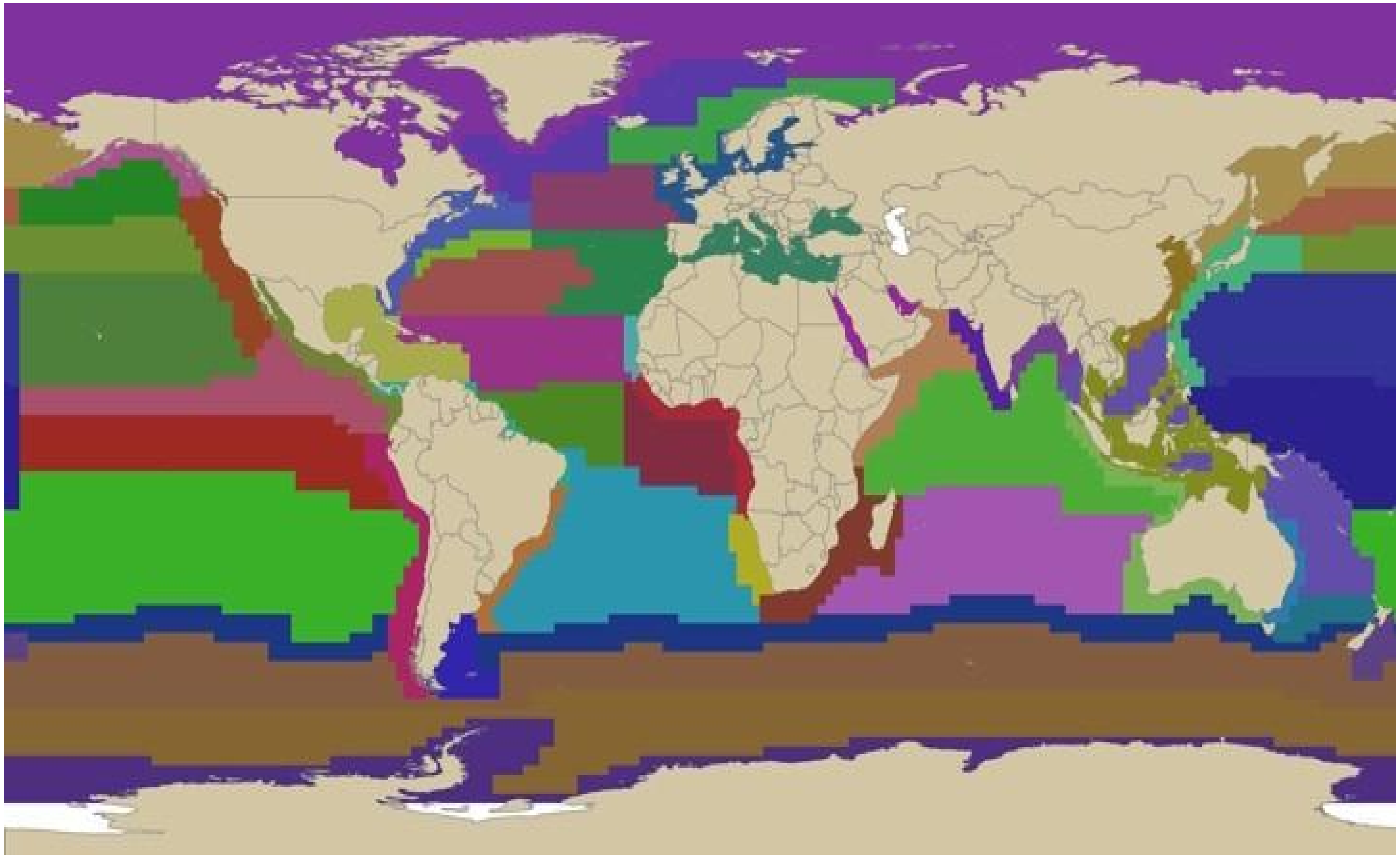
2. Drifters show a strong NE drift.

3. SST images indicate stratification between november and december (next slides)

This may explain why altimetry agrees with Chl but not with drifter trajectories

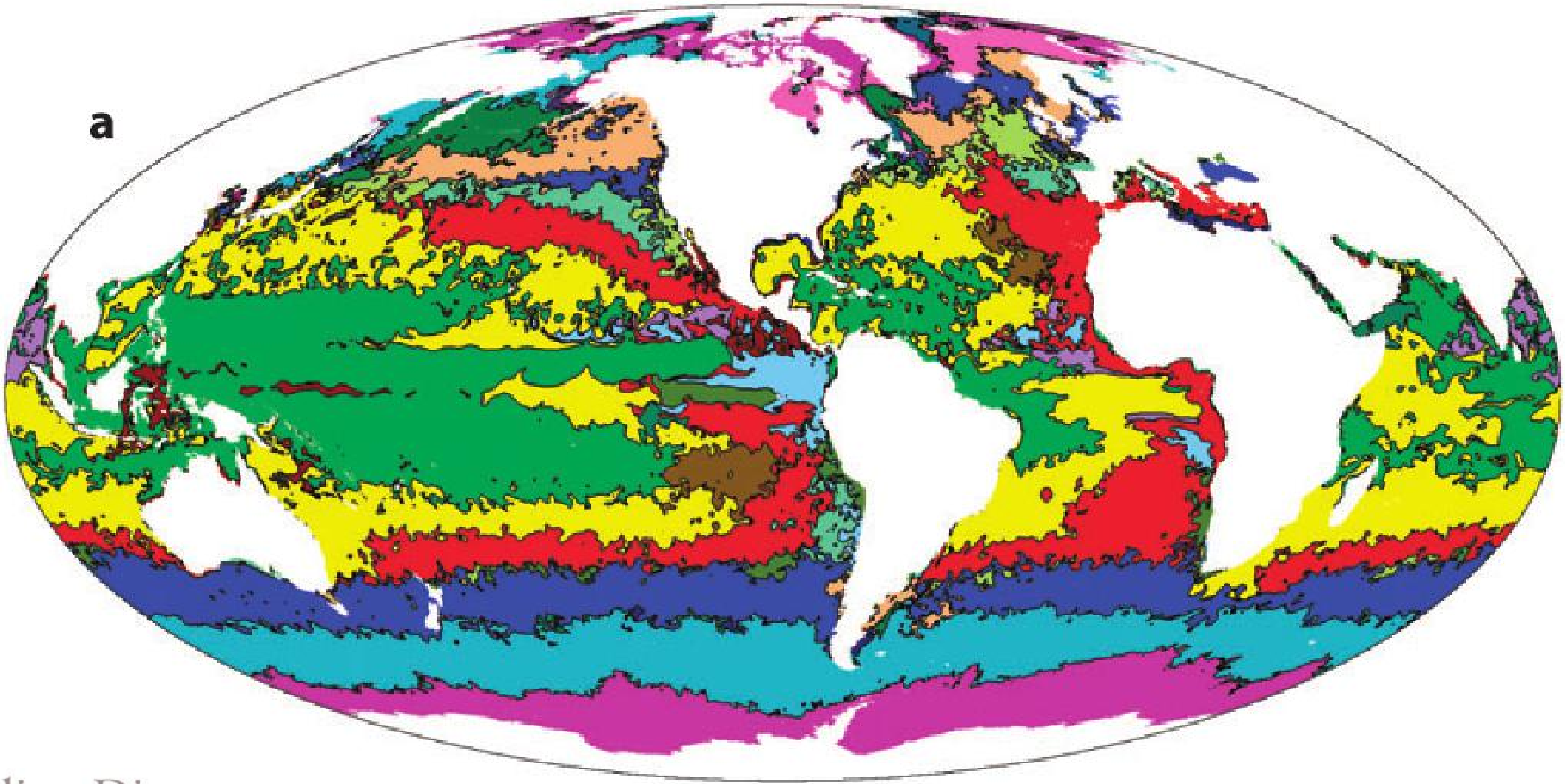
Part 2: Stirring and marine ecology

Phytoplankton biogeography



Alan Longhurst, *Ecological Geography of the Sea,* Academic Press (1998)

Phytoplankton biogeography in models



Modeling Diverse Communities of Marine Microbes

Michael J. Follows and Stephanie Dutkiewicz
Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology,

Annu. Rev. Mar. Sci. 2011. 3:427–51

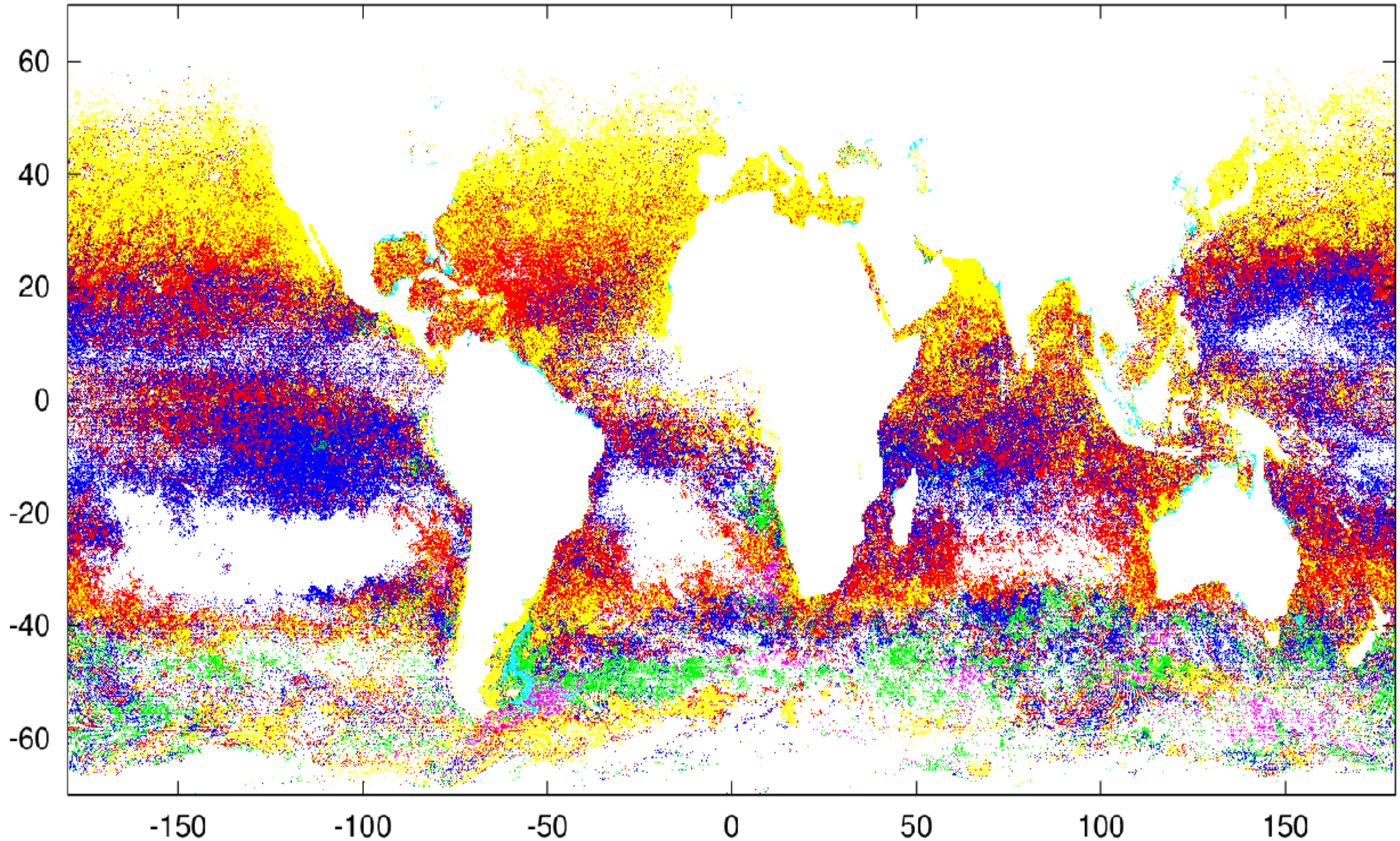
Emergent Biogeography of Microbial Communities in a Model Ocean

Michael J. Follows,[1*] Stephanie Dutkiewicz,[1] Scott Grant,[1,2] Sallie W. Chisholm[3]

SCIENCE VOL 315 30 MARCH 2007

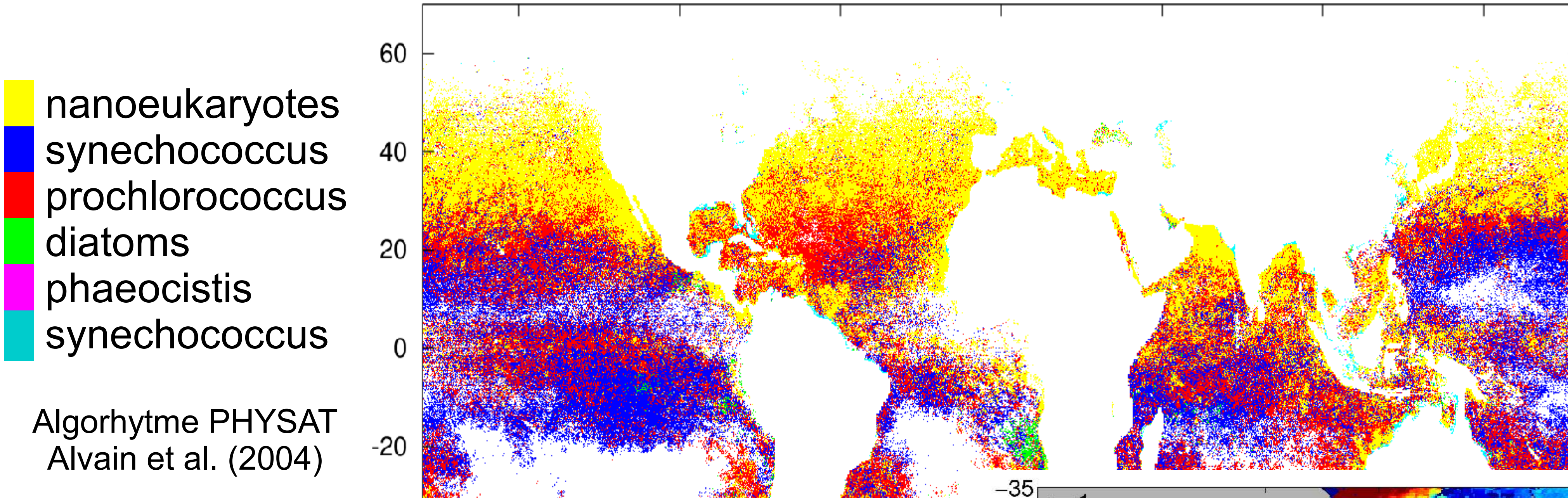
Remotely sensed biogeography of dominant phytoplankton types in the global ocean

nanoeukaryotes
synechococcus
prochlorococcus
diatoms
phaeocistis
Coccolithophores
Algorithm PHYSAT
Alvain et al. (2004)

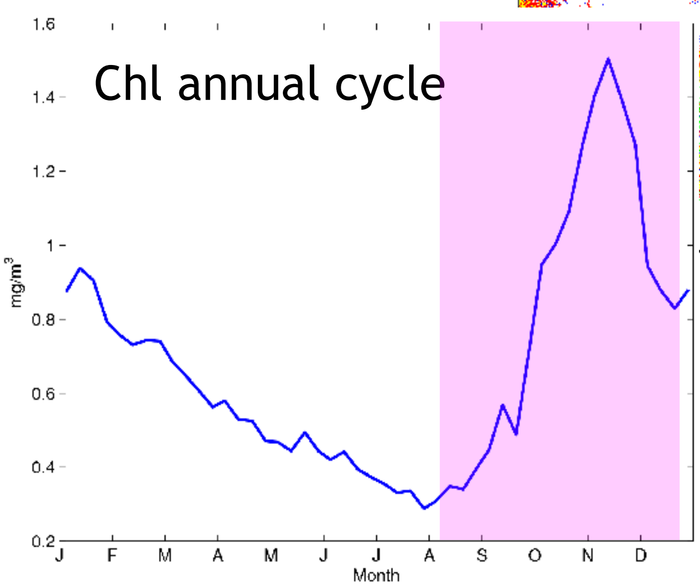


High spatiotemporal resolution
but
Only provides the dominant phytoplanktonic type

Remotely sensed biogeography of dominant phytoplankton types in the global ocean

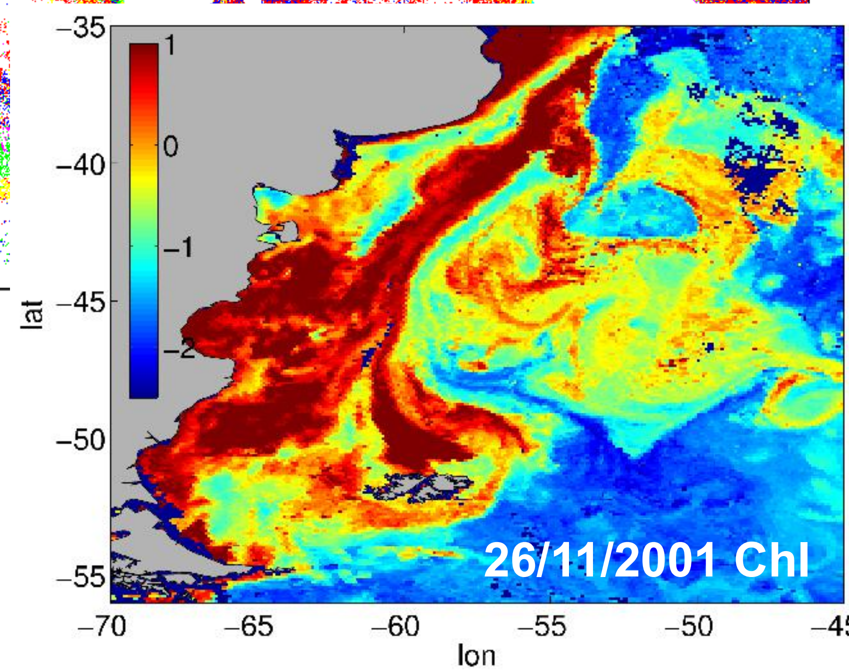


Algorhytme PHYSAT
Alvain et al. (2004)



Spring bloom

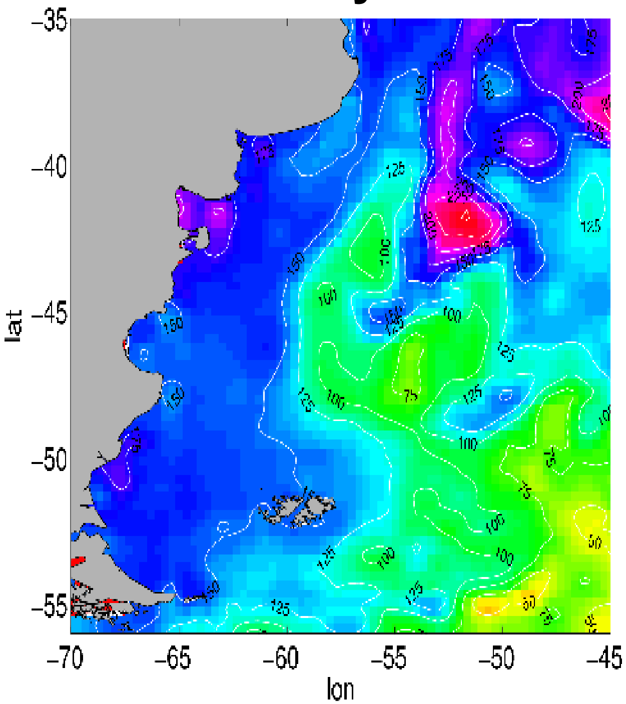
ZOOM IN



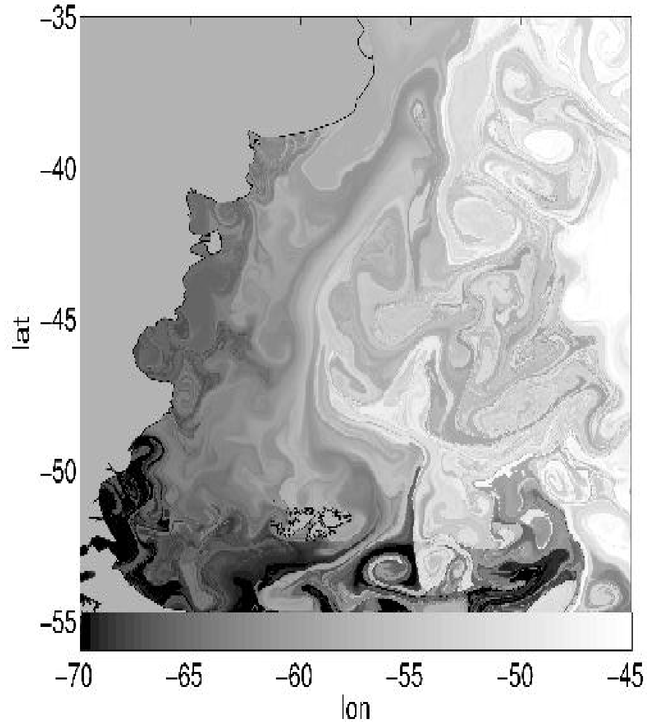
A case-study
stirring at the confluence of Malvinas' and Brazil currents

Effect of stirring by advection of synthetic tracers

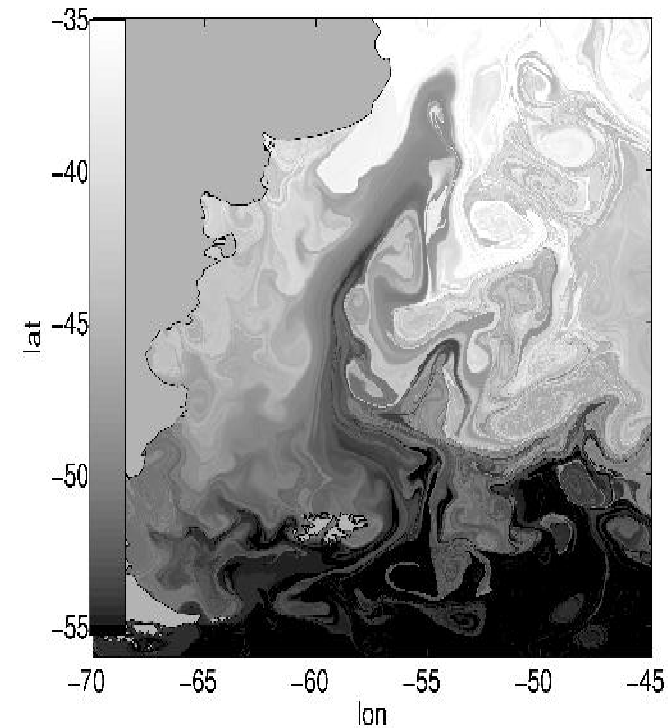
Velocity field



Satellite SSH
Mesoscale currents



Tracer initialized with a longitudinal gradient

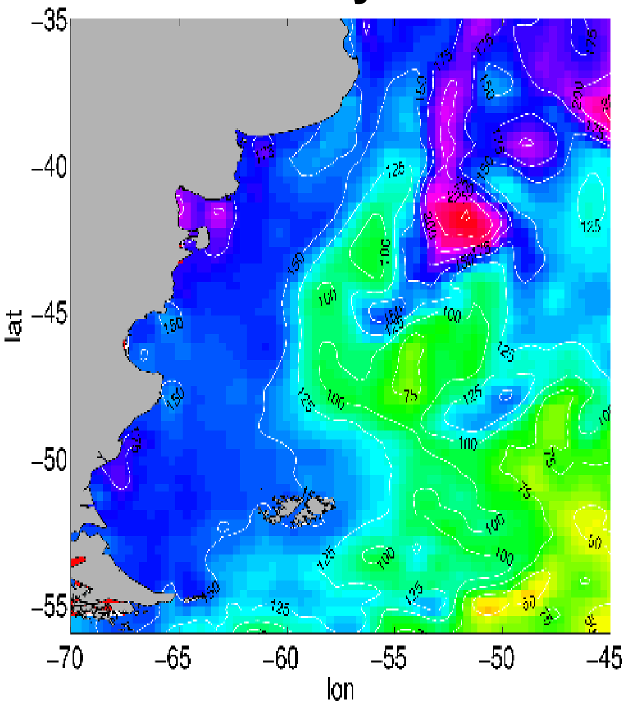


Tracer initialized with a latitudinal gradient

Filaments induced by stirring appear when a passive tracer is advected.
However, the spatial structures may depend on the tracer initial conditions

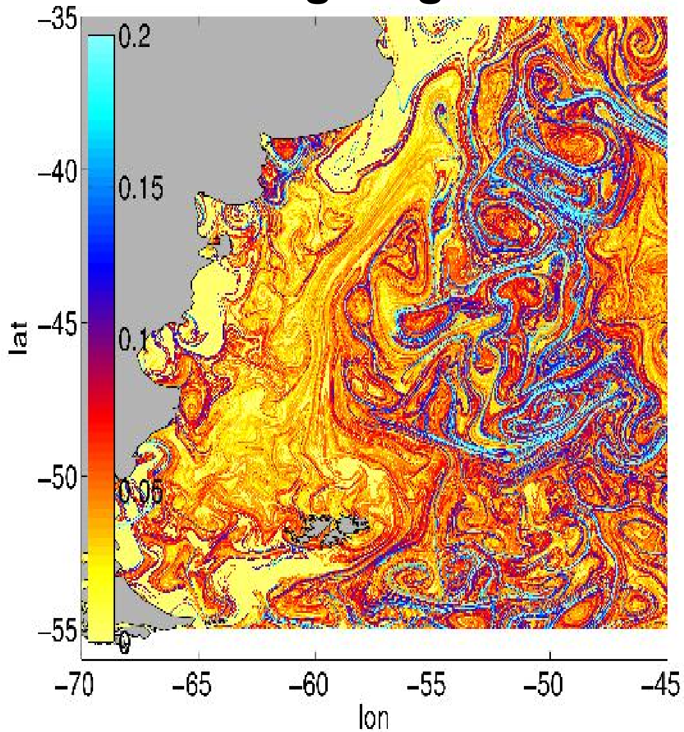
A case-study
stirring at the confluence of Malvinas' and Brazil currents

Velocity field



Satellite SSH
Mesoscale currents

Stirring diagnostic

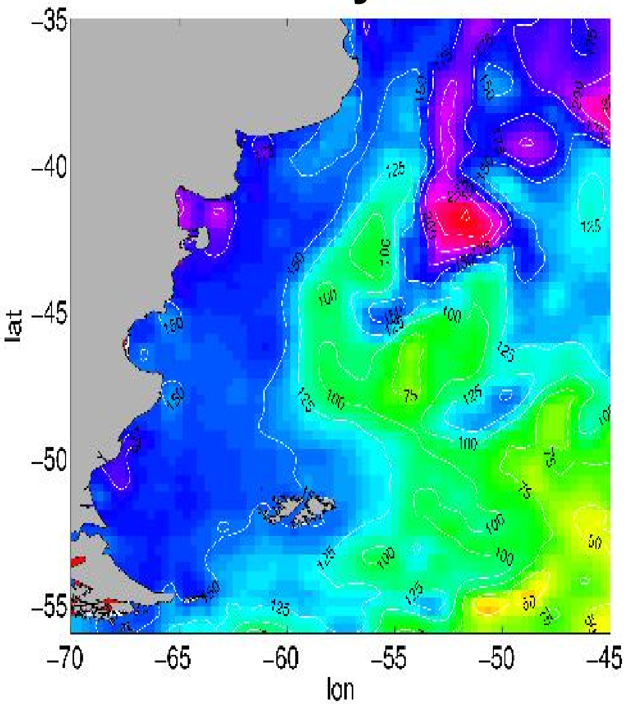


SSH-derived Lyapunov exponents

Stirring diagnostics like the Lyapunov exponents permits to detect stirring structures independently of specific initial conditions (in this case, fronts induced by stirring).

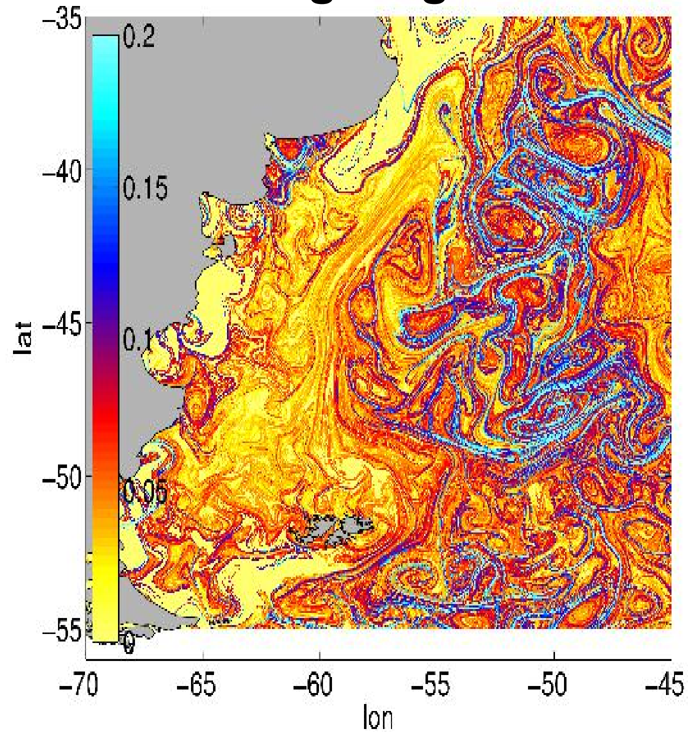
A case-study
stirring at the confluence of Malvinas' and Brazil currents

Velocity field



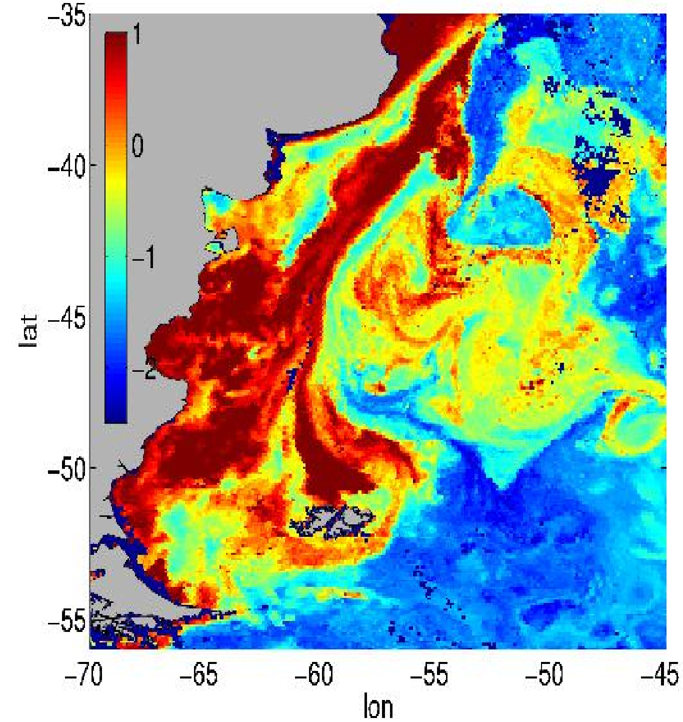
Satellite SSH
Mesoscale currents

Stirring diagnostic



SSH-derived Lyapunov exponents

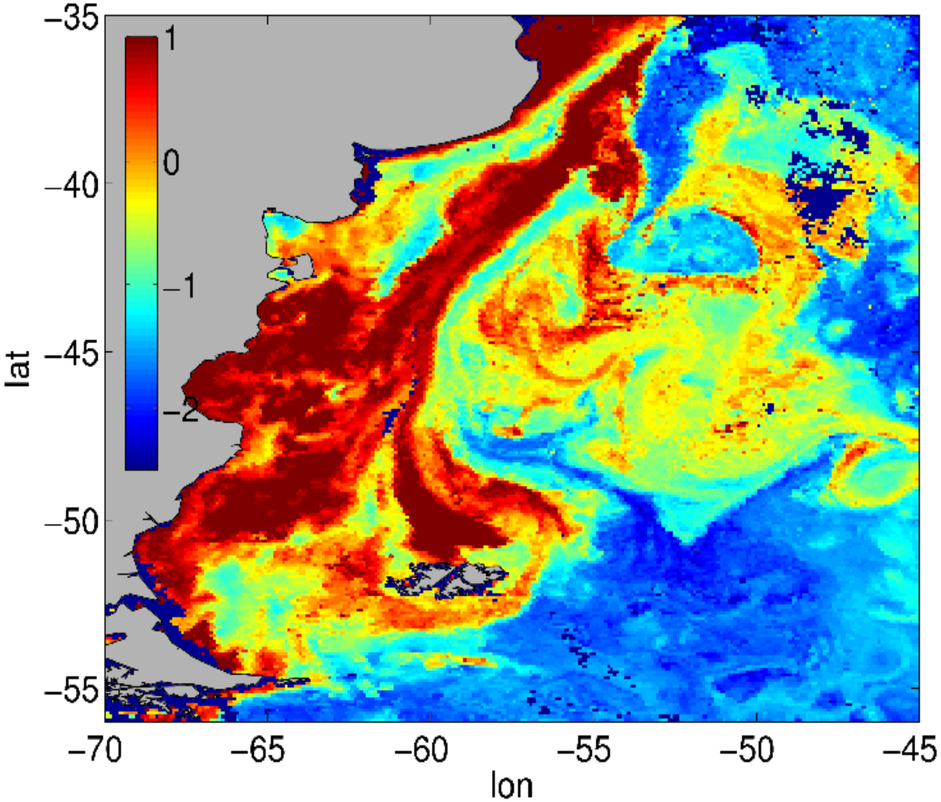
Stirred tracer



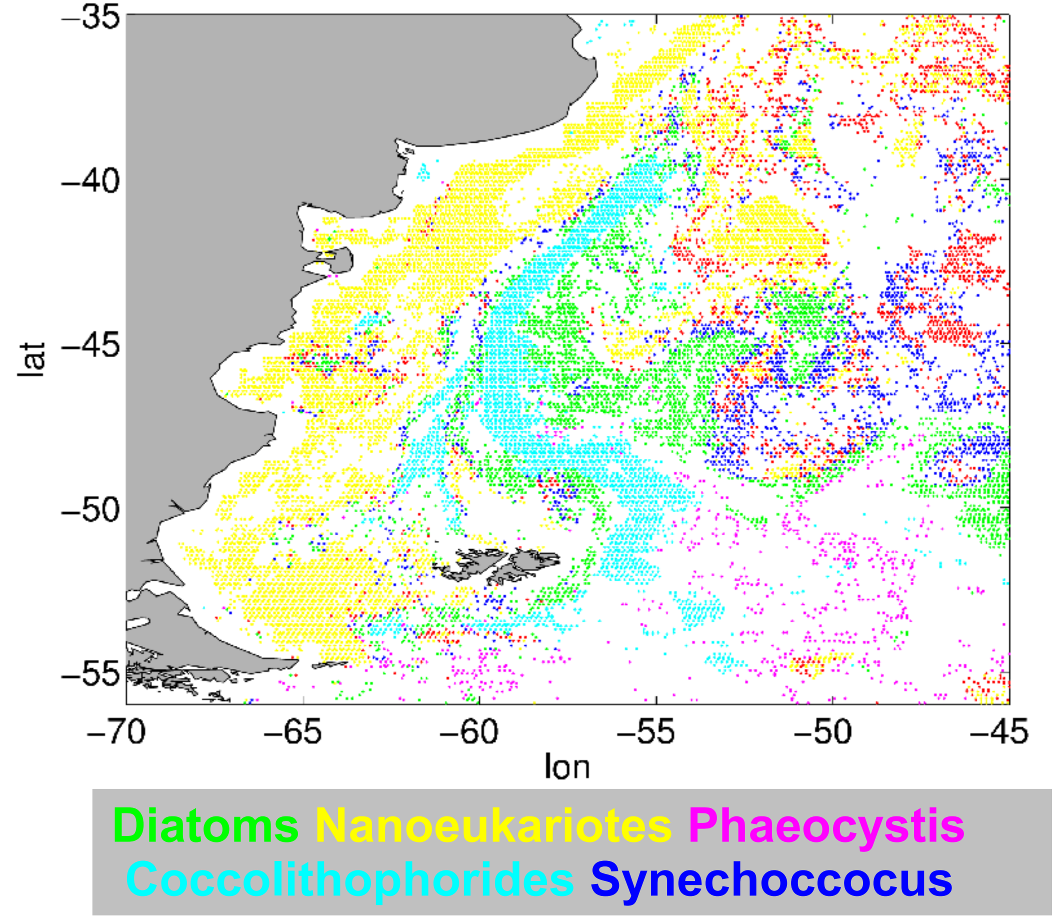
Satellite Chl

The Lyapunov exponent in particular identifies (sub-)mesoscale fronts which agree remarkably well (~10 km) with the boundaries of biogeochemical tracers like Chlorophyll

What is the effect of stirring on phytoplanktonic communities?

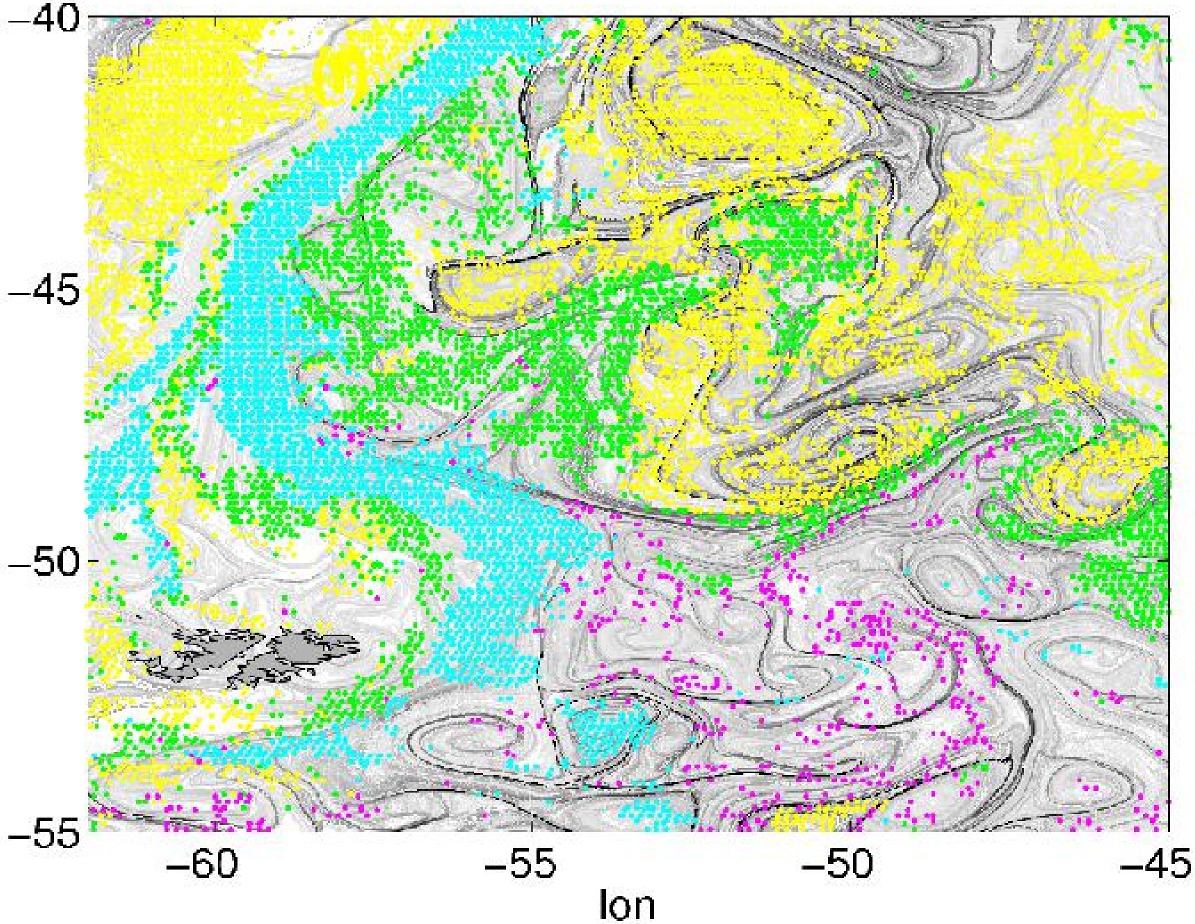


PHYSAT types (SeaWiFS)



Novel satellite products go beyond Chl concentration. PHYSAT estimates dominant planktonic types and unveils a patchy structure of the dominant community. **What is the origin of this ecological patchiness?**

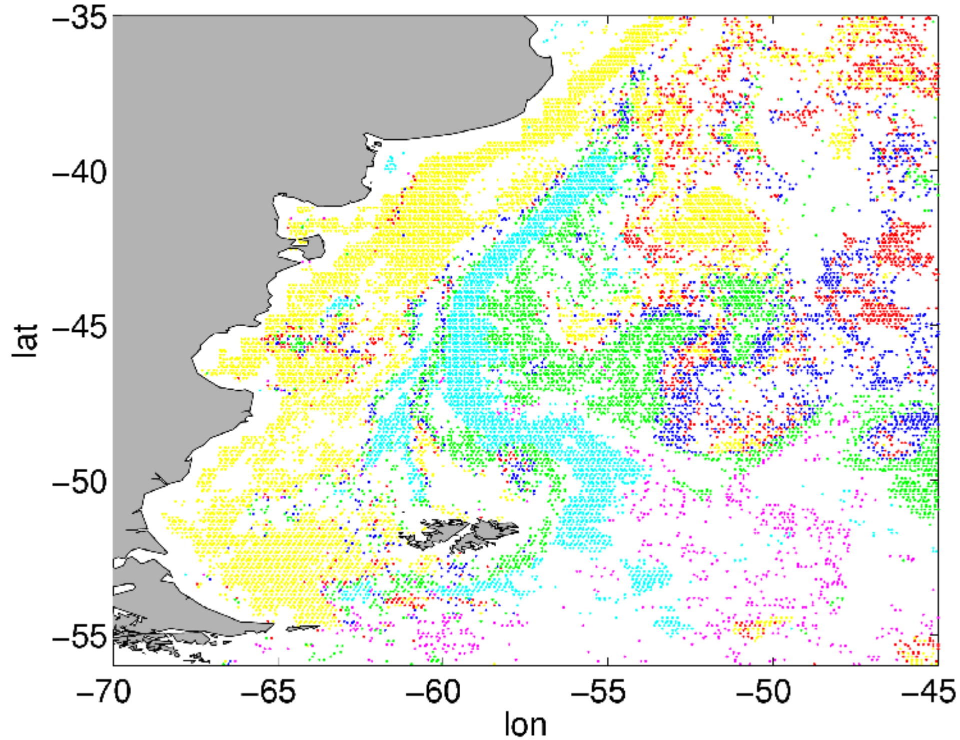
Superposition between PHYSAT types and Lyapunov exponents:

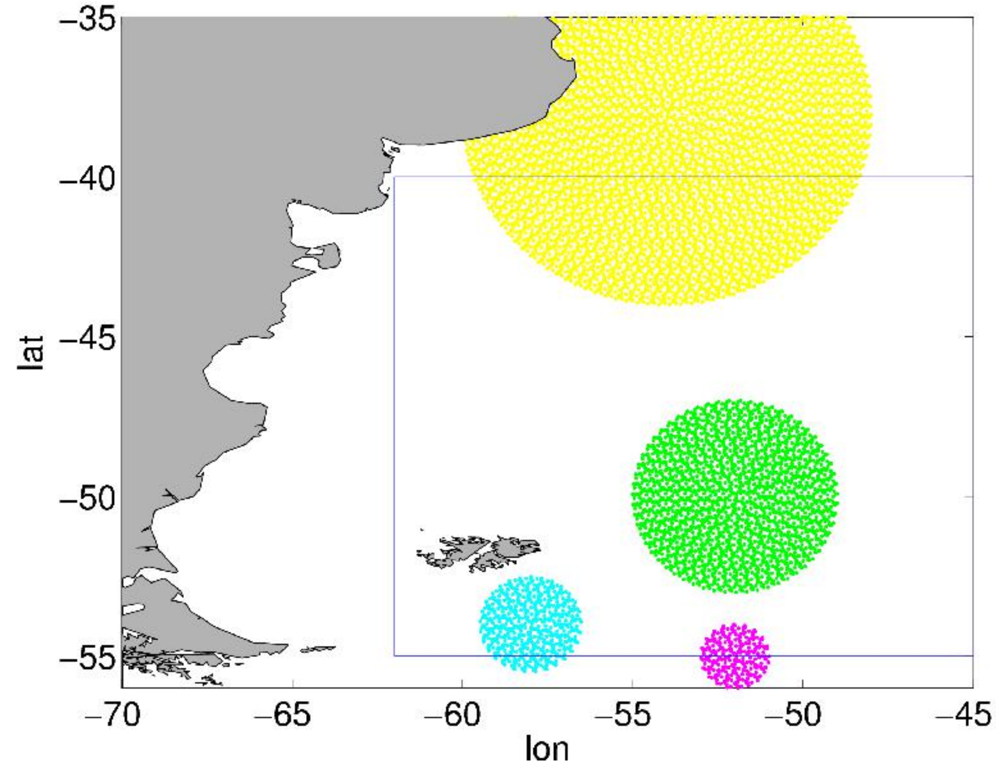


Frontiers among dominant types agree with Lyapunov lines
→ **stirring drives patchiness of dominant types**

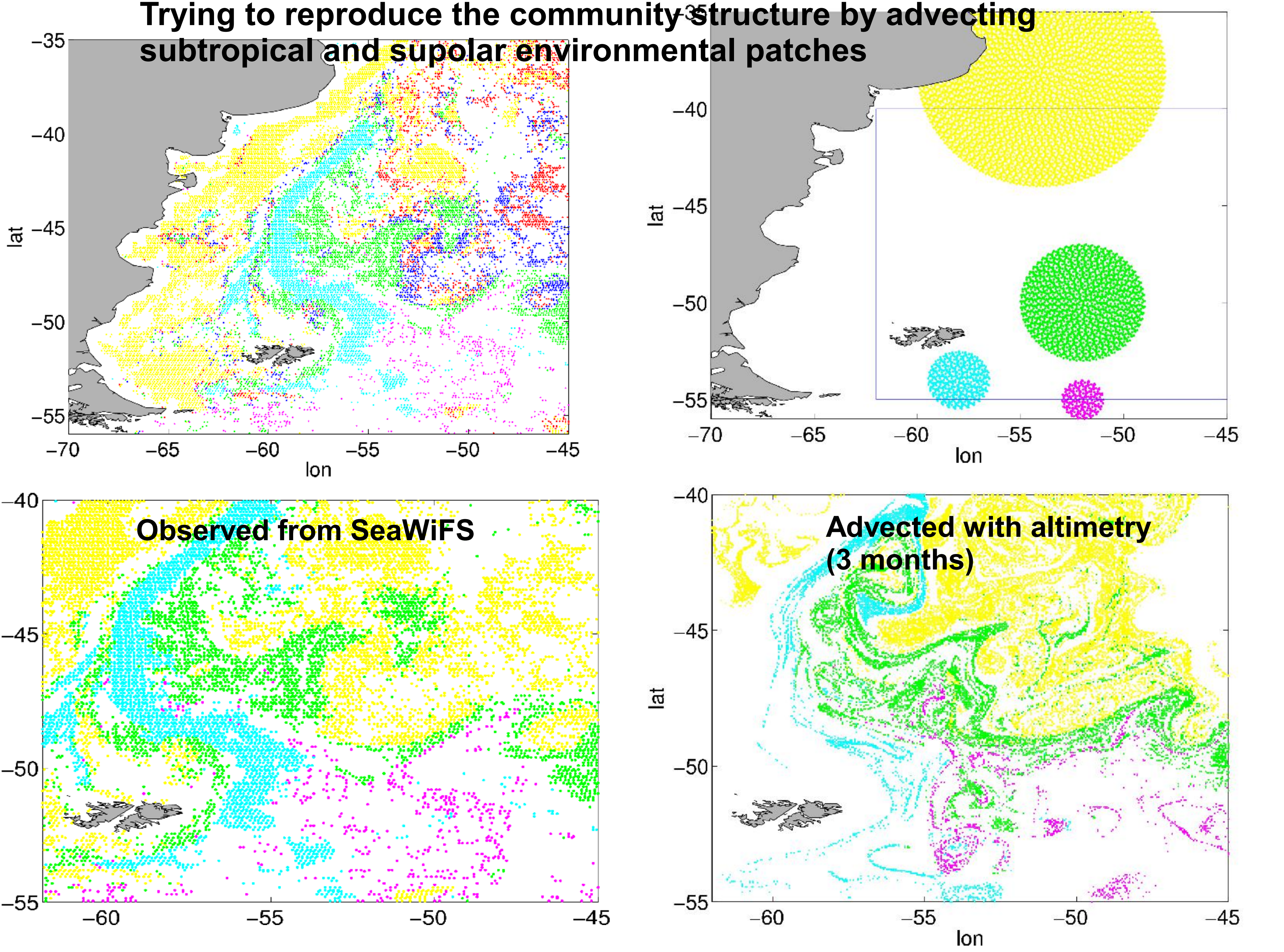
d'Ovidio et al., PNAS 2010

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

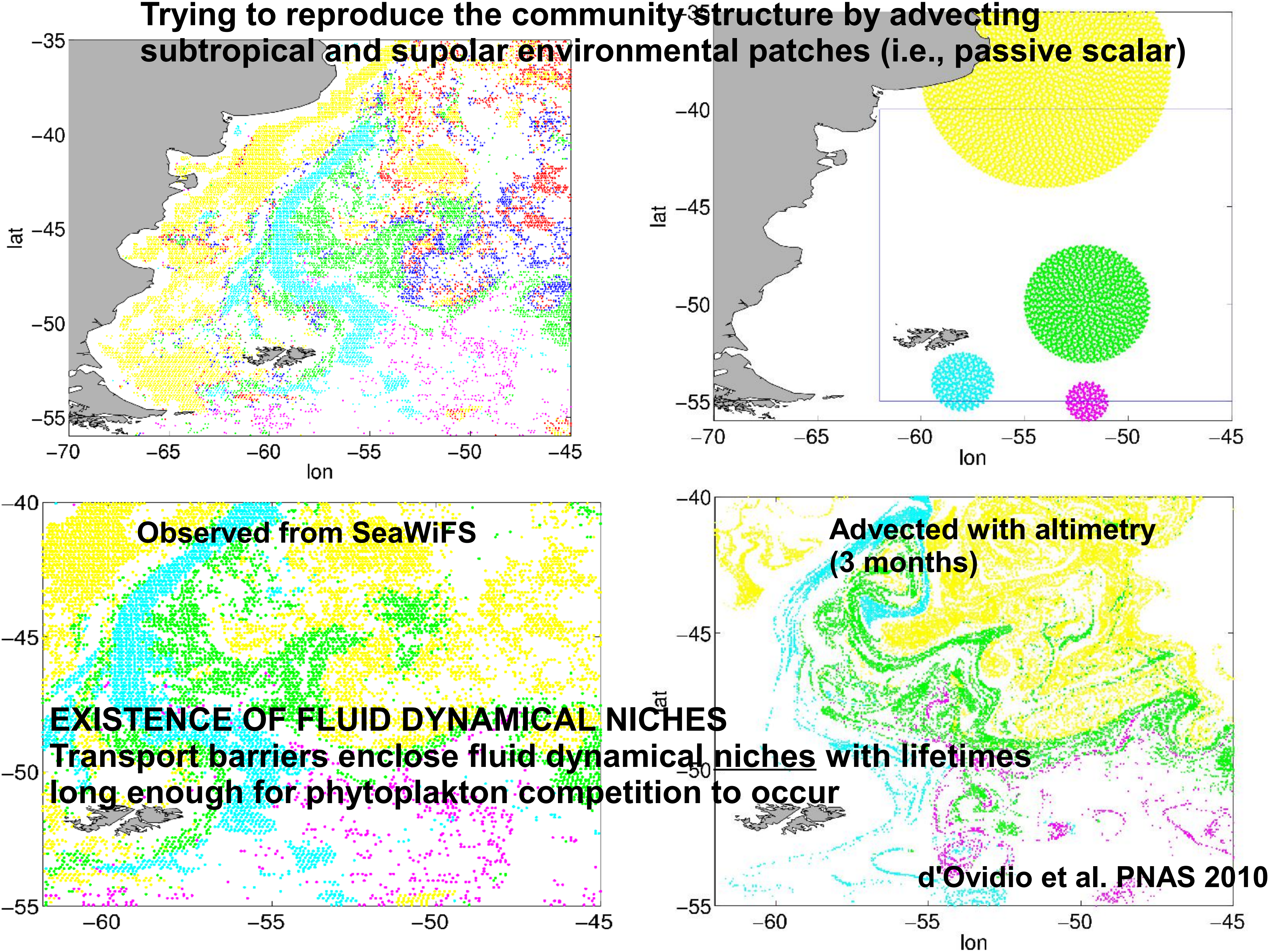




Trying to reproduce the community structure by advecting subtropical and supolar environmental patches



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



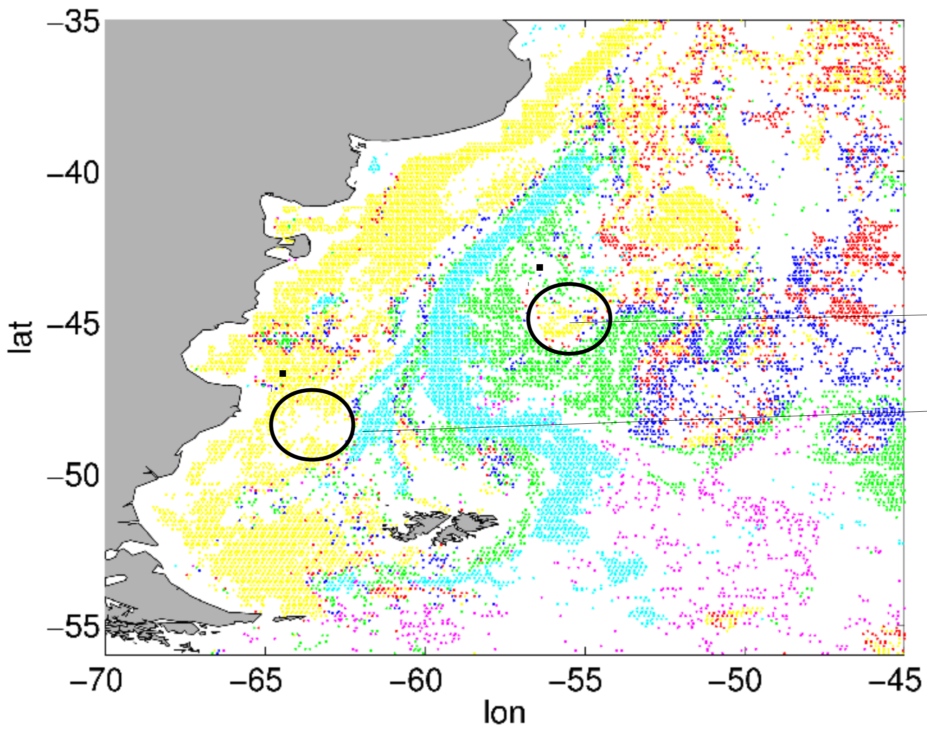
EXISTENCE OF FLUID DYNAMICAL NICHES

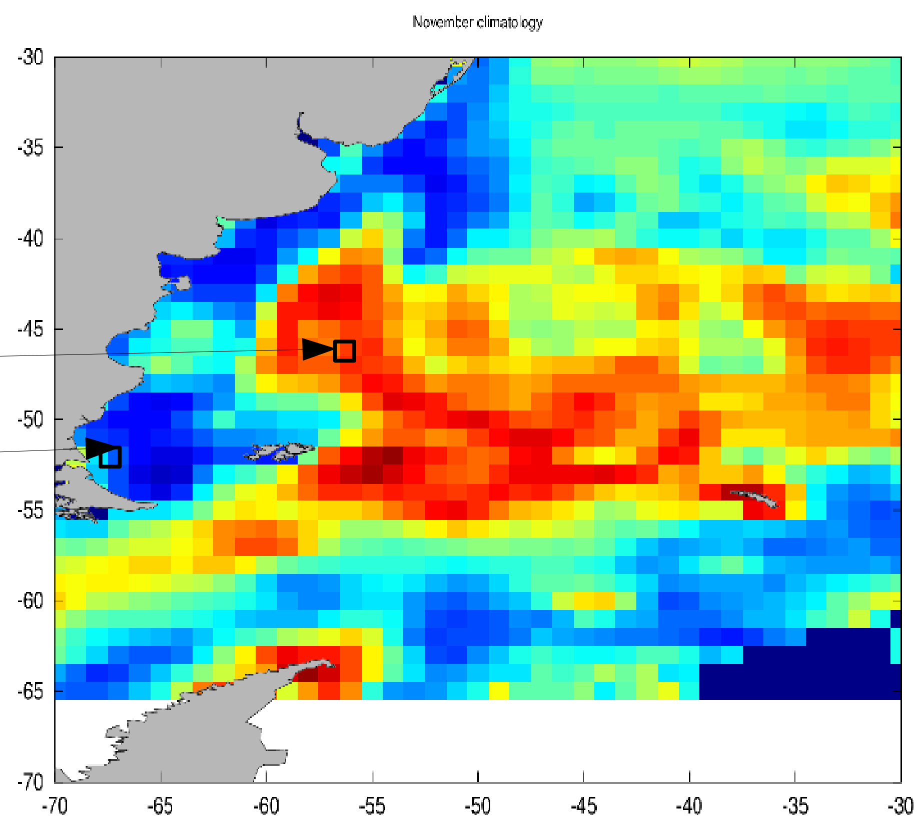
Transport barriers enclose fluid dynamical niches with lifetimes long enough for phytoplakton competition to occur

Patchiness of dominant types and diversity?

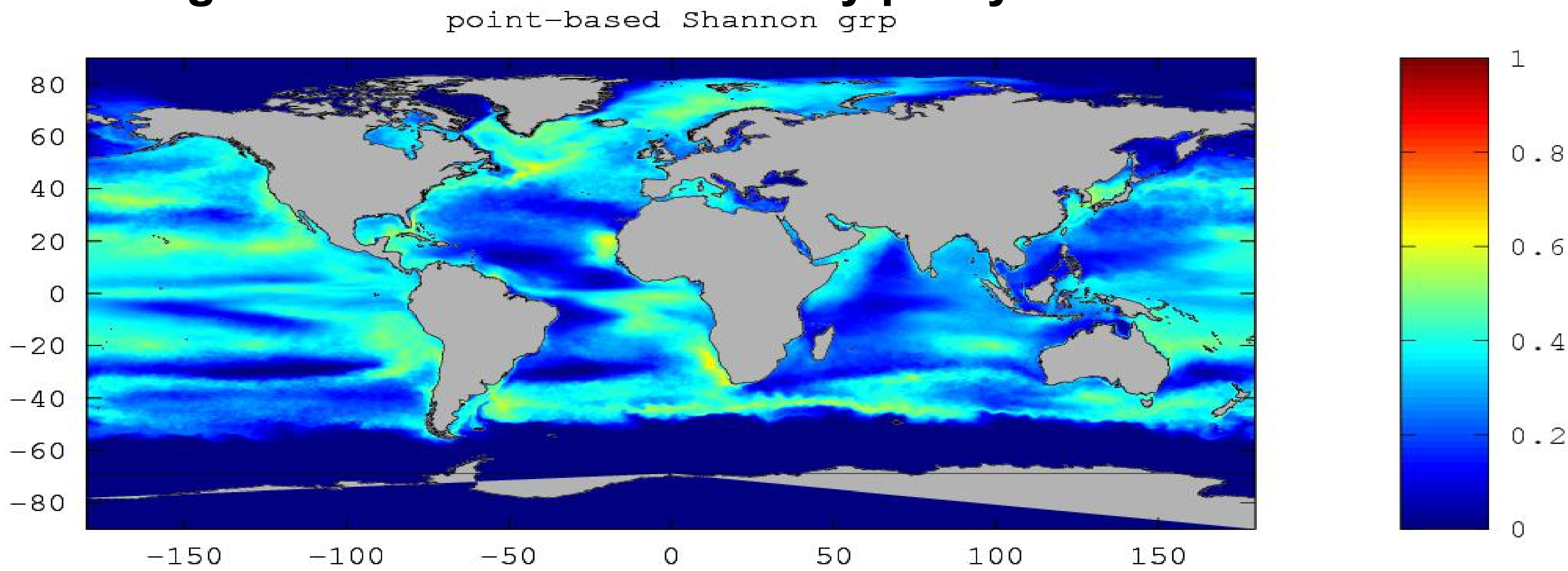
Working hypothesis: biodiversity is generated by mesoscale patchiness plus submesoscale mixing

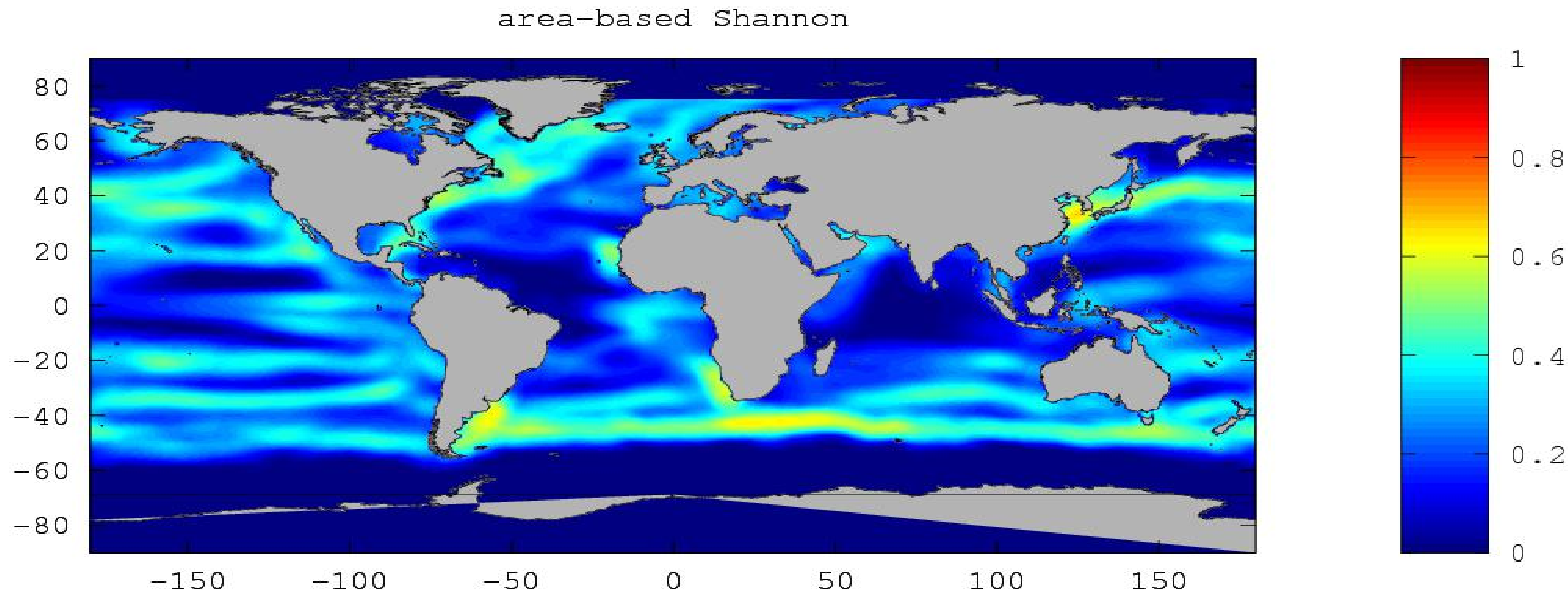
Area-based Shannon Index: $\tau = -\Sigma p_i \log p_i$





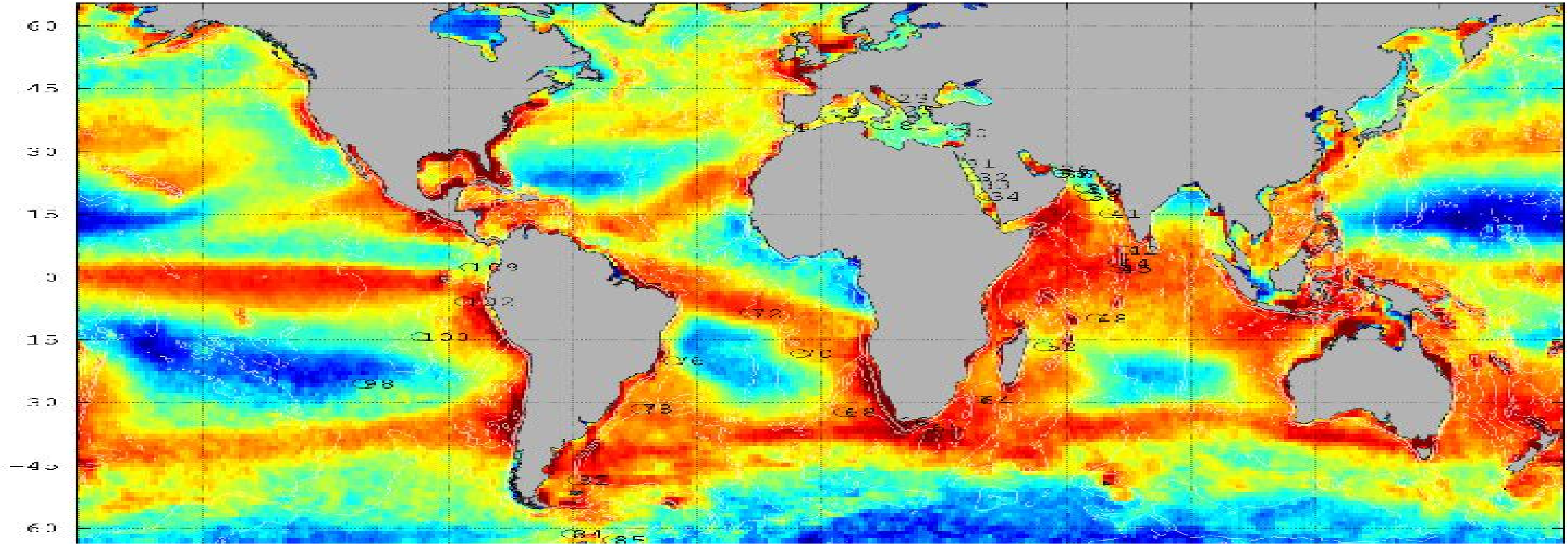
Validating the area-based biodiversity proxy with the MIT Darwin model

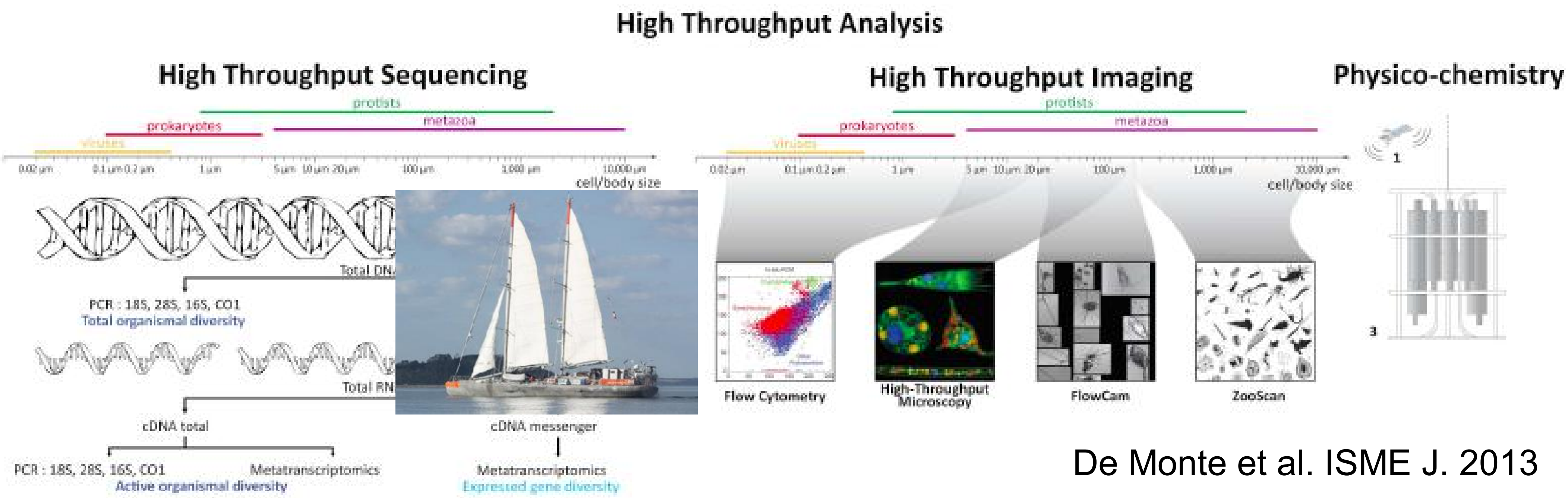




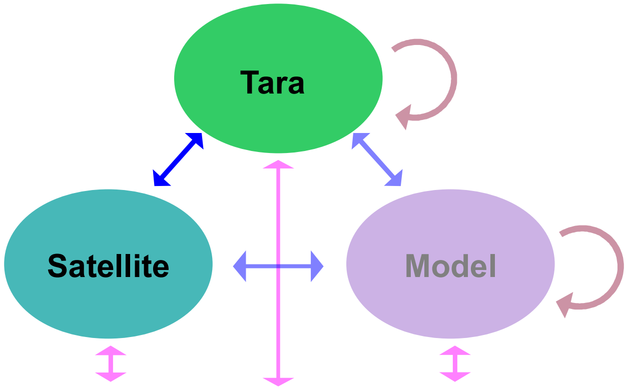
Soccodato et al., in preparation

Satellite map of diversity proxy: comparing with Tara data



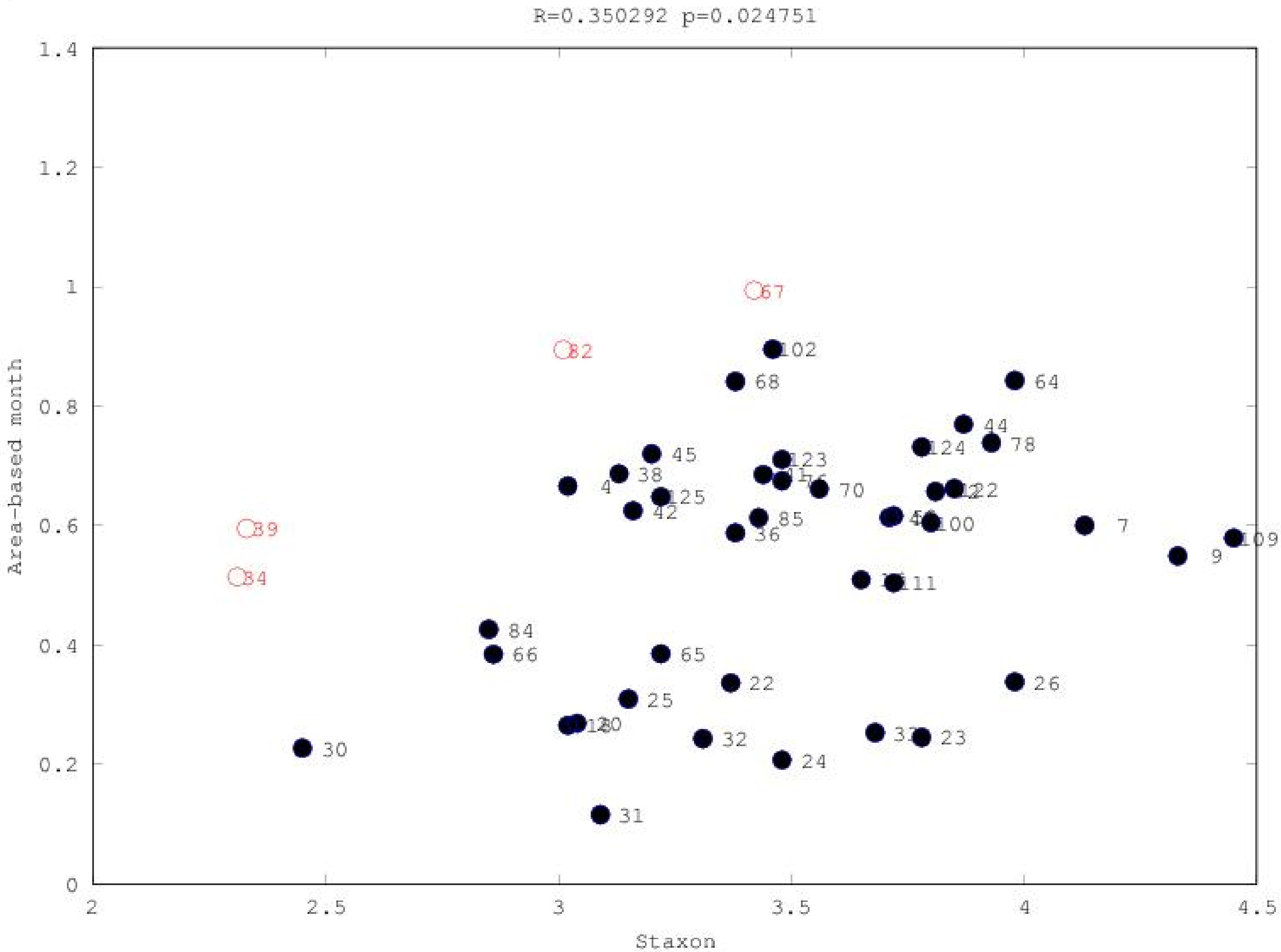


De Monte et al. ISME J. 2013

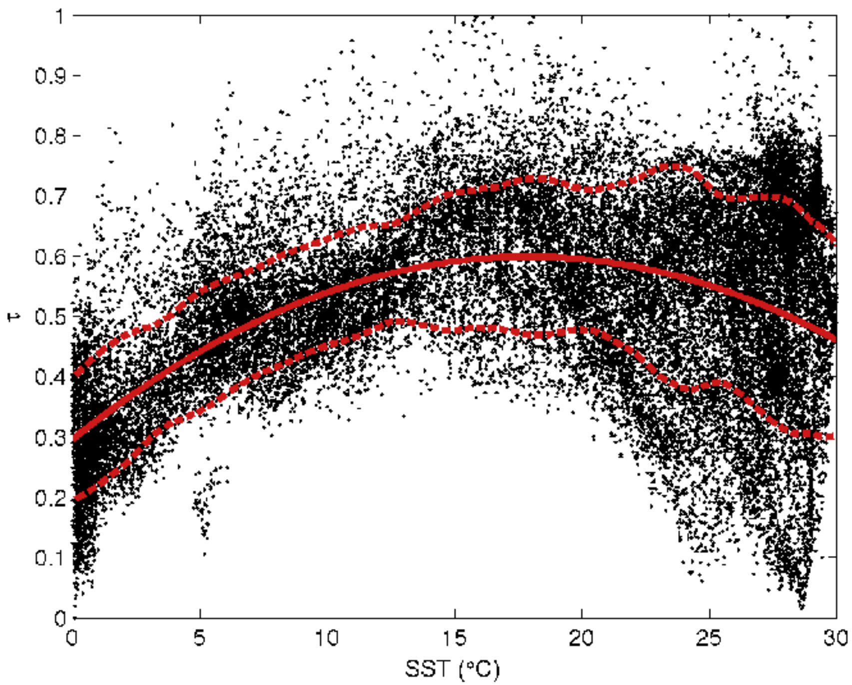


Comparison of Tara-Oceans Shannon index and remote sensing proxy

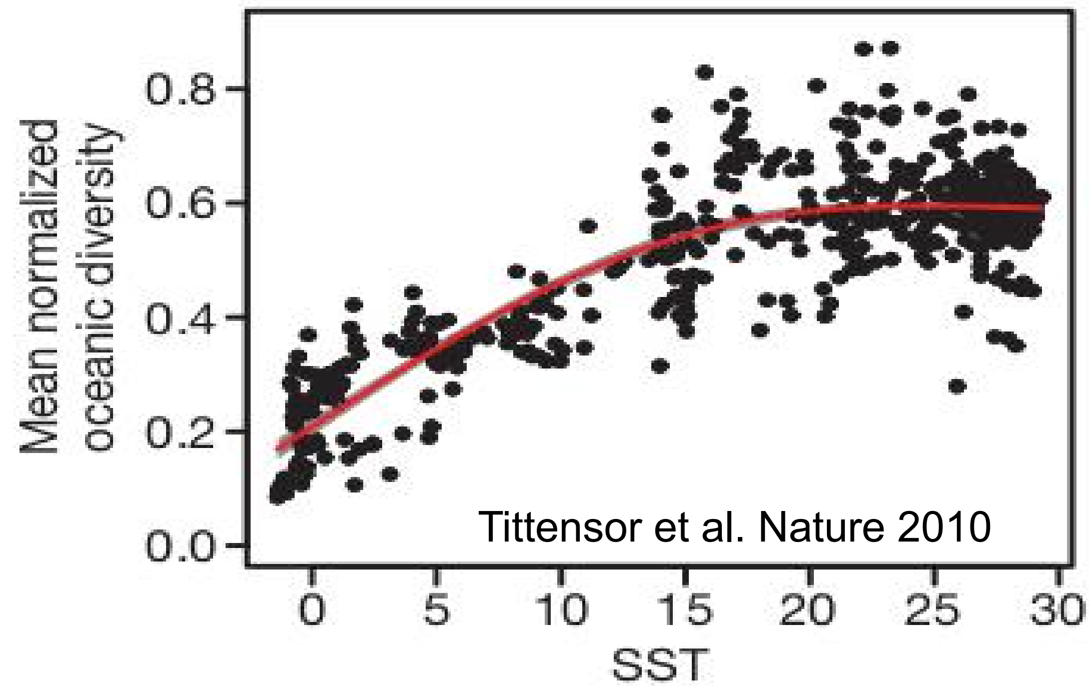
47 surface stations, area-based Shannon index from Physat reanalysis (montly average, filtered)

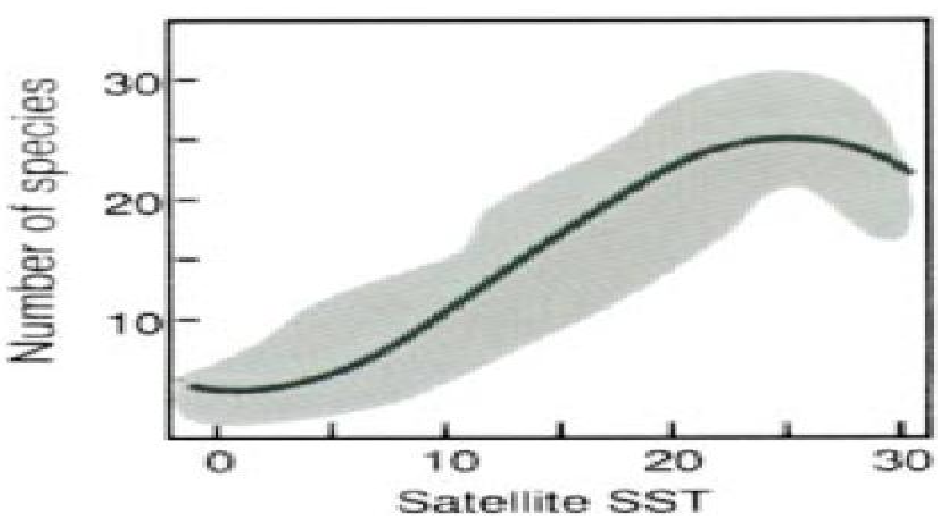


Relation with temperature

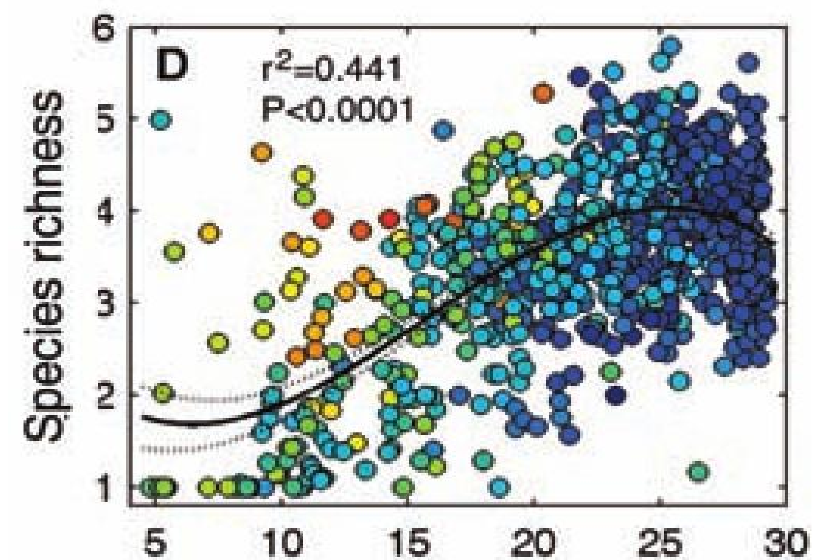


Total oceanic biodiversity from OBIS



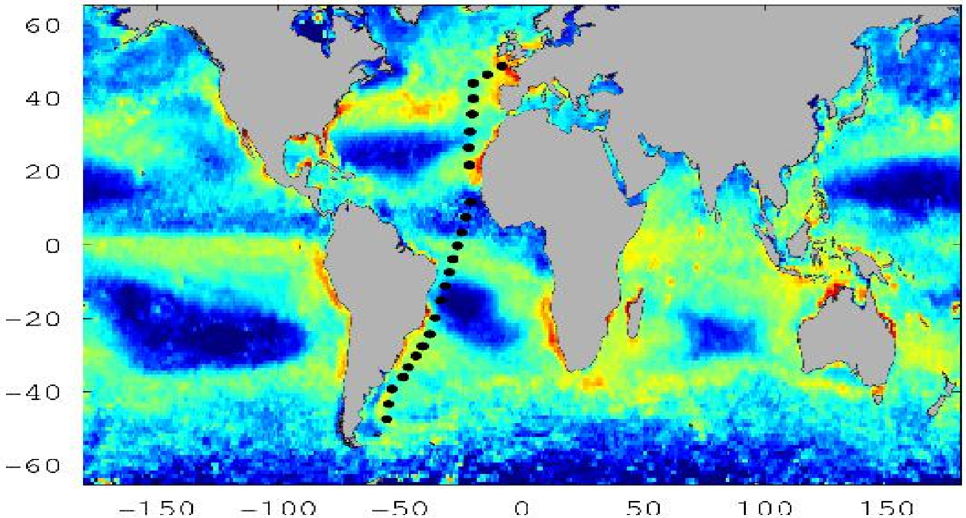


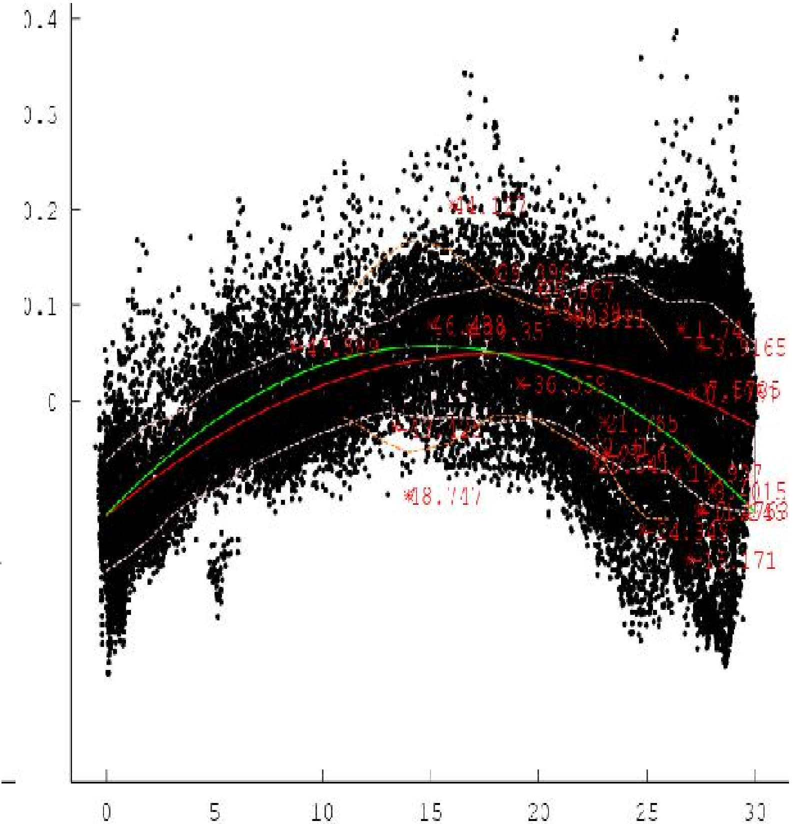
Rutherford et al. Nature 1999

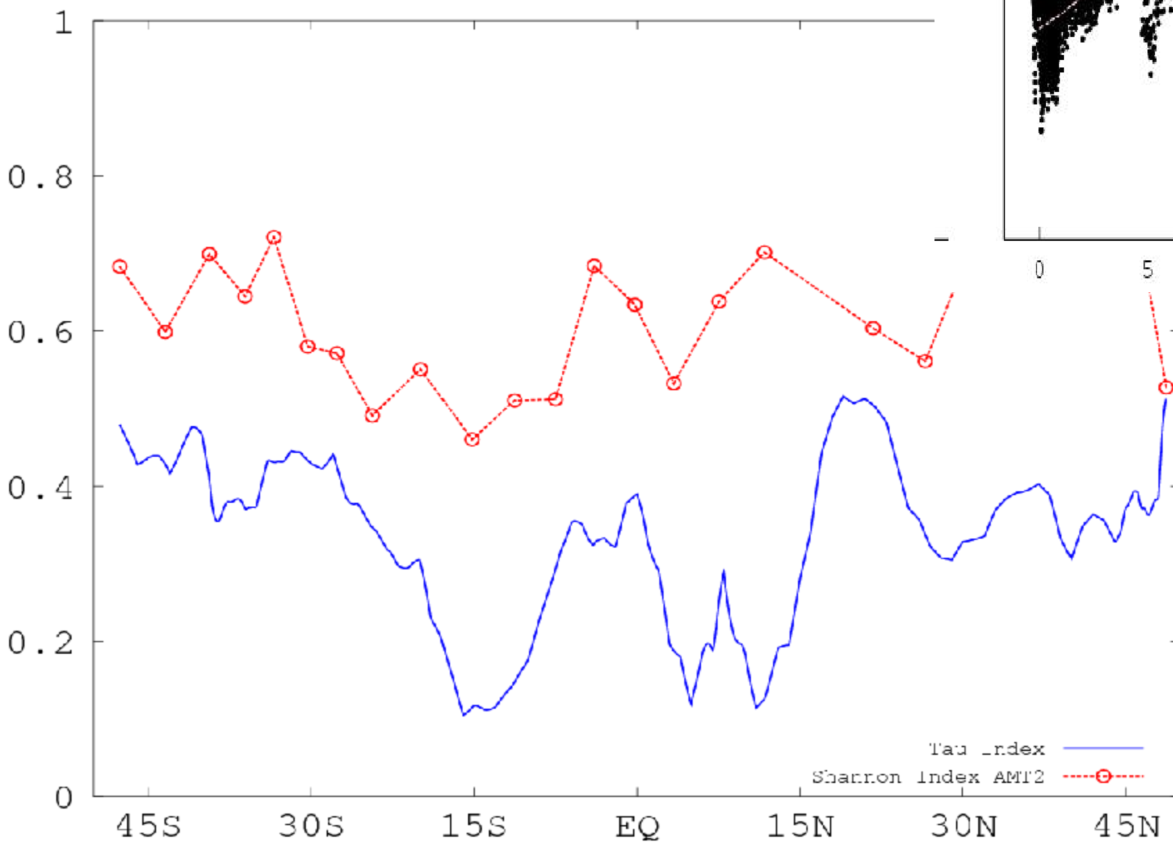


Worms et al. Science 2009

Relation with SST and comparison with in situ data







The satellite-based biodiversity proxy follows a compact relation with SST predicted by biodiversity theories and well in agreement with AMT biodiversity data.

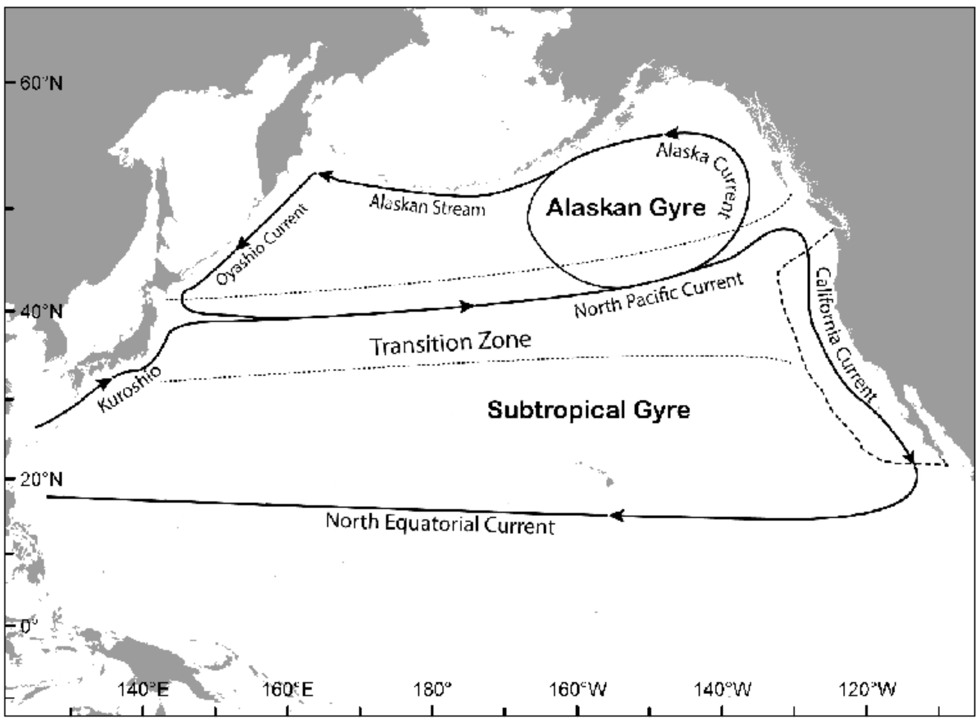
Comparison with predators biodiversity

LETTER

doi:10.1038/nature10082

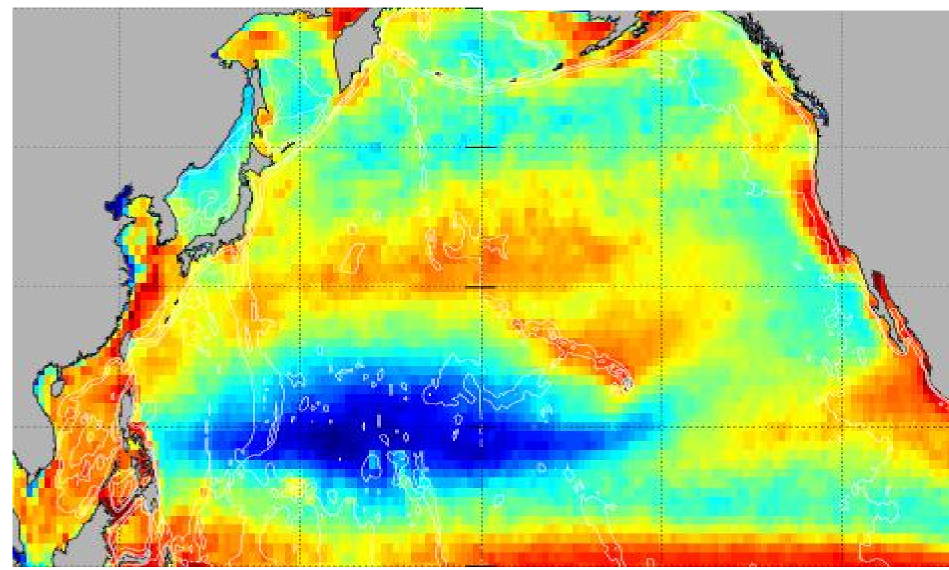
Tracking apex marine predator movements in a dynamic ocean

B. A. Block[1], I. D. Jonsen[2], S. J. Jorgensen[1], A. J. Winship[2], S. A. Shaffer[3], S. J. Bograd[4], E. L. Hazen[4], D. G. Foley[4], G. A. Breed[2,5], A.-L. Harrison[5], J. E. Ganong[1], A. Swithenbank[1], M. Castleton[1], H. Dewar[6], B. R. Mate[7], G. L. Shillinger[1], K. M. Schaefer[8], S. R. Benson[9], M. J. Weise[3], R. W. Henry[3] & D. P. Costa[3]



Our results indicate that the California Current large marine ecosystem and the North Pacific transition zone attract and retain a diverse assemblage of marine vertebrates.

NATURE | VOL 475 | 7 JULY 2011



biodiversity index from satellite

Conclusions

Satellites typically see the 2D surface of the ocean.

The ocean surface however is part of a 3D system.

For a single satellite detector, 3D signal is present, but it is typically the result of many confounding effects. It is usually treated as a noise over the 2D information, or simply neglected.

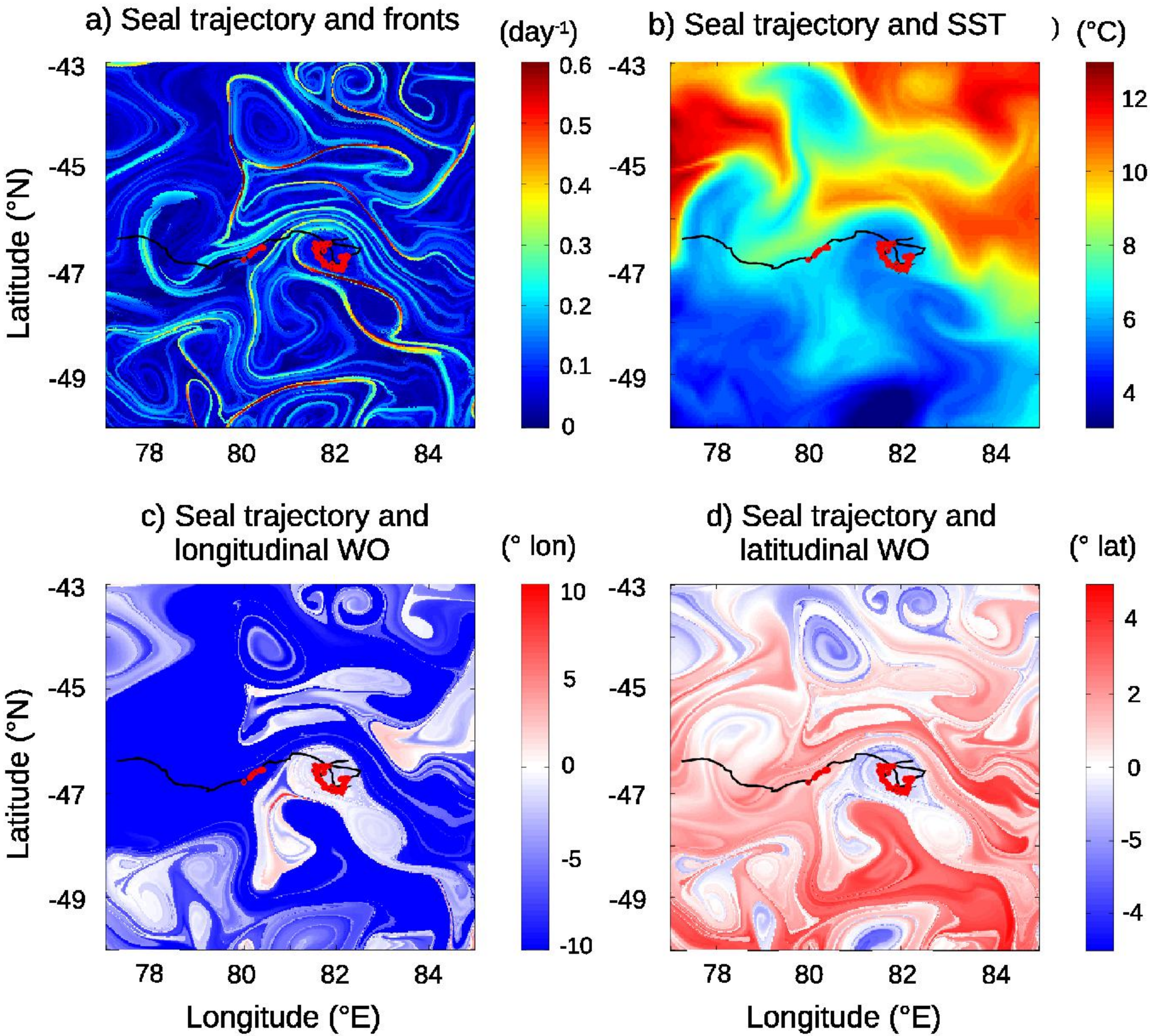
Mutltisatellite data analysis (with in situ) may allow to go one step further and disentangle some of the 3D sources

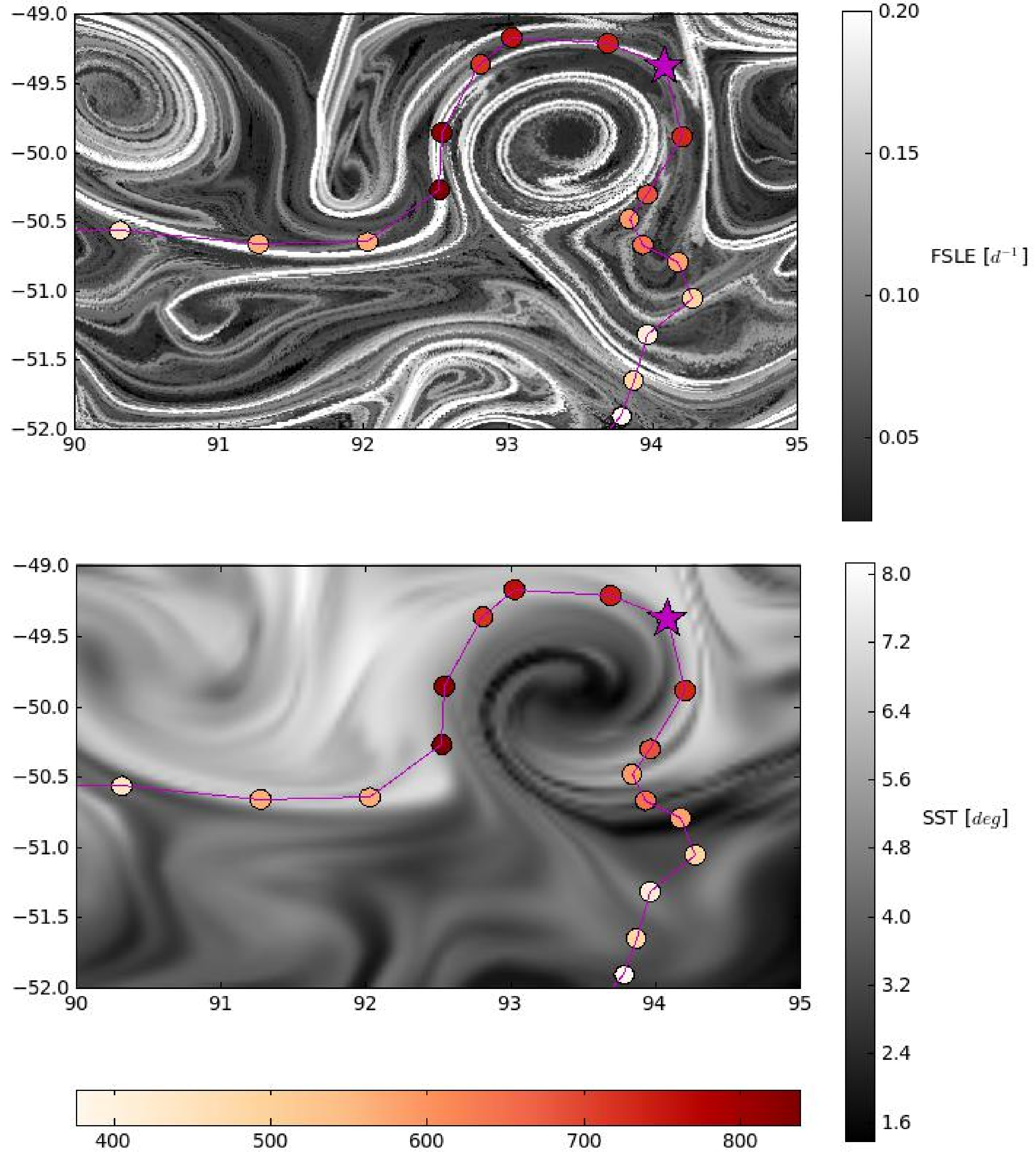
Some possible products:

- Estimation of vertical velocities

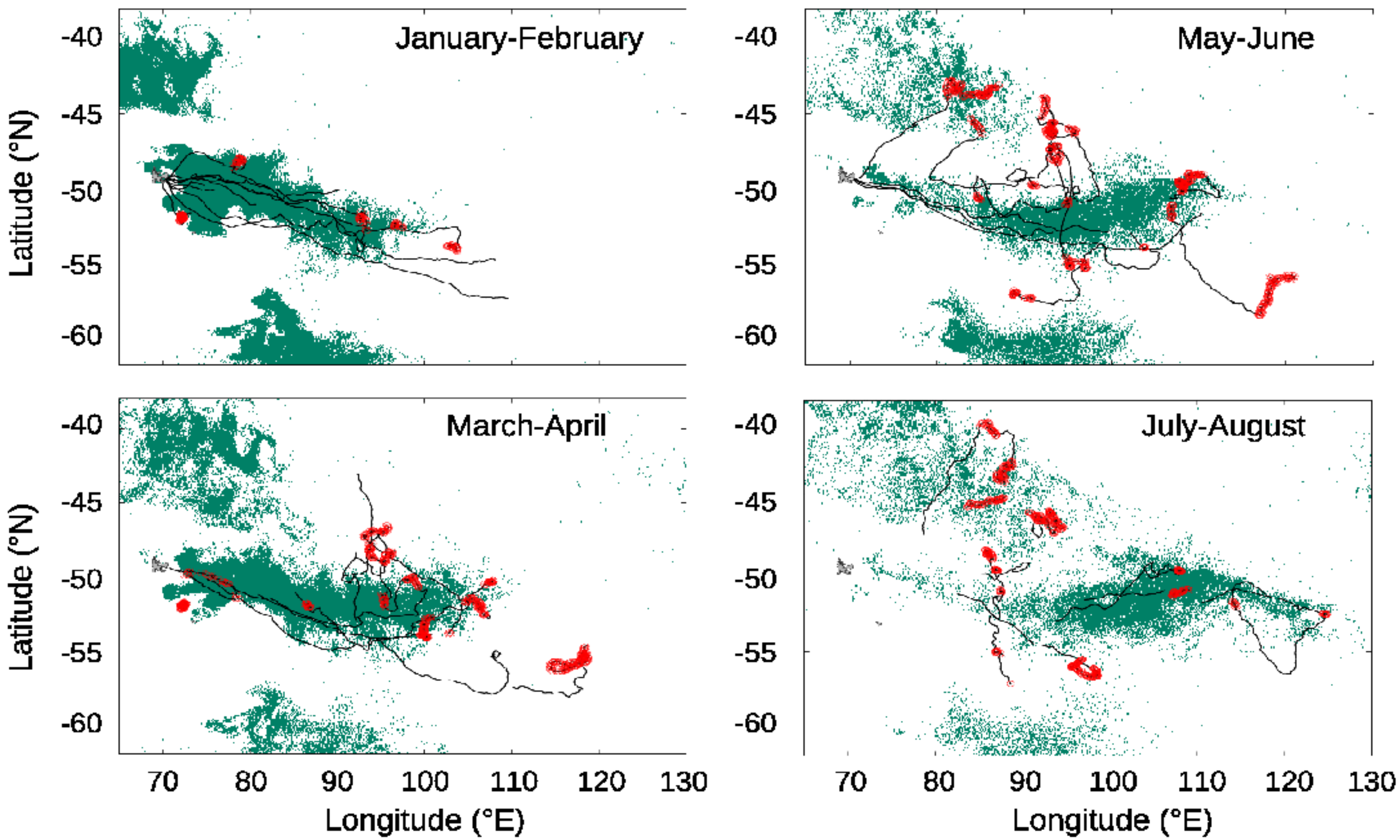
- Mixed layer/Ekman layer depth

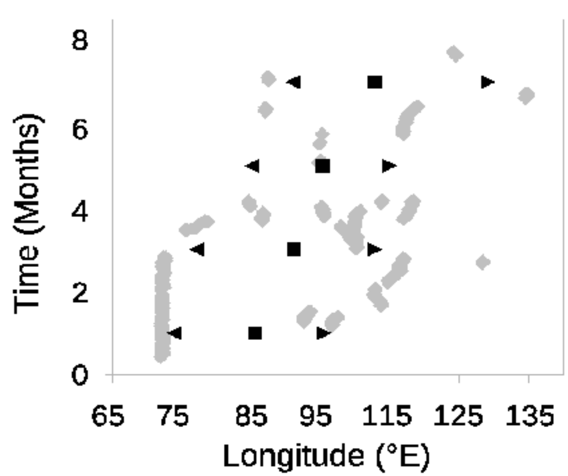
- proxies of ecological features
    - hotspots of biodiversity
    - hotspots of trophic interactions
    - biomass density for intermediate trophic levels?


a) Seal trajectory and fronts
(day-1)
0.6
0.5
0.4
0.3
0.2
0.1
0
b) Seal trajectory and SST
(°C)
12
10
8
6
4
c) Seal trajectory and longitudinal WO
(° lon)
10
5
0
-5
-10
d) Seal trajectory and latitudinal WO
(° lat)
4
2
0
-5
-4
-43
-45
-47
-49
Latitude (°N)
78
80
82
84
Longitude (°E)



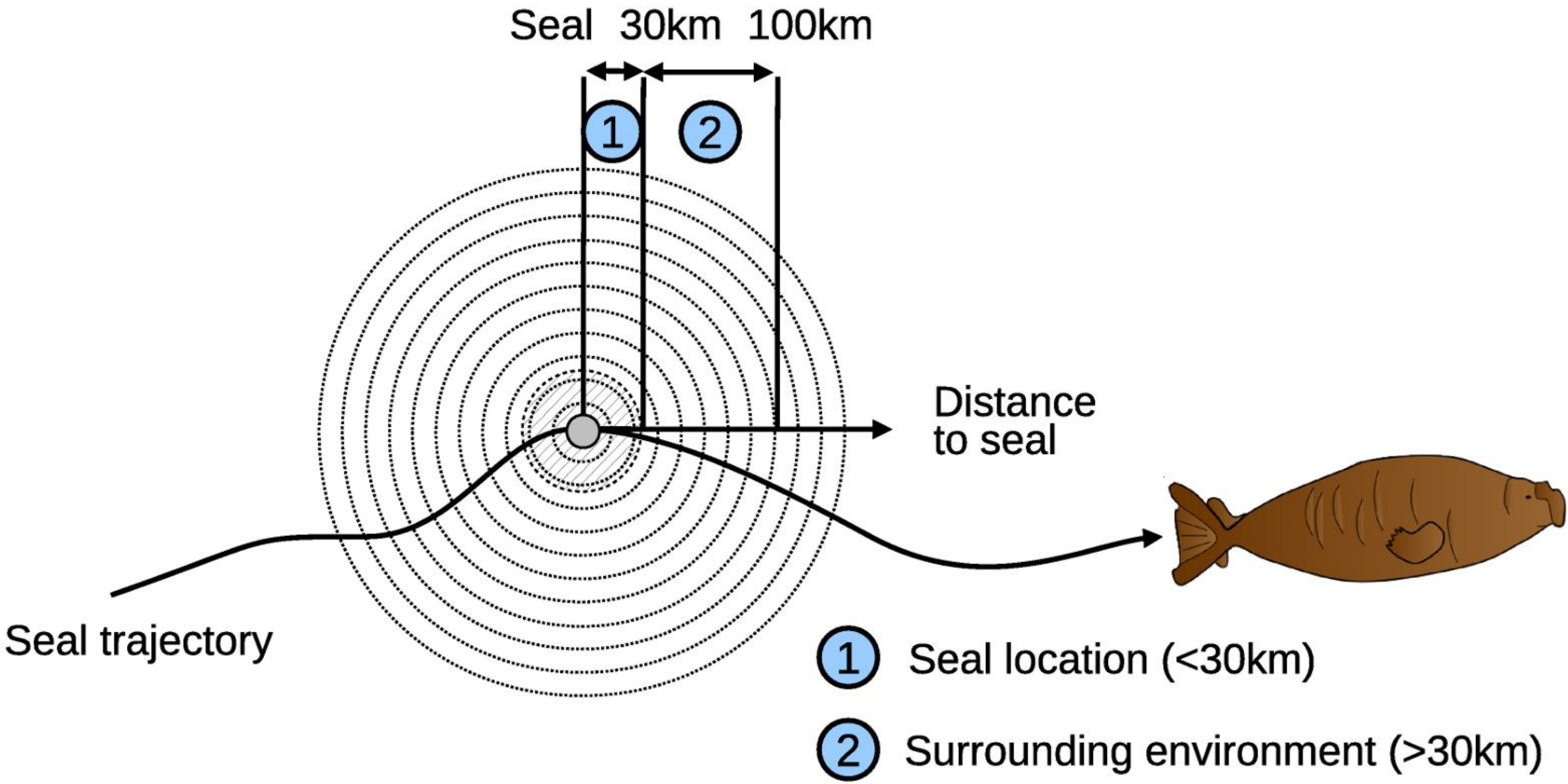
−49.0
−49.5
−50.0
−50.5
−51.0
−51.5
−52.0
90
91
92
93
94
95
0.20
0.15
0.10
0.05
FSLE $[d^{-1}]$
−49.0
−49.5
−50.0
−50.5
−51.0
−51.5
−52.0
90
91
92
93
94
95
8.0
7.2
6.4
5.6
4.8
4.0
3.2
2.4
1.6
SST $[deg]$
400
500
600
700
800

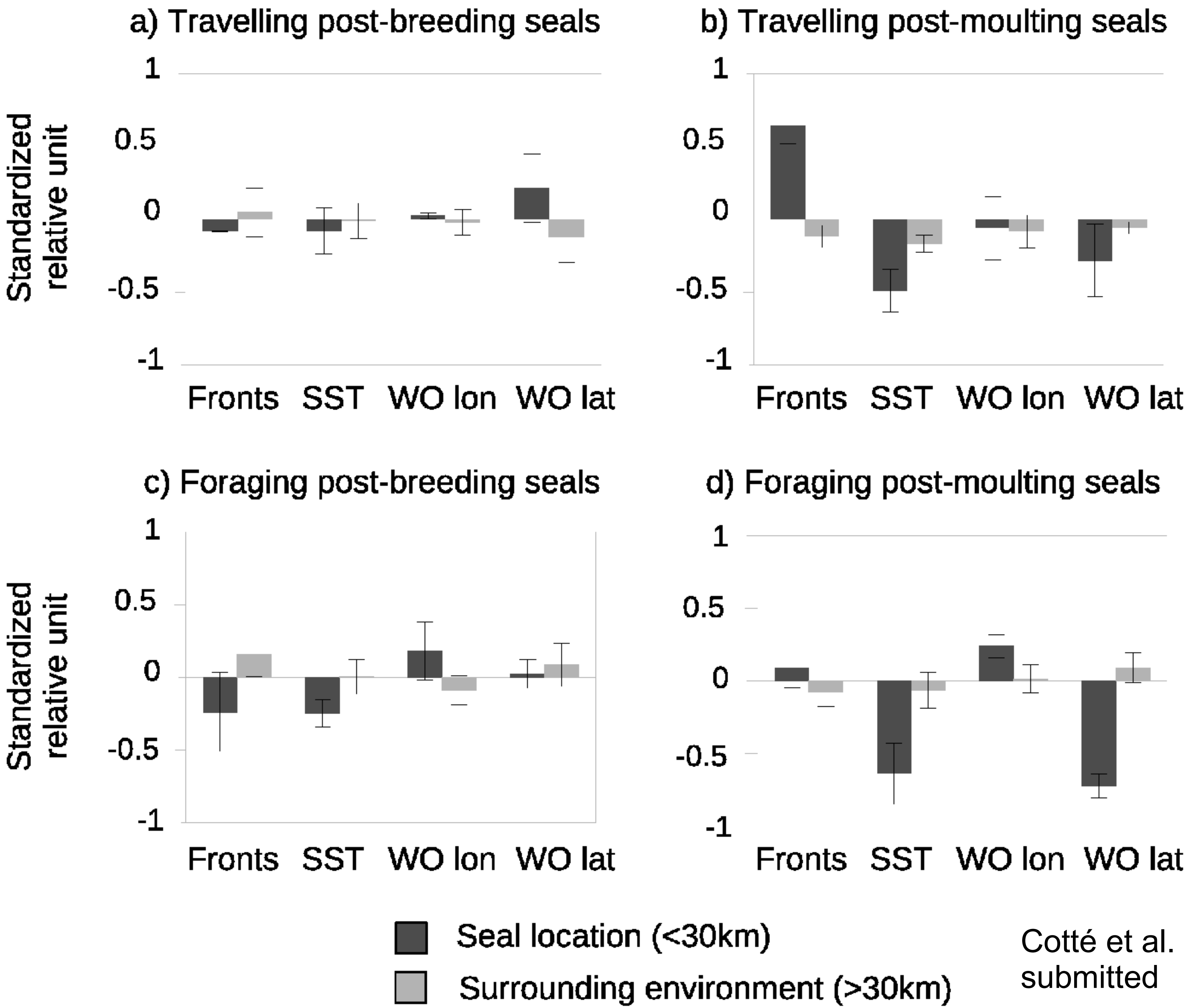




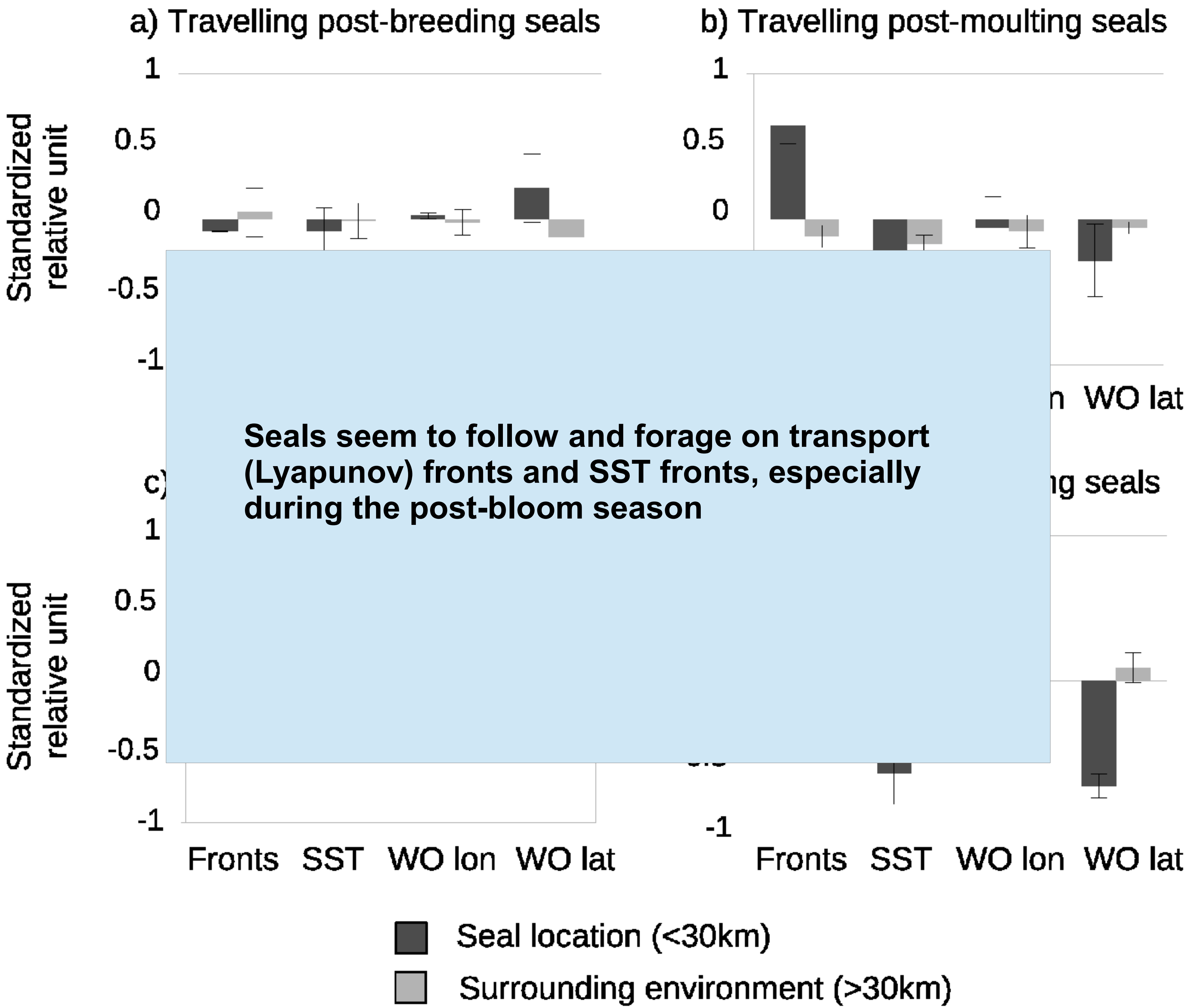
During autumn:winter, seals appear to track the drifting water mass that has bloomed

Cotté et al. submitted


Seal
30km
100km
1
2
Distance
to seal
Seal trajectory
1 Seal location (<30km)
2 Surrounding environment (>30km)



a) Travelling post-breeding seals
b) Travelling post-moulting seals
c) Foraging post-breeding seals
d) Foraging post-moulting seals
Standardized relative unit
1
0.5
0
-0.5
-1
Fronts
SST
WO lon
WO lat
Seal location (<30km)
Surrounding environment (>30km)
Cotté et al. submitted



a) Travelling post-breeding seals
b) Travelling post-moulting seals
c)
ng seals
Standardized relative unit
1
0.5
0
-0.5
-1
Fronts
SST
WO lon
WO lat
Seals seem to follow and forage on transport (Lyapunov) fronts and SST fronts, especially during the post-bloom season
Seal location (<30km)
Surrounding environment (>30km)