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Looking for indicators to qualify coastal area dispersion capability

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Introduction

- A large and frequent demand for characterising coastal areas in simplified way
  - Policy makers / Stakeholders
  - Water Framework Directive
  - Scientist community

- Interpret a manifold of processes and observations
  - Fate of continental runoffs
  - Biological eutrophication impacts
  - Any kind of pollution (*e.g.* microplastics, virus)
  - Larvae dispersal, bivalve recruitments


Bloom


Microplastics


Flat oyster larvae

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- Monsen *et al.* (2002). The use of flushing time, residence time, and age as transport time scales. *Limnology and Oceanography*
- Deleersnijder *et al* (2001). The concept of age in marine modelling I. Theory and preliminary model results. *Journal of Marine Systems*
- Delhez *et al.* (2004). Residence time in a semi-enclosed domain from the solution of an adjoint problem. *Estuarine. Coastal and Shelf Science*
- Delhez (2006). Transient residence and exposure times. *Ocean Science*
- Cucco, Umgiesser (2006). Modeling the Venice lagoon water residence time. *Ecological Modelling*
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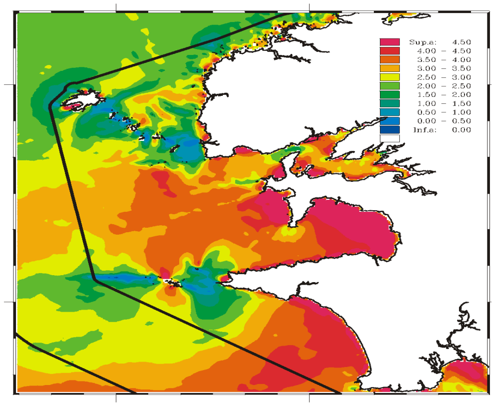
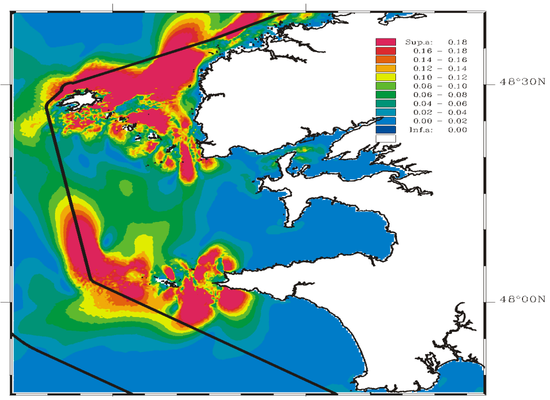
- de Brauwere *et al* (2011). Residence time, exposure time and connectivity in the Scheldt Estuary. *Journal of Marine System*
- Delhez *et al.* (2014) Residence time vs influence time. *Journal of Marine Systems*
- Viero *et al.* (2016). Water age, exposure time, and local flushing time in semi-enclosed, tidal basins with negligible freshwater inflow. *Journal of Marine Systems*

Indicators review : what is known ?

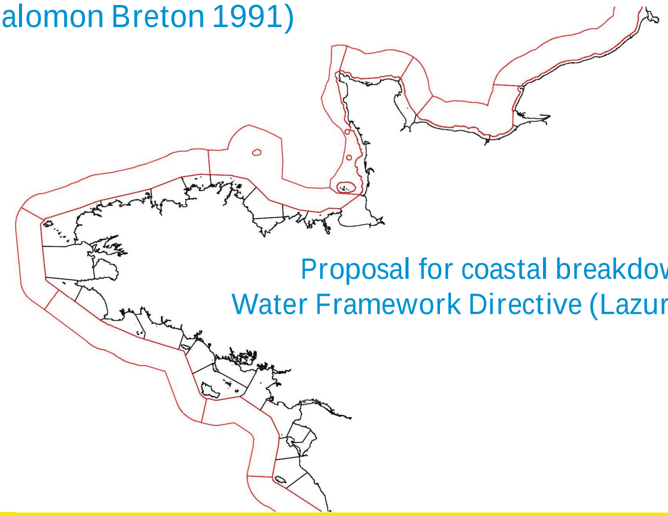
- Notion of transport
  - Residual circulations
  - Connectivity between areas (MPAs)
  - Transport matrix method



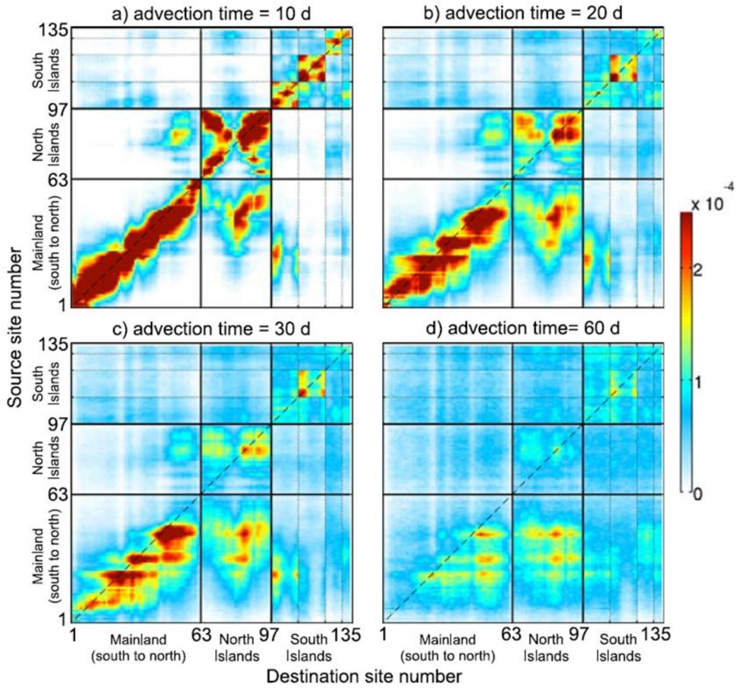
Intensity of tidal residual currents (Salomon Breton 1991)



Simpson Hunter criterion (1974)



Proposal for coastal breakdown Water Framework Directive (Lazure 2005)

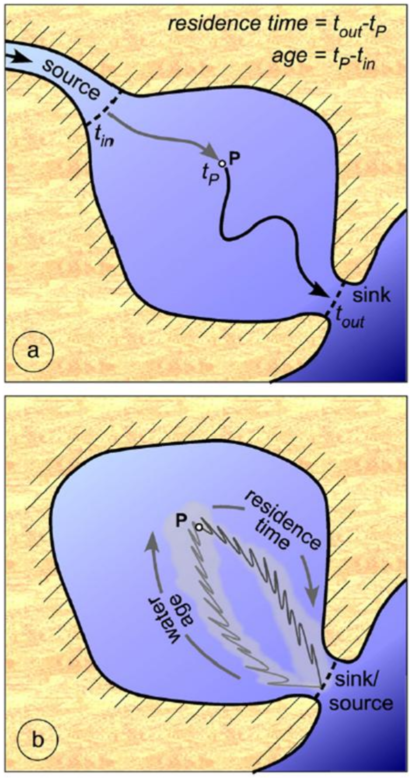


Mitarai *et al* (2009)

Indicators review : what is known ?

- Notion of transport
  - Residual circulations
  - Connectivity between areas (MPAs)
  - Transport matrix method

- Concepts of time
  - Flushing time / Local flushing time
  - Water age / Residence time
  - Influence time / Exposure time



Viero, Defina (2016)

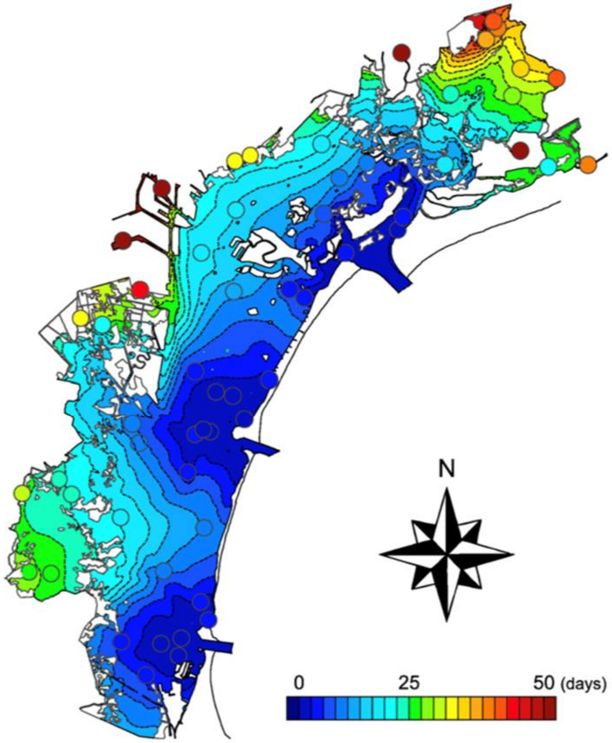
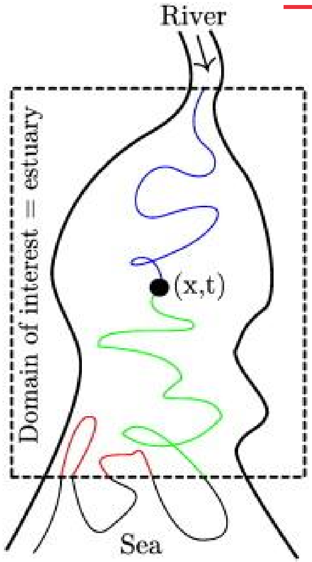


Fig. 8. Comparison between the 1/e threshold exposure time calculated using the adjoint approach by (Delhez et al., 2004) (color-graded map) and the standard forward approach (color-graded circles).



de Brye *et al* (2013)

Indicators review : what is known ?

- Notion of transport
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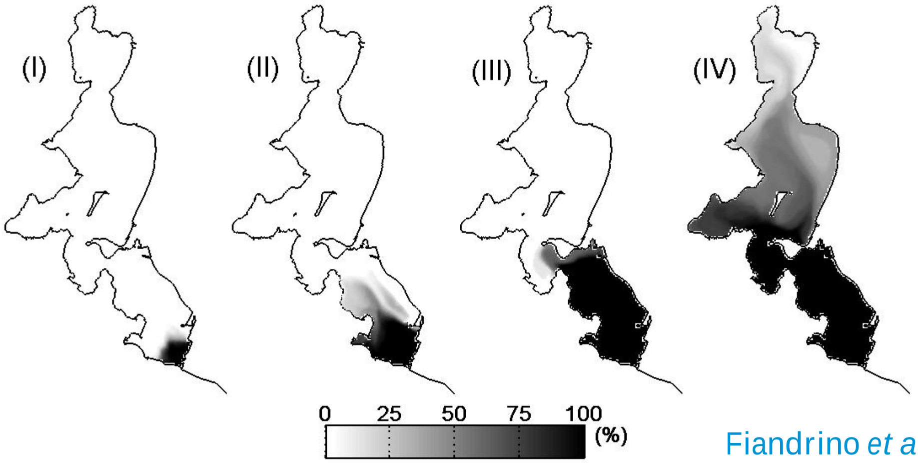
  - Transport matrix method

- Concepts of time
  - Flushing time / Local flushing time
  - Water age / Residence time
  - Influence time / Exposure time

- Notion of volume



Fiandrino *et al* (2017)

Maps of probabilities for cells in the lagoon to belong to the Marine Mixed Volume V_{MM} of the lagoon at different timescale

It generally applies to a large volume of control with a thin ocean entrance : lagoon / inside bay

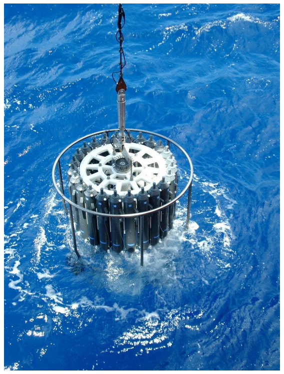
➔ Depends on the typology of areas

Flung wide open domain ?

Semi-enclosed area with large exchange fluxes ?

Objectives

- Try to exhibit an indicator that might be call a « dispersiometer »

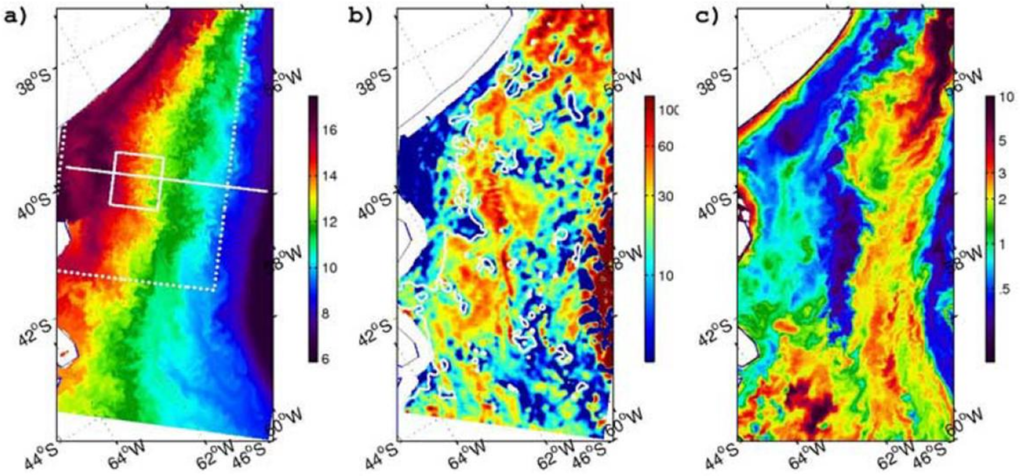


- Requirements :
  - Must be local
  - Must give at a glance a measurement / indicator
  - Must be suited to a macro-tidal coastal environment
  - Must be intrinsic (independent of the field that is being dispersed) or inherent to the fluid regime

An approach from Capet *et al* (2008)
Submesoscale activity over the Argentinian shelf. GRL

$$\kappa_s = -\frac{\langle \tilde{\mathbf{u}}\tilde{T}\rangle_s \cdot \nabla_h \langle T\rangle_s}{|\nabla_h \langle T\rangle_s|^2}$$

- Assumptions:
  - Homogeneous turbulence
  - None advective area
  - Isotropic property



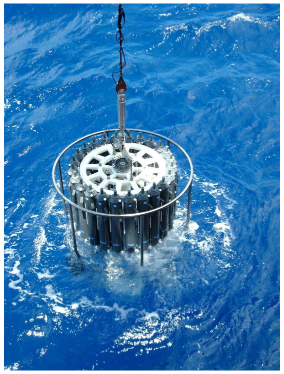
Modelled sea temperature

Horizontal diffusivity κ_s

Seawifs chlorophyll

Objectives

- Try to exhibit an indicator that might be call a « dispersiometer »



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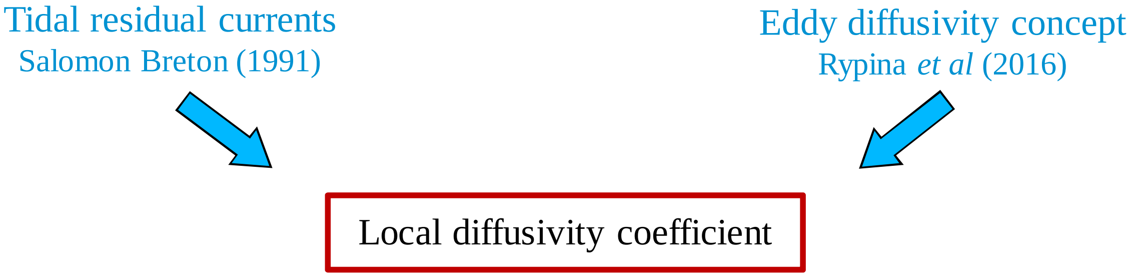
➔ Combination of two lagrangian approaches



Tidal residual currents
Salomon Breton (1991)

Eddy diffusivity concept
Rypina *et al* (2016)

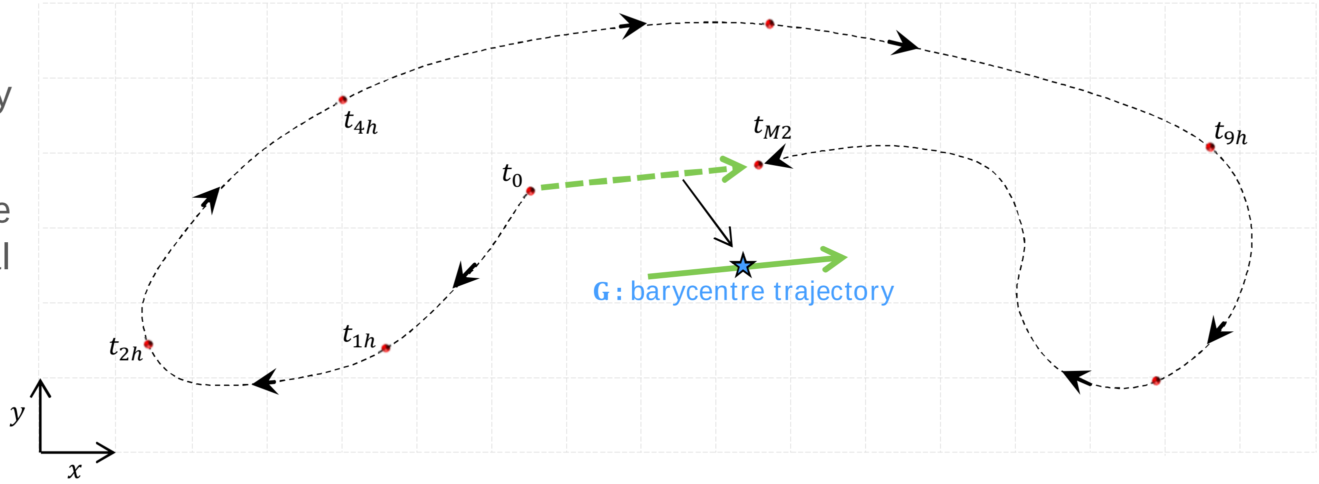
Local diffusivity coefficient

Method : residual tidal currents

Steady simulation

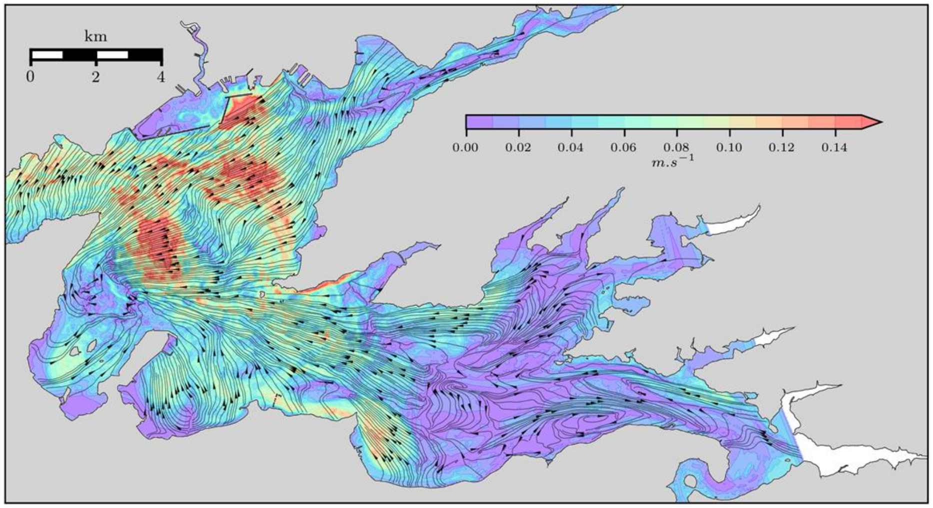
Follow a single particle trajectory during exactly 1 tidal cycle T_{M_2}

Estimate residual current from the distance between initial and final positions

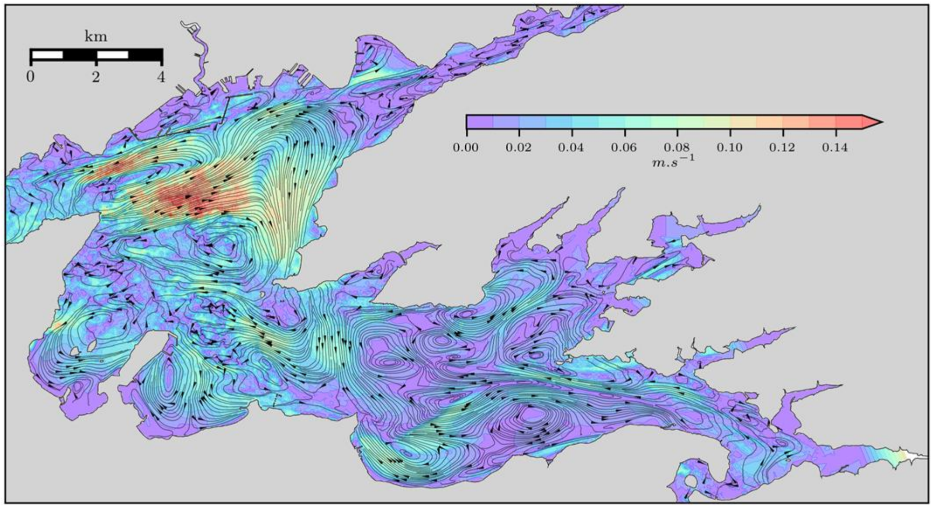


$$\overrightarrow{U_{res}} = \frac{x_{M_2} - x_0}{T_{M_2}} \qquad \overrightarrow{V_{res}} = \frac{y_{M_2} - y_0}{T_{M_2}} \qquad L = \frac{1}{T_{M_2}} \int_0^{T_{M_2}} \sqrt{dx^2 + dy^2}\, dt$$

➔ Barycentre repositioning sharpen the residual current field



Residual tidal currents for mean tide conditions



Residual tidal currents after barycentric repositioning

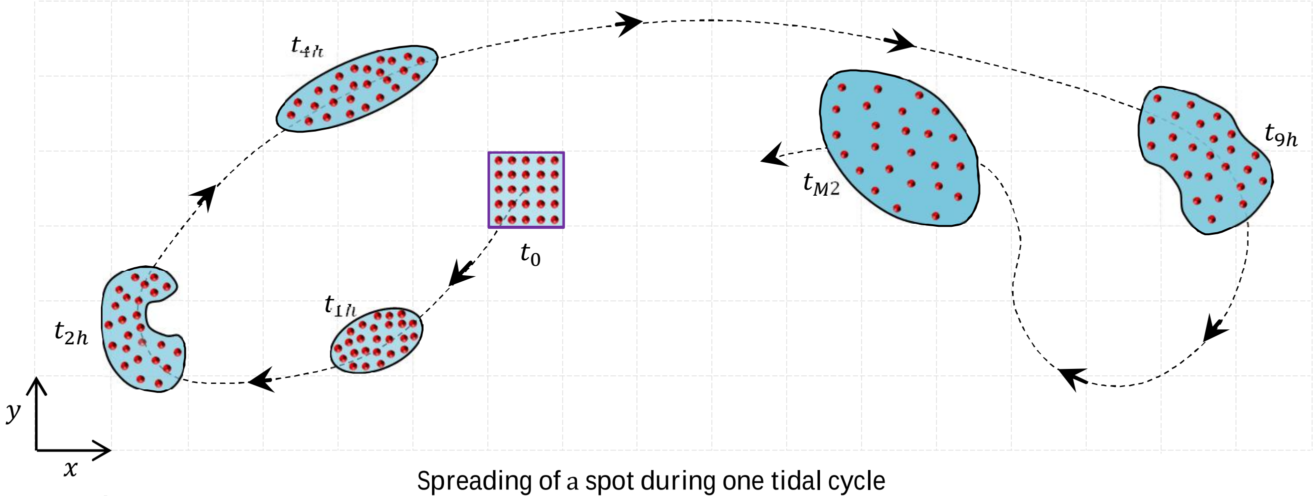
Salomon, Breton (1991). *Numerical study of the dispersive capacity of the bay of Brest, France towards dissolved substances. EH*

Method : local diffusivity coefficient

Steady simulation

Follow a patch of particles trajectories during exactly 1 tidal cycle T_{M_2}

Estimate diffusivity coefficient from the spreading of the spot between the initial and final positions



Spreading of a spot during one tidal cycle

For each grid cell : N virtual floats

- ➔ Evenly distributed with respect to x and y
- ➔ Randomly distributed over z

$$\Delta X(t) = \frac{1}{N}\sum_{n=1}^{N}\Delta x_n(t)$$

Δx_n: Zonal displacement of the n^th^ particle from its initial position

Δy_n: Meridional displacement of the n^th^ particle from its initial position

$$\Delta Y(t) = \frac{1}{N}\sum_{n=1}^{N}\Delta y_n(t)$$

$\left.\begin{matrix}\Delta X(t)\\ \Delta Y(t)\end{matrix}\right\}$ Ensemble-mean displacements (or barycentre movement)

$$D_{xx}(t;y) = \frac{1}{N}\sum_{n=1}^{N}[\Delta x_n(t) - \Delta X(t)]^2$$

Single particle dispersion tensor
for a group of N particles

$$D = \begin{pmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{pmatrix}$$

$$D_{xy}(t;y) = \frac{1}{N}\sum_{n=1}^{N}[\Delta x_n(t) - \Delta X(t)][\Delta y_n(t) - \Delta Y(t)]$$

$$D_{yy}(t;y) = \frac{1}{N}\sum_{n=1}^{N}[\Delta y_n(t) - \Delta Y(t)]^2$$

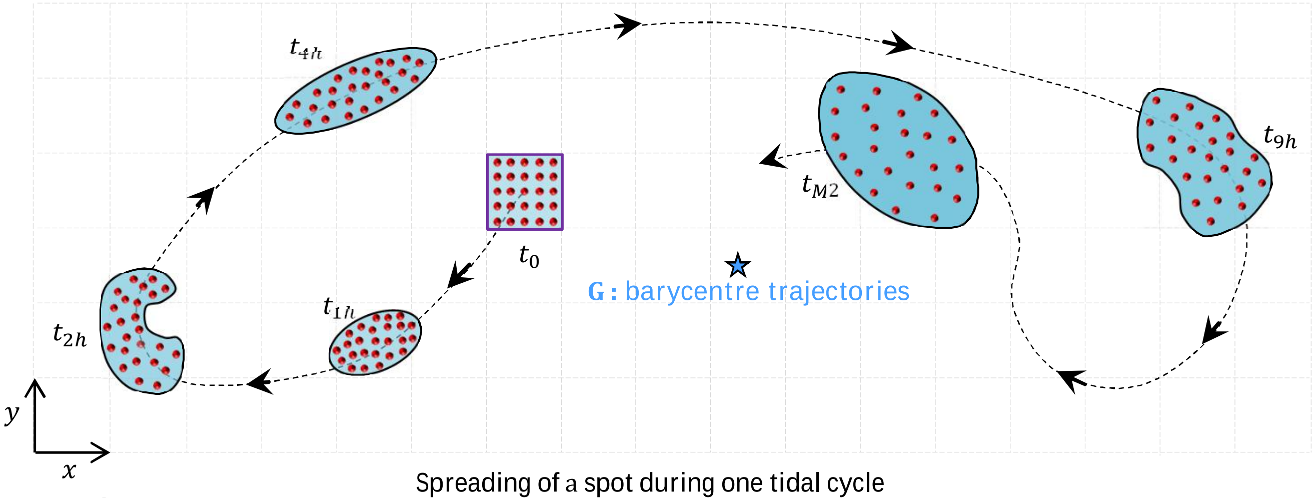
Rypina et al. (2016). *Investigating the Eddy Diffusivity Concept in the Coastal Ocean. JPO*

Method : local diffusivity coefficient

Steady simulation

Follow a patch of particles trajectories during exactly 1 tidal cycle T_{M_2}

Estimate diffusivity coefficient from the spreading of the spot between the initial and final positions



Spreading of a spot during one tidal cycle

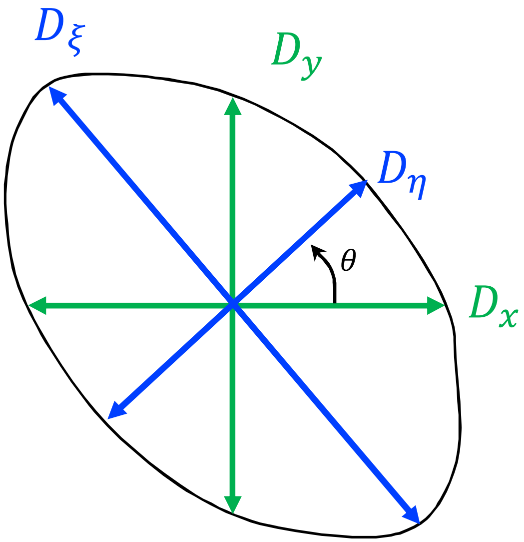
For each grid cell : N virtual floats

- ➔ Evenly distributed with respect to x and y
- ➔ Randomly distributed over z

$$\begin{pmatrix} D_\xi & 0 \\ 0 & D_\eta \end{pmatrix} = R^{-1} \begin{pmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{pmatrix} R$$

$$R = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$\tan(2\theta) = 2D_{xy} / (D_{xx} - D_{yy})$$



$$\boldsymbol{K_\xi(t) = \frac{1}{2}\frac{\partial D_\xi}{\partial t} \qquad K_\eta(t) = \frac{1}{2}\frac{\partial D_\eta}{\partial t}}$$

$$\boldsymbol{K(m^2.s^{-1}) = \mathrm{MAX}\ (K_\xi, K_\eta)}$$

→ $\boldsymbol{T_{M2} = 44712\ s \simeq 12h25}$

→ Barycentre repositioning

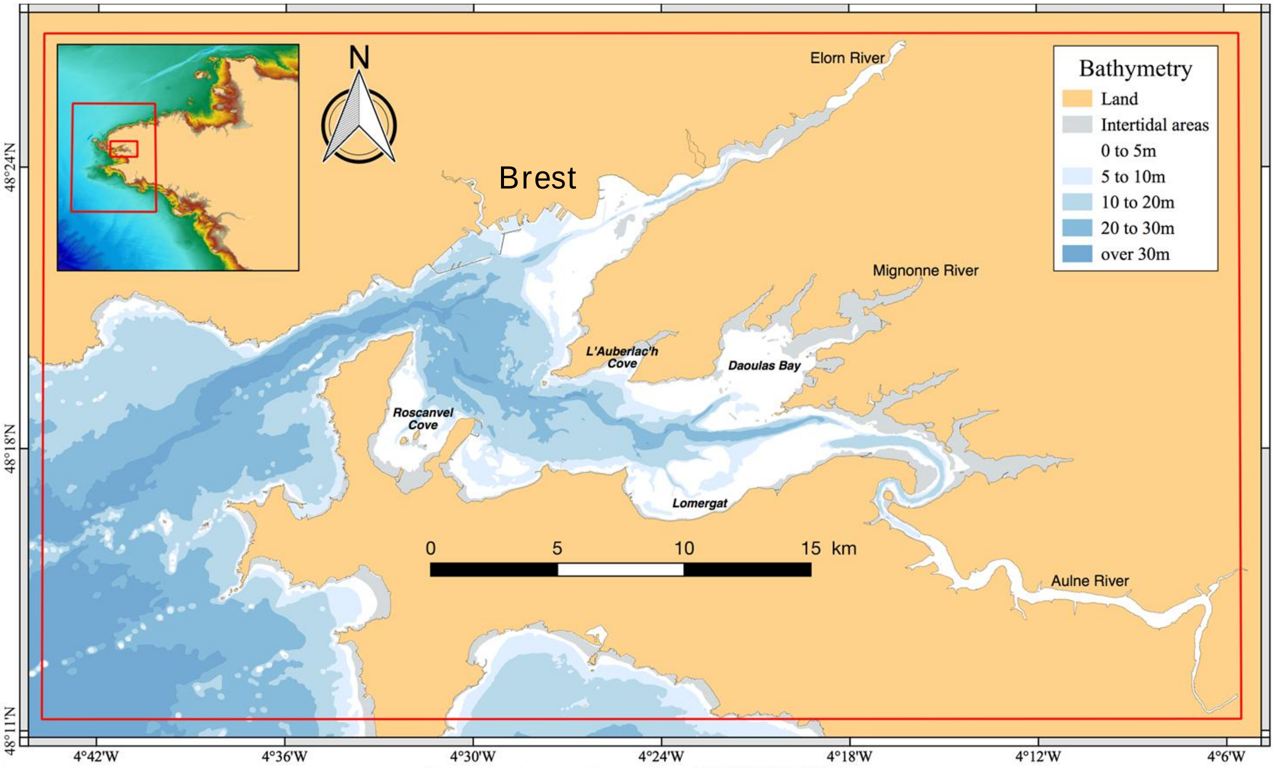
Rypina et al. (2016). *Investigating the Eddy Diffusivity Concept in the Coastal Ocean. JPO*

Setup: Bay of Brest

- Semi-enclosed marine ecosystem (180 km^2)
- Average bathymetry around 8m with many sheltered coves (only 13% of the inside area over 20m deep)
- Fractal like coastline
- Macro-tidal area : 7.3 m maximum tidal range - 85% governed by semidiurnal tidal waves

- Low freshwater inputs – Mean annual discharge $\simeq$ 30 m^3 s^{-1}
  - Aulne 71% / Elorn 15 % / Mignonne 5%
- Highly variable meteorological forcings

- Important societal challenges
  - Nearshore fisheries management
  - Shellfish aquaculture



Source : géotraitement multisources Ifremer/SHOM/IGN/EEA/DDTM

Setup: Bay of Brest

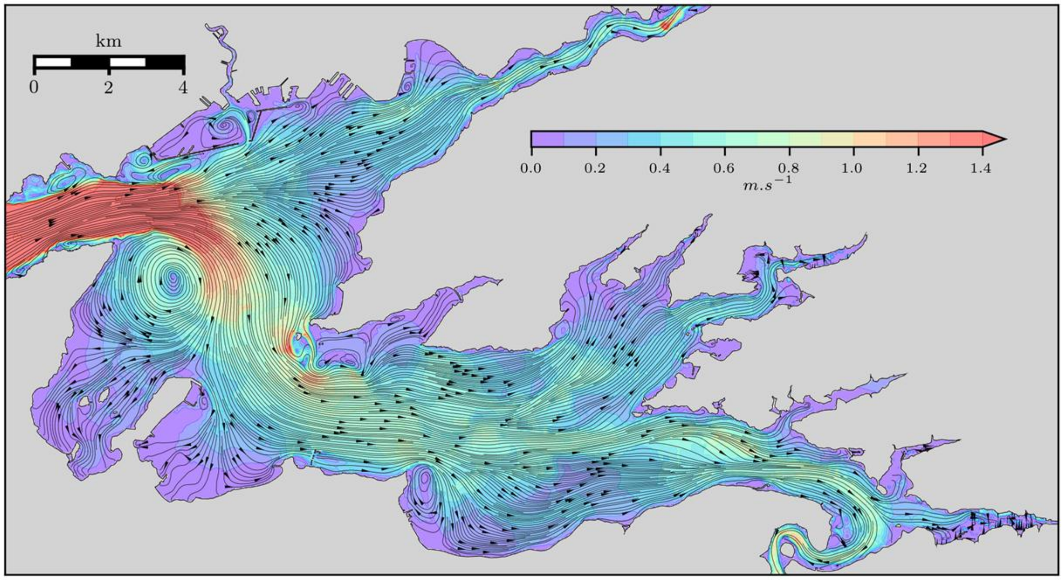
- High tidal prism

→25% of mean total volume in neap tides

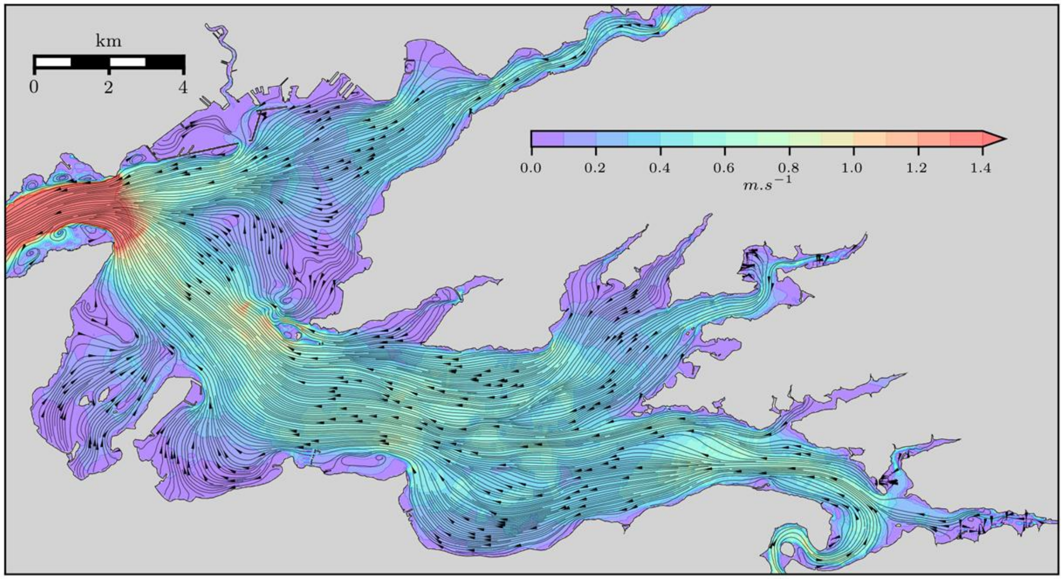
→60% of mean total volume in spring tides

- Heterogenous hydrodynamic
  - Strong currents next to the strait
  - Sheltered shallow water areas
  - Anisotropic conditions

- Quick evolutions during a tidal cycle
  - Small time scales : 15 mins
  - Small space scales : 250 m



Barotropic currents during flood tide – mean spring tides



Barotropic currents during ebb tide – mean spring tides

Setup: numerical model aspects

- Runs
  - Steady simulations (5 days spin-up)
  - Only semidiurnal tidal signal imposed at open boundaries
  - One release every hour over one tidal cycle → 13 releases
  - Reference run
    - ➔ Mean tides : 4.3 m tidal range
    - ➔ No wind
    - ➔ One tidal cycle T_{M2}

Hydrodynamic model

MARS 3D (Lazure Dumas 2008)
2 nesting grids
50m horizontal resolution
20 sigma layers
k-ε turbulence closure

Schematic forcings

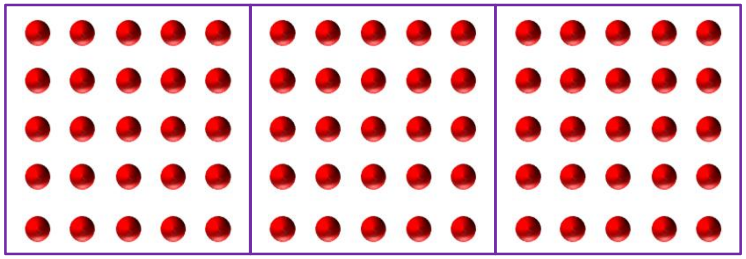
- Tidal components from SHOM
- No temperature or salinity gradient
- No air-sea exchange

- Lagrangian approach
  - 100 passive particles in each mesh : total number $\simeq 6.10^6$
  - Randomly spaced over vertical axis
  - Advection using either 2D or 3D currents
  - Non naïve random walk over the vertical (Visser 1997) to represent vertical turbulent dispersion
  - Coastal behaviour: beaching during wet-drying time

Setup: numerical estimation aspects

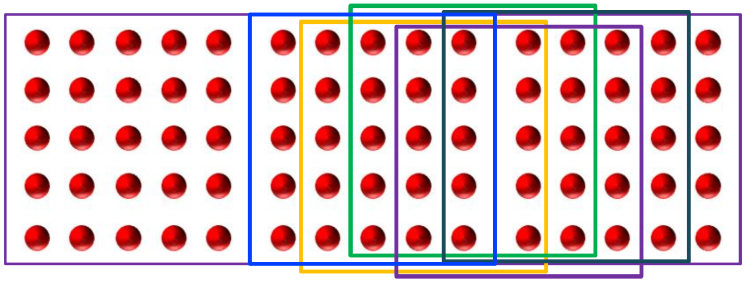
- Estimation of the local diffusivity coefficient
  - At least 90% of initial number of particles per patch
  - Centroid repositioning increases homogeneity of the final result
  - On the native hydrodynamic grid ➔ Not necessary

- Patches construction
  - Particles are used once within a unique patch



1 estimation
per initial mesh grid

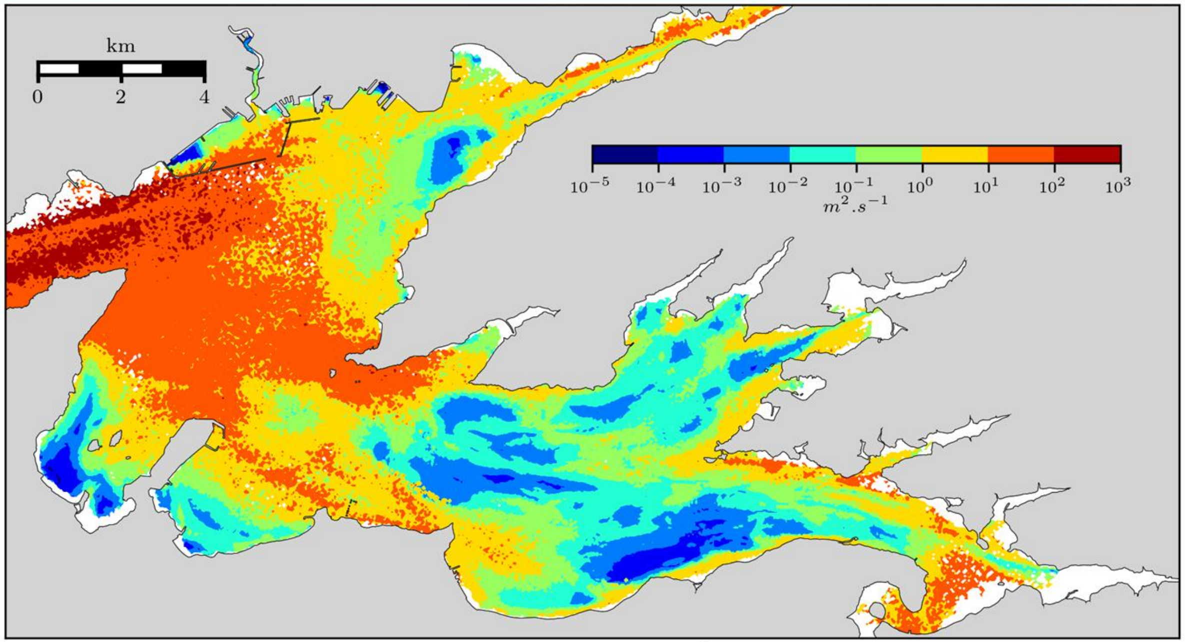
➔ Could be used in overlap patches



5 estimations
per initial mesh grid

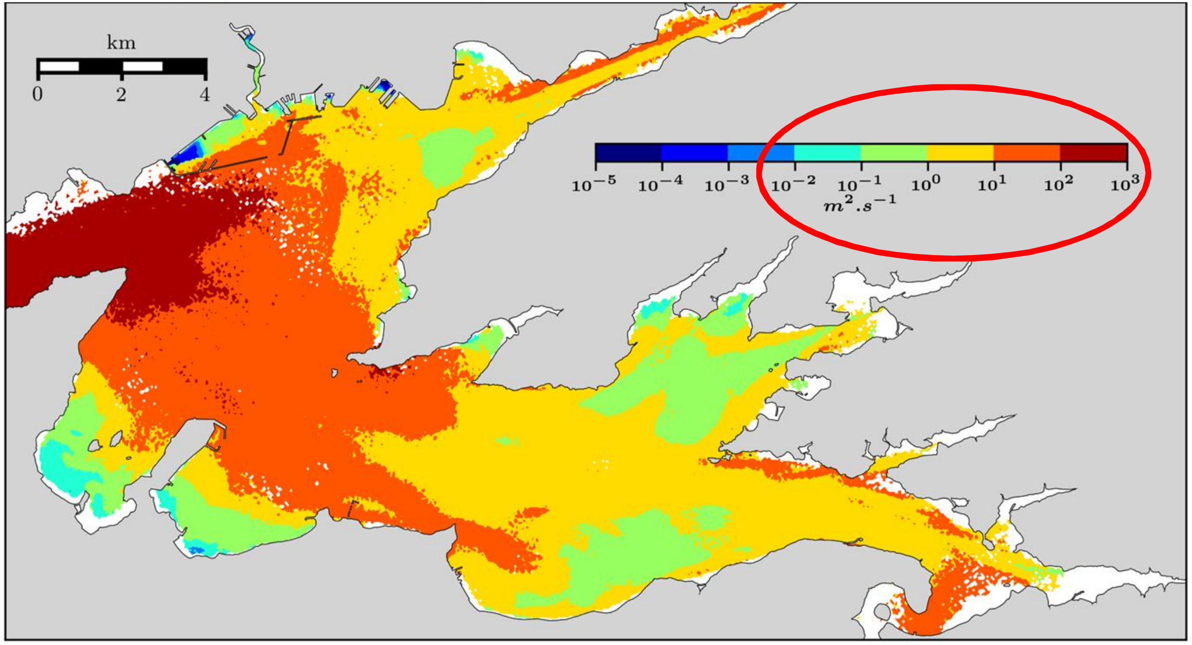
Benefits
of
lagrangian
approach

Methodological aspect



Local diffusivity coefficient
mean tides 4.3m

➔ Particles are advected with barotropic currents



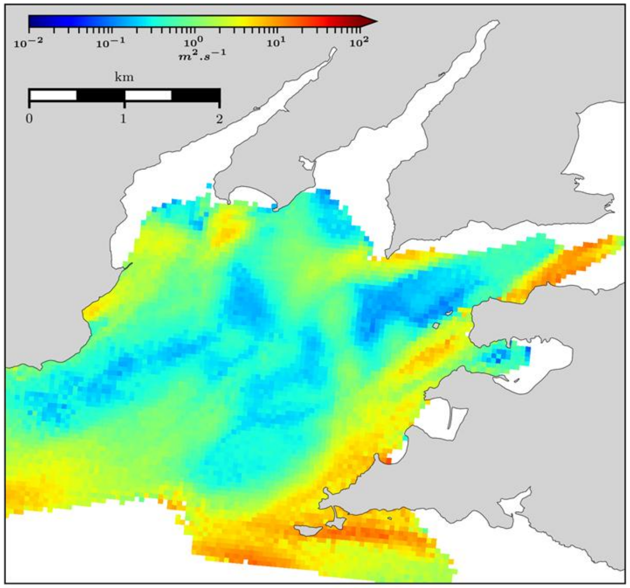
Local diffusivity coefficient
mean tides 4.3m

➔ Particles are advected with 3D currents

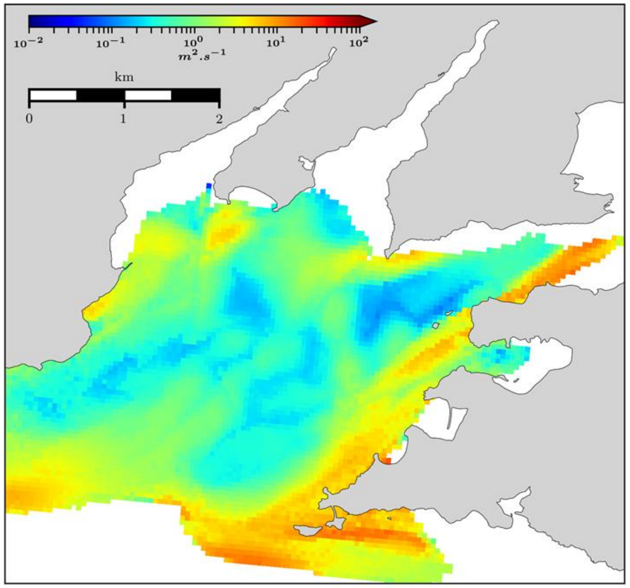
Methodological aspect

- Initial vertical distribution ➔ Weak influence
  - Even or random uniform distribution give the same results
  - Lagrangian approach allows to select *a posteriori* particles within any given initial subdomain / layer

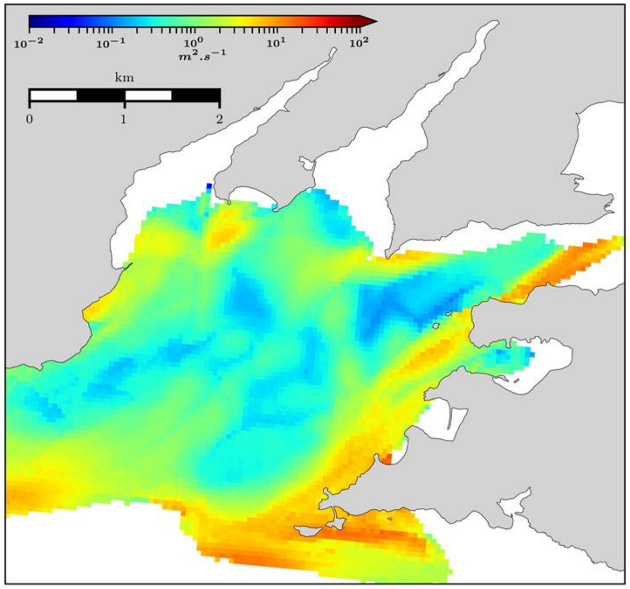
- Sensitivity to the number of particles used



100 particles per mesh



400 particles per mesh

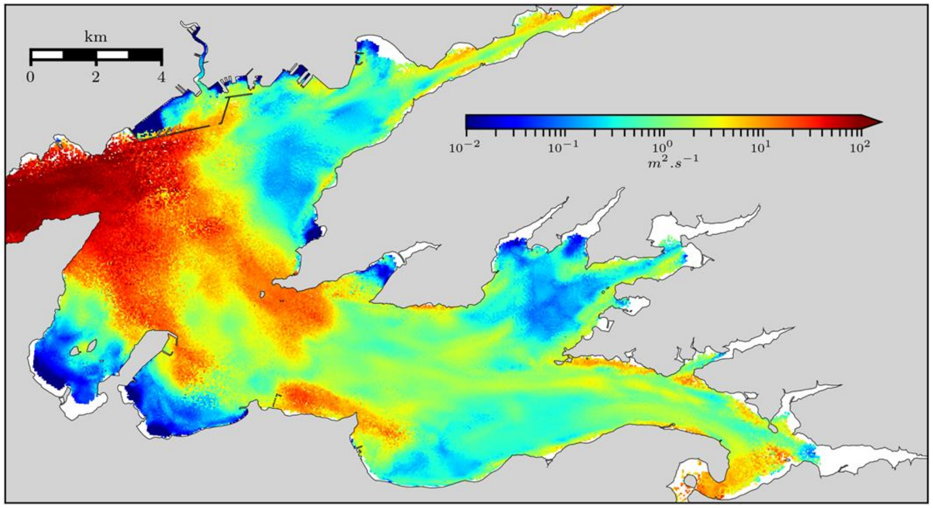


1600 particles per mesh

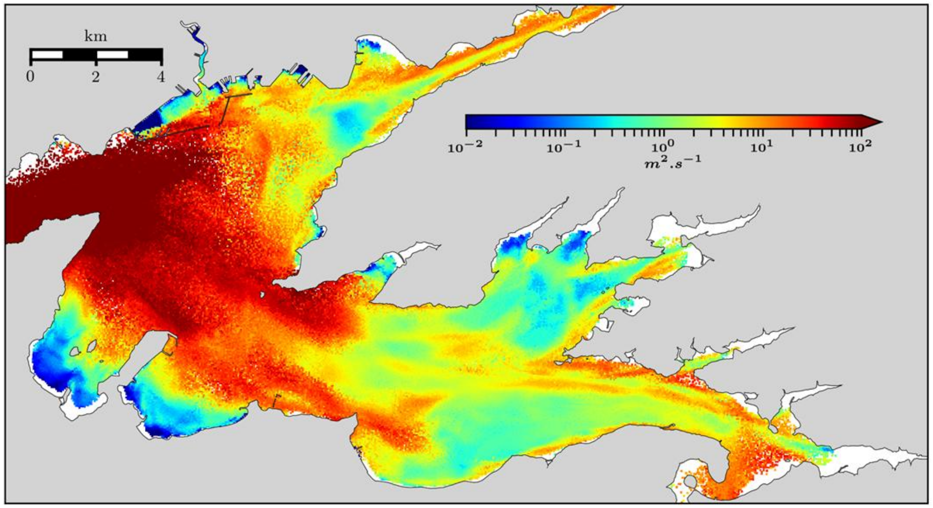
- Horizontal resolution
  - Definition at which the local diffusivity coefficient is assessed
  - Impact of the model resolution (lack of subgrid diffusivity)

Tidal impact

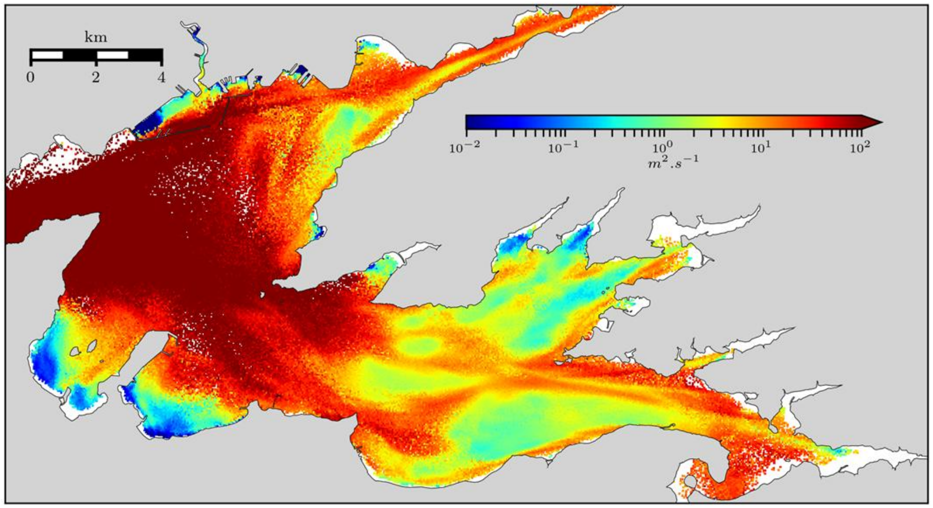
Mean neap tides
2.7 m tidal range



Mean tides
4.3 m tidal range

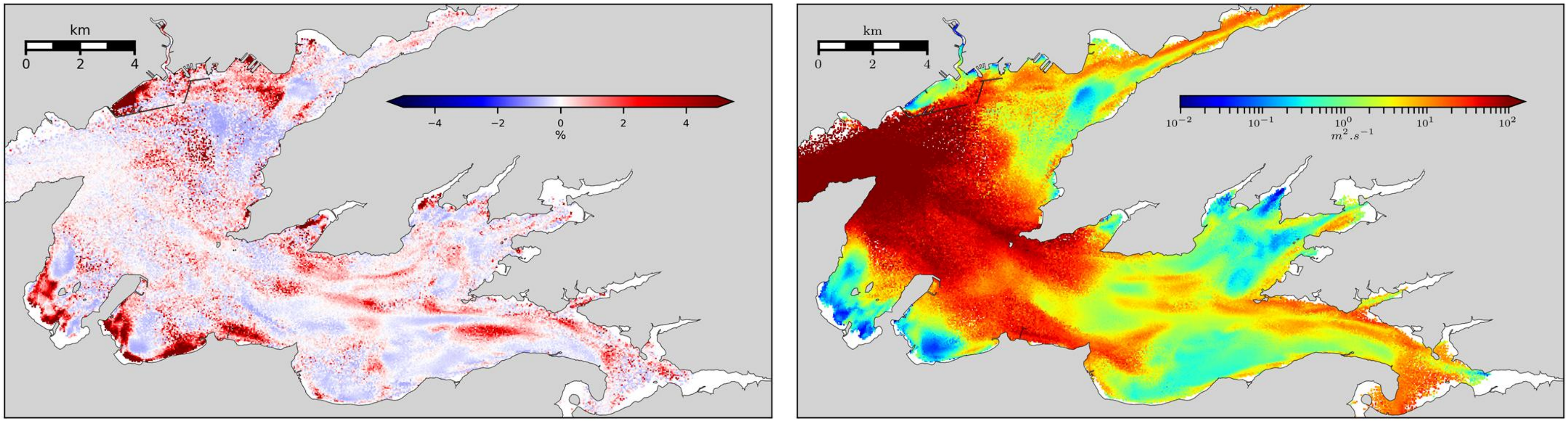


Mean spring tides
5.9 m tidal range

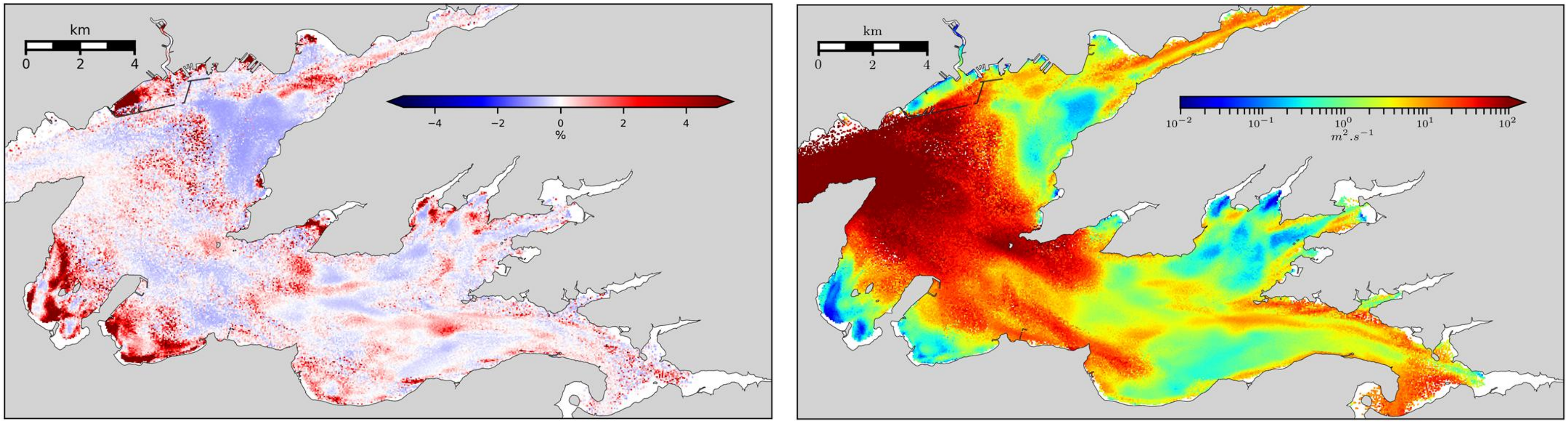


Wind forcings impact : schematic constant winds

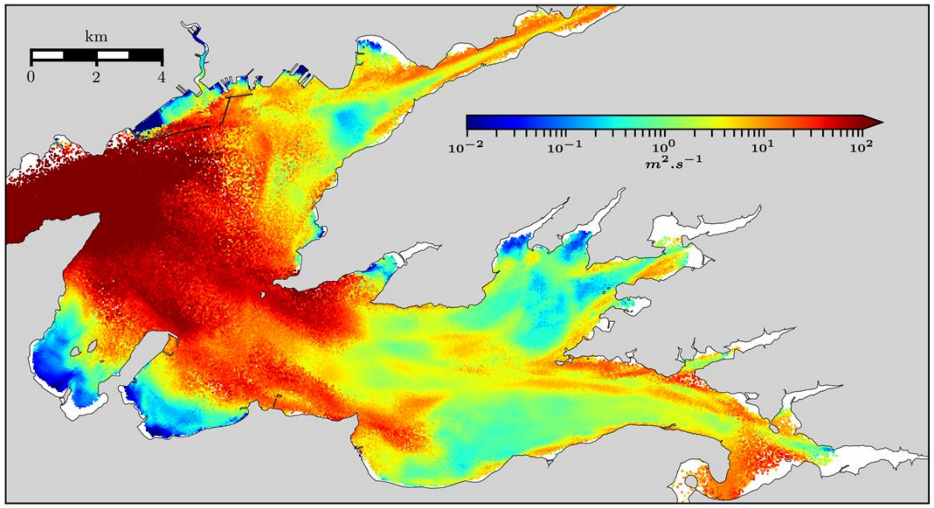
Mean tides
5 m.s^{-1} NE



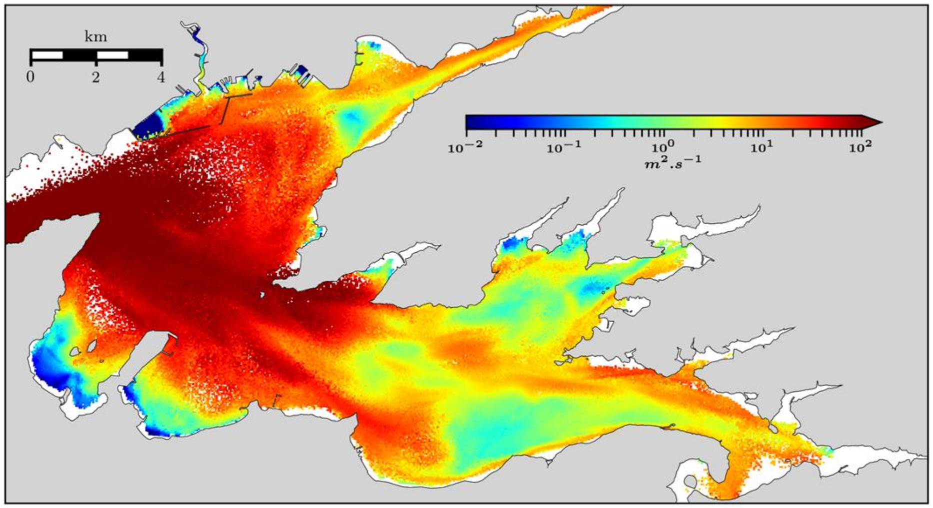
Mean tides
5 m.s^{-1} SW



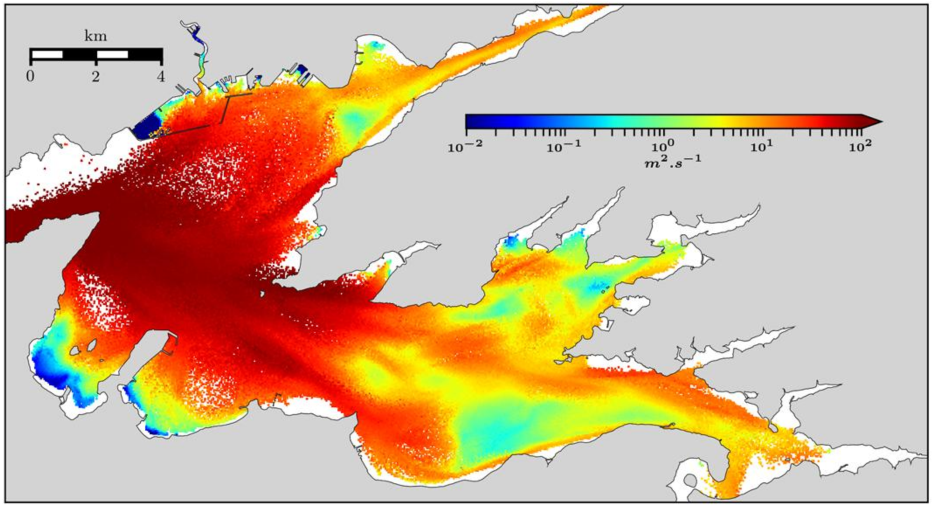
Evolution over longer time scale



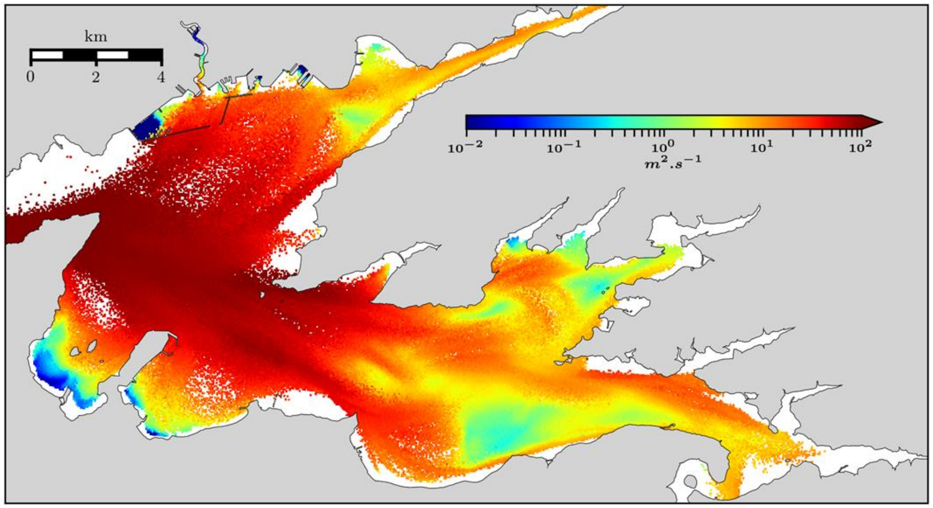
After **1** tidal cycle



After **2** tidal cycles



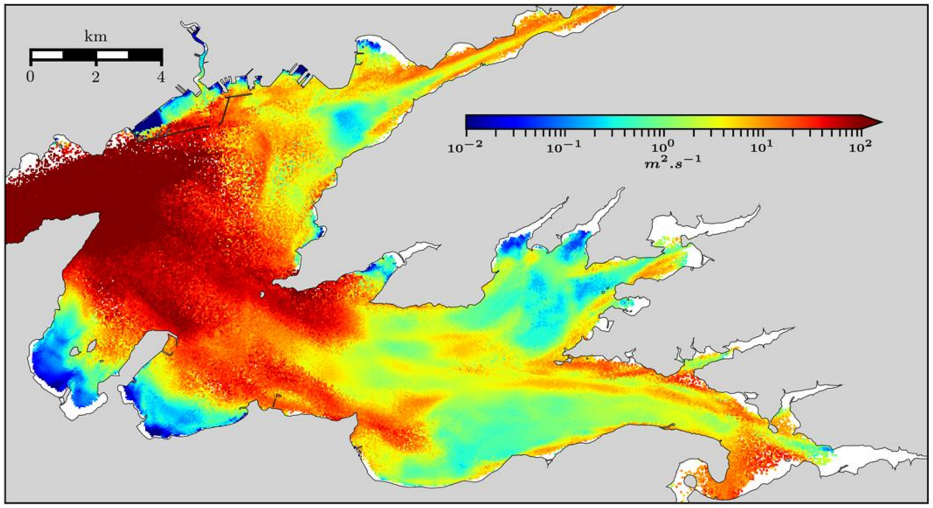
After **3** tidal cycles



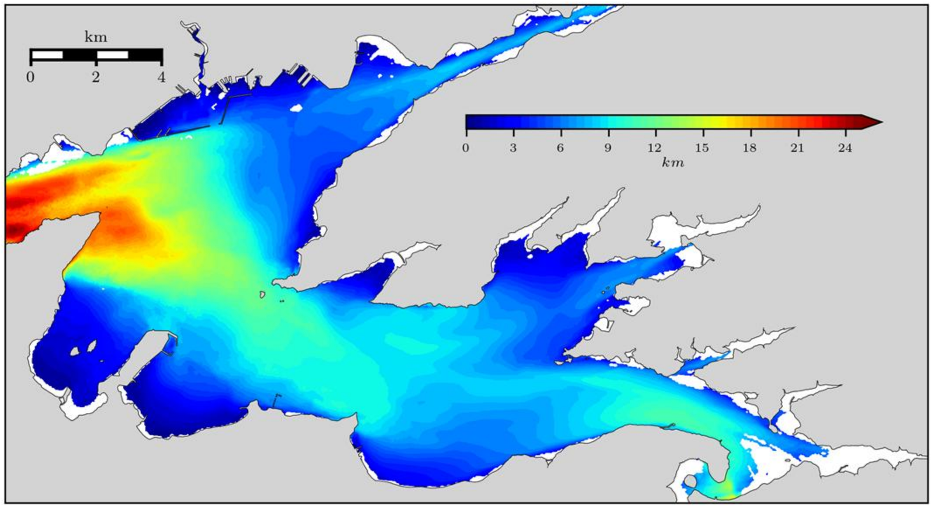
After **4** tidal cycles

➔ Limit of the indicators : sensitive to time integration

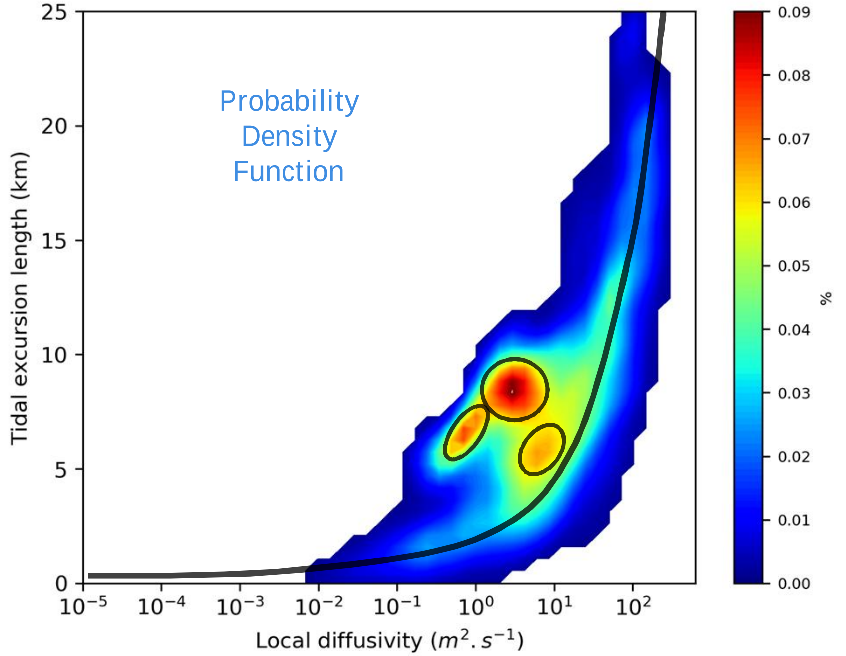
Link between indicators

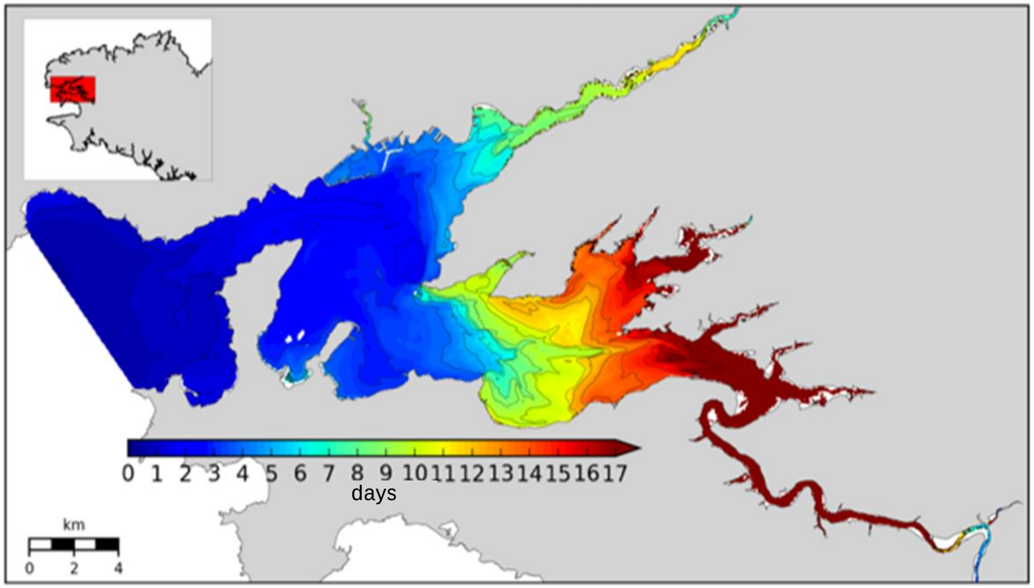


Local diffusivity coefficient – Mean tides



Tidal excursion length– Mean tides



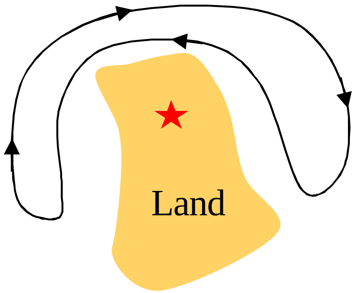


e-local flushing time applied to the bay of Brest
Neap tide and low flow situation

Perspectives

- Conclusions
  - This indicator enables a quantitative comparison of different areas
  - Understanding of biological processes (values of 0.1 to 100 $m^2.s^{-1}$)
  - Structures with good robustness even under different hydrodynamic or atmospheric forcings
  - *A priori* knowledge of an area in addition to many previous indicators
  - Superiority and performance of lagrangian approach (without particles behaviour)

- Limitations are here raised
  - Still depends on time integration
  - Centroid repositioning within complex coastlines, rivers
  - Number of particles needed to well characterize an area
  - Hydrodynamic model resolution



- Relevancy
  - Validation with *in-situ* data (Rypina *et al,* 2016)
  - Compare to *in-silico* experience :

➔ Realistic run *vs* Combined use of residual currents and local diffusivity coefficient

- Challenges
  - More realistic applications : Surface and Bottom coefficients
  - Bridging the gap between short timescale (tidal cycles) and longer timescale (larval life duration)

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