Lagrangian Flow Network: theory & applications

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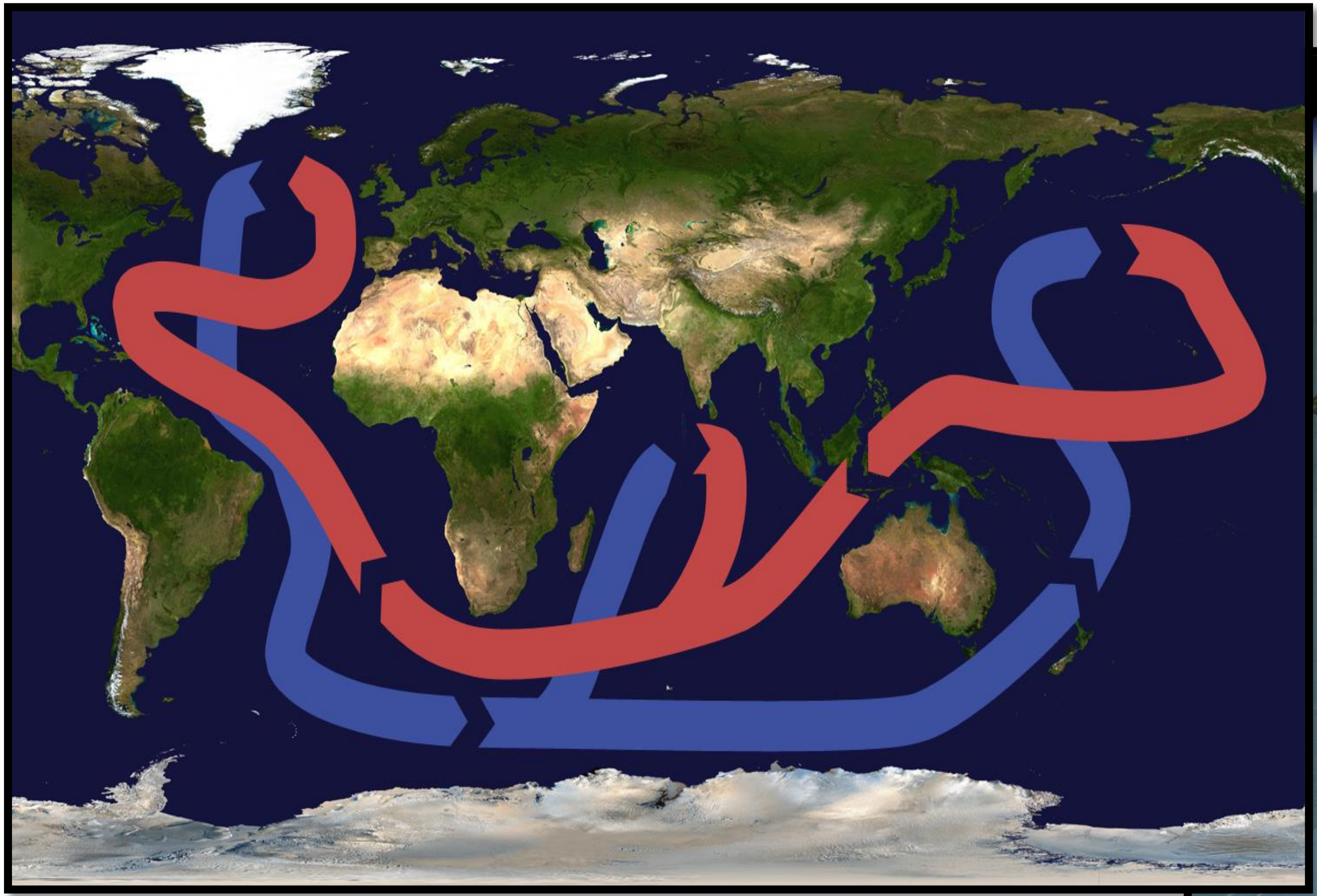
Fluid transport in the ocean and the atmosphere



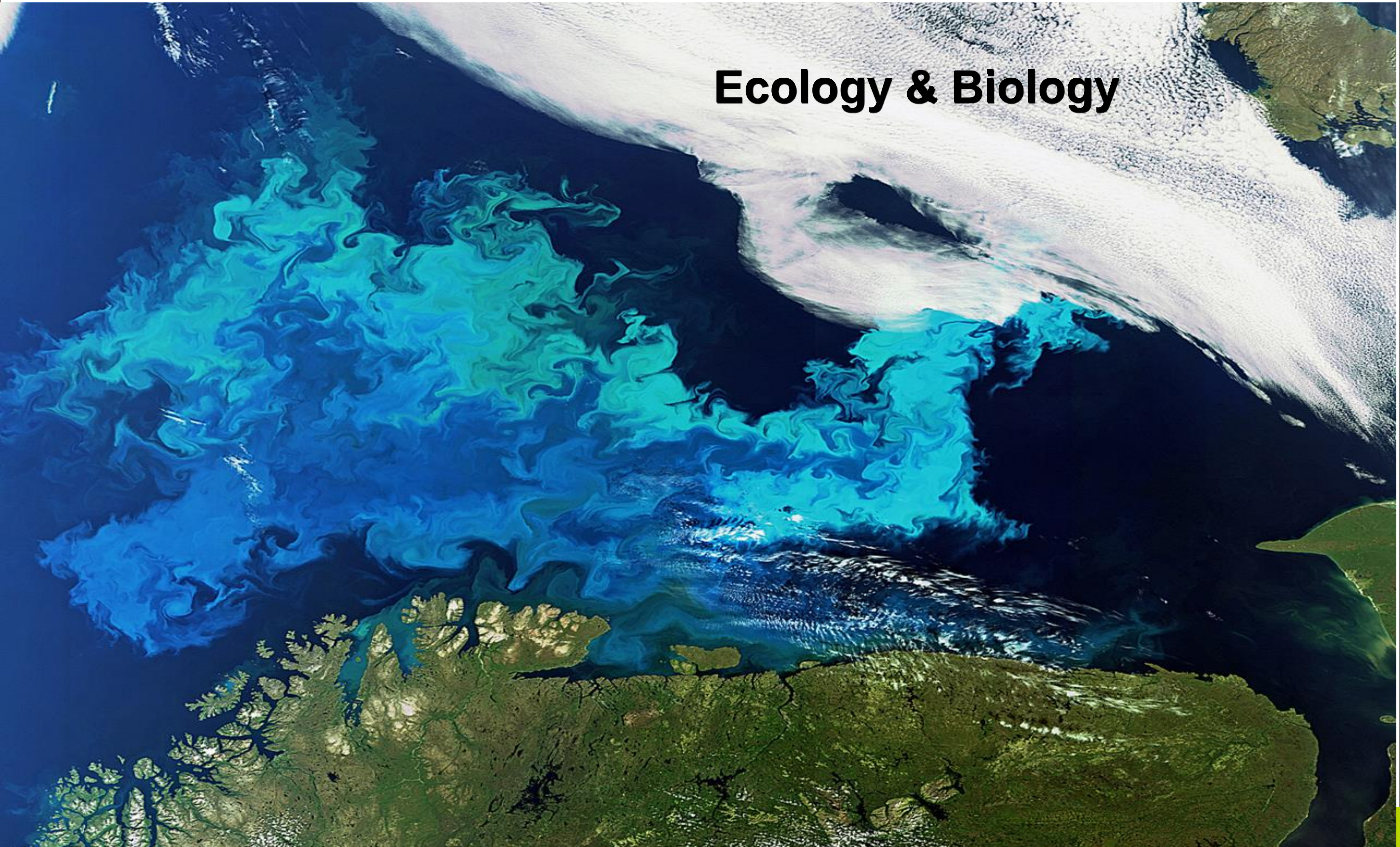
Global climate

Advection of fluid masses plays an important role in many contexts and at different scales of space and time.

Fluid transport in the ocean and the atmosphere

Pollutants spreading

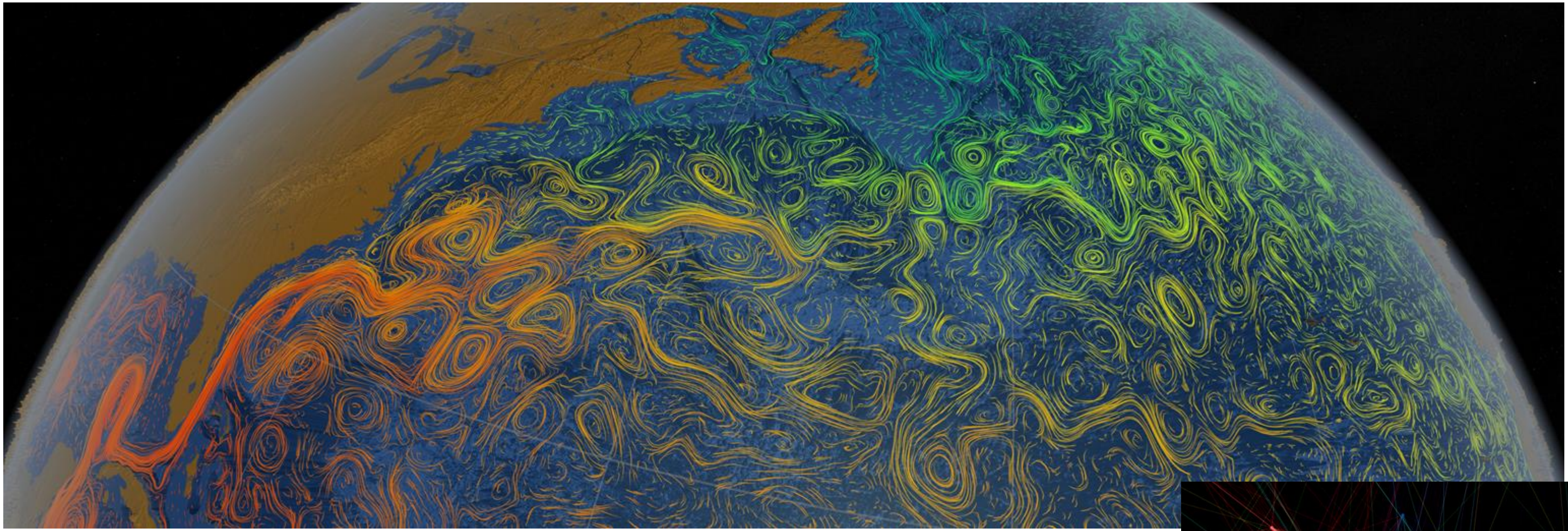
Fluid transport in the ocean and the atmosphere



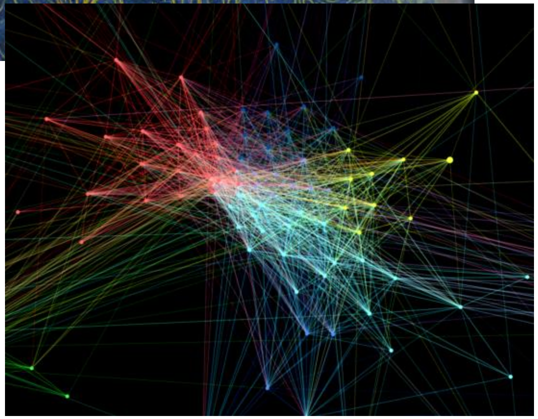
Ecology & Biology

Networks and Geophysical Flows

Transport processes (fluid advection) in a continuous, time-dependent, 2 or 3-dimensional flow (ocean and atmosphere)



Set of point-like objects (nodes) and pairwise connections among them (links)

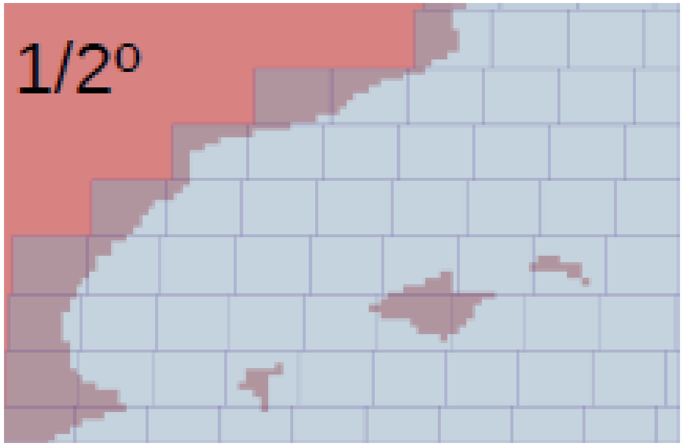


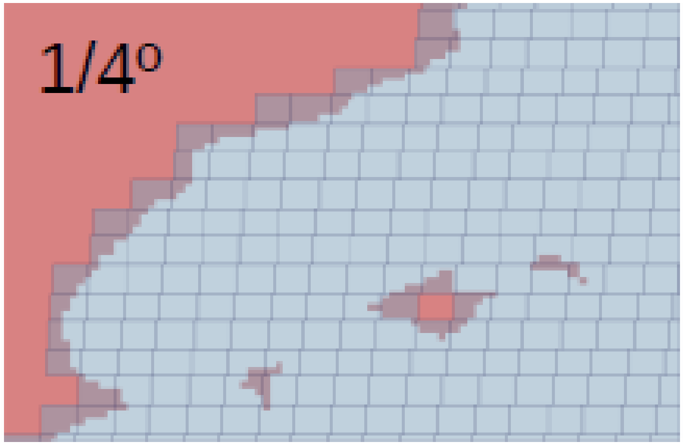
Network Theory 1: nodes

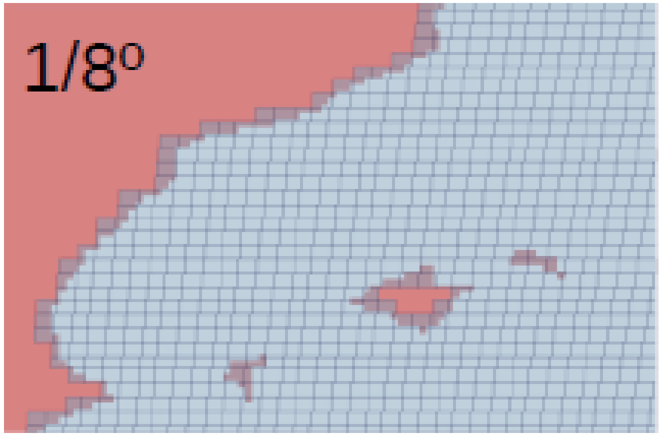
Discretization: from continuous to point-like

We define **nodes** as 2-dimensional boxes { B_i ; i=1, …, N } covering the whole domain.

- Equal area constraint: linear size = Δ
- Induced diffusion at box-size scale

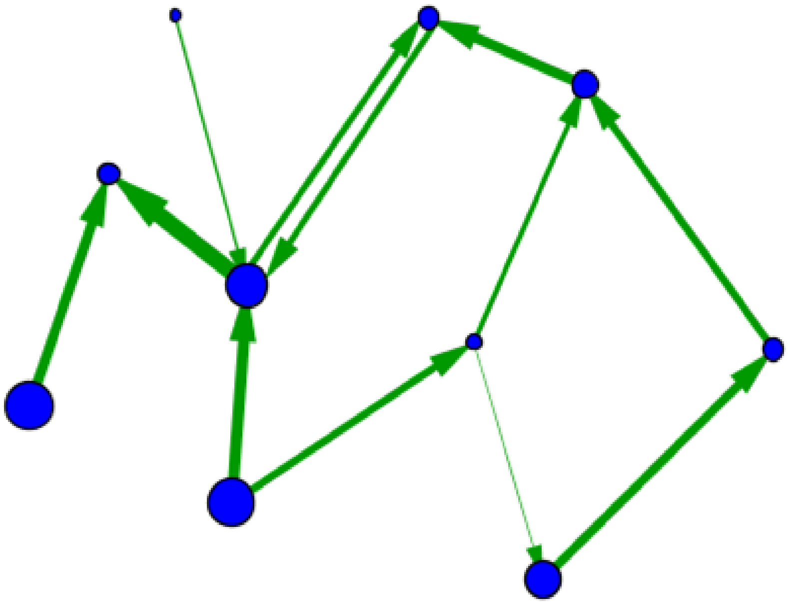






Network Theory 2: links & weights

Given a starting time t_0 and we want to quantify the amount of fluid exchanged between each pair of nodes during a time interval τ.



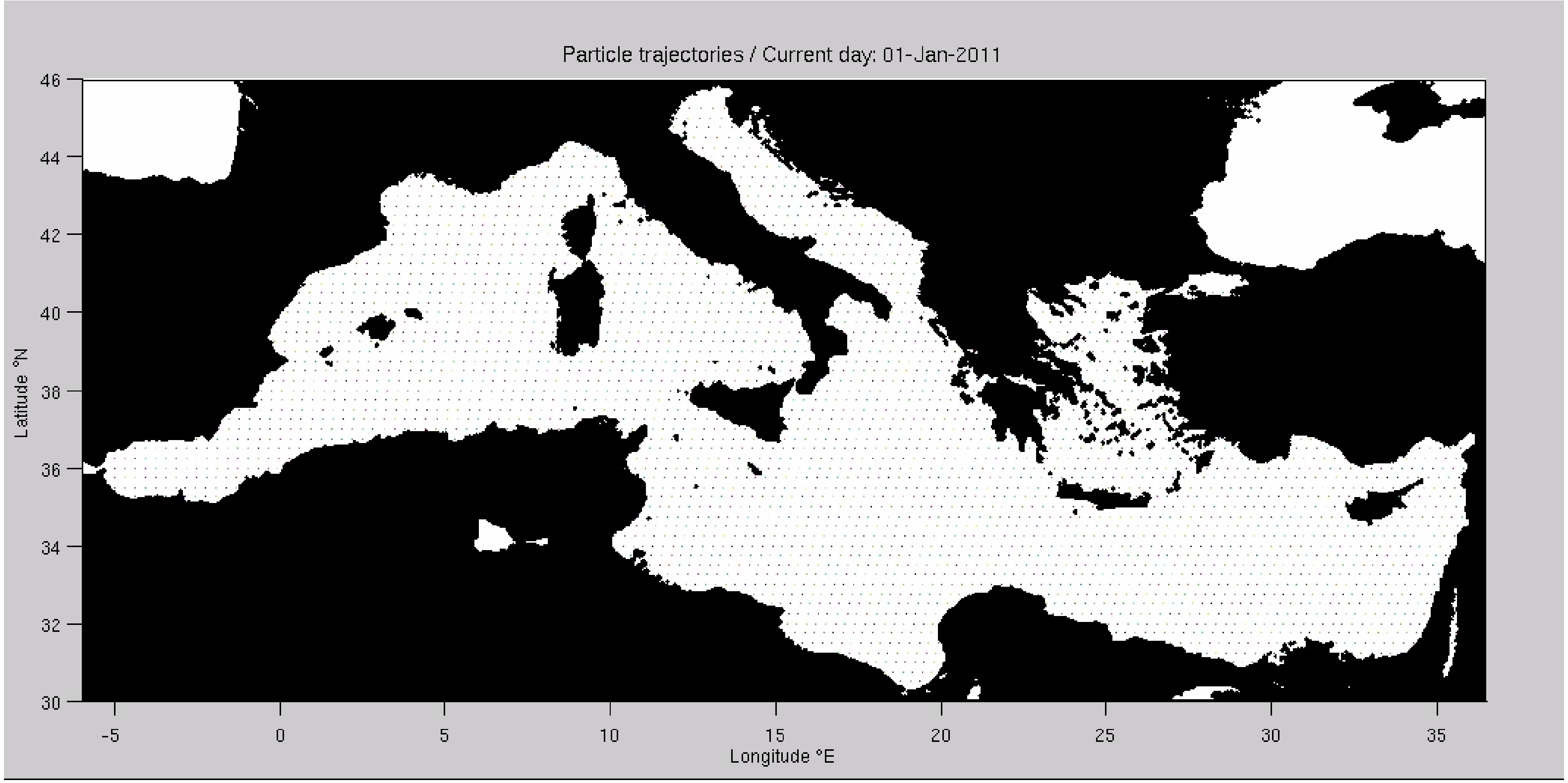
■ A directional **link** is established when an exchange of fluid occurred among two nodes.

■ The **weight** of such link will be proportiona to the amount of fluid transported.

Lagrangian simulations

How to estimate the amount of fluid exchanged among different regions by currents/winds?

- Time dependent velocity field (2-dim)
- Fill each box B_i with **ideal fluid particles** (tracers)



RK4 algorithm to compute trajectories of particles advected by the flow.

Lagrangian Flow Networks

We give a **coarse-grained** (spatial scales fixed by the box-size Δ) **description** of the flow dynamics.

DIRECTED + WEIGHTED + TEMPORAL

P → Adjacency Matrix

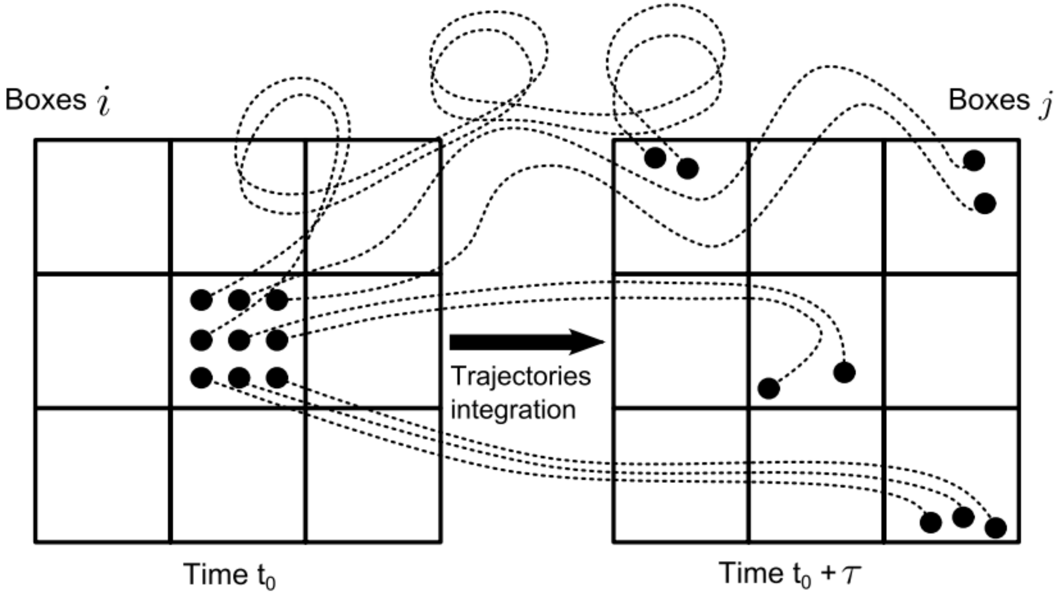
B_i → Node *i*

P_{ij} → Weight of link *i-j*

Transport matrix construction

Once we obtained the trajectories we are able to build a **transport matrix P:**

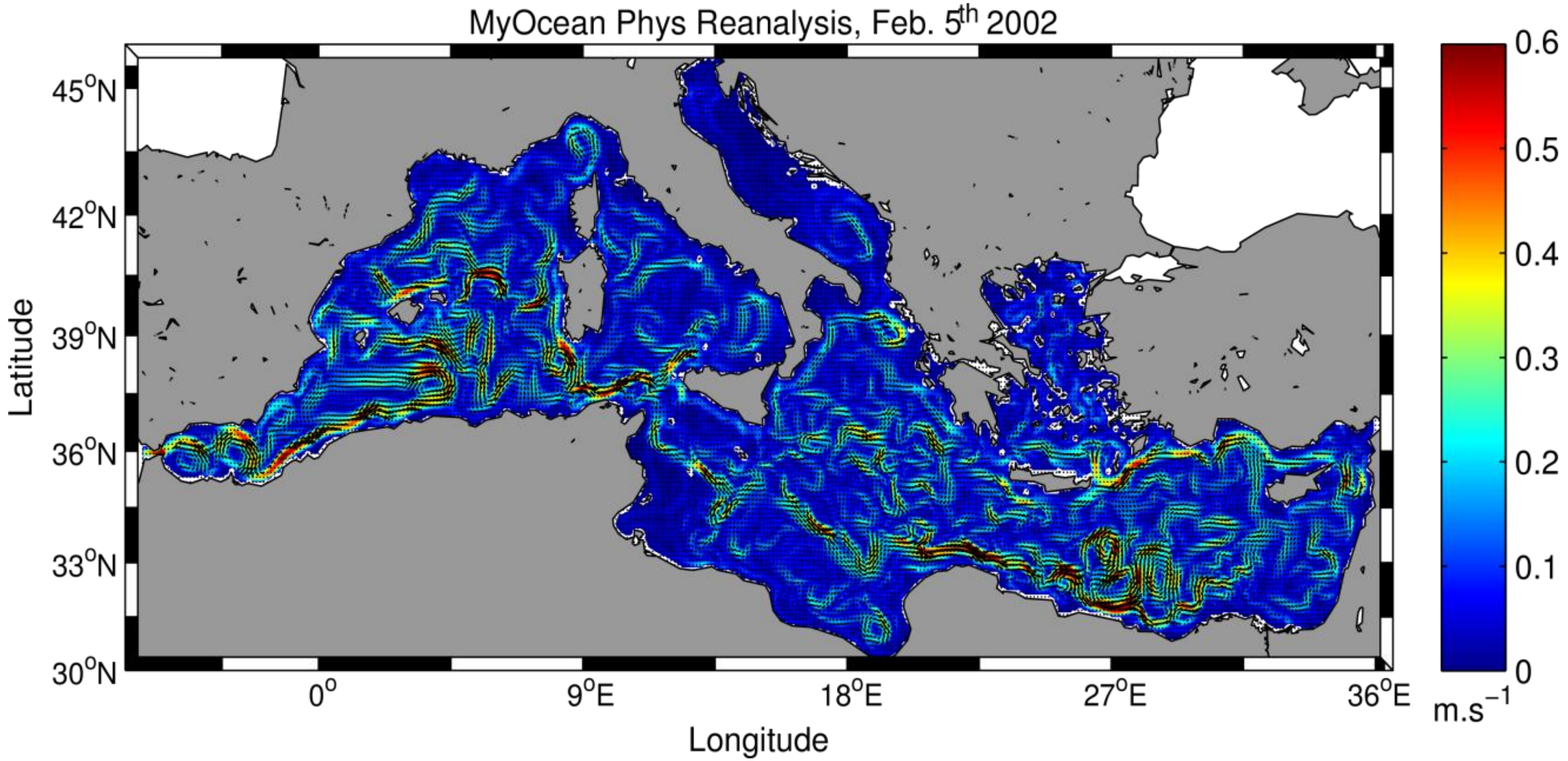
$$P_{ij} = \frac{\#\ \text{tracers from box } i \text{ to box } j}{\#\ \text{tracers of box } i}$$



Ocean set-up

- Velocity field from MyOcean (NEMO): 1/16º, daily, 1987-2011 [Oddo et al. 2009]
- From 2040 to 33,000 equal-area boxes of 1º, ½º, ¼º, 1/8º horizontal resolution.
- From 100 to 2000 Lagrangian particles evenly launched in each box.

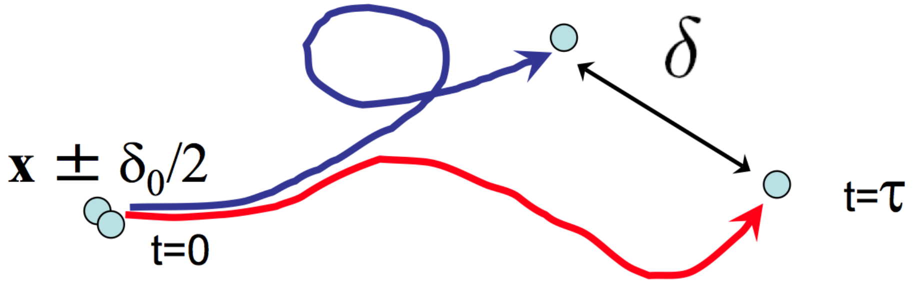
[Rossi et al. 2014; Ser-Giacomi et al. 2015]

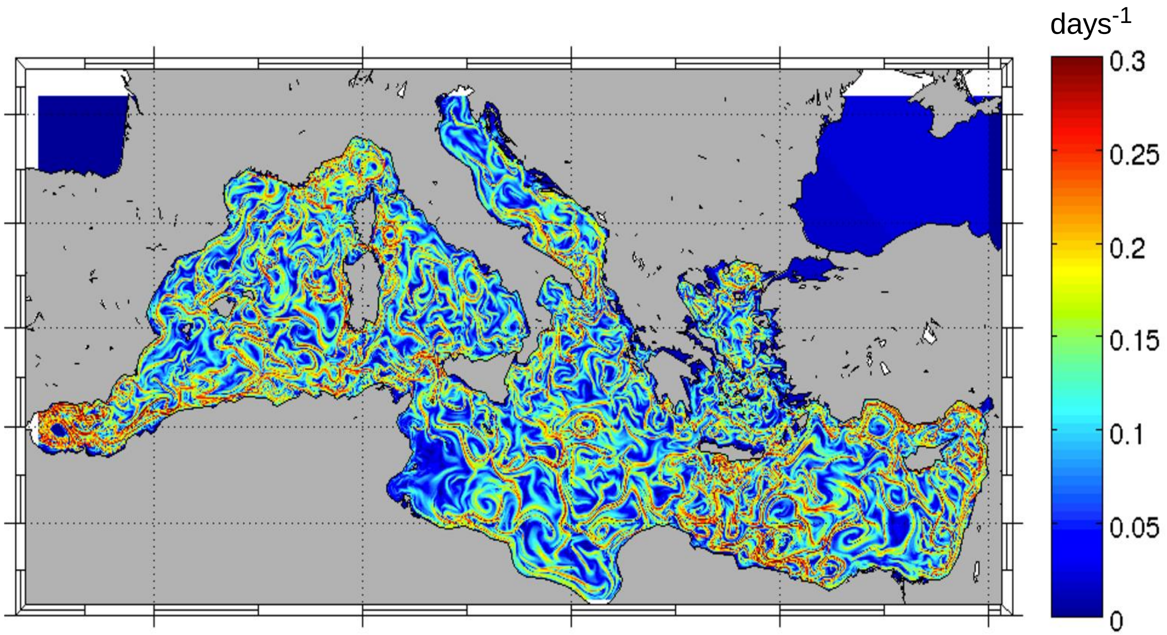


Dynamical system perspective: dispersion and mixing

How the fluid masses are dispersed and mixed by the flow?

$$\lambda(\mathbf{x}, t_0, \tau) = \lim_{||\delta_0|| \to 0} \left[\frac{1}{\tau} \log \frac{||\delta(\mathbf{x}, t_0 + \tau)||}{||\delta_0||} \right]$$

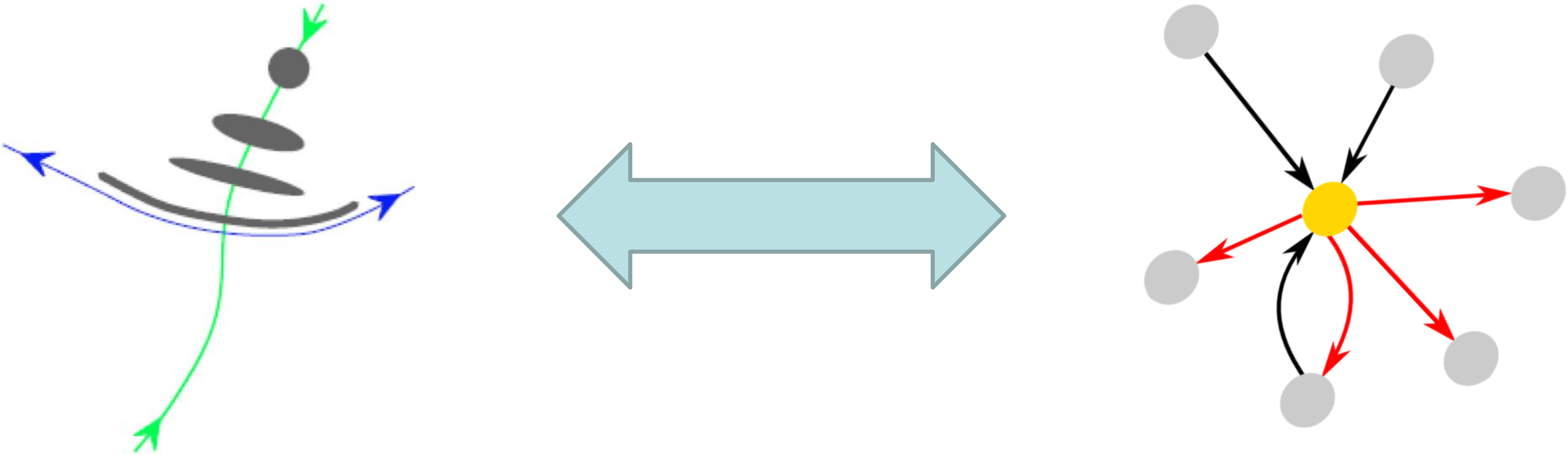




Finite **T**ime **L**yapunov **E**xponents

A local measure of maximum separation between trajectories of infinitesimally close inital conditions.

Linking network measures with FTLE



By relating the **out-degree** of the node-i to the **length of the filament**, we found:

$$K_{out}(i) \approx \bar{L}/\Delta = \langle e^{\tau\lambda(\mathbf{x_0},t_0,\tau)} \rangle_{B_i}$$

(Ser-Giacomi et al. (2015), Chaos 25, 087413)

Network entropies

Pushing forward the analogy, we can define a sequence of Renyi-like entropies associated to the node i as (**P** = adjacency matrix):

$$H_i^q(t_0,\tau) \equiv \frac{1}{(1-q)|\tau|} \log \sum_{j=1}^{N} (\mathbf{P}(t_0,\tau)_{ij})^q$$

They measure the **diversity** of the amounts of fluid sent by the node-i to all the nodes connected to it:

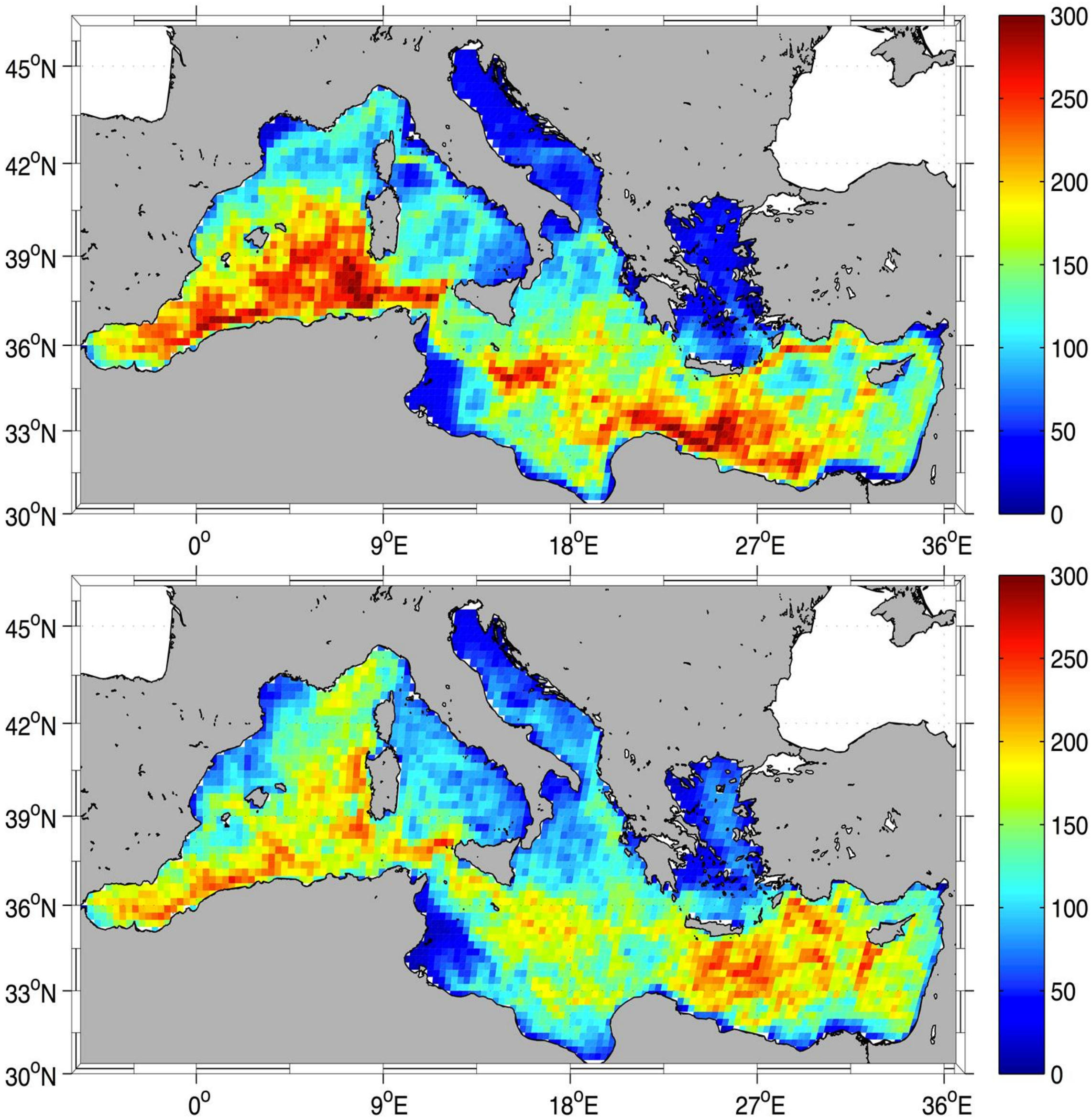
- limit: q → 0:

$$H_i^0(t_0,\tau) = \frac{1}{\tau} \log K_{out}(i)$$

- limit: q → 1:

$$H_i^1(t_0,\tau) = -\frac{1}{\tau} \sum_{j=1}^{N} \mathbf{P}(t_0,\tau)_{ij} \log \mathbf{P}(t_0,\tau)_{ij}$$

Flow network perspective: dispersion and mixing



Average out-degree plot:

- τ=30 days
- winter (top) ; summer (bottom)

Dispersion patterns from degree reflect most of the **oceanographical features** in the Mediterranean

FROM: Dynamical Systems
→ TO: Network Theory

Studying connectivity and the structure of marine populations with LFNs

Same team &

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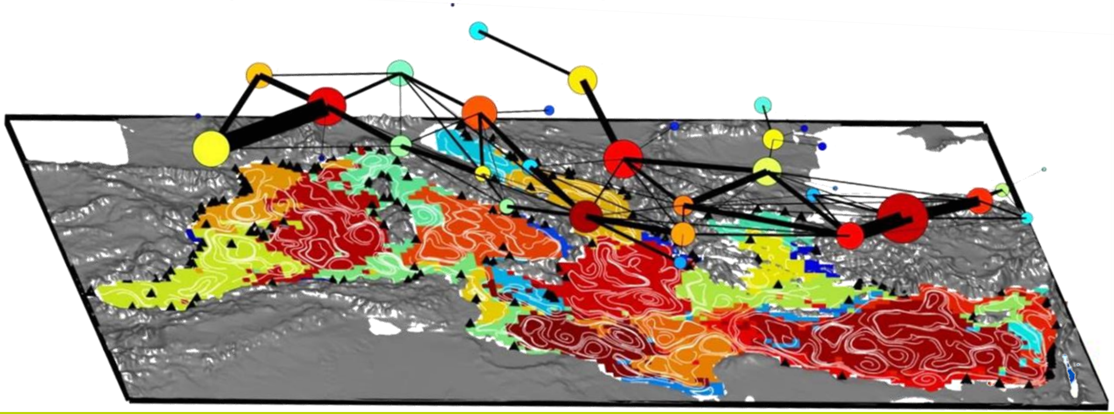
CSIC

Mélodie DUBOIS, Manuel HIDALGO, Sophie ARNAUD-HAOND

Projects: HYDROGENCONNECT, ESCOLA, LINC, LAOP



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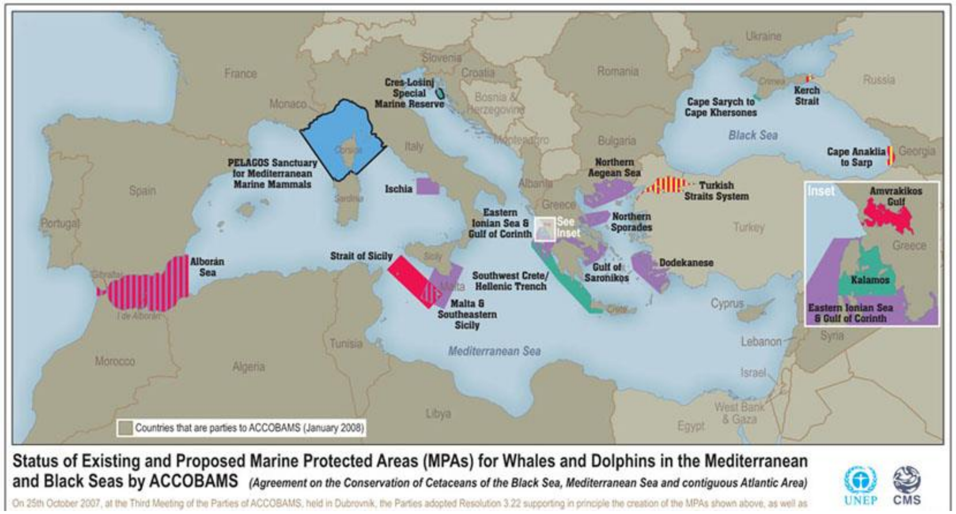
TSUTAYA

Characterizing the structure and connectivity of marine populations is the BASE of spatial conservation planning.

➢ Protection

Implementation of coastal & pelagic reserves

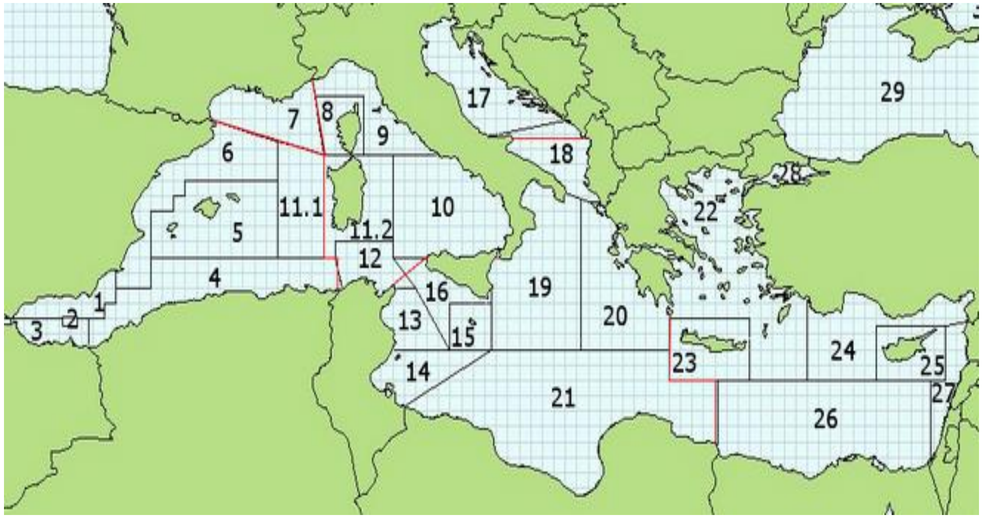
[Lester et al. 2009; Game et al. 2010; Kaplan et al. 2010; Guizien et al. 2012; Pala, 2013; Guidetti et al. 2013; Edgar et al. 2014]



➢ Management

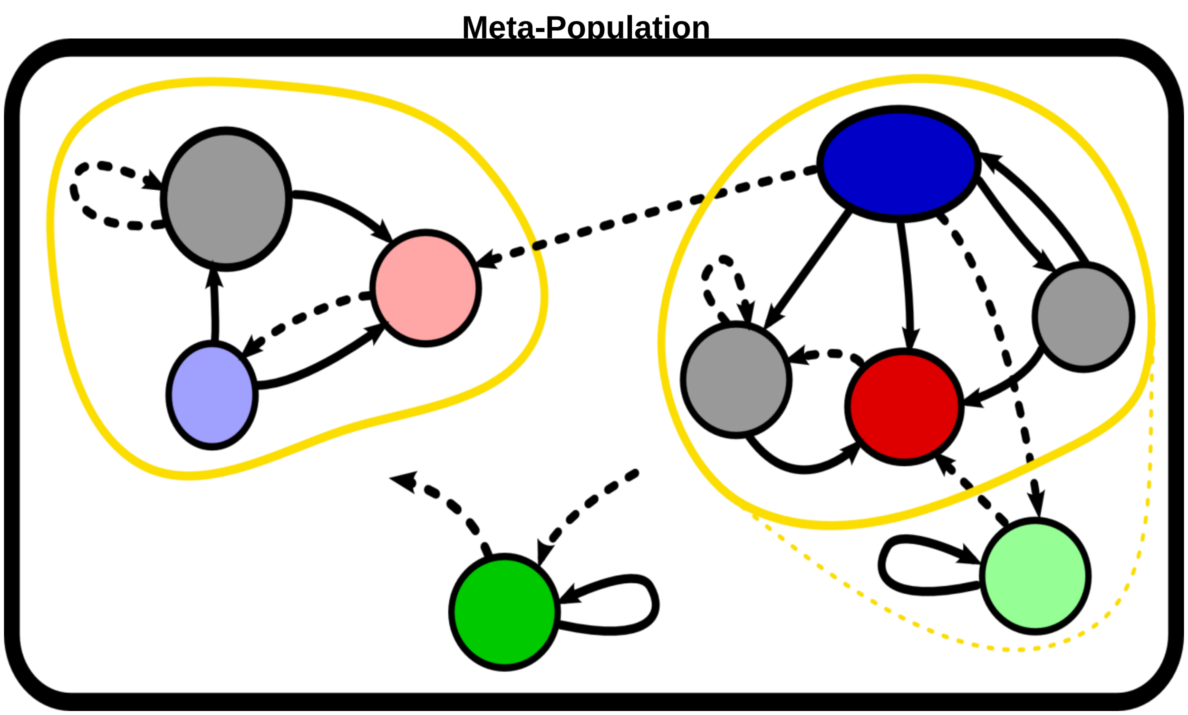
Assessment of "spatialized" fish stocks

[Colleter et al. 2012; Kough et al. 2014]



Characterizing marine populations and their connectivities

Population Connectivity = Exchanges of individuals (larvae & adults) among sub-populations [Cowen and Sponaugle, 2009]

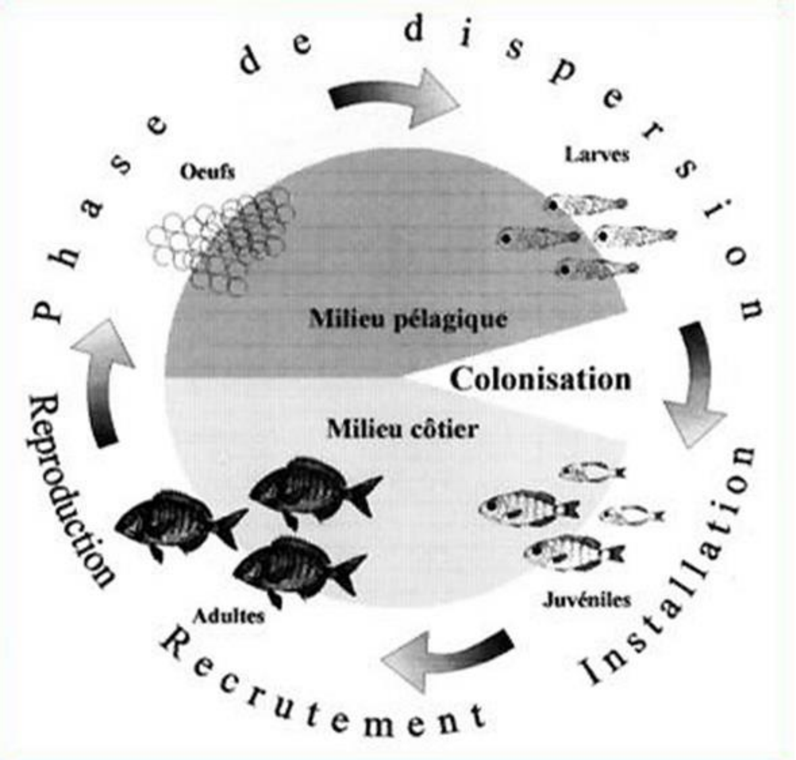


- CLOSED subpopulation
  (limited exchanges)
- OPEN subpopulation
  (significant exchanges)
  - SOURCE subpopulation
    (exports more than imports)
  - SINK subpopulation
    (imports more than exports)
- COMMUNITIES

It structures genetically marine populations (**Genetic Connectivity**) and influences demographic rates (**Demographic Connectivity**) [Palumbi 2003]

Population Connectivity = F (spawning strategy + larval dispersal + habitat availability + trophic interactions + adult movements + …)

[Cowen and Sponaugle, 2009]



BUT for most marine species: **territorial adults** (limited movements) and **planktonic pelagic larvae** (efficient dispersion by ocean currents).

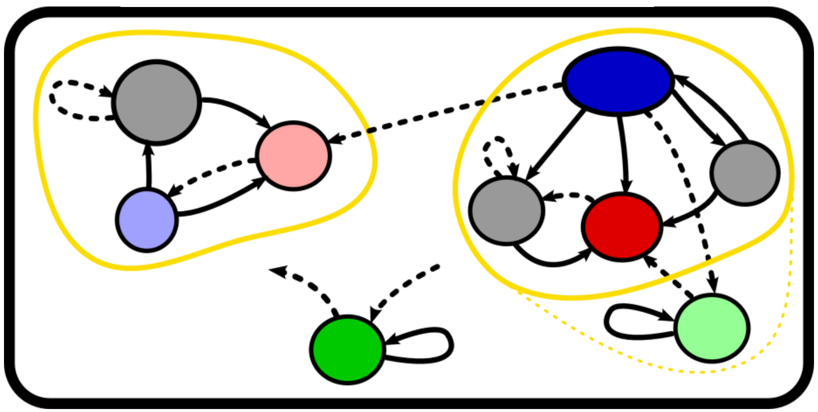
OBJECTIVES:

Characterize **larval transport and dispersal** at multiple scales to reveal marine population structures and connectivity, providing key information to **protect** and **manage** marine ecosystems.

Lagrangian Flow Network

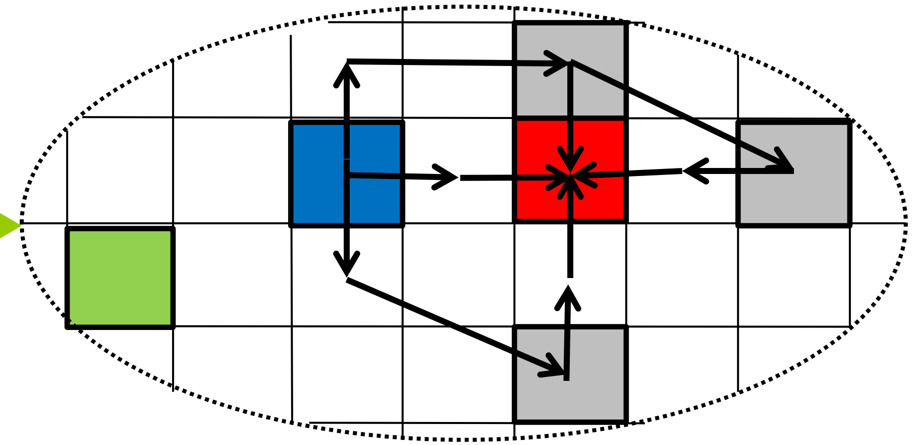
(= Lagrangian bio-physical modelling + Graph Theory tools)

Metapopulation



Sub-populations (e.g. habitat patches) **interconnected**

Mediterranean basin



Oceanic sub-regions interconnected

Ecological Objectives

Describe the **direction** and **quantity of larvae** transported between sub-populations (e.g. habitat patches)

Network Theory Equivalent

Describe the **direction** and **strength** of the links existing between all the nodes of our transport network

Oceanic boxes ↔ Nodes

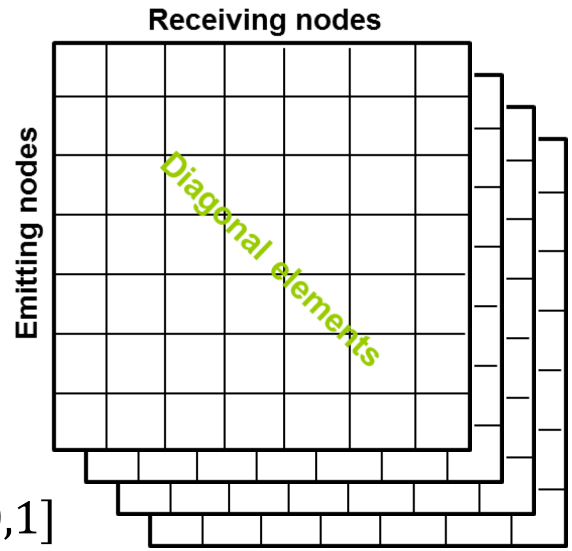
Larval flow ↔ strenght & direction of all links

[Ser-Giacomi et al. 2015]

BIOLOGICAL PARAMETERS & ASSUMPTIONS

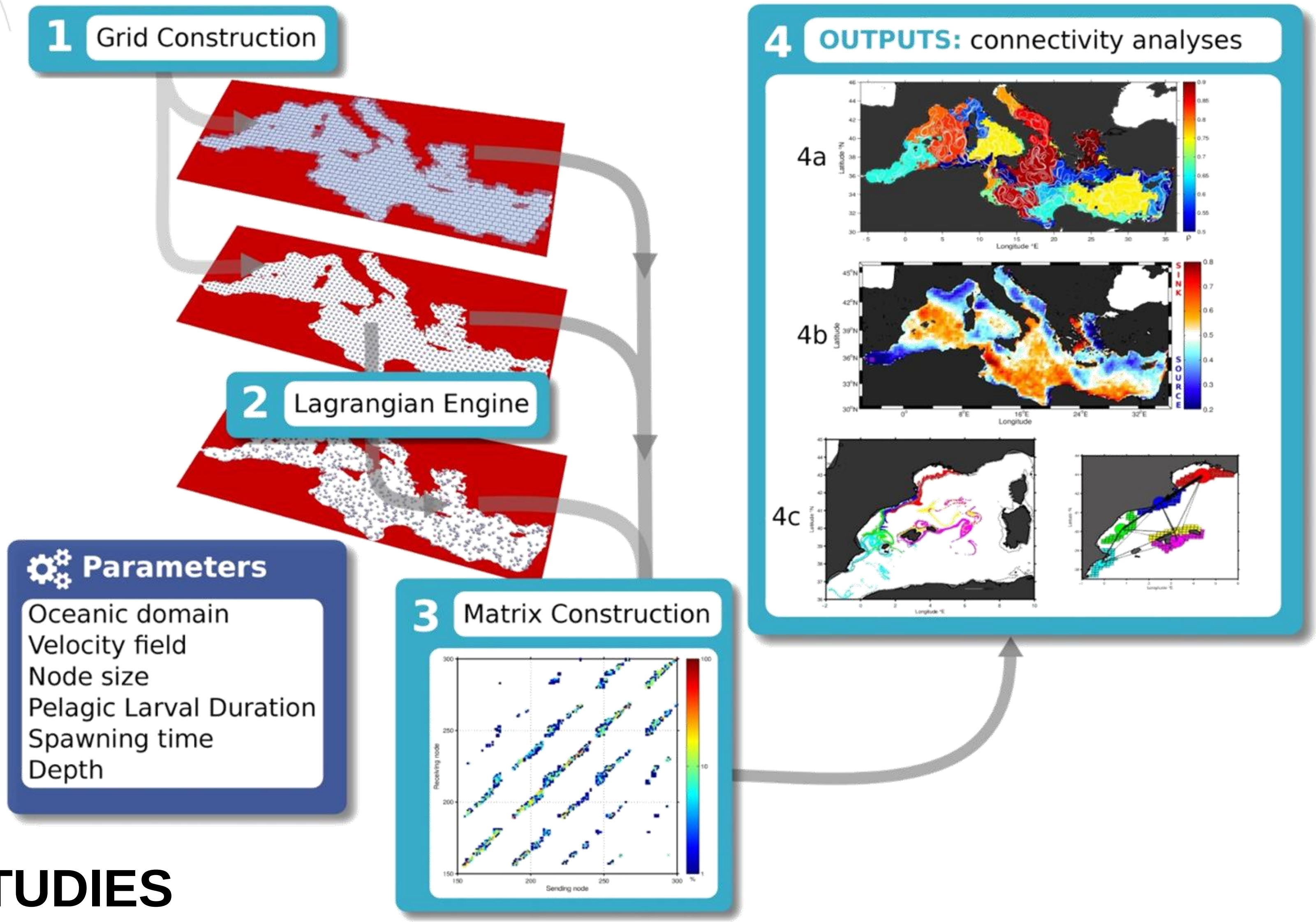
- Larvae with passive horizontal drift (future implementation of realistic larval traits).
- Starting time t_0 ~ spawning, considering seasonal & successive spawning events.
- Tracking duration τ ~ Pelagic Larval Duration (PLD).
- Larval production, mortality & success of recruitment are assumed homogeneous in space & time (easy to modulate due to spatial discretization and post-processing of matrices).

Probabilistic connectivity matrix (~ adjacency matrix) built from millions of trajectories.



$\in [0,1]$

Averaged analyses of ensemble of matrices



CASE-STUDIES

1) **Generic parameters: ecosystem approach to connectivity**
2) **Specific parameters: connectivity of a target species**

Generic parameters for an Ecosystem Approach to connectivity

[Guidetti et al. 2013; Dubois et al. 2016]

Literature review of biological traits of mediterranean species.

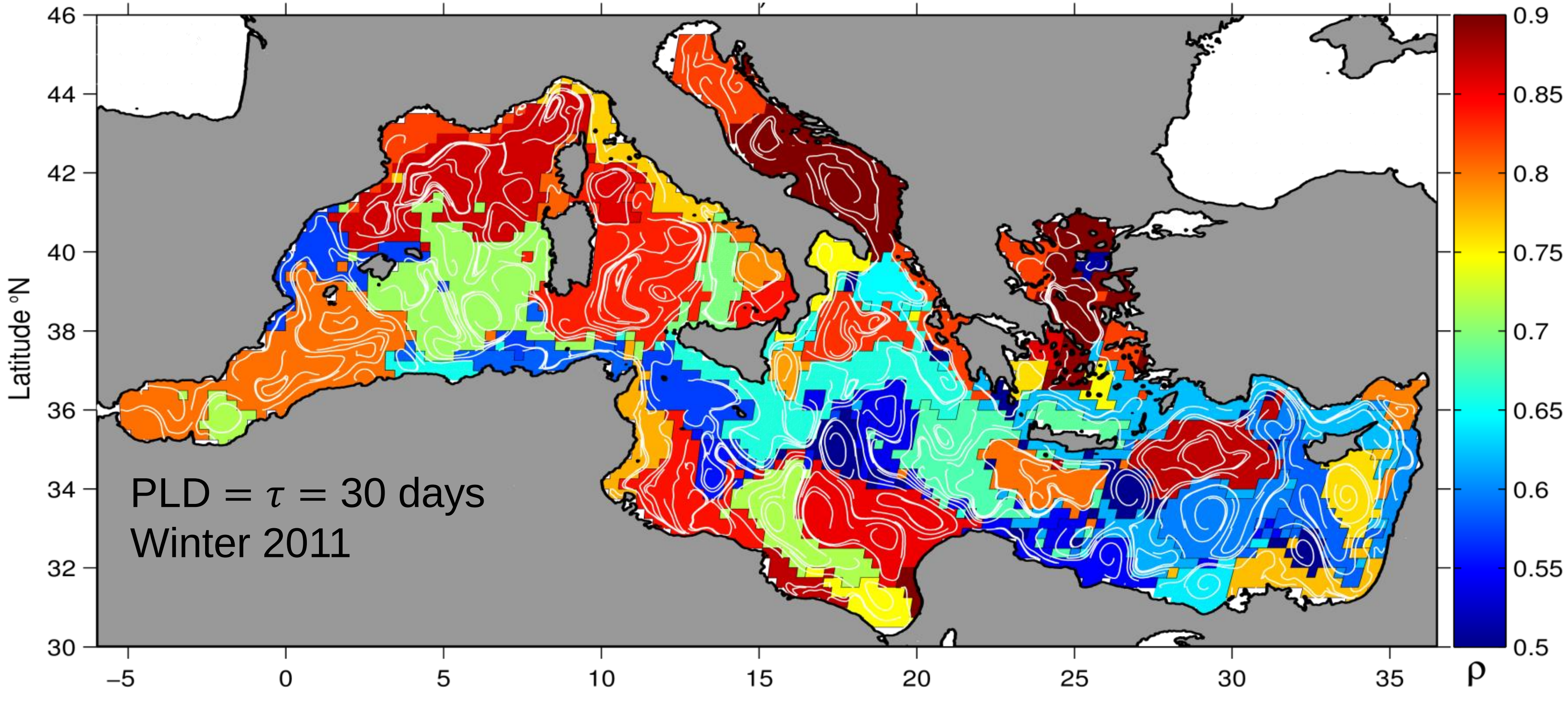
Parameters:

- PLD: 15 – 90 days.
- 2 main spawning seasons.
- Successive and random spawning events.

Marine species	Taxonomy	Category (adults habitats)	Larval distribution	Estimated PLD (days)	Larval season (following spawning)	References
Blenny *Lipophrys trigloides*	Vertebrate, Fish	Littoral demersal (benthic)	Inshore	67	Winter	[MacPherson & Raventós 2006]
Blenny *Lipophrys canevai*	Vertebrate, Fish	Littoral demersal (benthic)	Offshore	30	Summer	[MacPherson & Raventós 2006]
Rainbow Wrasse *Coris julis*	Vertebrate, Fish	Littoral demersal (benthopelagic)	Offshore	21-34	Summer	[MacPherson & Raventós 2006; Torres *et al.* 2011]
Green Wrasse *Labrus viridis*	Vertebrate, Fish	Littoral demersal (benthopelagic)	Inshore	31-34	Spring/ Summer	[Bauchot & Quignard 1979; Raventós & MacPherson 2001; MacPherson & Raventós 2006]
Goat Fish *Mullus surmuletus*	Vertebrate, Fish	Littoral demersal (benthopelagic)	Offshore	30	Spring/ Summer	[MacPherson & Raventós 2006]
Dusky Groper *Epinephelus marginatus*	Vertebrate, Fish	Littoral demersal (benthopelagic)	Offshore	25-30	Summer	[MacPherson & Raventós 2006; Andrello *et al.* 2013]
Salema Porgy *Sarpa salpa*	Vertebrate, Fish	Littoral demersal (benthopelagic)	Offshore	32	Winter	[MacPherson & Raventós 2006]
Shore Rockling *Gaidropsarus mediterraneus*	Vertebrate, Fish	Littoral demersal (benthic)	Offshore	43	Winter	[MacPherson & Raventós 2006]
Two-banded Seabream *Diplodus vulgaris*	Vertebrate, Fish	Littoral/Shelf demersal (benthopelagic)	Offshore	29-58	Winter	[MacPherson & Raventós 2006]
White Seabream *Diplodus sargus*	Vertebrate, Fish	Littoral demersal (benthopelagic)	Inshore	28	Winter	[Bauchot & Hureau 1990; MacPherson & Raventós 2006]
Gilthead Seabream *Sparus aurata*	Vertebrate, Fish	Littoral/Shelf demersal (benthopelagic)	Offshore	40-50	Winter	[Bauchot & Hureau 1990]
Bullet Tuna *Auxis rochei*	Vertebrate, Fish	Shelf pelagic (epipelagic)	Offshore	16	Spring/ Summer	[Houde & Zastrow 1993; Reglero *et al.* 2012]
Sandsmelt Fish *Atherina spp.*	Vertebrate, Fish	Littoral pelagic (epipelagic)	Inshore	9-15	Spring/ Summer	[MacPherson & Raventós 2006; Torres *et al.* 2011]
Dolphin Fish *Coryphaena hippurus*	Vertebrate, Fish	Shelf pelagic (epipelagic)	Offshore	?	Spring/ Summer	[Dulčić 1999]
European Anchovy *Engraulis encrasicolus*	Vertebrate, Fish	Oceanic pelagic (epipelagic)	Offshore	37	Summer	[Houde & Zastrow 1993]
Bluefin Tuna *Thunnus thunnus*	Vertebrate, Fish	Oceanic pelagic (epipelagic)	Offshore	30	Summer	[Rooker *et al.* 2007]
Ray Bream *Brama brama*	Vertebrate, Fish	Oceanic pelagic (epipelagic)	Offshore	?	Summer	[Dulčić 1999]
Gilt Sardine *Sardinella aurita*	Vertebrate, Fish	Oceanic pelagic (epipelagic)	Offshore	60	Summer	[Ramirez *et al.* 2001; Sabatés *et al.* 2003; Torres *et al.* 2011]
European Hake *Merluccius merluccius*	Vertebrate, Fish	Shelf/Oceanic demersal (benthopelagic)	Offshore	40-60	Summer/ Autumn	[Morales-Nin & Moranta 2004]
Horse Mackerel *Trachurus mediterraneus*	Vertebrate, Fish	Shelf/Oceanic pelagic (epipelagic)	Offshore	?	Summer	[Smith-Vaniz 1986]
European Seabass *Dicentrarchus labrax*	Vertebrate, Fish	Littoral/Shelf demersal (benthopelagic)	Offshore	40	Winter	[Smith 1990]
Sea Star *Astropecten aranciacus*	Invertebrate, Echinoderms	Littoral demersal (benthic)	Inshore	60	Spring/ Summer	[Zulliger *et al.* 2009]
Marbled Crab *Pachygraptus marmoratus*	Invertebrate, Crustaceans	Littoral/Shelf demersal (benthic)	Inshore	30	Spring/ Summer	[Fratini *et al.* 2013]
Other crustaceans (e.g. Lobster)	Invertebrate, Crustaceans	Littoral/Shelf demersal (benthic)	Variable	~30-300	Variable	[Queiroga *et al.* 2007; Shanks 2009]
Other molluscs (e.g. Oyster)	Invertebrate, Molluscs	Littoral demersal (benthic)	Variable	~10-100	Variable	[Shanks 2009; Kough *et al.* 2013]

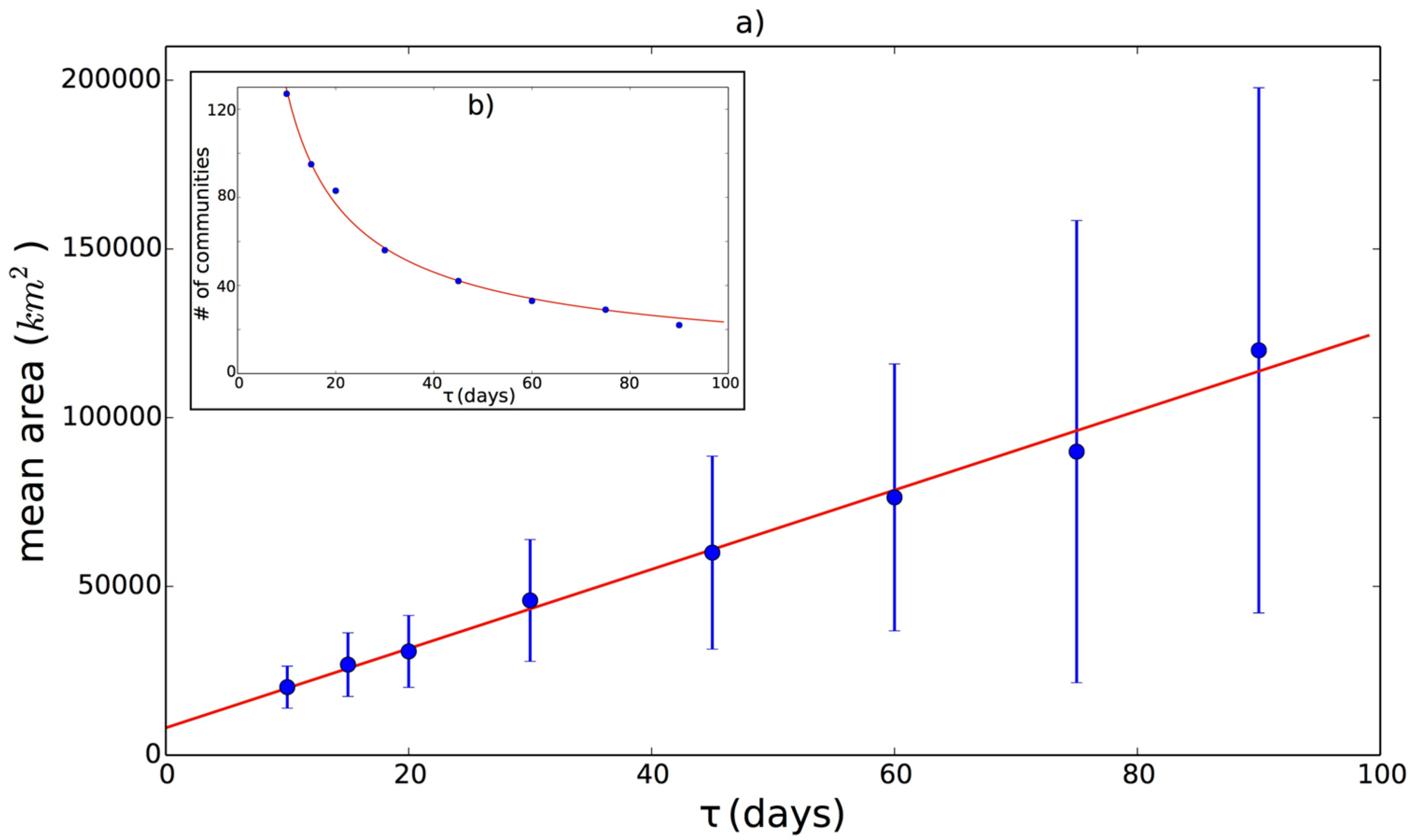
Community detection with *Infomap*: finds the sets of nodes strongly connected among them and weakly connected with the rest.

→ Hydrodynamical provinces in which larvae are more likely to disperse within each other than among them for a given time-scale.



- Hydrodynamical provinces evolve in space and time.
- Boundaries match multi-scale oceanic processes.

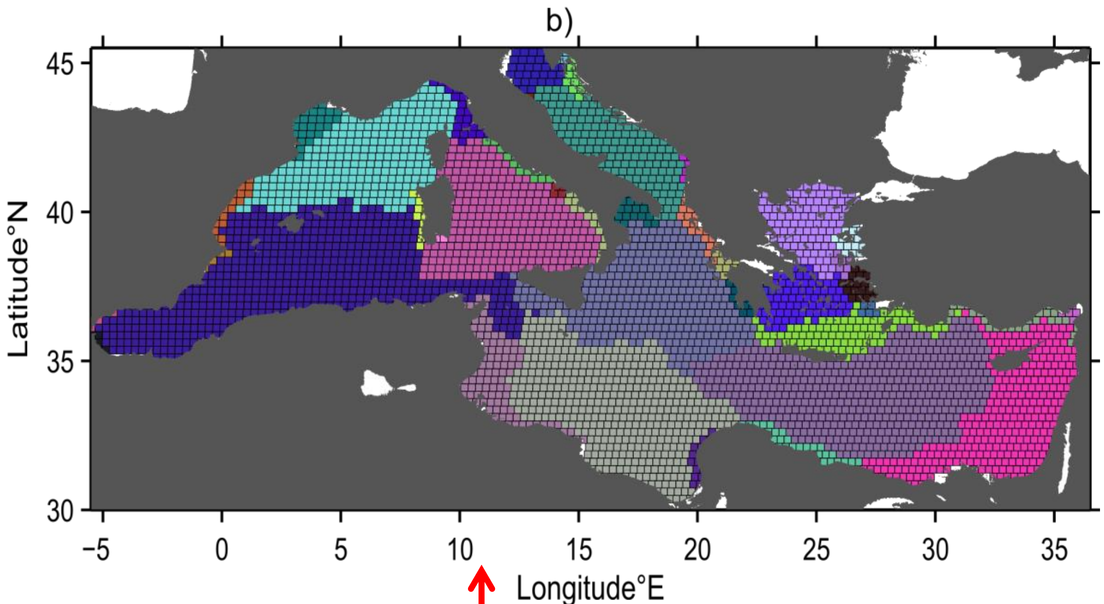
Communities as hydrodynamical provinces



Number of communities decreases and area increases with integration time

(Ser-Giacomi et al. (2015), Chaos 25, 087413)
(Rossi et al. (2014), GRL 41, 2883–2891)

A global partition of the ocean



How to give an average description of the main transport features accross many years?

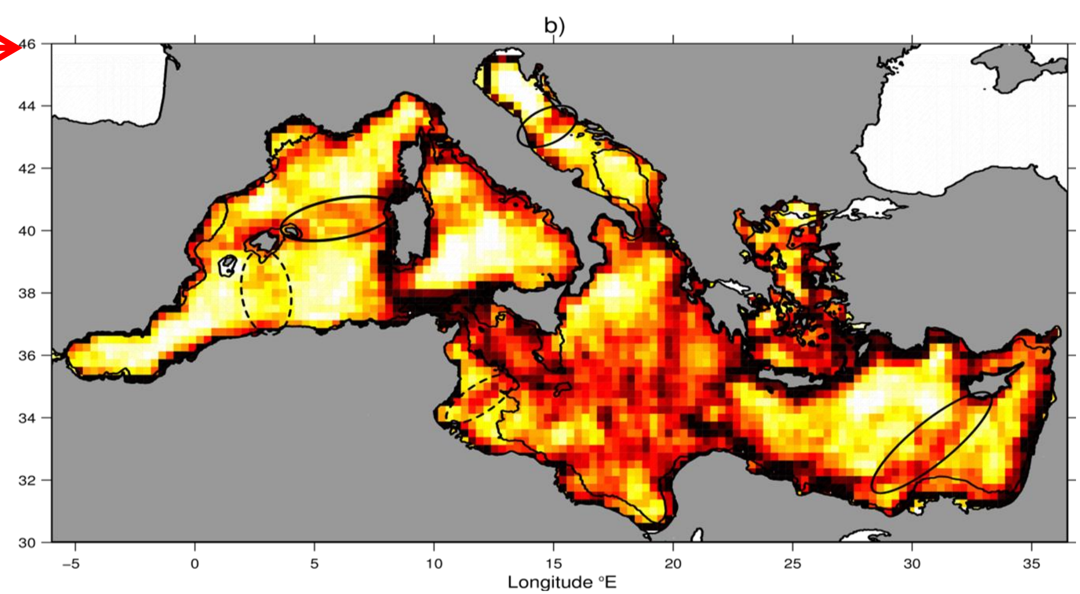
From single snapshots to temporal means

Pre-average

Average matrices & run Infomap once

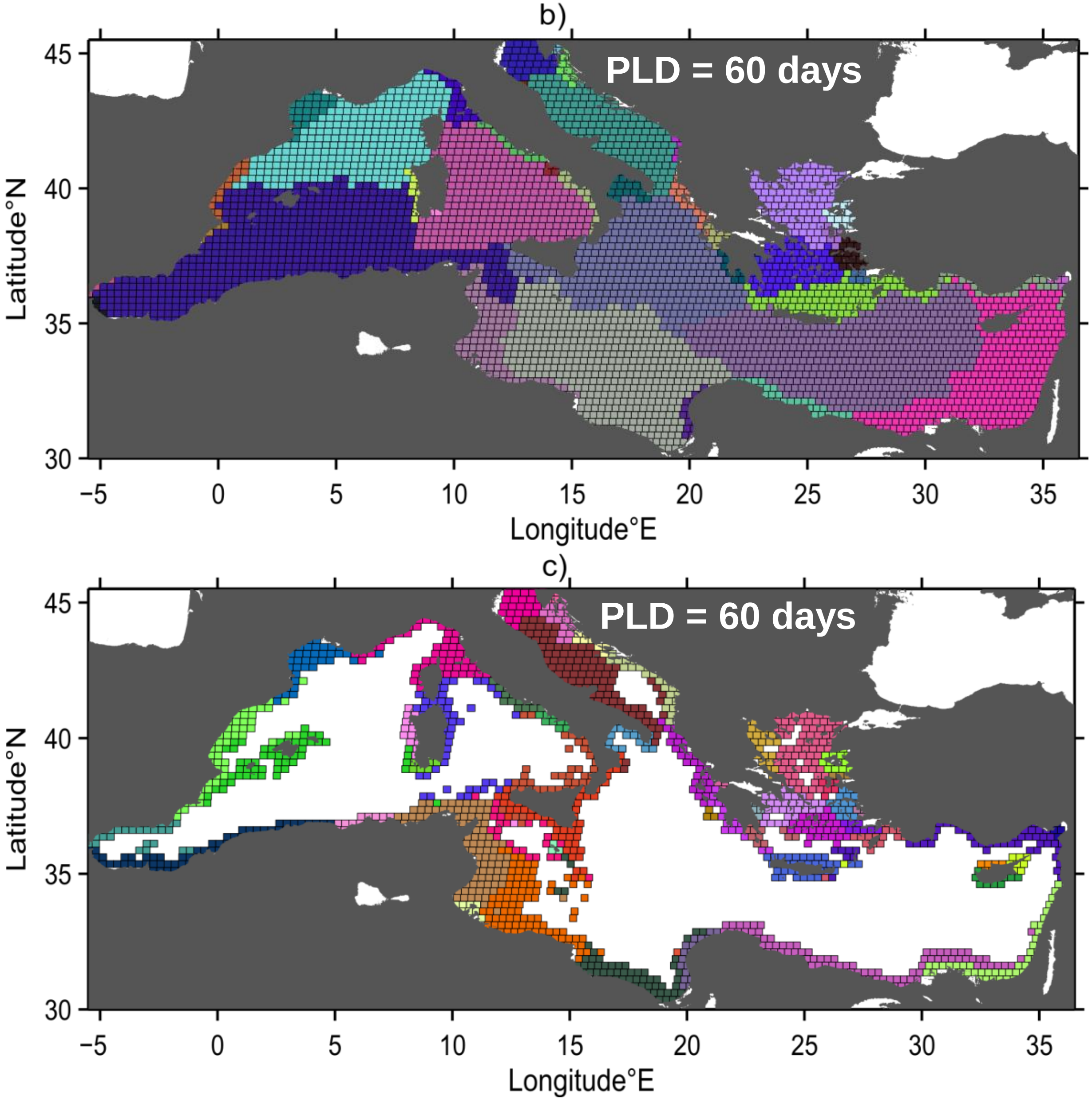
Post-average

Run infomap on each matrix and count boundaries occurence



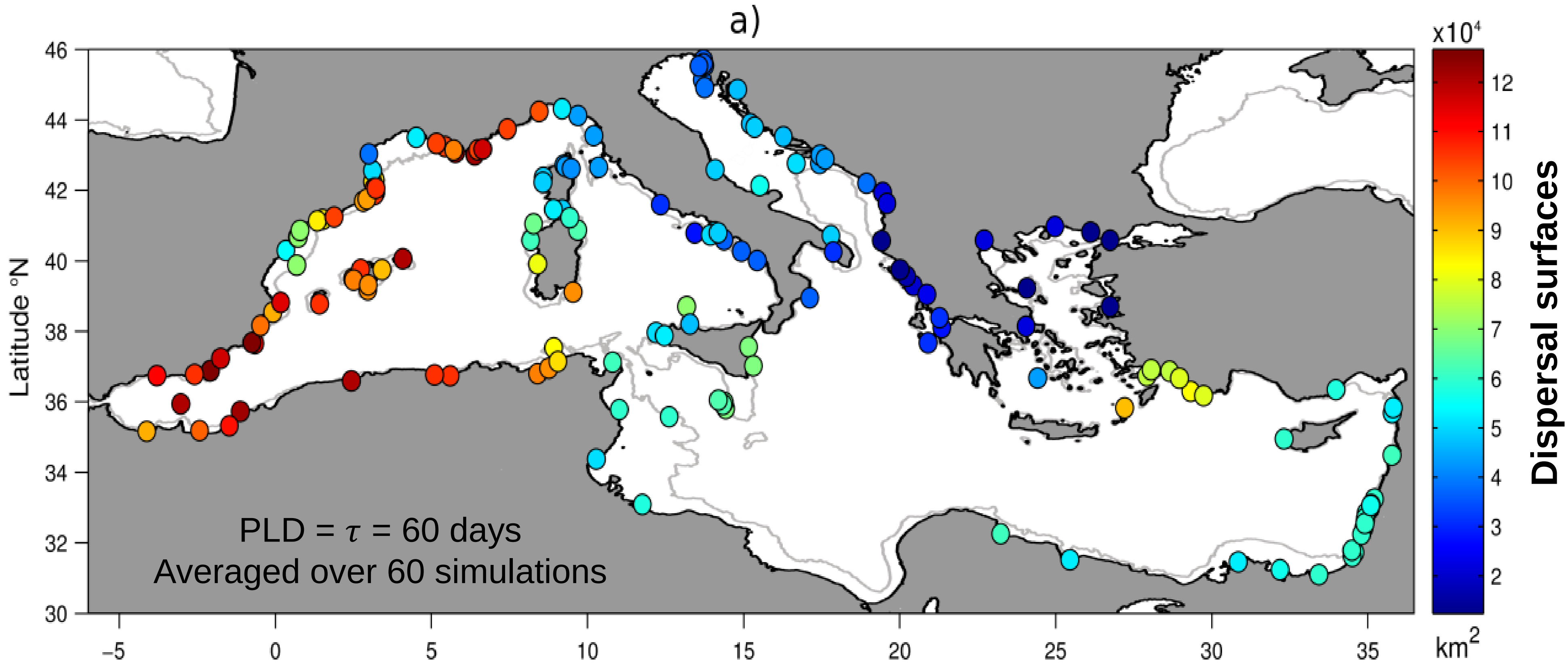
→ Identification of recurrent frontal systems and stable oceanic units (gyres, extended continental shelves…) which organise larval dispersion across the basin.

Mean hydrodynamical provinces



→ Impacts on population genetics:

- Help **designing adequate sampling** for genetics studies.
- Are these **hydrodynamic provinces** consistent with **genetic clusters**?



- Large variability of dispersion potential.
- Small surfaces: favoring retention (e.g. Adriatic, Aegean, Gulf of Lyon…).
- Large surfaces: favoring larval export (e.g. islands, narrow shelves with boundary currents…).
- Sizing and spacing guidelines (large/distant or small/nearby?): in accord with basin-scale dispersal patterns.

RETENTION (self-persistence)

LOCAL RETENTION (LR)

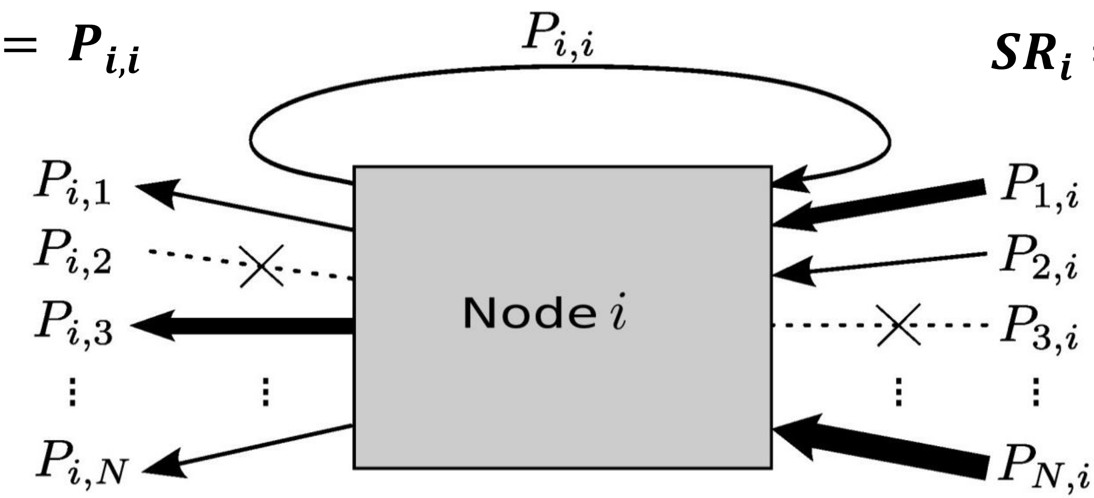
Proportion of locally produced settlement to local larval release [Bostford et al. 2009]

$$LR_i = P_{i,i}$$

SELF-RECRUITEMENT (SR)

Ratio of locally produced settlement to settlement of all origins at a given site [Bostford et al. 2009]

$$SR_i = \frac{P_{i,i}}{\sum_{x=1}^{N} P_{x,i}}$$



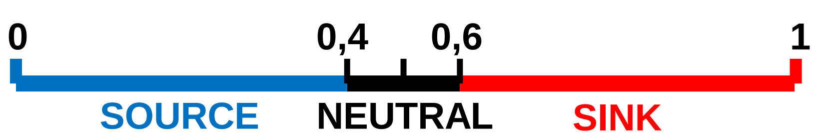
$$OUT_i^{flux} = \sum_{x=1}^{N} (P_{i,x}) - P_{i,i}$$

$$IN_i^{flux} = \sum_{x=1}^{N} (P_{x,i}) - P_{i,i}$$

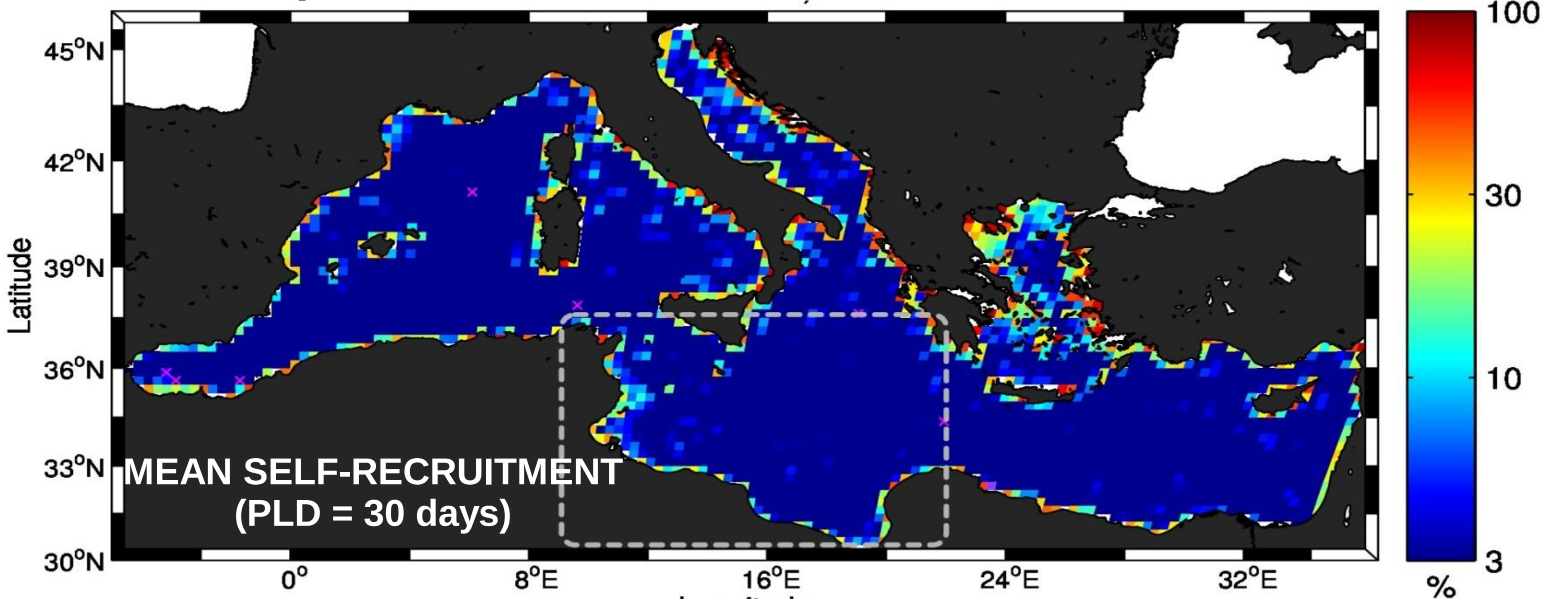
EXCHANGE (network persistence)

SOURCE-SINK

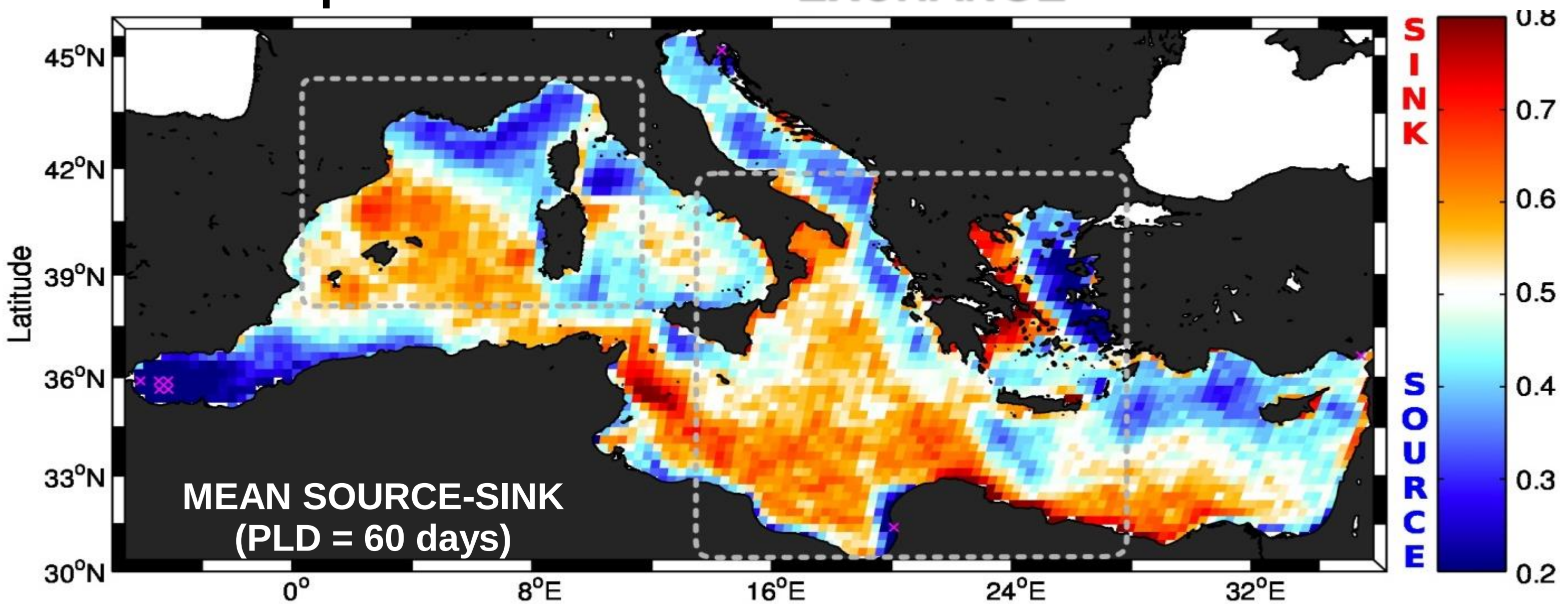
$$SS_i^{flux} = \frac{IN_i^{flux}}{IN_i^{flux} + OUT_i^{flux}}$$



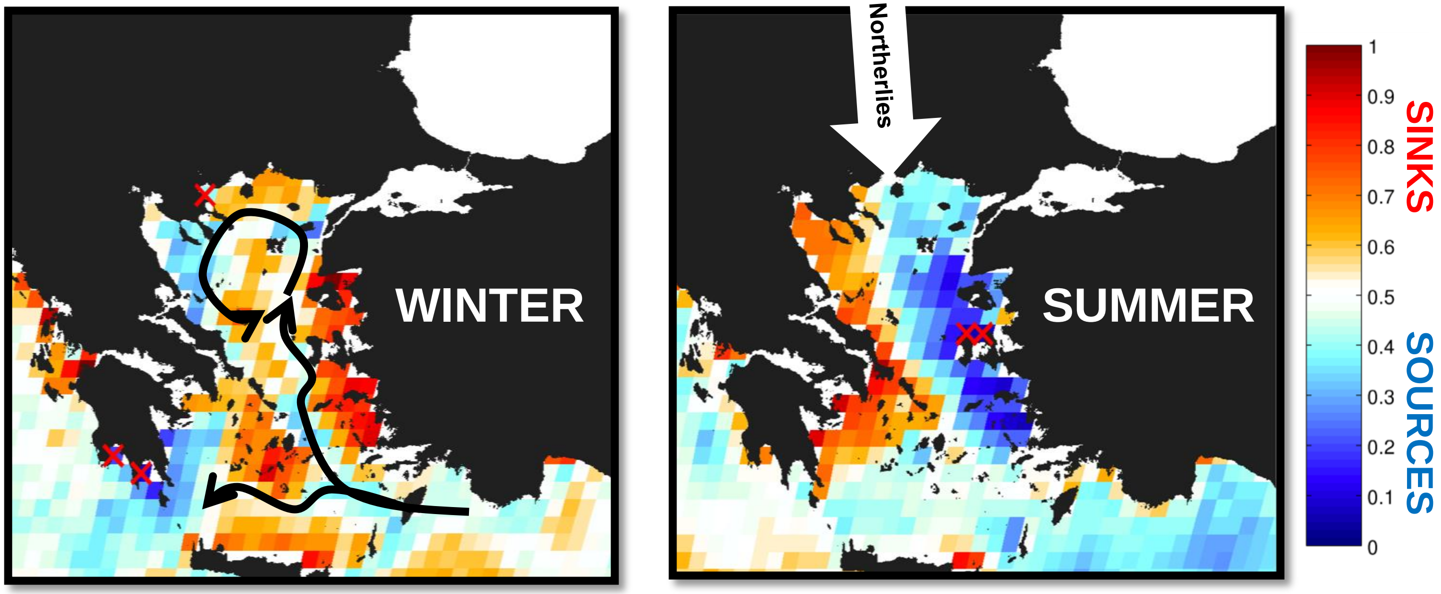
Spatial distribution of RETENTION indices



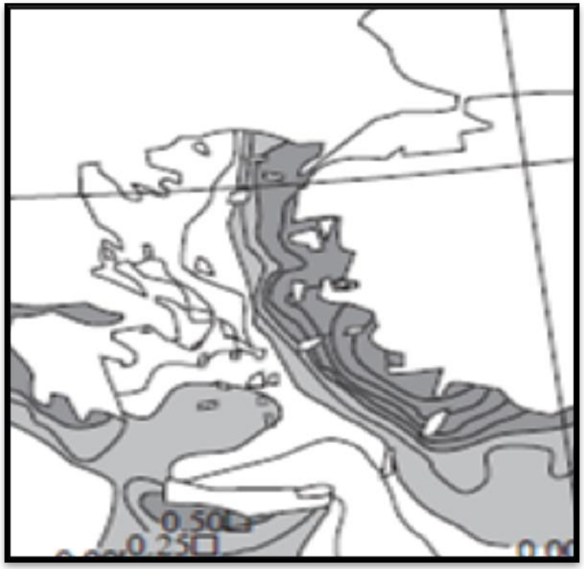
Spatial distribution of EXCHANGE indices



Regional zoom on the Aegean Sea: Local Oceanography explains Source/Sink patterns



- **In winter: coasts is sinks but some veins of sources; well explained by the surface circulation.**
- **In summer: Western coasts are sinks and Eastern coast behave as sources ; well explained by the dipole upwelling/downwelling forced by the summer Northerlies.**



Vertical Ekman Velocities
[Bakun and Agostini, 2001]

Impacts on population genetics: characterizing the genetic structures of source/sink populations.

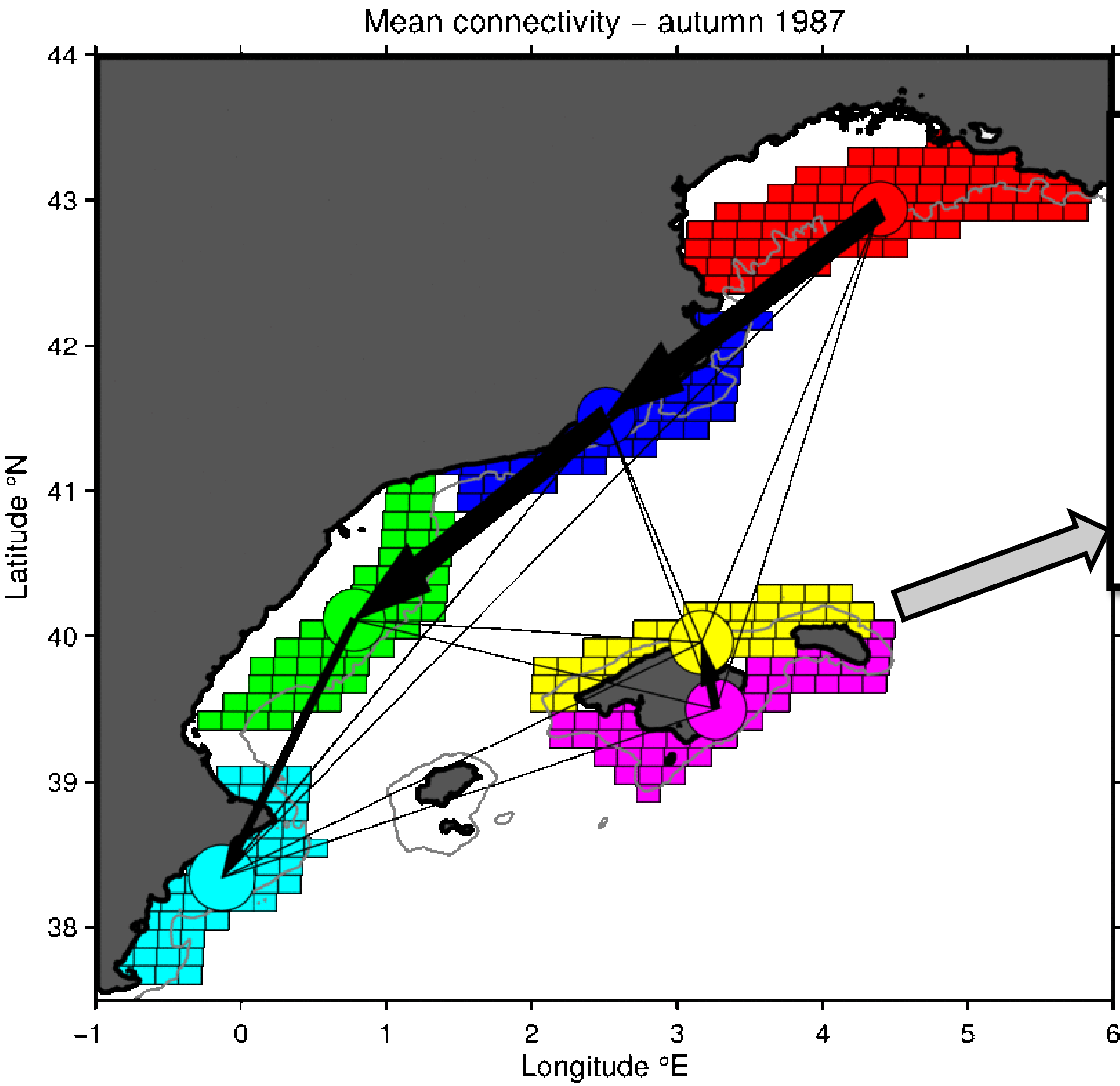
Use the *Lagrangian Flow Network* to investigate the impact of connectivity processes on population structure of Hake in the Western Mediterranean.

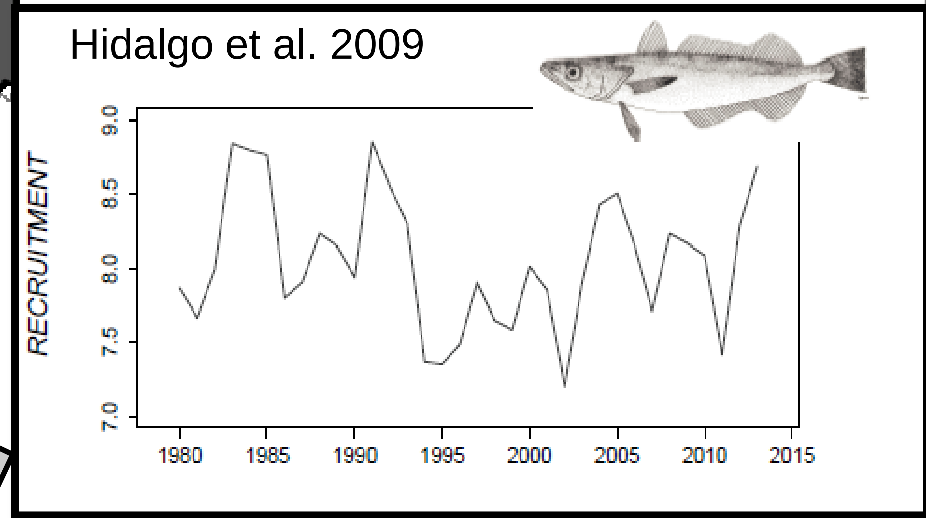



European Hake *(Merluccius merluccius):*

- exploited demersal fish, important landings
- largely distributed, PLD of about 40 days → potential for large dispersal
- larvae drifting at the subsurface.

How are connected the 6 *a-priori* identified sub-populations?





Inter-annual variability

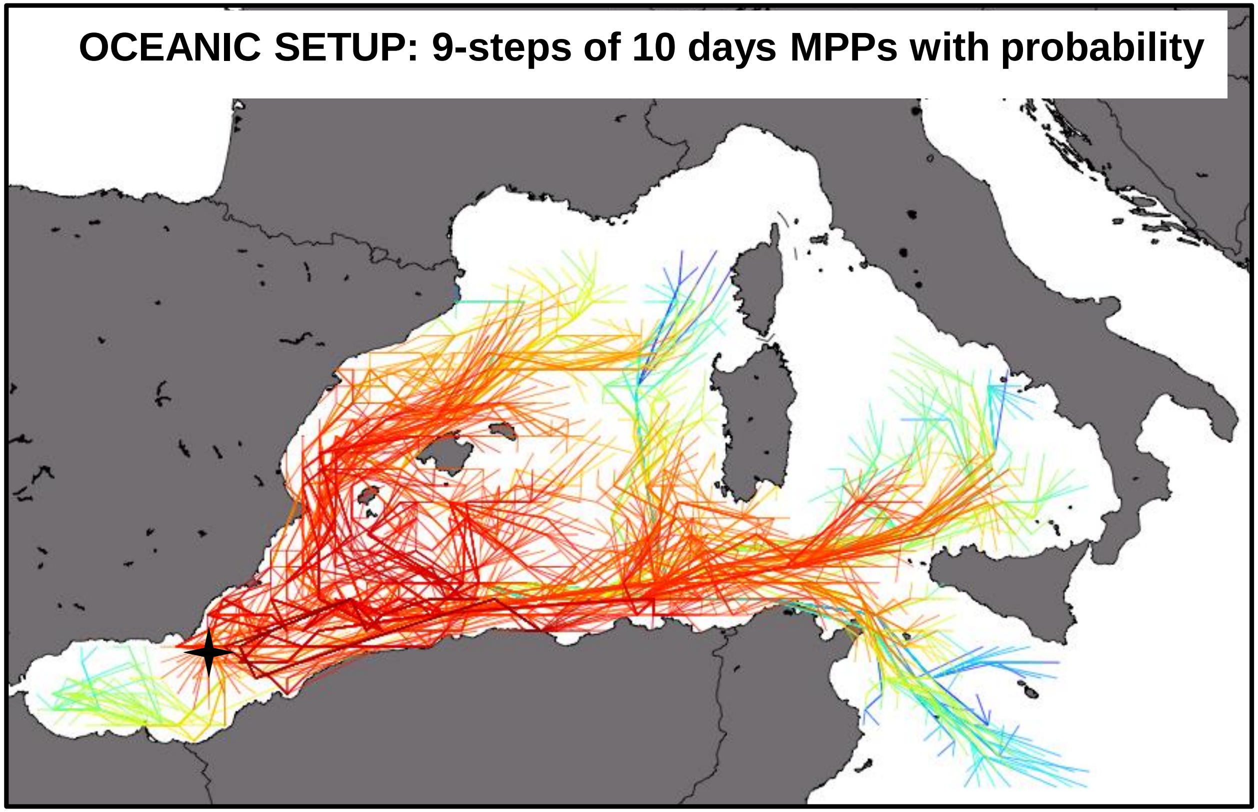
Quantifying inter-exchange and retention of Hake´s larvae within the metapopulation

Recruitment ~ Larval survival = f (larval retention & exchange & environment)

Paths in complex networks

How unveil pairwise long-range (space/time) connectivity?

"Walking" across the network (1 step = 1 link) → **Paths**



Definition:

- PROBABILITY:
  Weights product
- TIME SCALE:
  Number of steps * Step duration

Most Probable Paths
=
Maximum Flow Paths

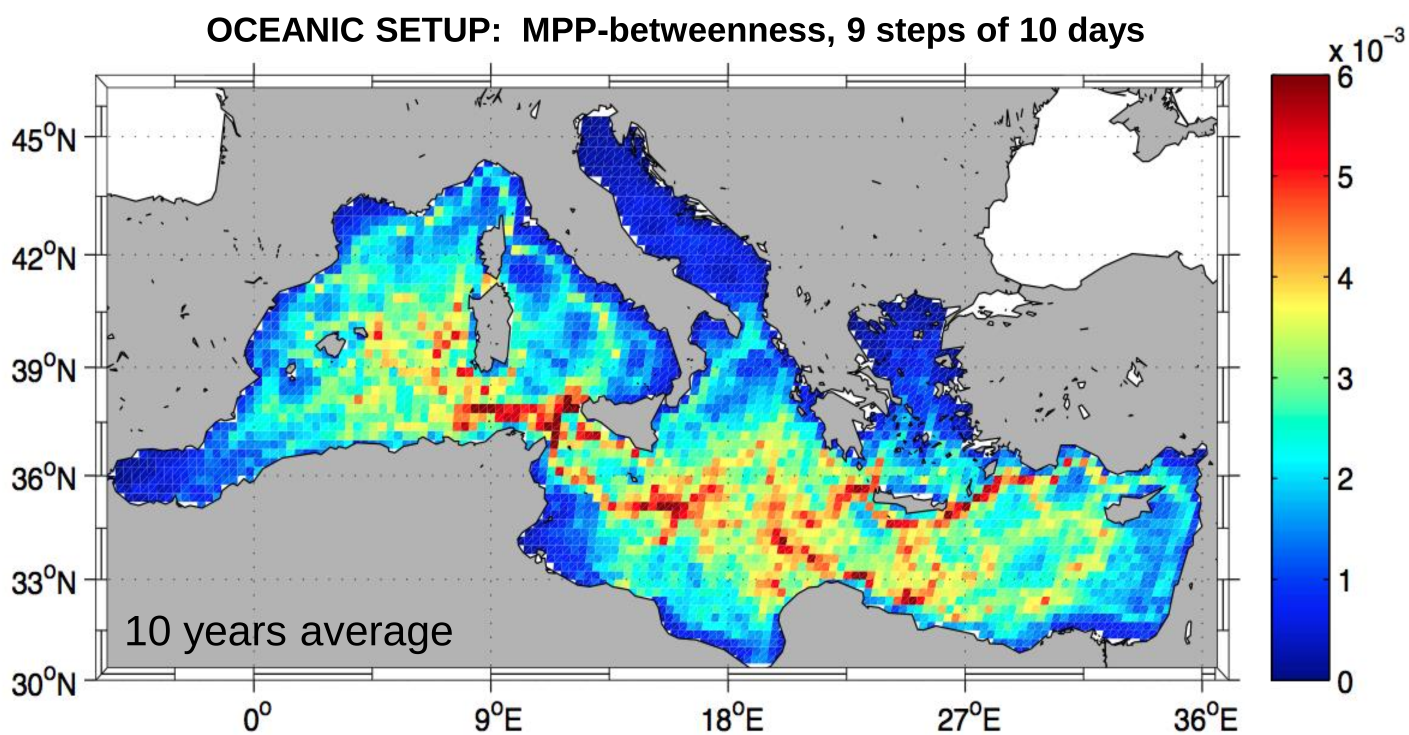
Path that maximizes the **connection probability** ; it **relates** the concepts of **probabilities** and **fluid fractions** (multiplicative under the Markovian assumption)

(Ser-Giacomi et al. (2015), PRE 92, 012818)

Betweenness calculation

One example of many possible MPP-based **centrality measures**

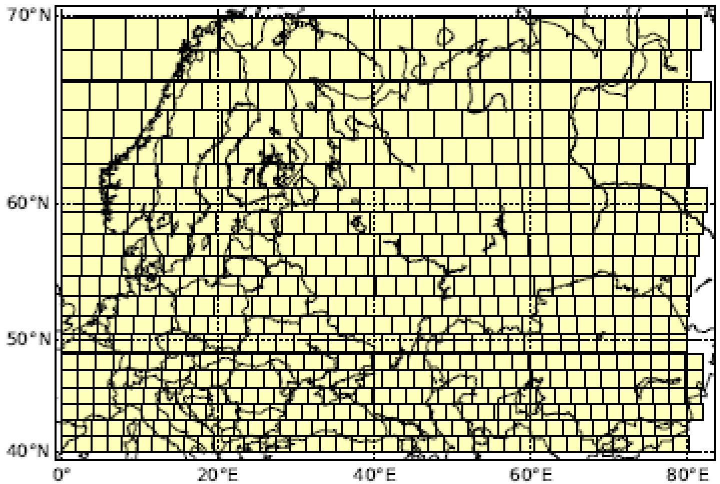
$$\mathcal{B}_K^M = \frac{\sum_{I,J} g_{IJ;K}}{N_M}$$

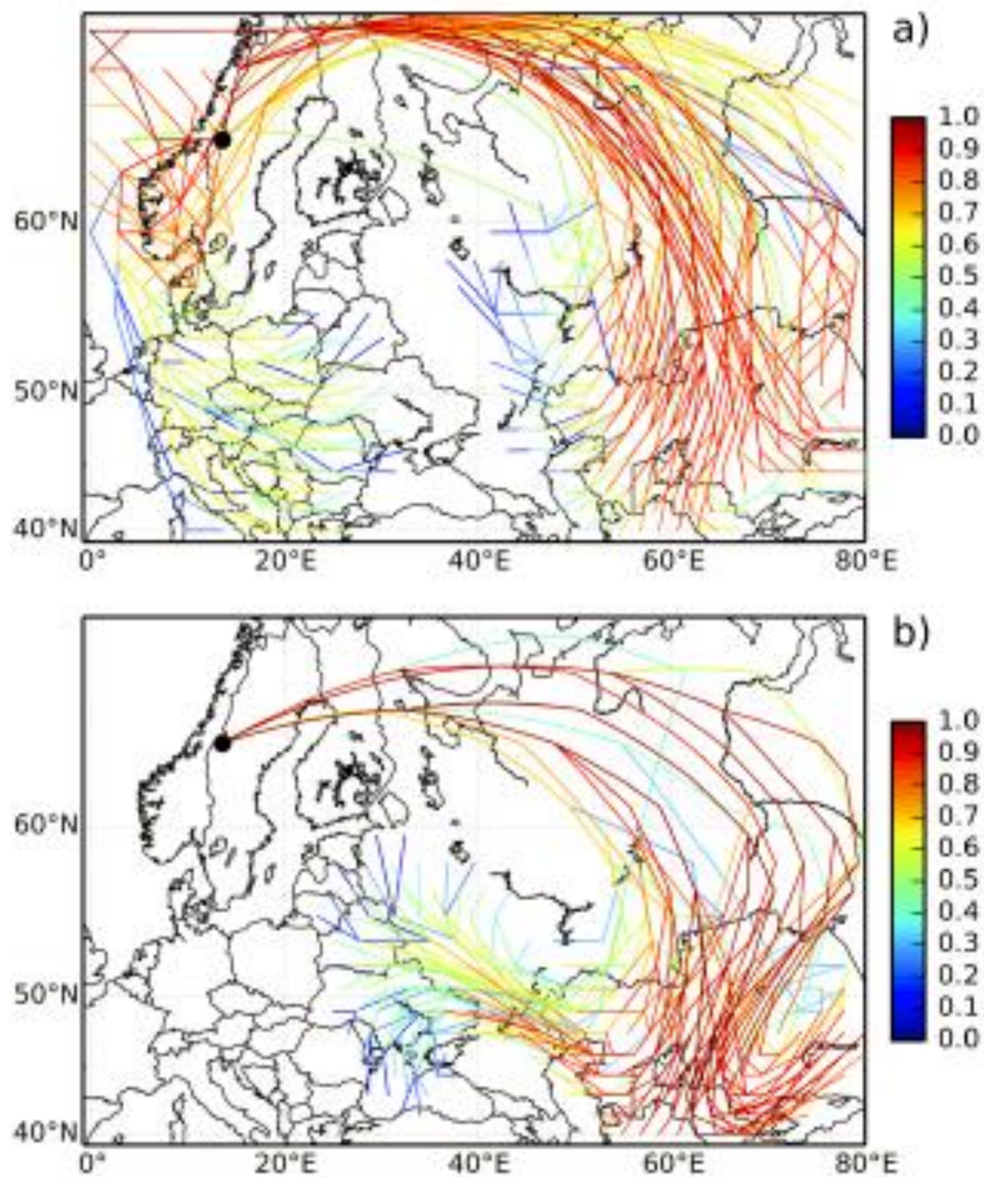


Interpretation:

One-dimensional-like structures corresponding to the **main corridors of transport**.

Atmosphere dynamics





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S Dominant transport pathways in an atmospheric blocking event CrossMark

Enrico Ser-Giacomi[1], Ruggero Vasile[2], Irene Recuerda[1], Emilio Hernández-García[1] and Cristóbal López[1]

+ VIEW AFFILIATIONS

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Chaos **25**, 087413 (2015); http://dx.doi.org/10.1063/1.4928704

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Conclusions & Perspectives

■ A simple paradigm that could explain many different features in a unified view.

■ Robust coarse-grained descriptions of complicated continuous systems.

■ Numerically cheap and flexible coding architecture.

■ Applications in marine Ecology (biological traits, non-conservative dynamics)

■ Concepts transferable to any type of transport network (not only geophysics).

Thanks for your attention!

Questions?

http://ifisc.uib-csic.es/users/vincent

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