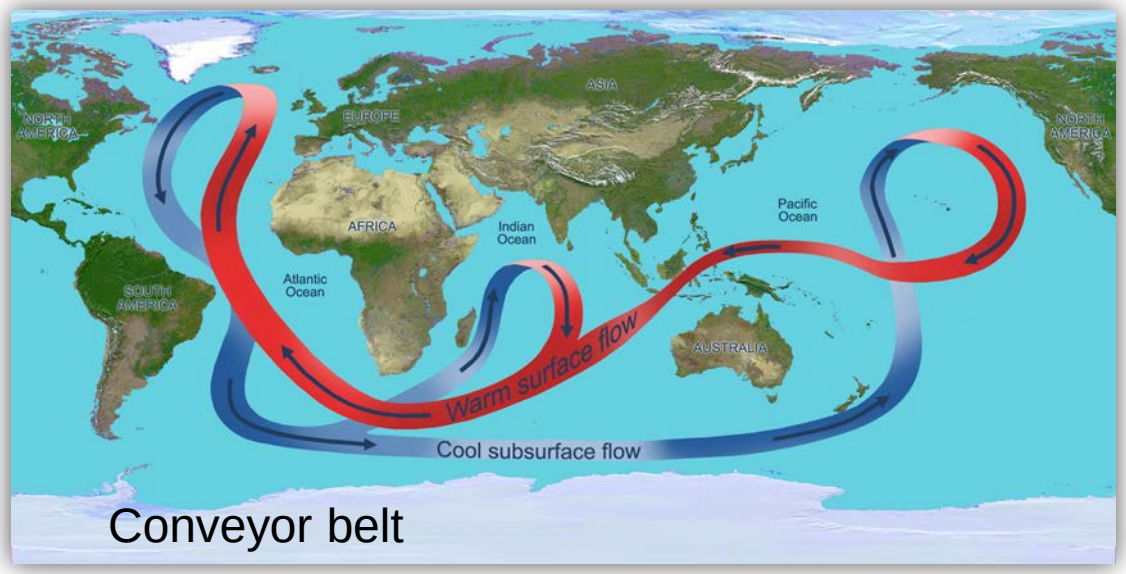
Connectivity bottlenecks in ocean flows characterized by the Lagrangian betweenness

EMILIO HERNÁNDEZ-GARCÍA
IFISC (CSIC-UIB),
Instituto de Física Interdisciplinar y Sistemas Complejos,
Palma de Mallorca, Spain

With Cristóbal López, Enrico Ser-Giacomi (IFISC, Mallorca)
Mick Follows (MIT, Cambridge)
Alberto Baudena (Sorbonne, Villefranche-sur-Mer)
Vincent Rossi (MIO, Marseille)
Sophie Clayton (Old Dominion, Norfolk (VA))
Ruggero Vasile (UP Transfer & GFZ, Potsdam)

OUTLINE

- Lagrangian Flow networks: network representation of fluid transport.
- Betweenness: a quantification of bottlenecks in networks and flows.
- Lagrangian betweenness: betweenness from Lyapunov exponents
- Bottlenecks in the ocean
- Conclusions



FLUID FLOWS: TRANSPORT OF WATER, MOMENTUM,HEAT, SUBSTANCES, BIOTA…

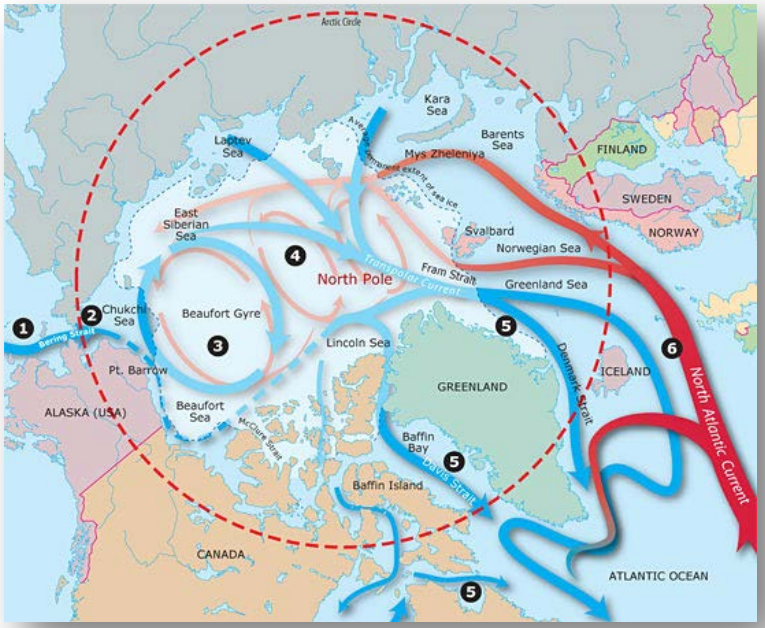
TRANSPORT: BARRIERS AND CONNECTIVITY

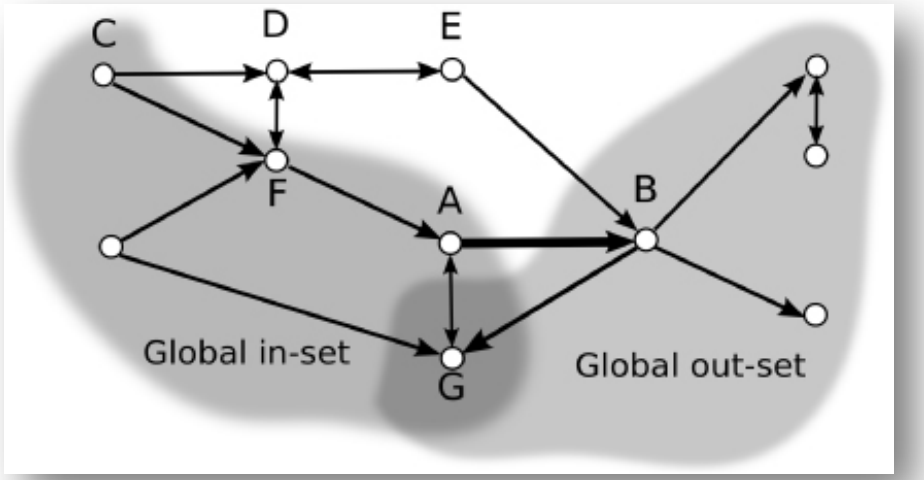
FLUID FLOW AS TRANSPORT NETWORKS

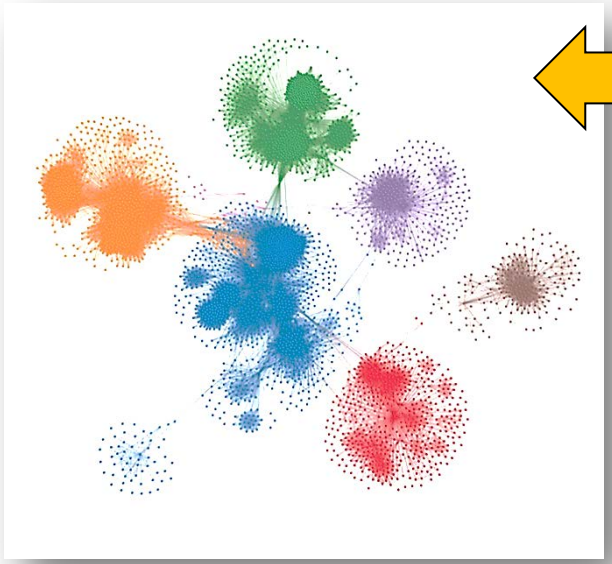
Lagrangian Flow Networks

Ser-Giacomi et al. (2015) Chaos 25, 036404

Powerful techniques of network theory become available



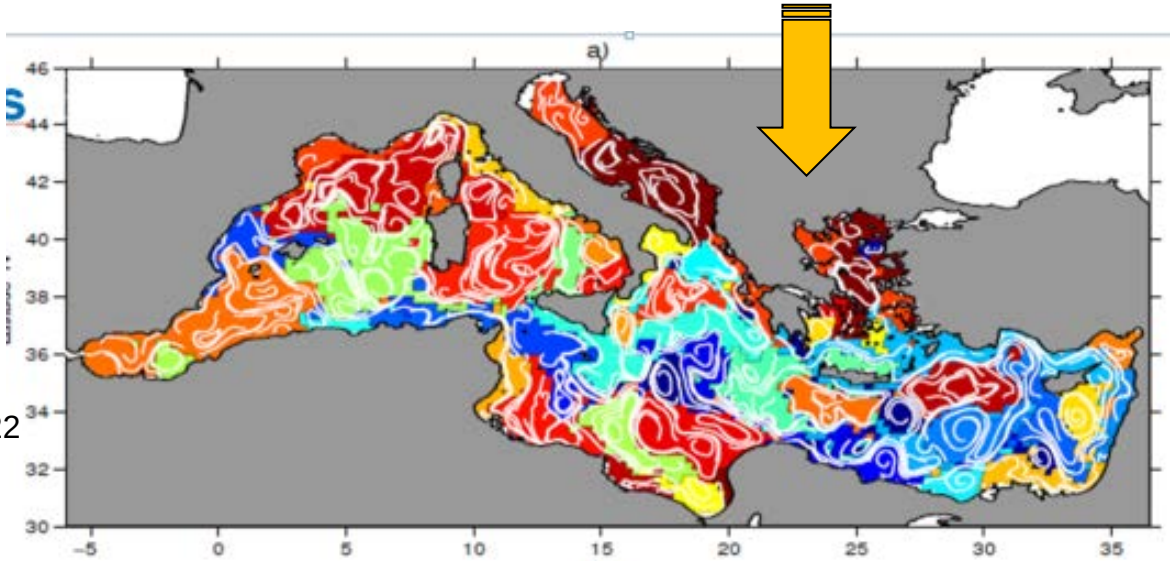




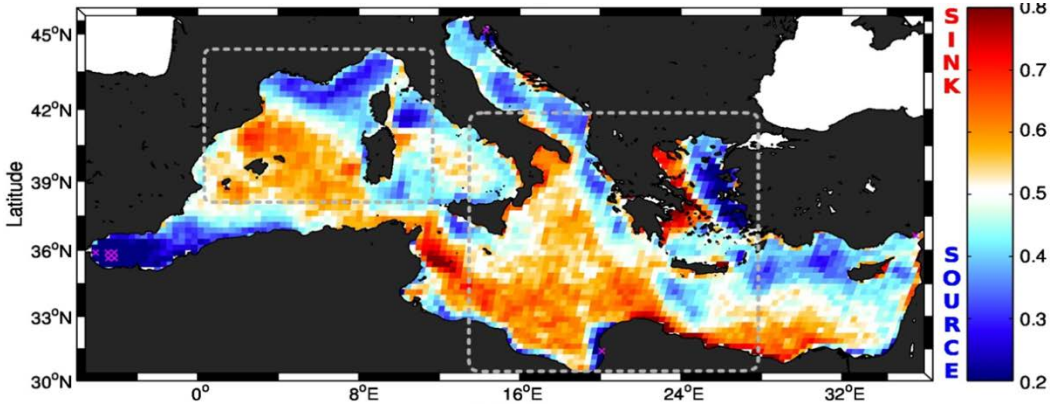
Facebook network,Fortunato & Newman, Nature 2022

PARTITION IN COMMUNITIES

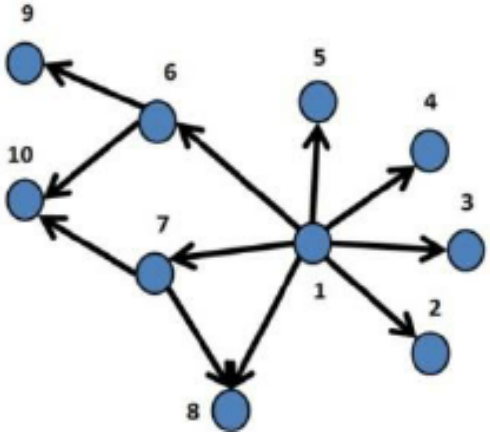
MARINE PROVINCES



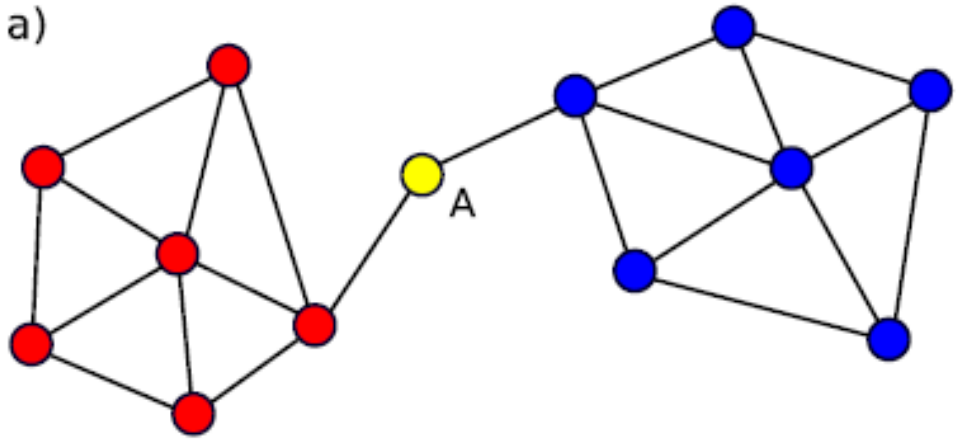
Ser-Giacomi et al. (2015), Chaos 25, 087413, Rossi et al. (2014), Geophys Res Lett 41, 2883



SOURCES AND SINKS

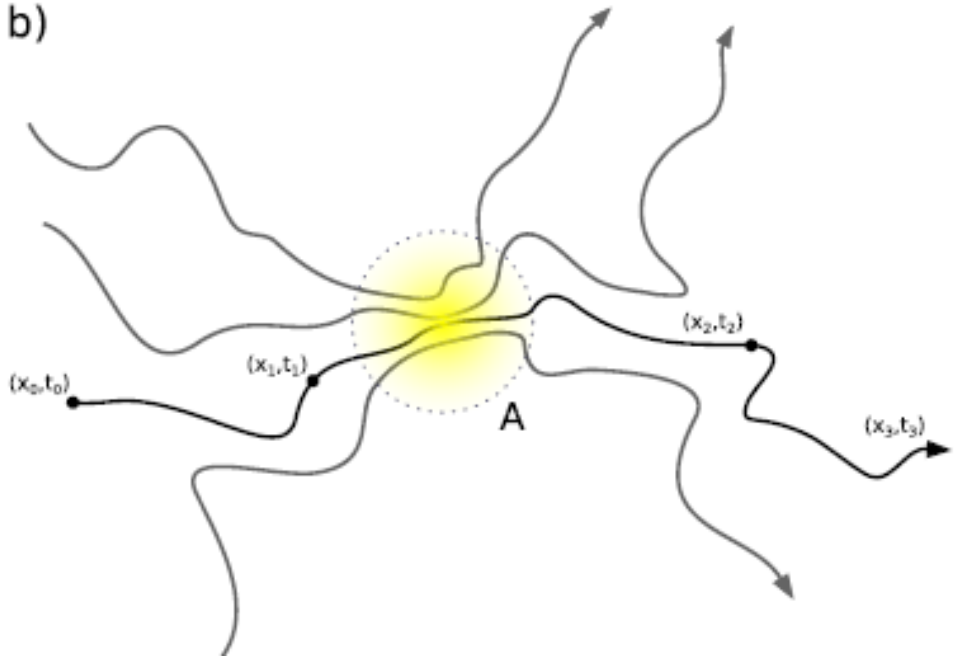


Dubois, Rossi, Ser-Giacomi, Arnaud-Haond, Lopez, Hernandez-Garcia, Global Ecology and Biogeography **25**, 503 (2016)



Betweenness in networks:

Bi = Proportion of optimal paths (shorter, faster, most probable, maximum flow, …) crossing node *i* among all optimal paths between all pairs of nodes



Betweenness in flow networks or dynamical systems:

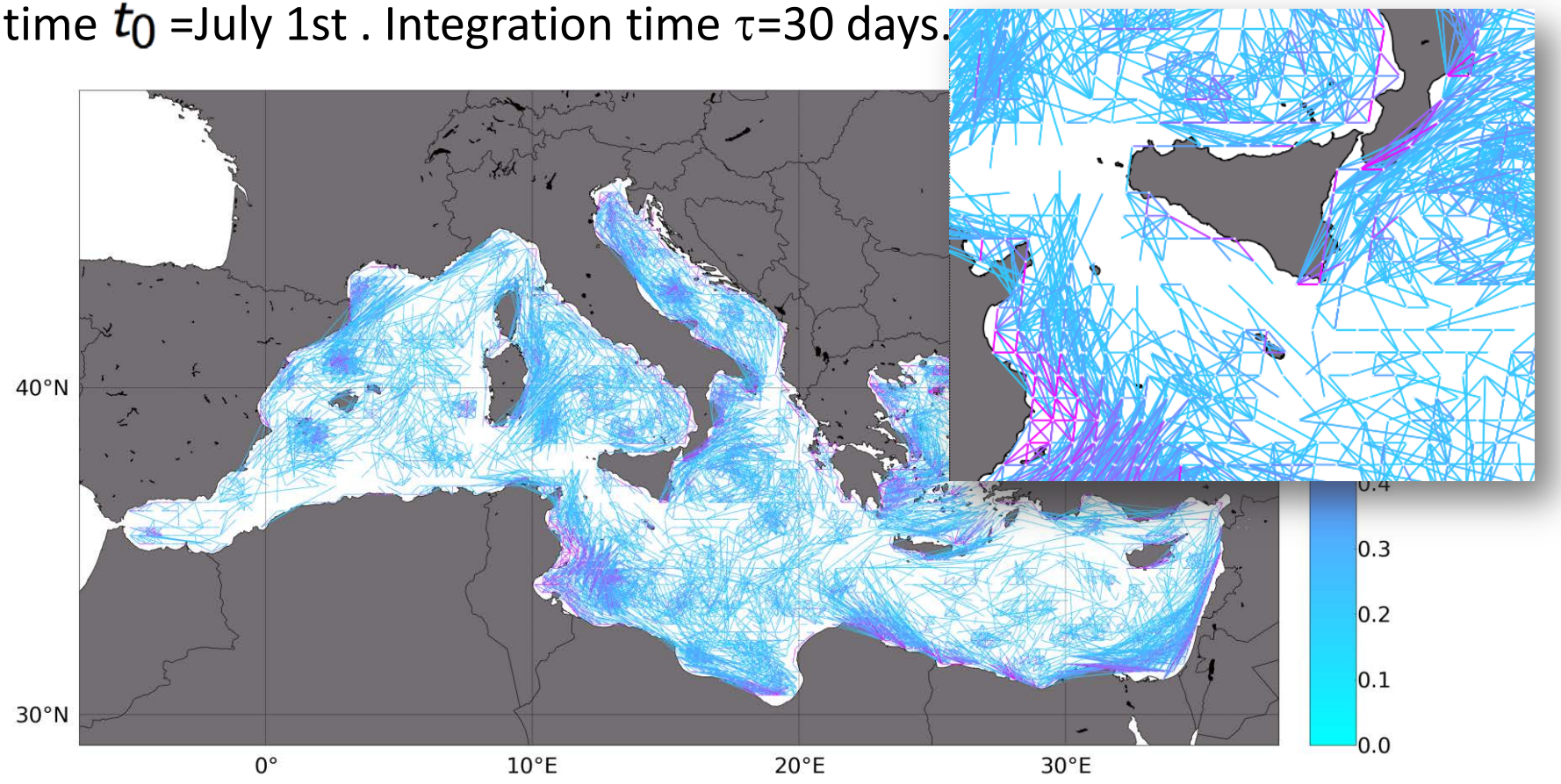
Flow bottlenecks

Importance: mixing, dispersion, ecological hot spots, …

Ser-Giacomi, Baudena, Rossi, Follows, Clayton, Vasile, López, Hernández-García, Nature Comm. **12**:4935 (2021)

Example of LAGRANGIAN FLOW NETWORK construction

start at time t_0 =July 1st . Integration time τ=30 days.



Lagrangian Flow network

$P_{ij}(t_0, \tau)$

Probability for a Lagrangian tracer to be in location `j` after a time τ if starting in location `i` at time t_0.

STANDARD CONSTRUCTION OF BETWEENNESS IN FLOW NETWORKS

Example: Surface circulation in the Mediterranean (2002-2011)

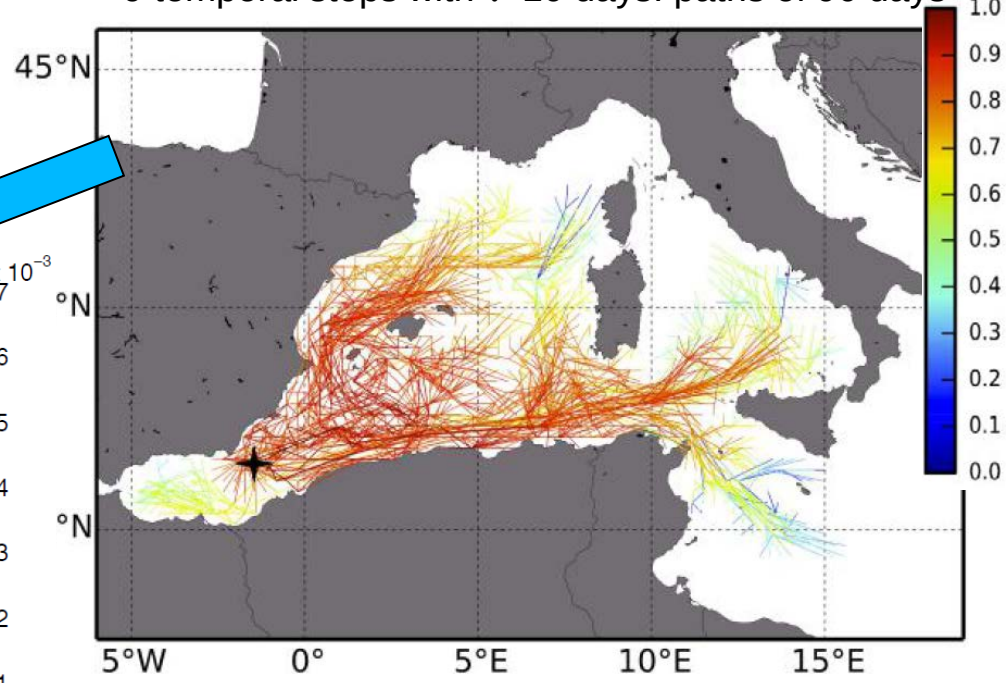
Ser-Giacomi et al, Physical Review E **92**, 012818 (2015)

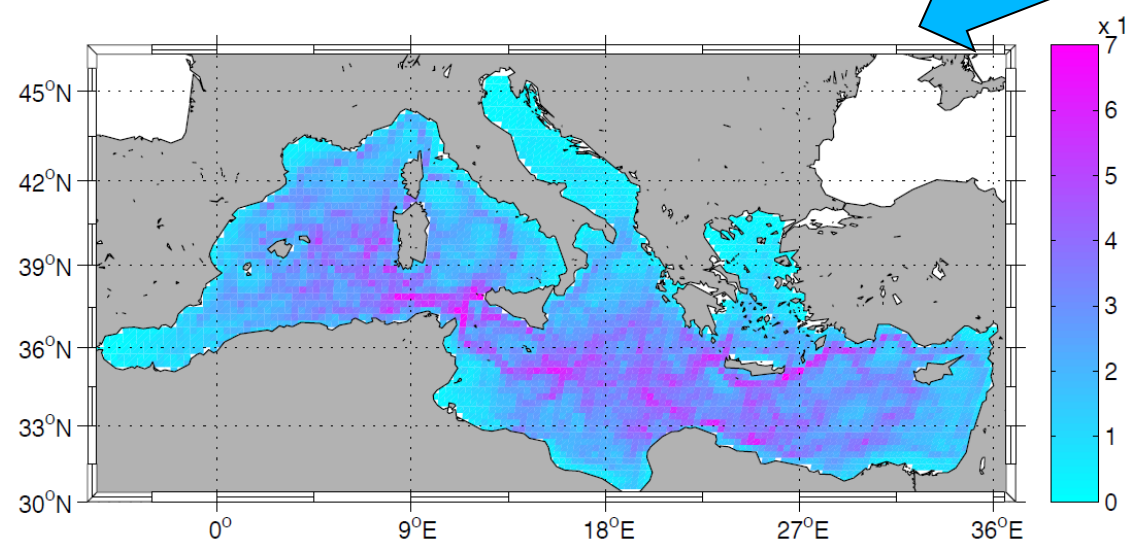
Lagrangian Flow network

$P_{ij}(t_0, \tau)$

t_0 = January 1st 2011

9 temporal steps with τ=10 days: paths of 90 days



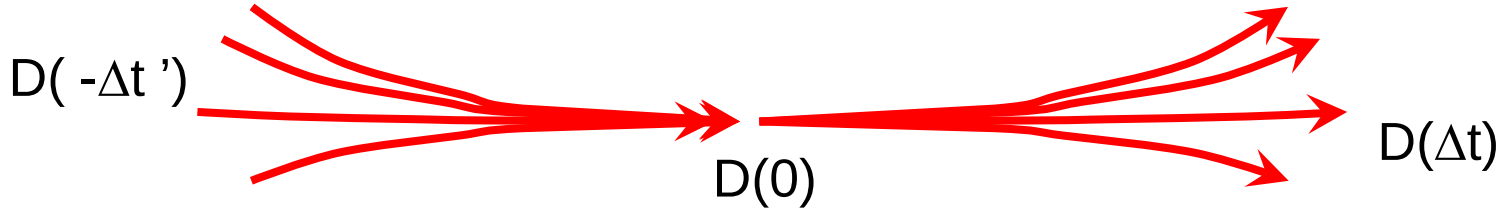


Most-probable paths between locations.
Dijkstra-type algorithms in
Ser-Giacomi et al, Chaos **25**, 087413 (2015),
Physical Review E **92**, 012818 (2015)

MPP-Betweenness: bottlenecks of the flow (2002-2011)

In fluids or dynamical systems –

(Finite Time)Lyapunov exponent: rate of divergence of close trajectories



$D(-\Delta t') = D(0)\exp[\,\lambda(\mathbf{x_0},t_0,-\Delta t')\,\Delta t'\,]$ $D(\Delta t) = D(0)\exp[\,\lambda(\mathbf{x_0},t_0,\Delta t)\,\Delta t\,]$

This motivates: Definition of **LAGRANGIAN BETWEENNESS** AT POINT $\mathbf{x}_i$ AND TIME t_0=0, for trajectories of duration τ :

$$B_i^L(0,\tau) = \frac{1}{\tau}\int_0^\tau e^{t\lambda(\mathbf{x}_i,t,-t)}\, e^{(\tau-t)\lambda(\mathbf{x}_i,t,\tau-t)}\, dt.$$

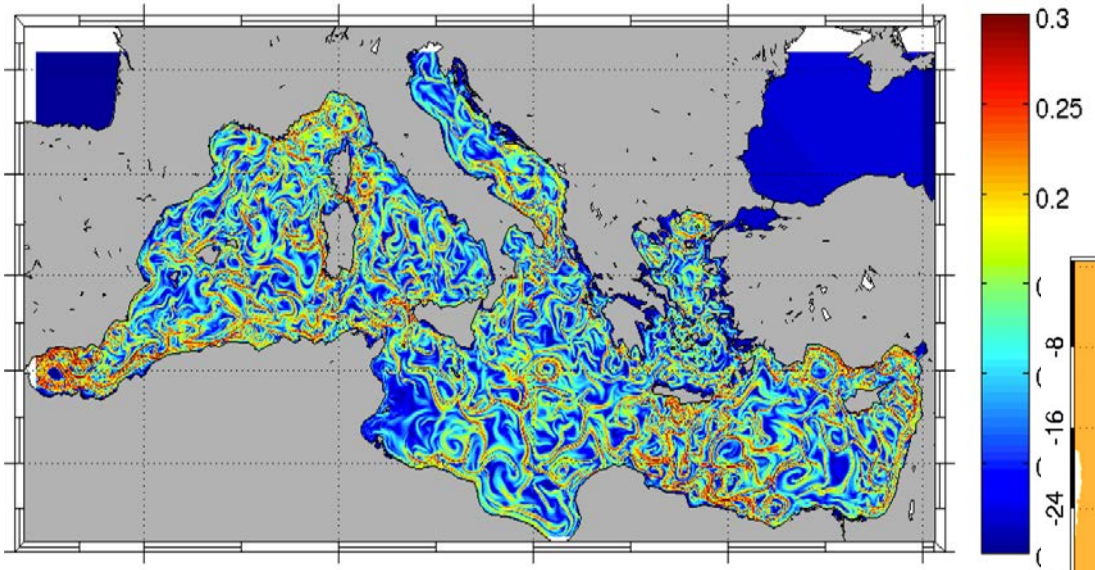
Ser-Giacomi, et al, Nature Comm. **12**:4935 (2021)

Computationally easier, numerically similar to MPP-betweenness

In Lagrangian Flow networks, quantitative relationship between
Finite-time (local) Lyapunov exponent $\lambda(x_0,t_0,\tau)$
and **out-degree** Kout(i)
(Ser-Giacomi et al. Chaos 25, 036404 (2015))

$$\left\langle e^{\tau\lambda(\mathbf{x}_0,t_0,\tau)}\right\rangle_{B_i} \approx \text{Kout(i)}$$

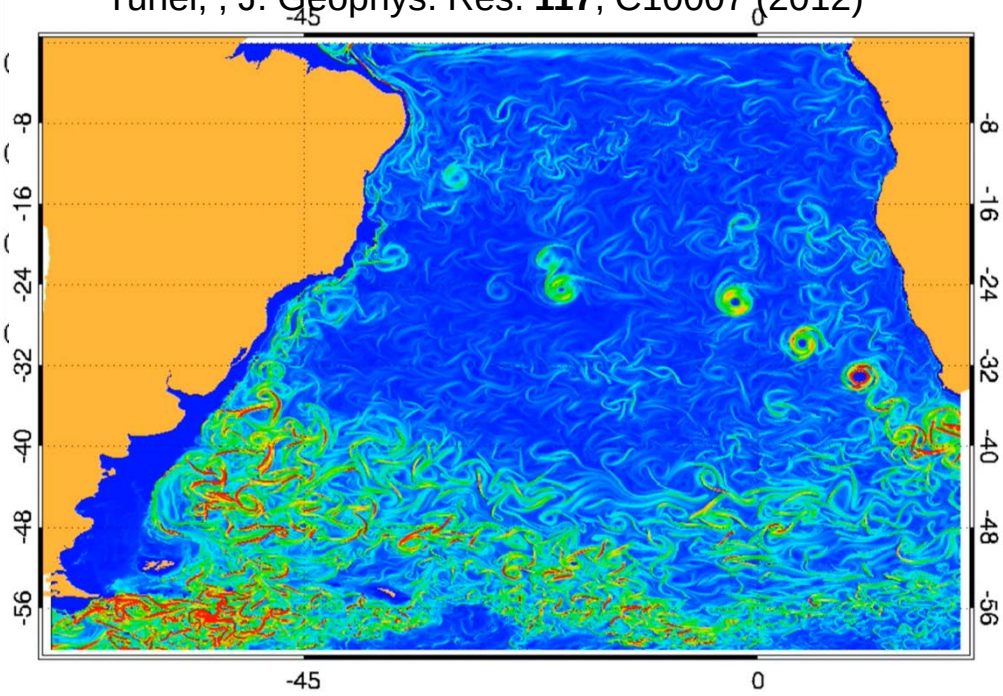
LYAPUNOV EXPONENT FIELDS IN SURFACE CIRCULATION

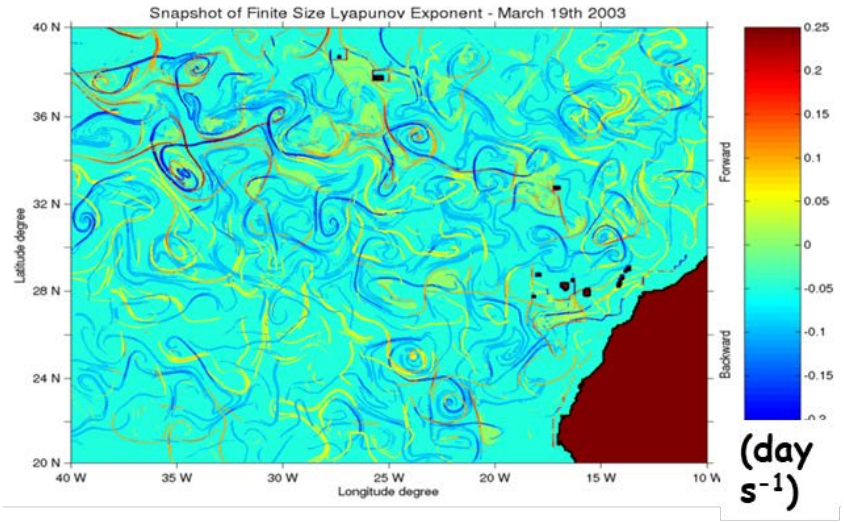


Input: velocity fields from simulations, reanalysis or altimetry

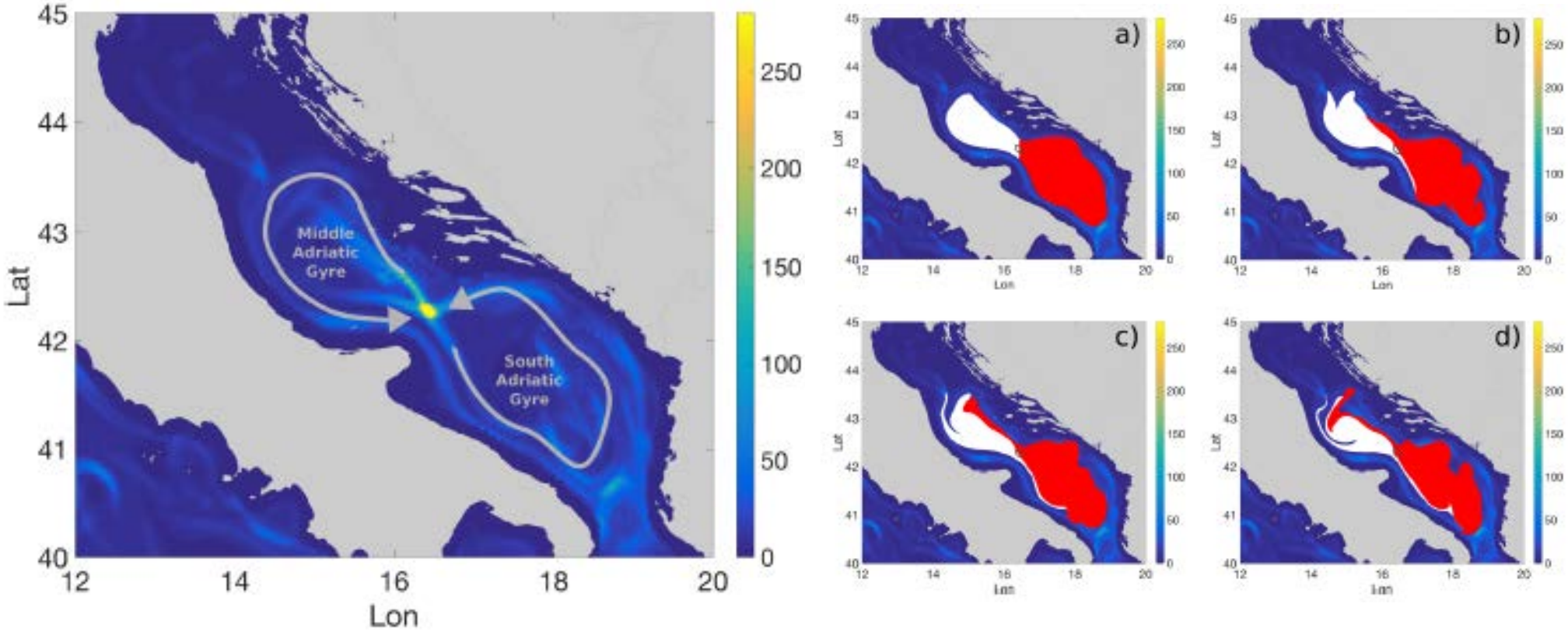
Ser-Giacomi et al. (2015), Chaos 25, 087413,

Hernández-Carrasco, López, Hernández-García, Turiel, , J. Geophys. Res. **117**, C10007 (2012)





Rossi, Hernández-Carrasco et al., Geophys, Res. Lett. 2008, Nonlin. Proc. Geophys. 2009, Deep Sea Research I, 2014

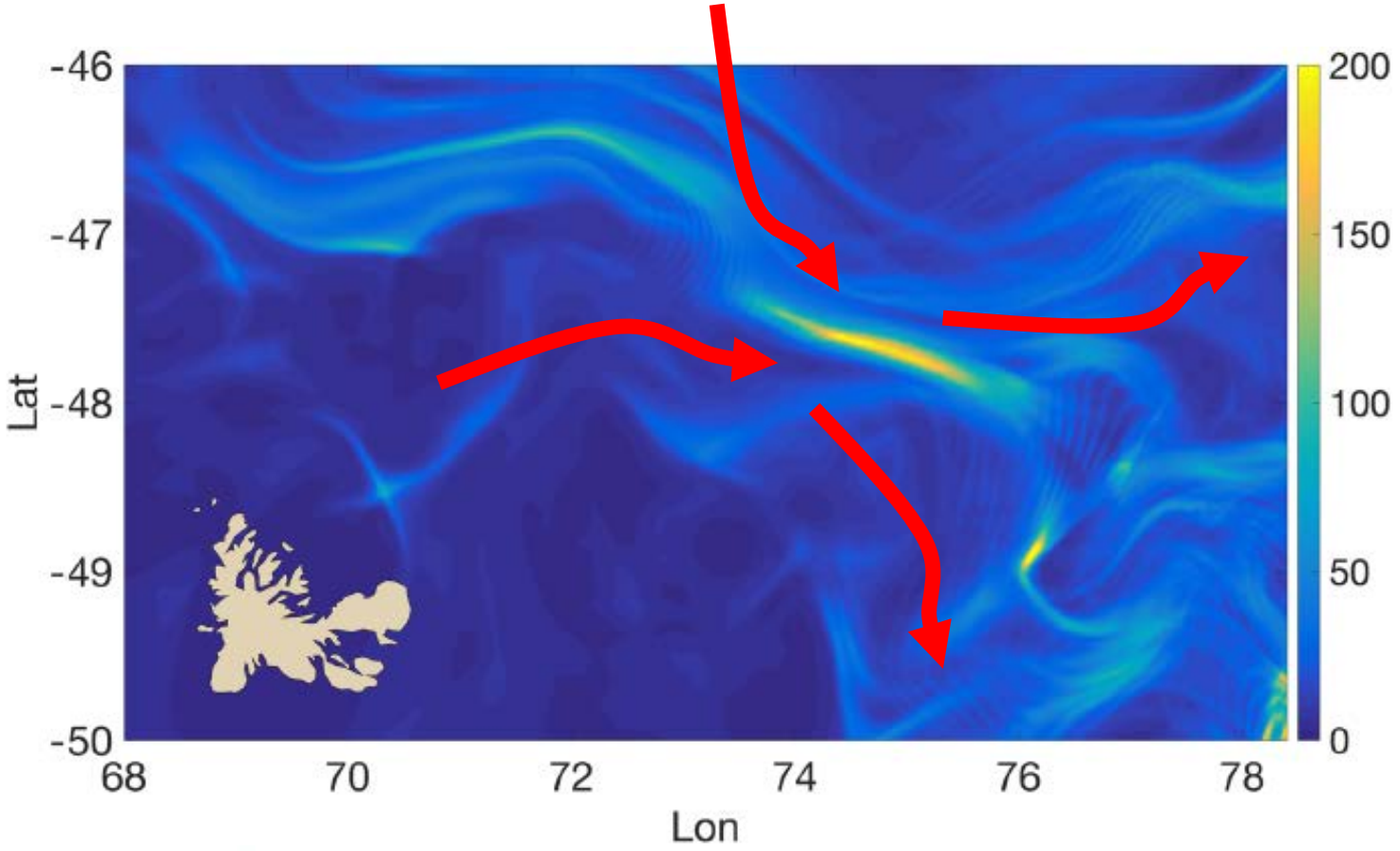


Lagrangian betweenness in the Adriatic sea (13 Dec. 2013. τ= 15 days). Currents's data from Med Copernicus reanalysis at (1/16)º.

Time evolution of (red and white) water mases, to show the bottleneck character of the high-betweenness zones.

Ser-Giacomi, Baudena, Rossi, Follows, Clayton,Vasile, López, Hernández-García, Nature Comm. **12**:4935 (2021)

Betweenness in the Kerguelen

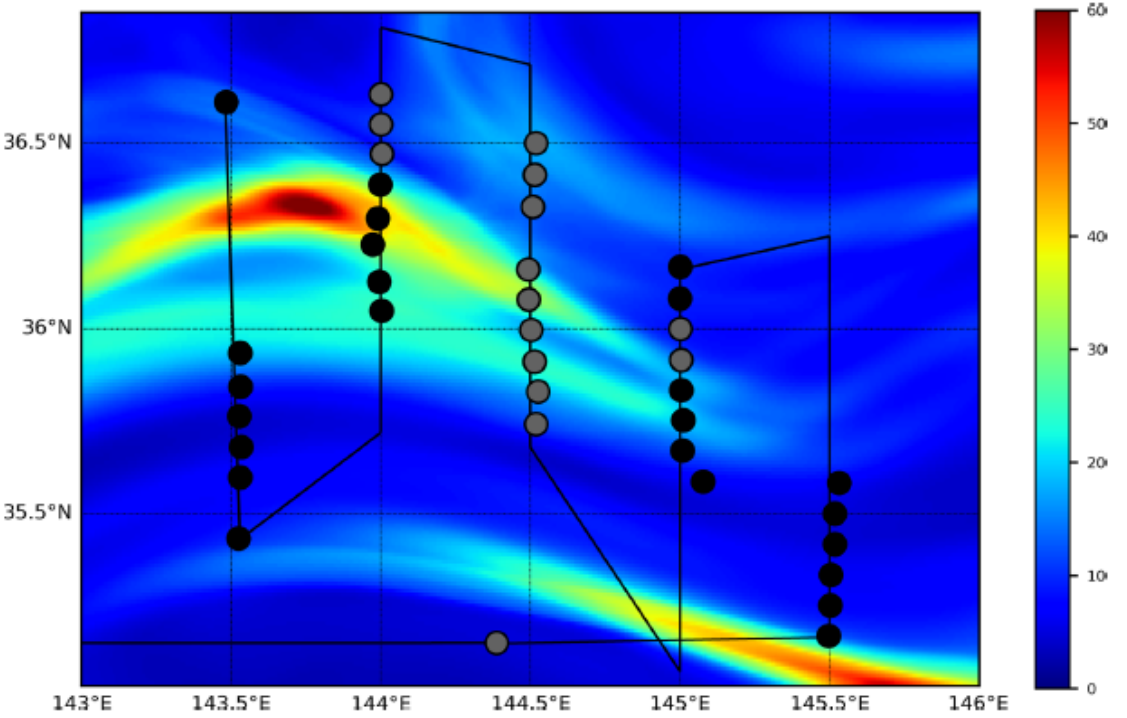


Kerguelen region (Southern ocean), τ=20 days, December 2007

Velocities from SSALTO/DUACS Altimetry

Betweenness and biodiversity

Betweenness in the Kuroshio extension front (North Pacific). Velocities from GLORYS12V1 reanalysis.
20 October 2009, τ=7 days



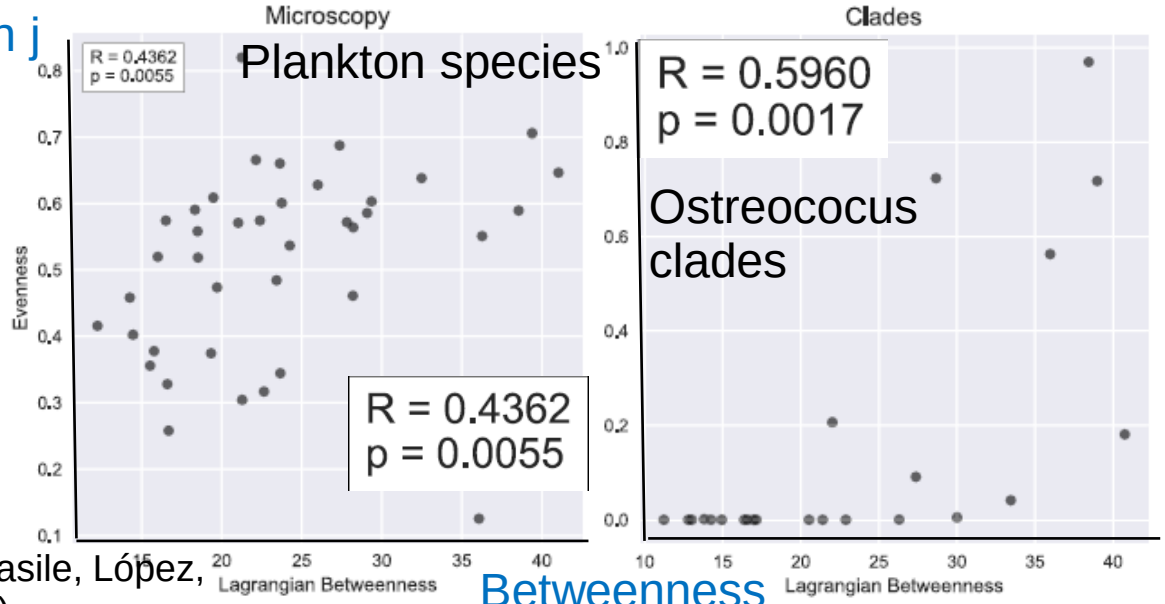
Cruise measurements of planktonic diversity

- Microscopy-based plankton species
- Phylogenetically derived abundances of Ostreococcus clades

Ej= Evenness at location j

$$E_j = -\frac{\sum_i p_i \log(p_i)}{\log(S_j)}$$

pi = relative species abundances
S= # of species



Ser-Giacomi, Baudena, Rossi, Follows, Clayton,Vasile, López, Hernández-García, Nature Comm. **12**:4935 (2021)

CONCLUSIONS

- The concept of betweenness can be extended from the network context to fluid flows and dynamical systems, by relating it to Lyapunov exponents: **Lagrangian betweenness.**
- Locations with large Lagrangian betweenness identify circulation **bottlenecks**: regions in which flow is constrained: fluid parcels from different origins first converge and then diverge.
- **High betweenness** regions are seen to be **hot spots of biodiversity**.

Ser-Giacomi, Baudena, Rossi, Follows, Clayton,Vasile, López, Hernández-García, Nature Comm. **12**:4935 (2021)

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

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