Aix-Marseille University
Master 2, OPB
2023 - 2024

Aude Joël
June 12, 2024

Lagrangian analysis of fine-scale dynamics during BioSWOT-MED

Tutors:
Andrea Doglioli (MIO),
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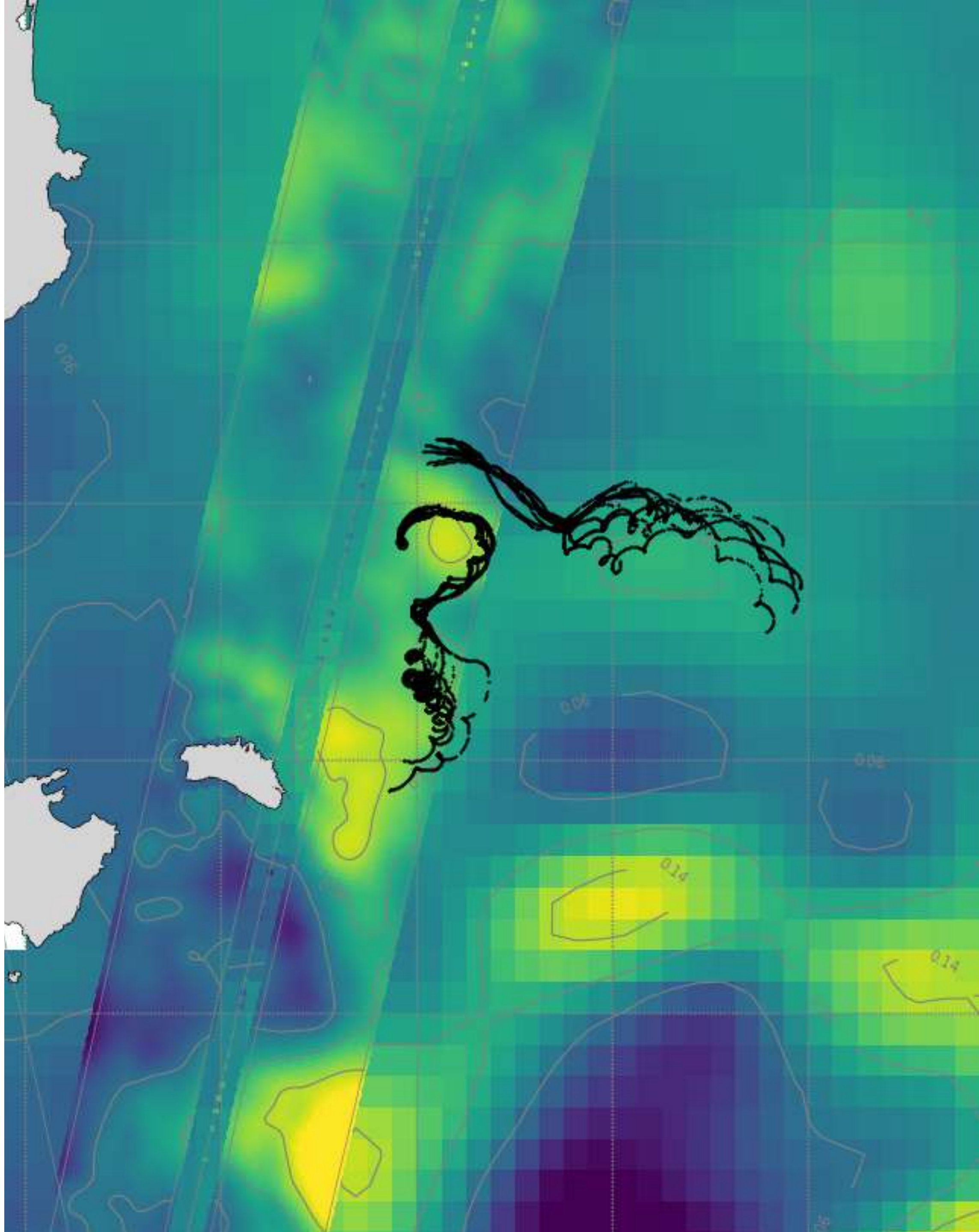
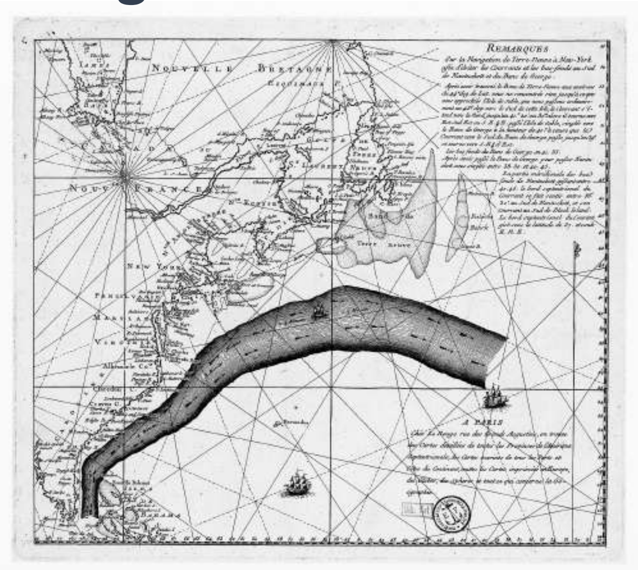
Louise Roussellet (LOCEAN)



1. Oceanic circulation & fine-scale dynamics

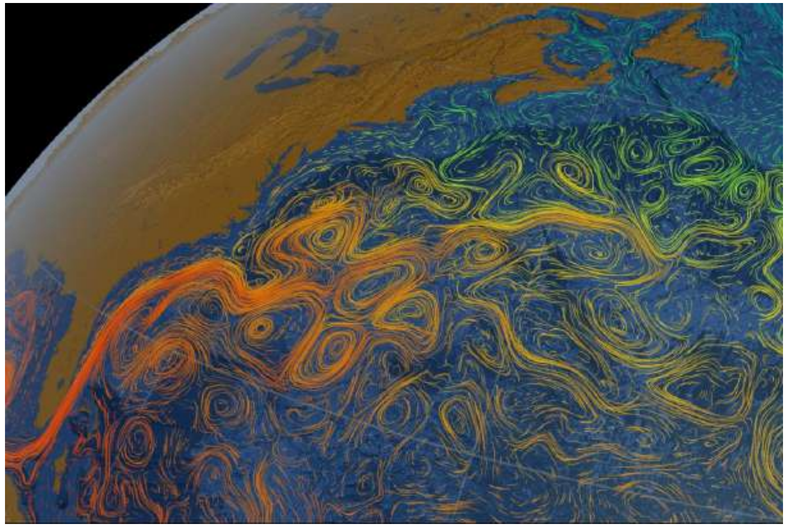
Large-scale



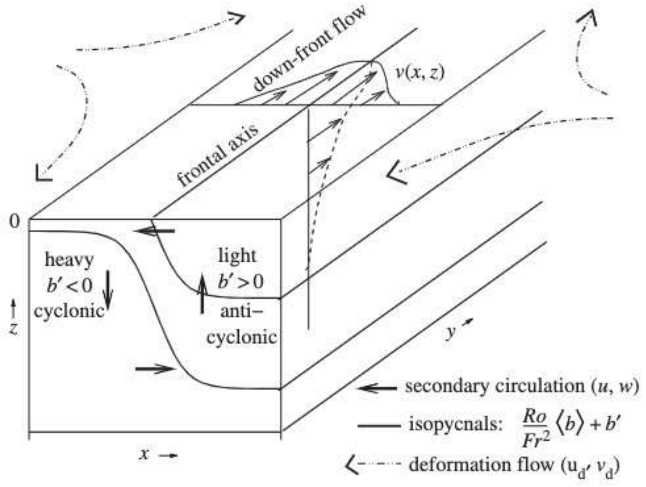
sources: Franklin, 1769

1000 - 10000 km
1 to > 1000 years
Thermo-haline circu.
Decadal oscillation

Fine-scale



NASA



McWilliams, 2016

1 - 100 km
1 day up to a year
Eddies & meander features (mesoscale)
Front & filaments features (sub-mesoscale)
→ **Impact on biogeochemical processes due to 3-D circulation**

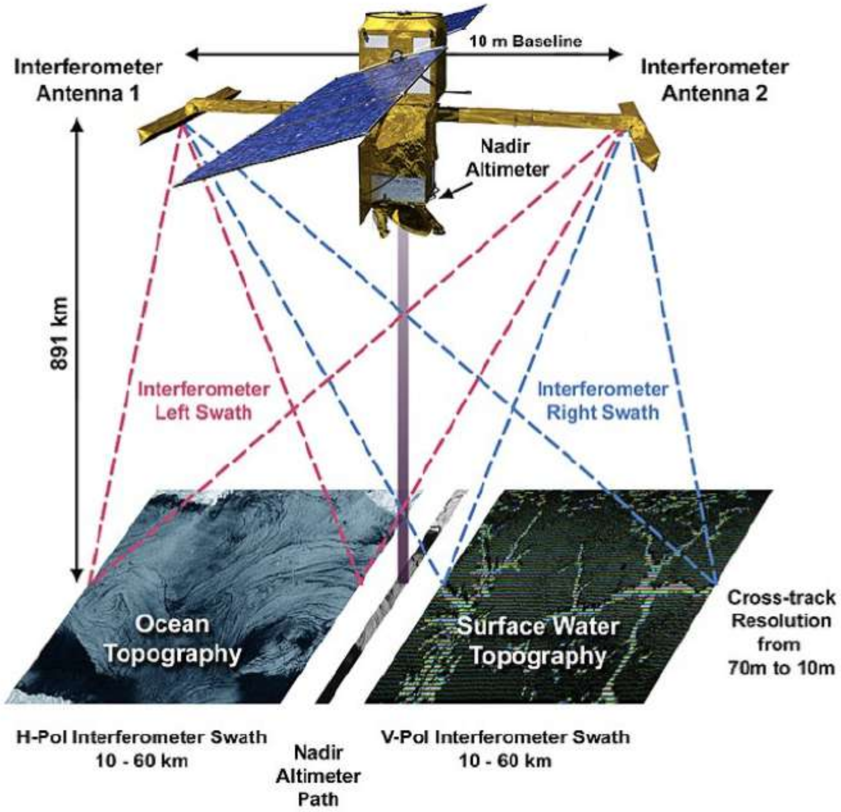
1. The new SWOT-satellite

SWOT

Surface Water and Ocean Topography

4-months CalVal phase – SWOT-AdAC

(d'Ovidio et al., 2019)



Source: NASA

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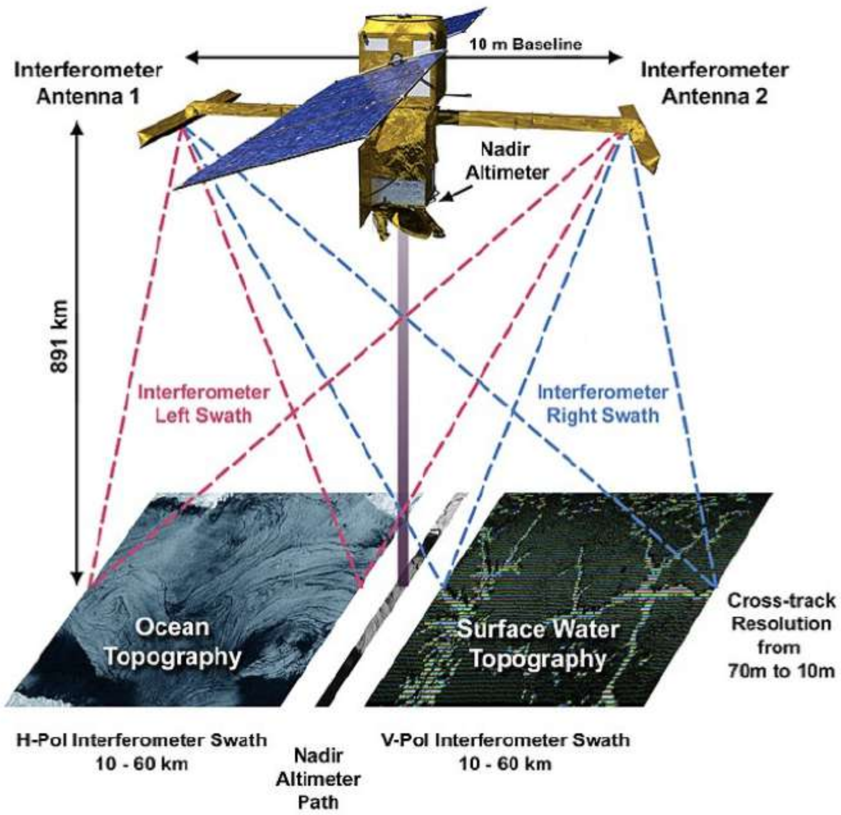
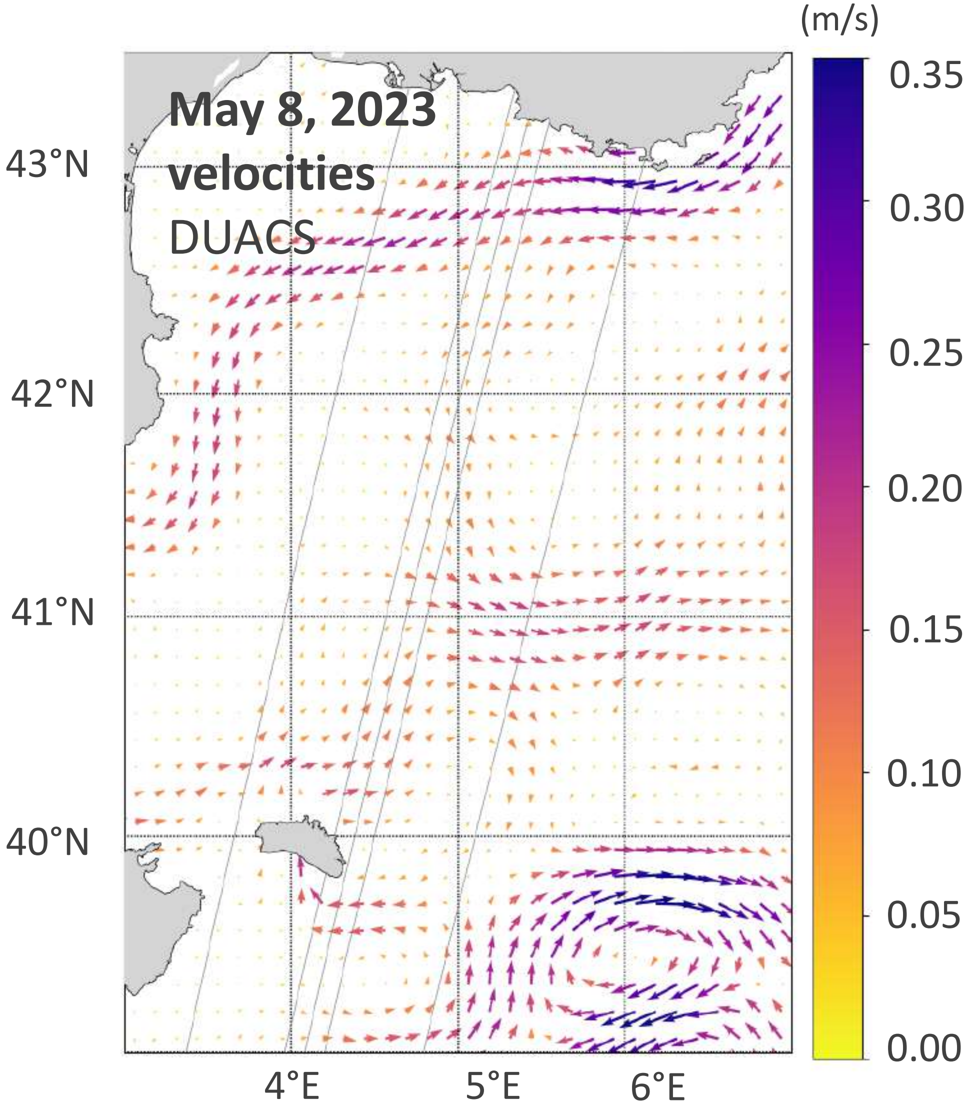


Source: NASA



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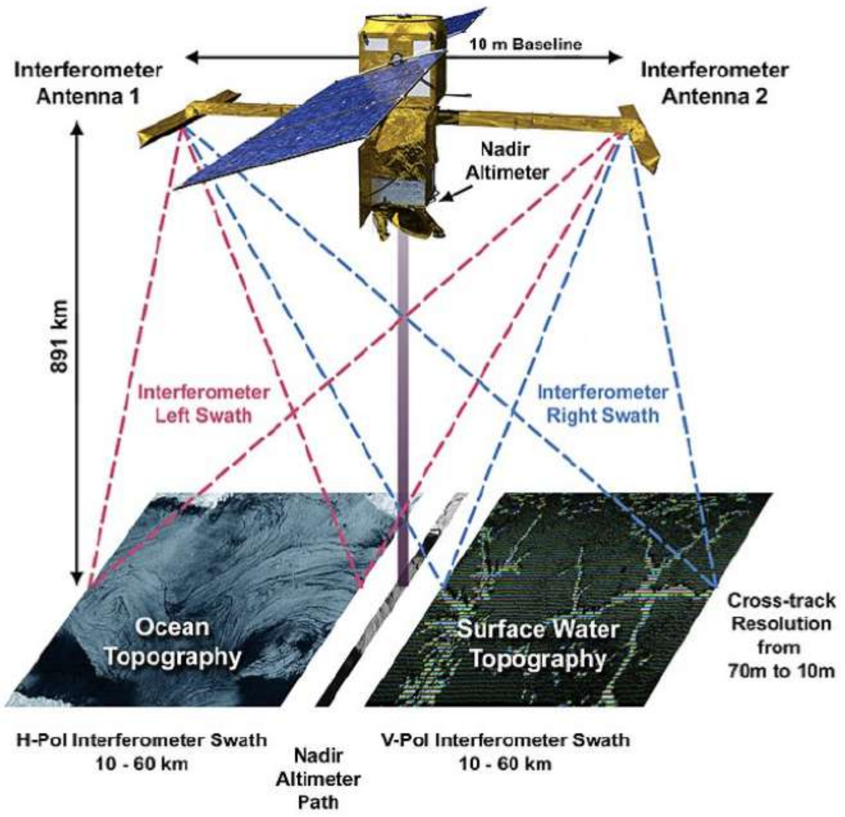
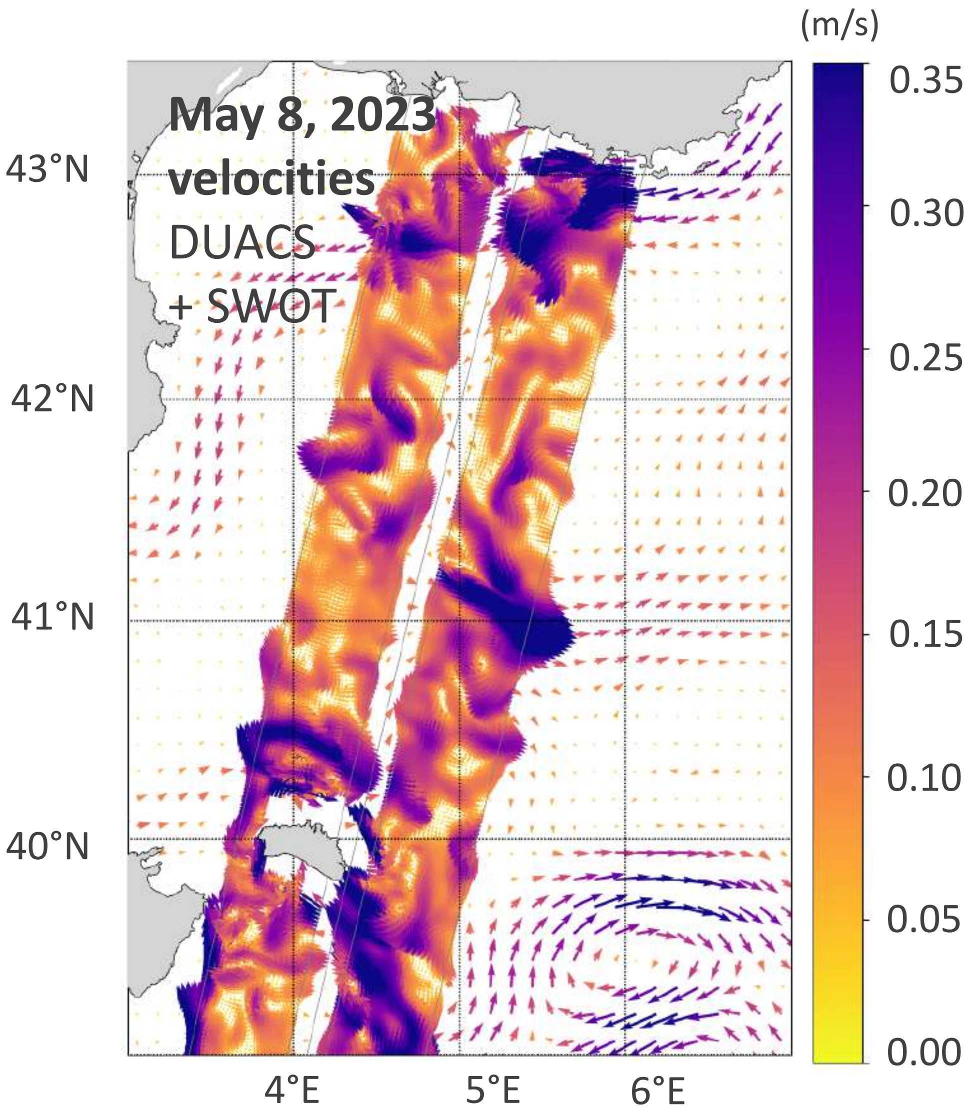
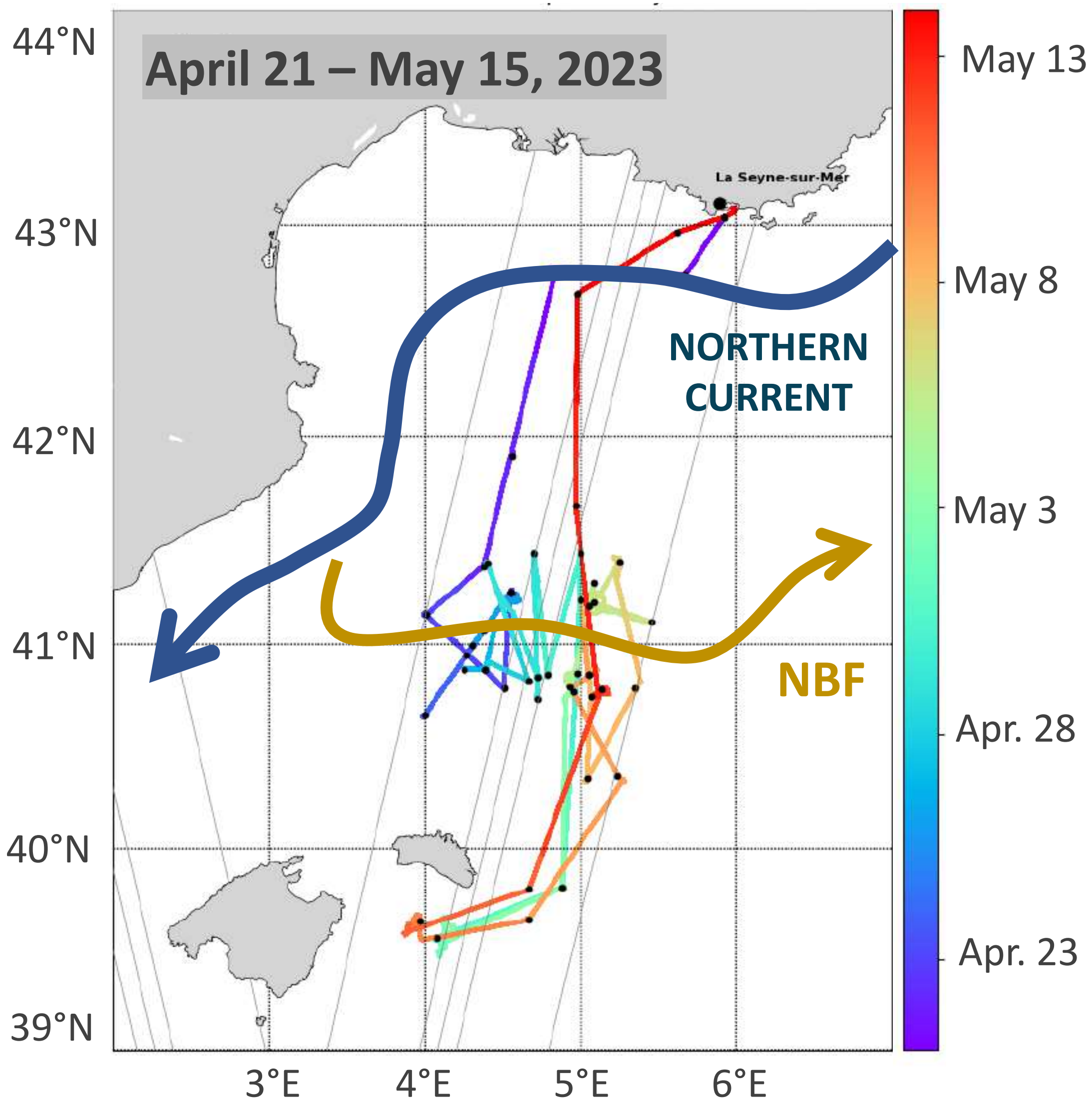


Source: NASA



1. The BioSWOT-Med campaign

https://doi.org/10.17600/18002392



- Area: **North Balearic Front (NBF)**
- Study of **fine-scale dynamics** & interactions with **biogeochemical** processes
- **Adaptative** (to target oceanic features) and **Lagrangian** (to follow them) **sampling strategy** (Doglioli et al, 2024 cruise report)
- In particular, Lagrangian instruments: drifters and floats

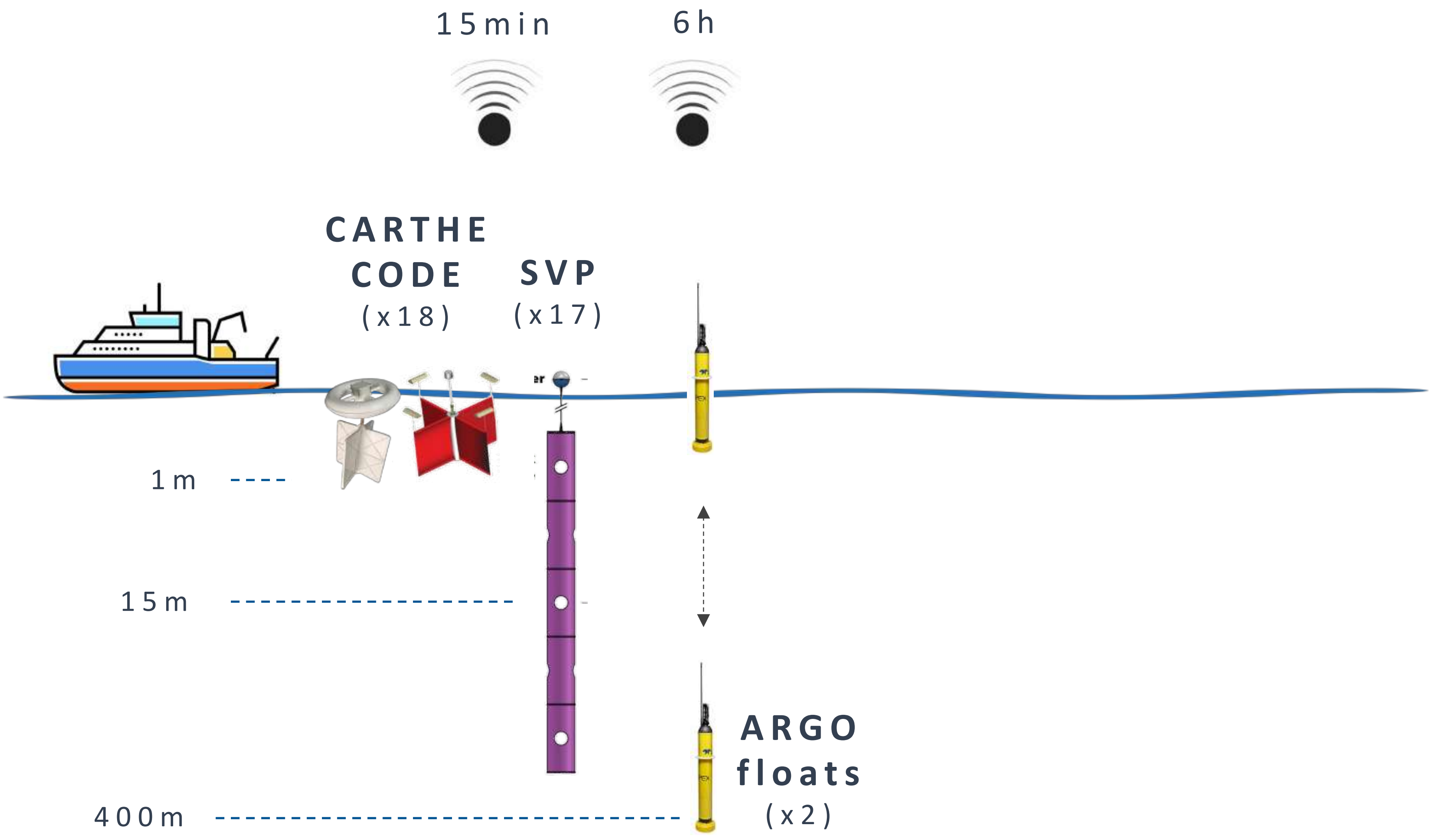
1. Scientific objectives

- Characterize **local surface ocean dynamics** thanks to **Lagrangian instruments** and **SWOT data**

- Contribute to the understanding of **fine-scale structures in moderate-energetic marine environments**

2. Data collection

2. Data collection



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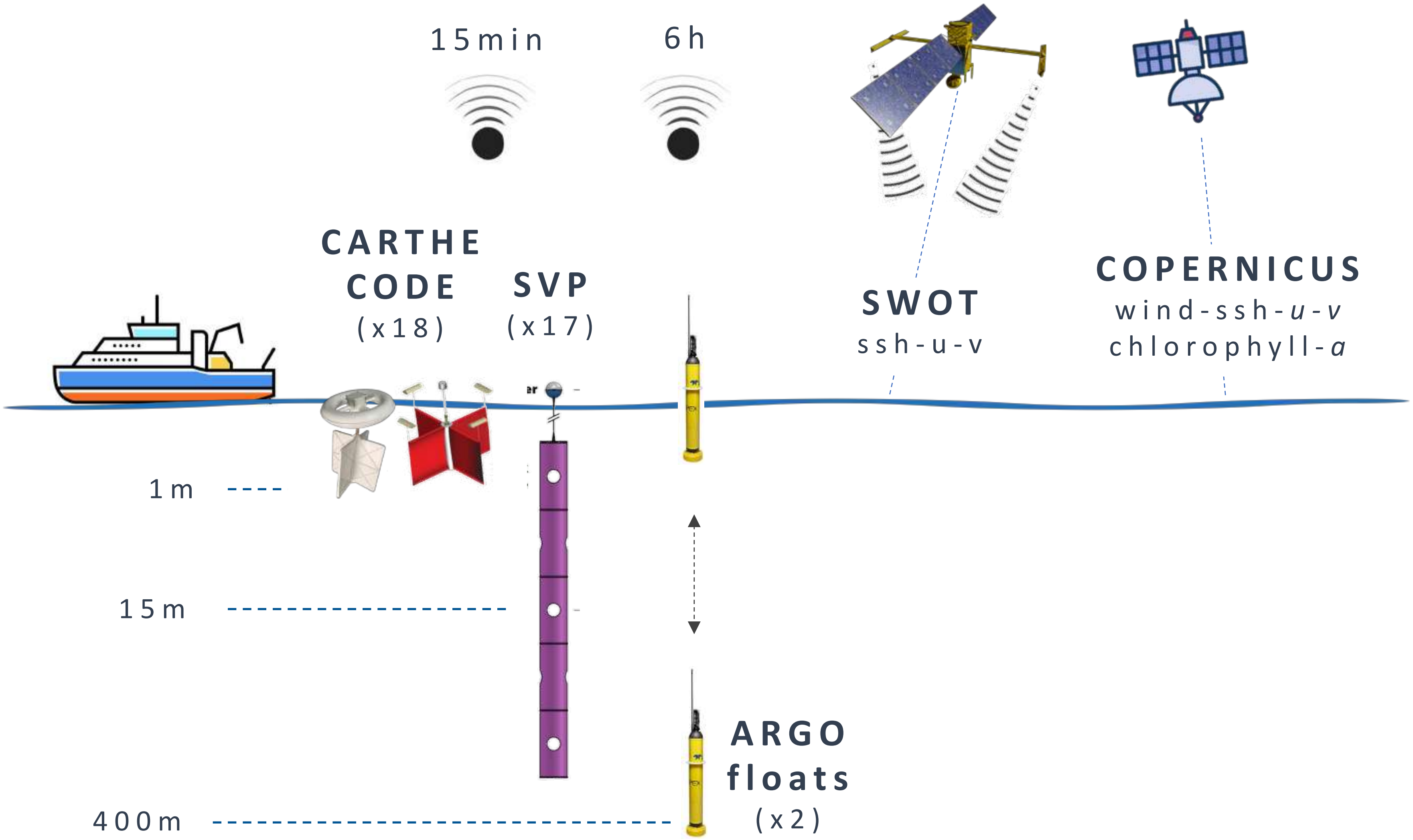

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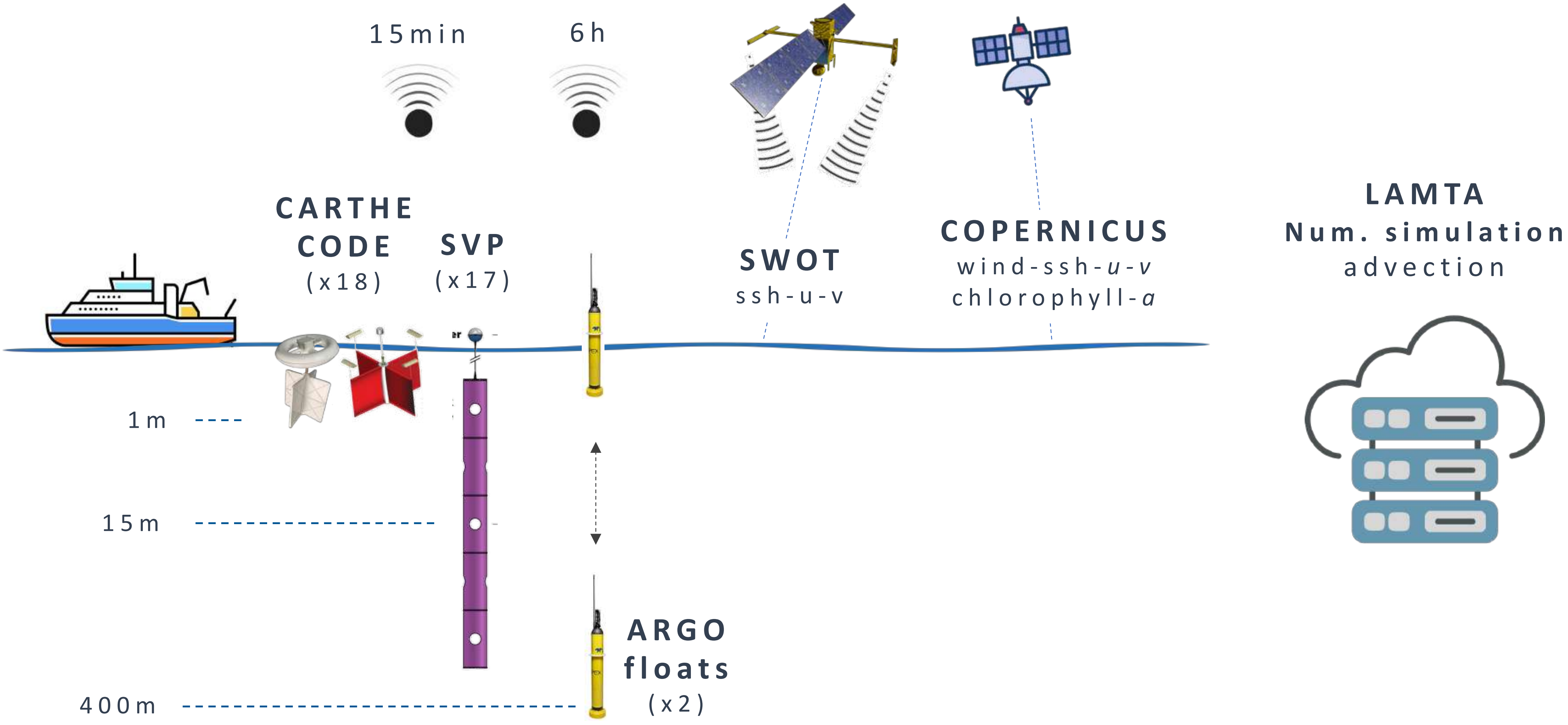
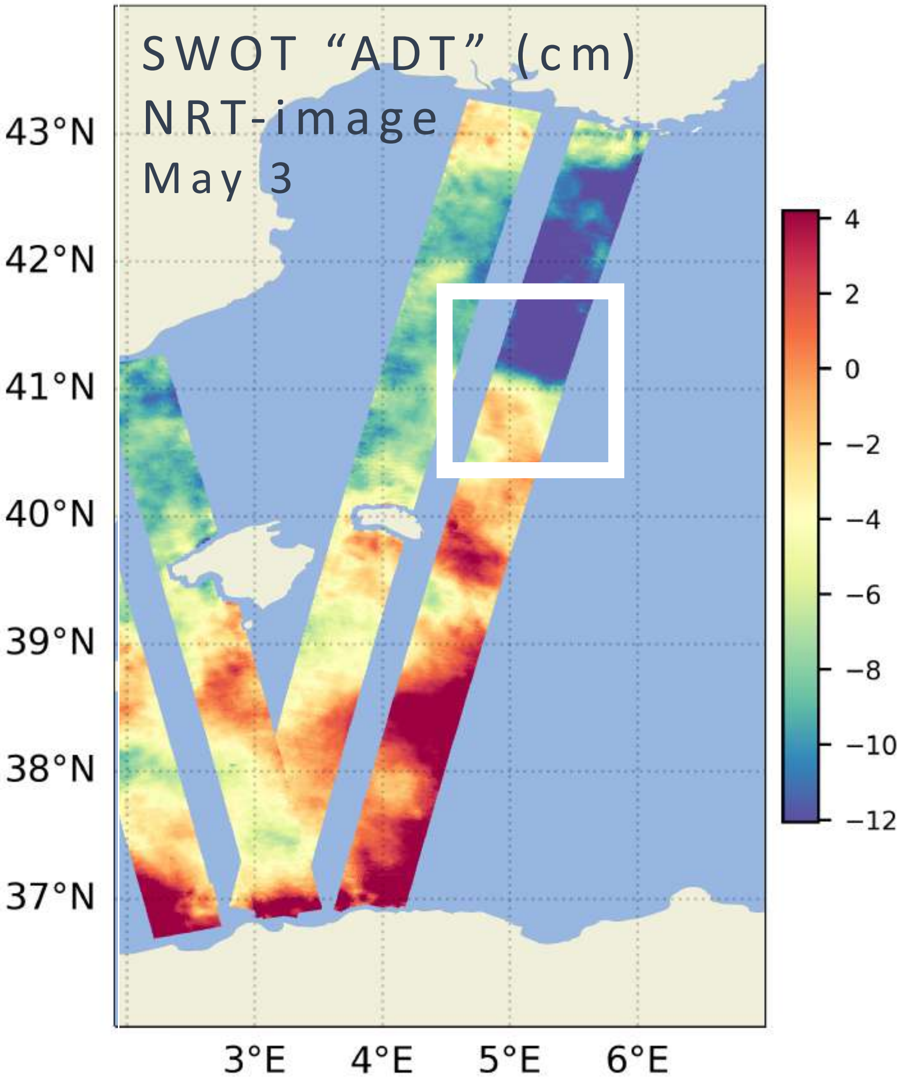
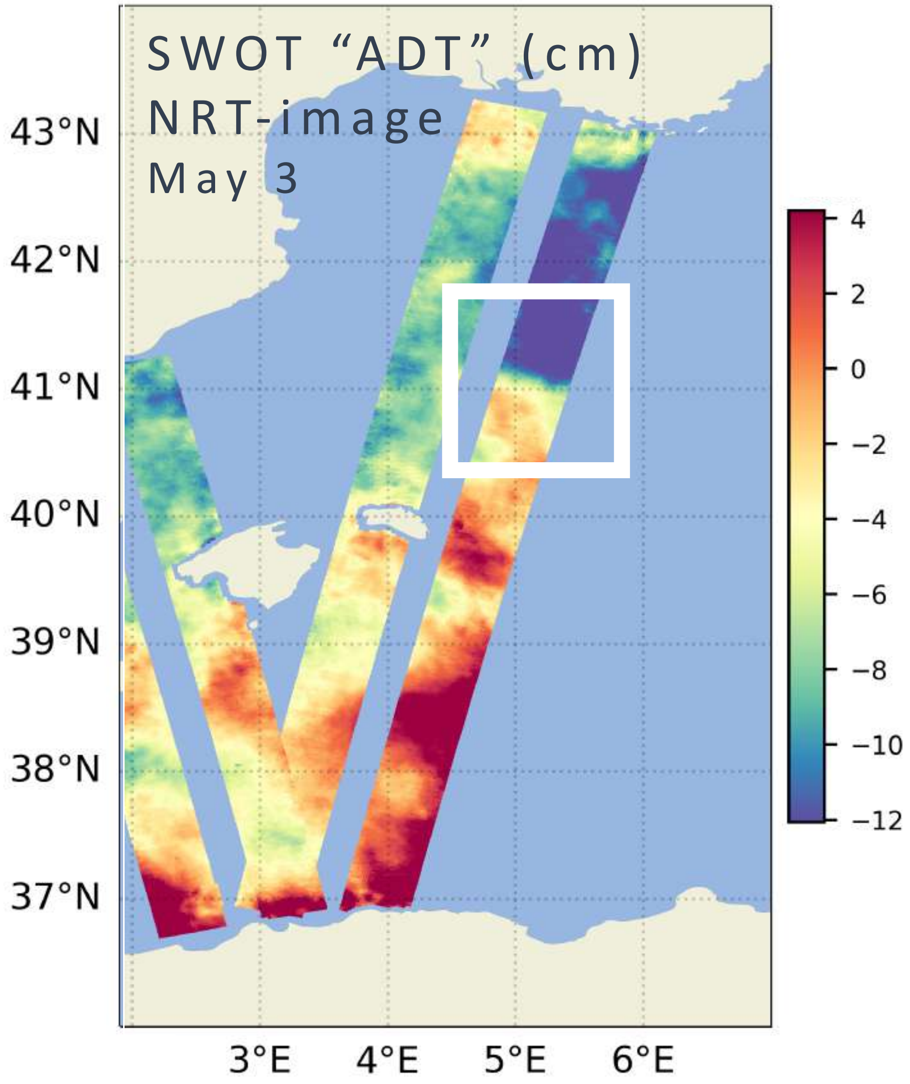


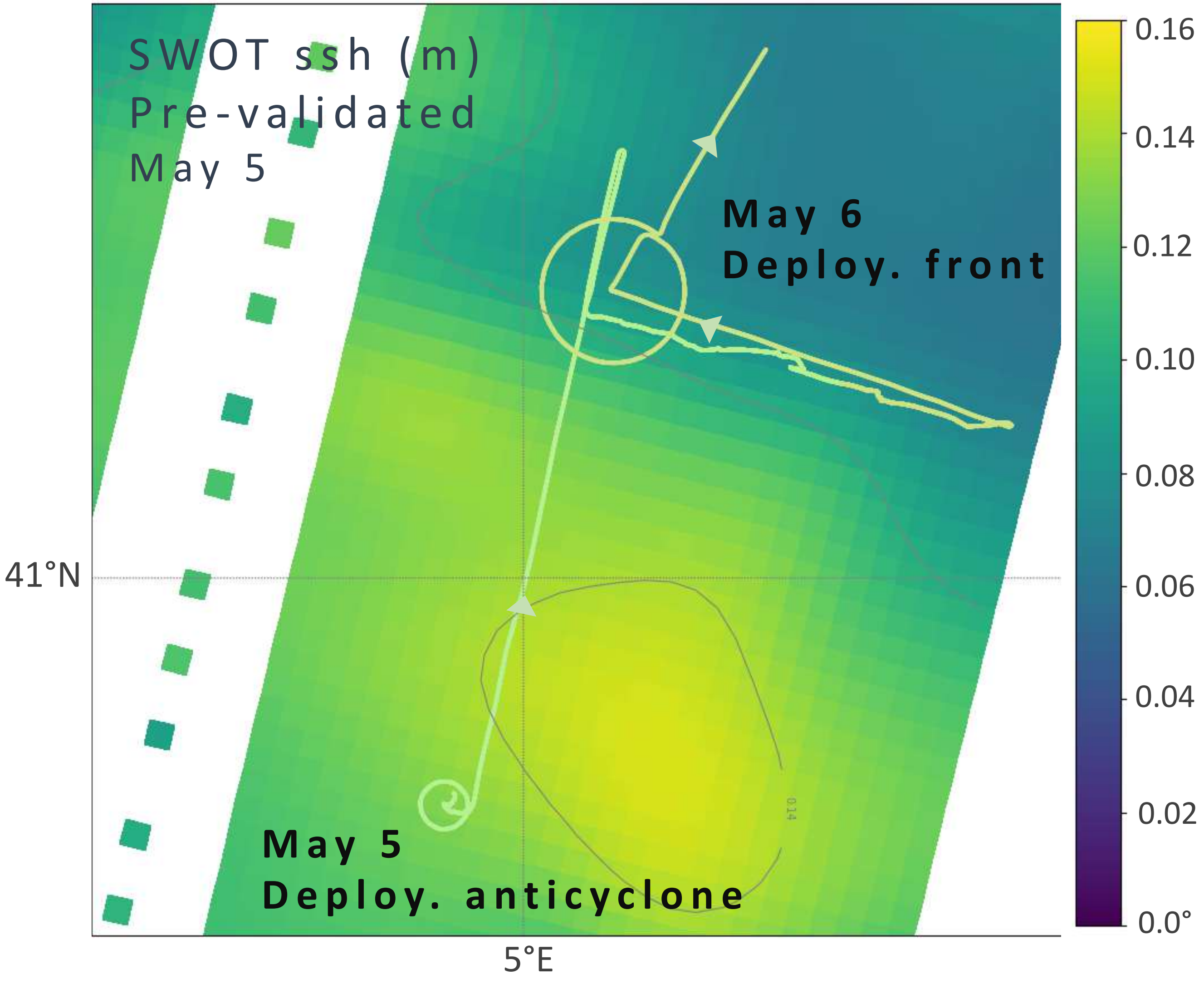
2. Fine-scale features targeted: May 5 & 6



41°N

2. Fine-scale features targeted: May 5 & 6

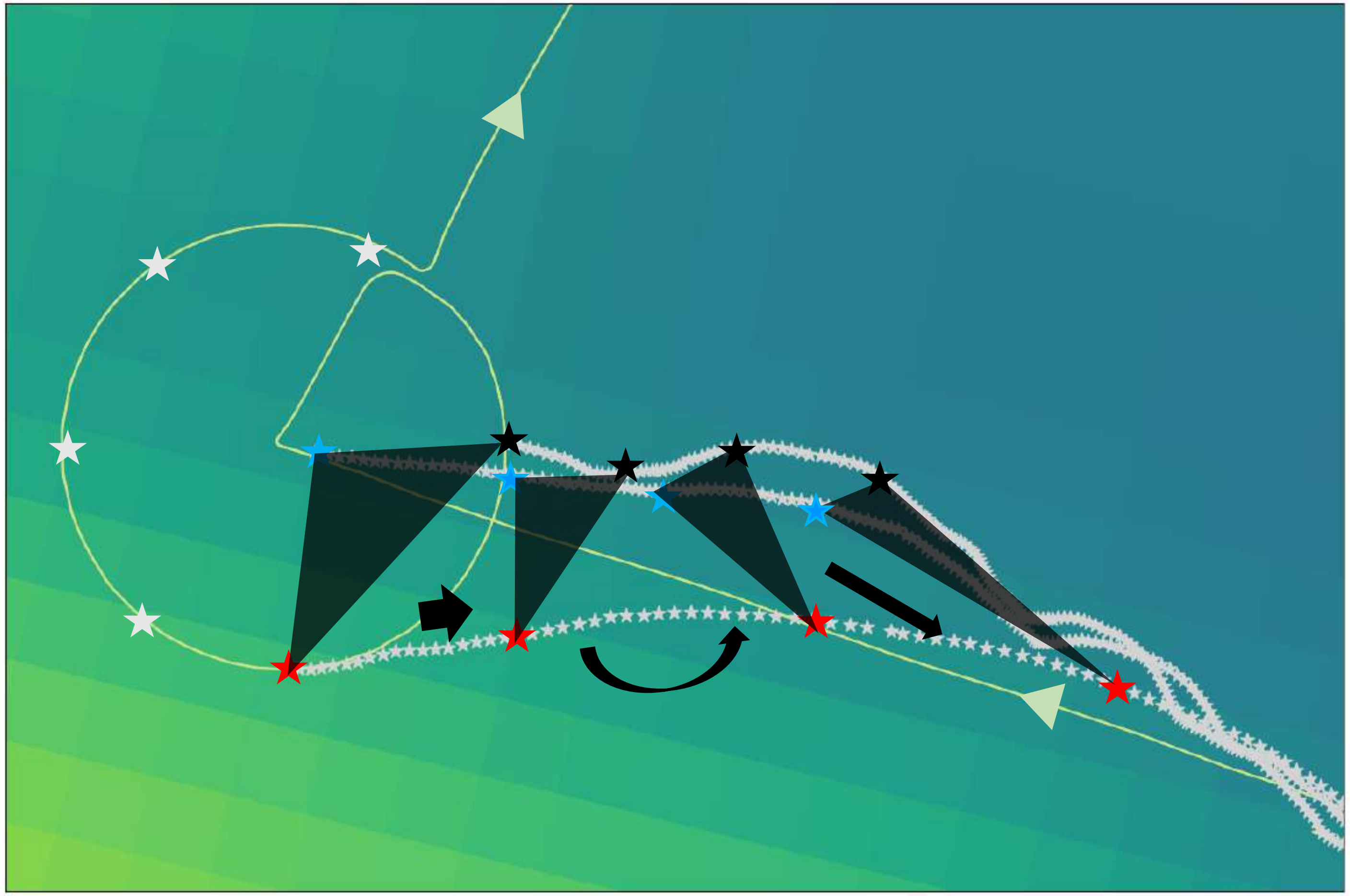




2. Drifter deployment strategy & KP

AREA RATE OF CHANGE METHOD
(Molinari & Kirwan, 1975):

2. Drifter deployment strategy & KP



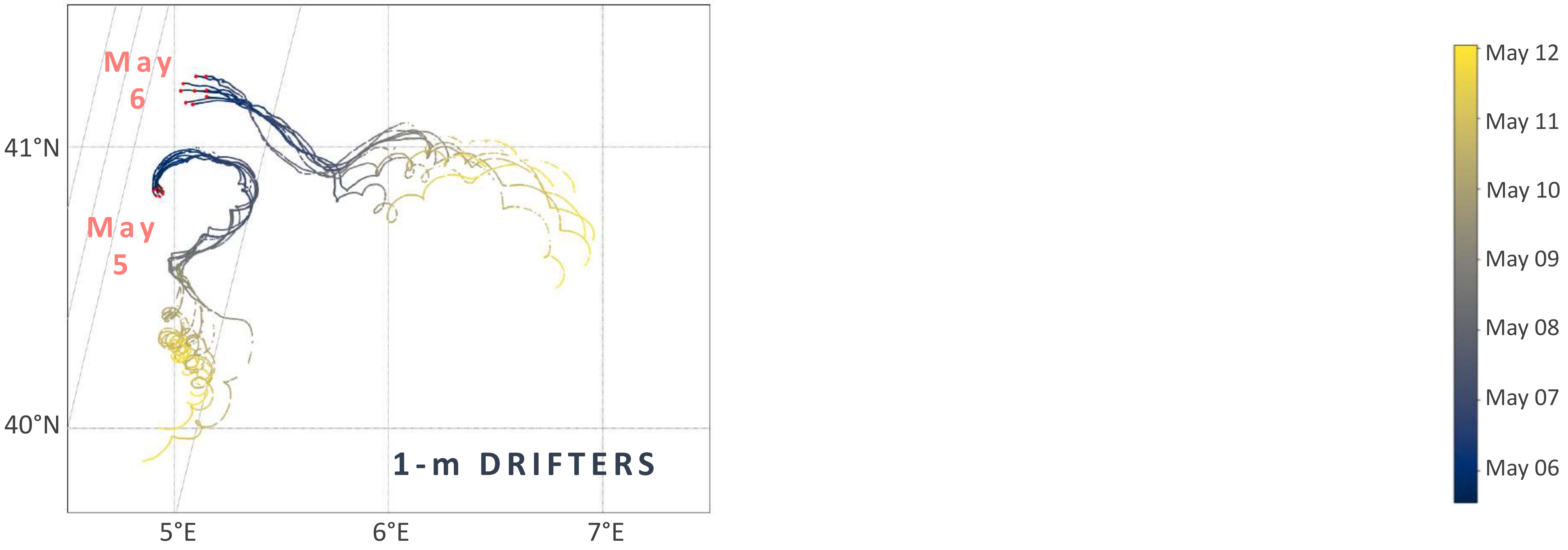
AREA RATE OF CHANGE METHOD
(Molinari & Kirwan, 1975):

- size: **DIVERGENCE**

$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \rightarrow \frac{1}{A}\frac{dA}{dt}$$

- orientation: **VORTICITY**
- shape: **STRAIN**
- mass conservation: **VERTICAL VELOCITIES *w***

3. Drifter's trajectories – May 5 to 12



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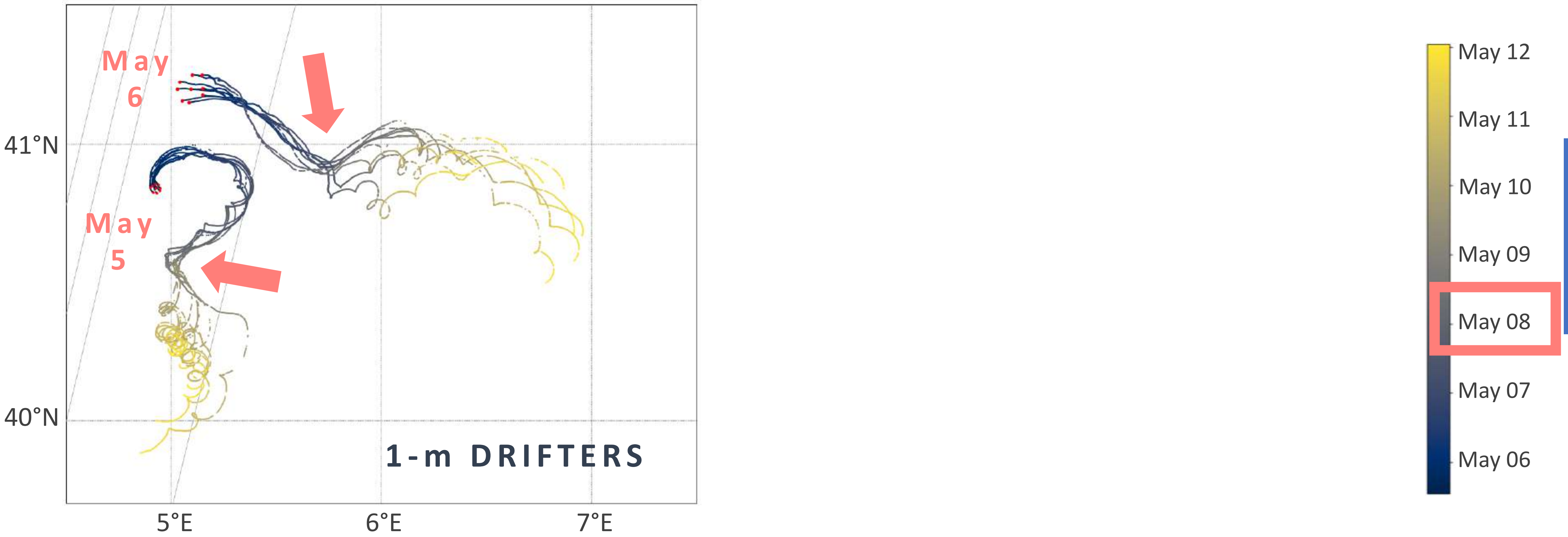

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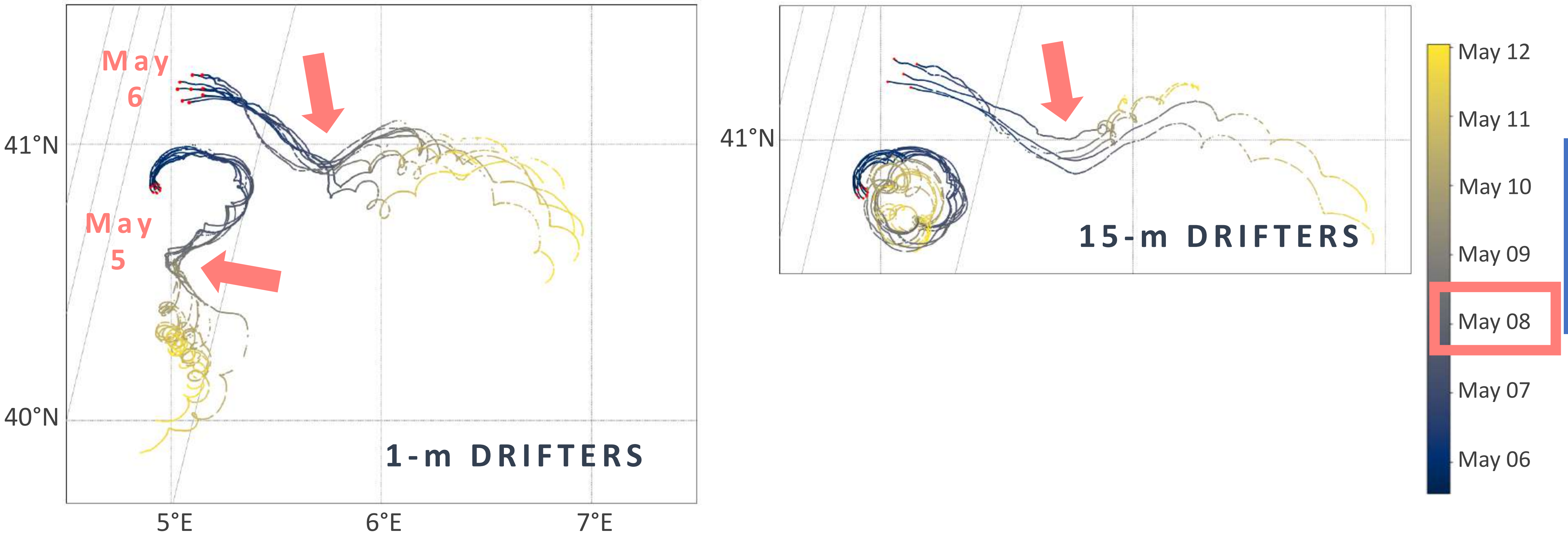

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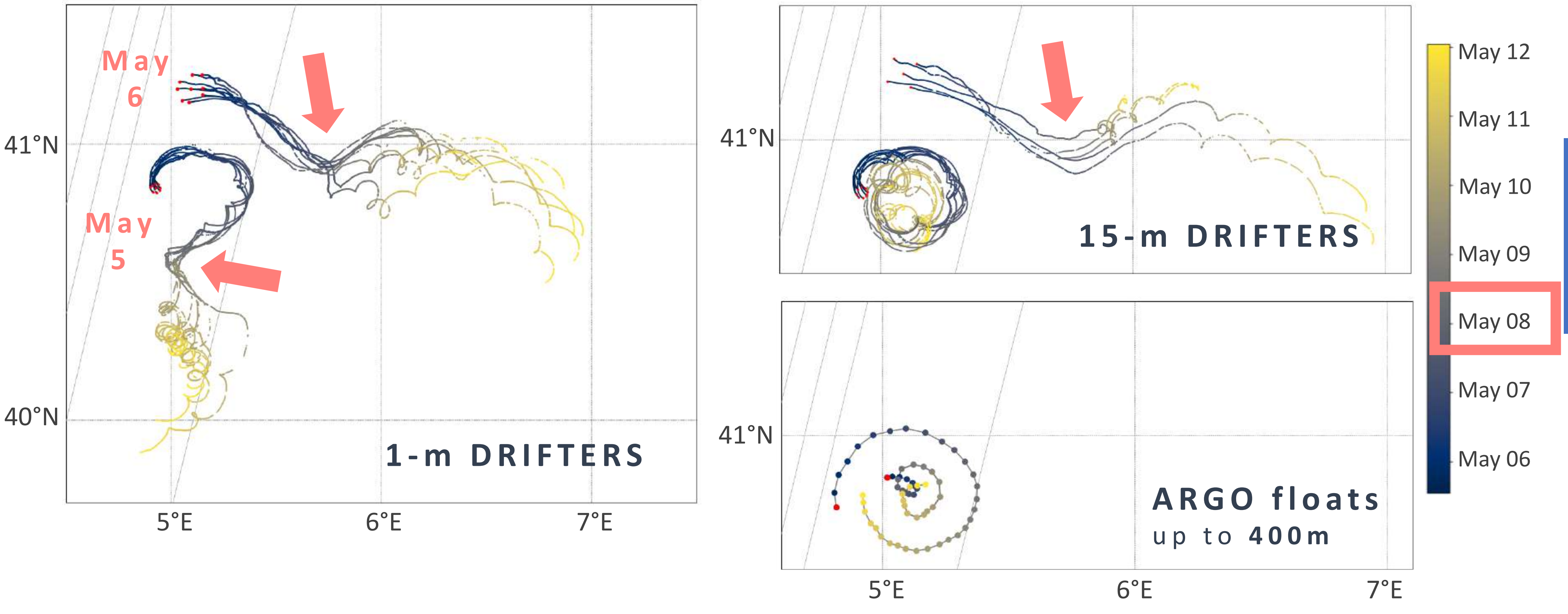
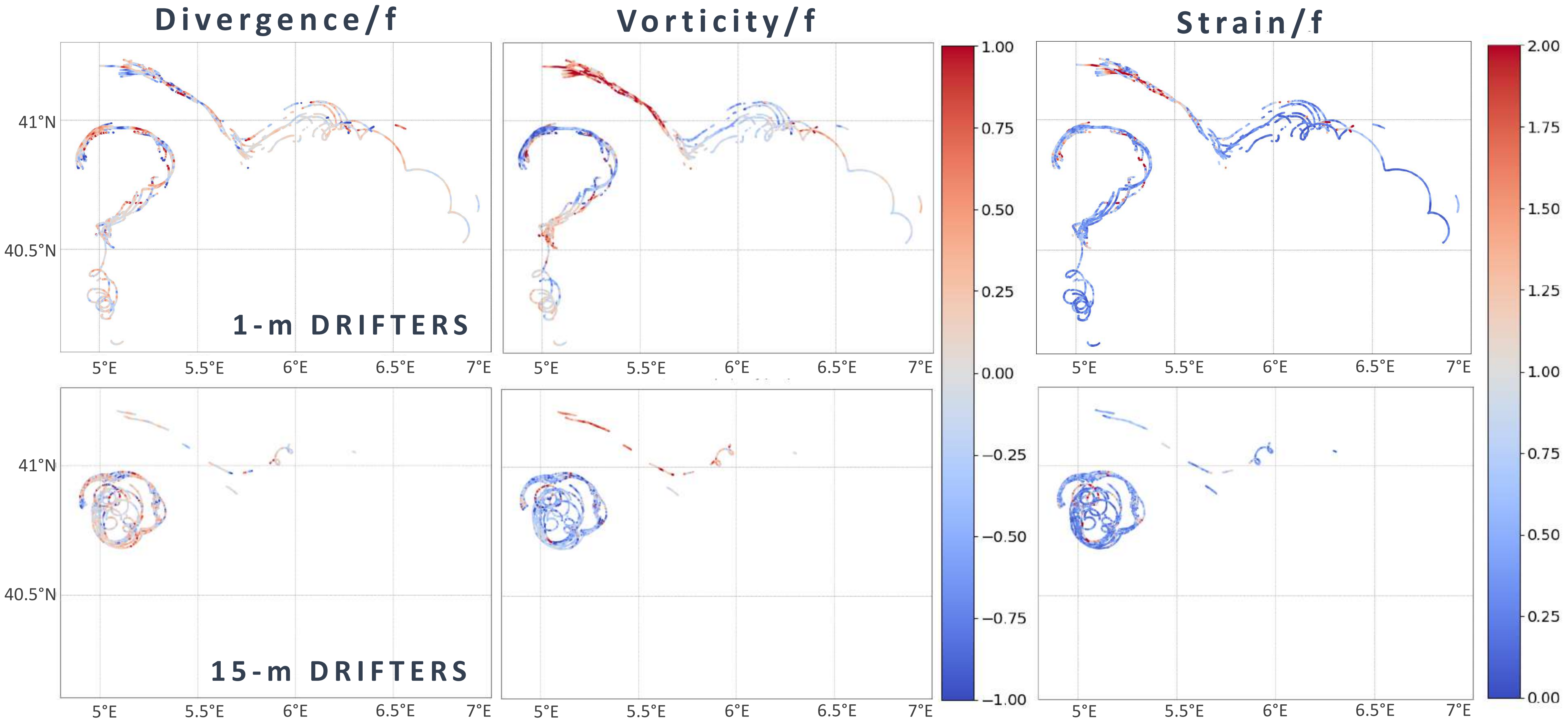
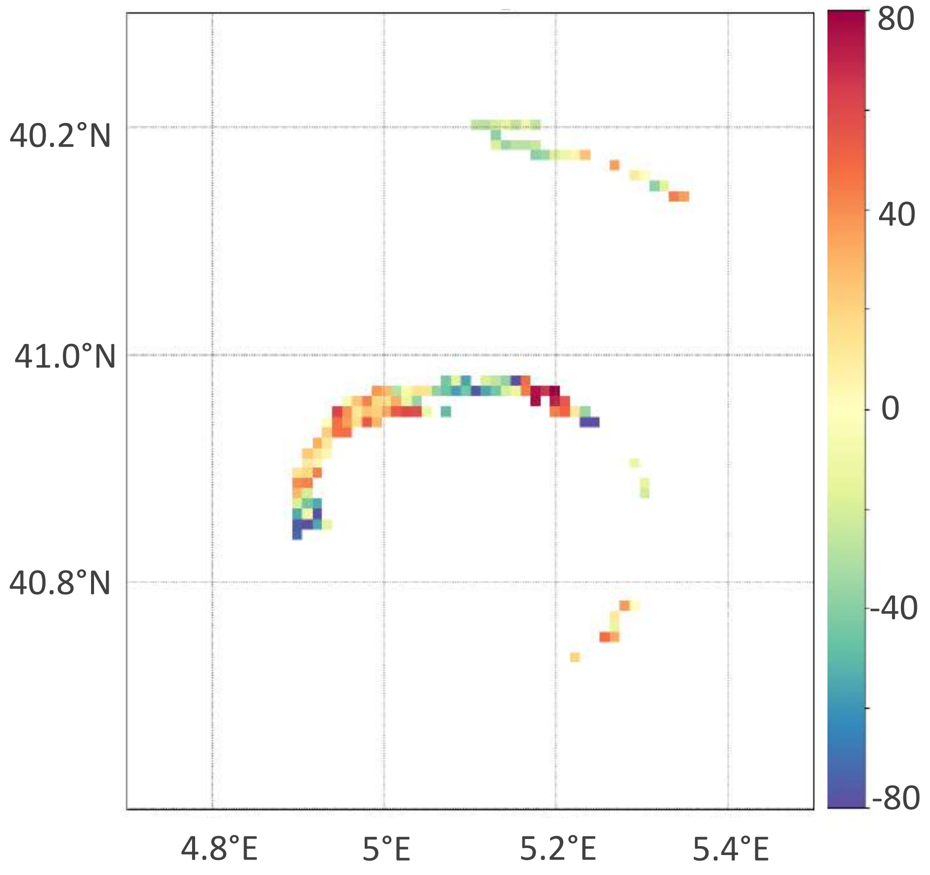


3. Lagrangian diagnostics



3. Vertical velocities *w*

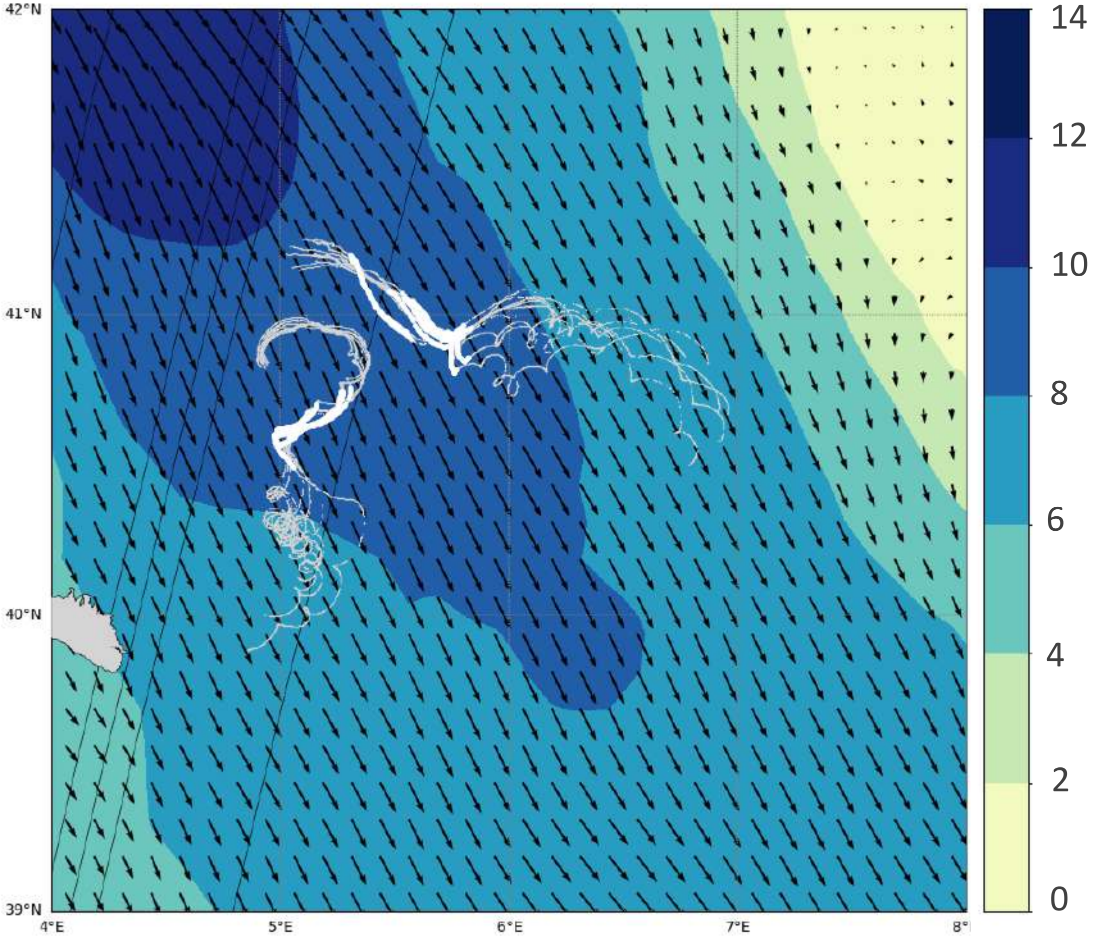
May 5-12 - *w* velocities (m/d)



- alternating pattern of positive and negative w
- **+/- 80 m/d**
  (less than 1mm/s)
- Consistent with literature
  (Tarry et al, 2021, 2022, Esposito et al. 2023)

4. Influence of the wind: friction

May 8 - Wind velocities (m/s)
1-m drifters trajectories



May 7:

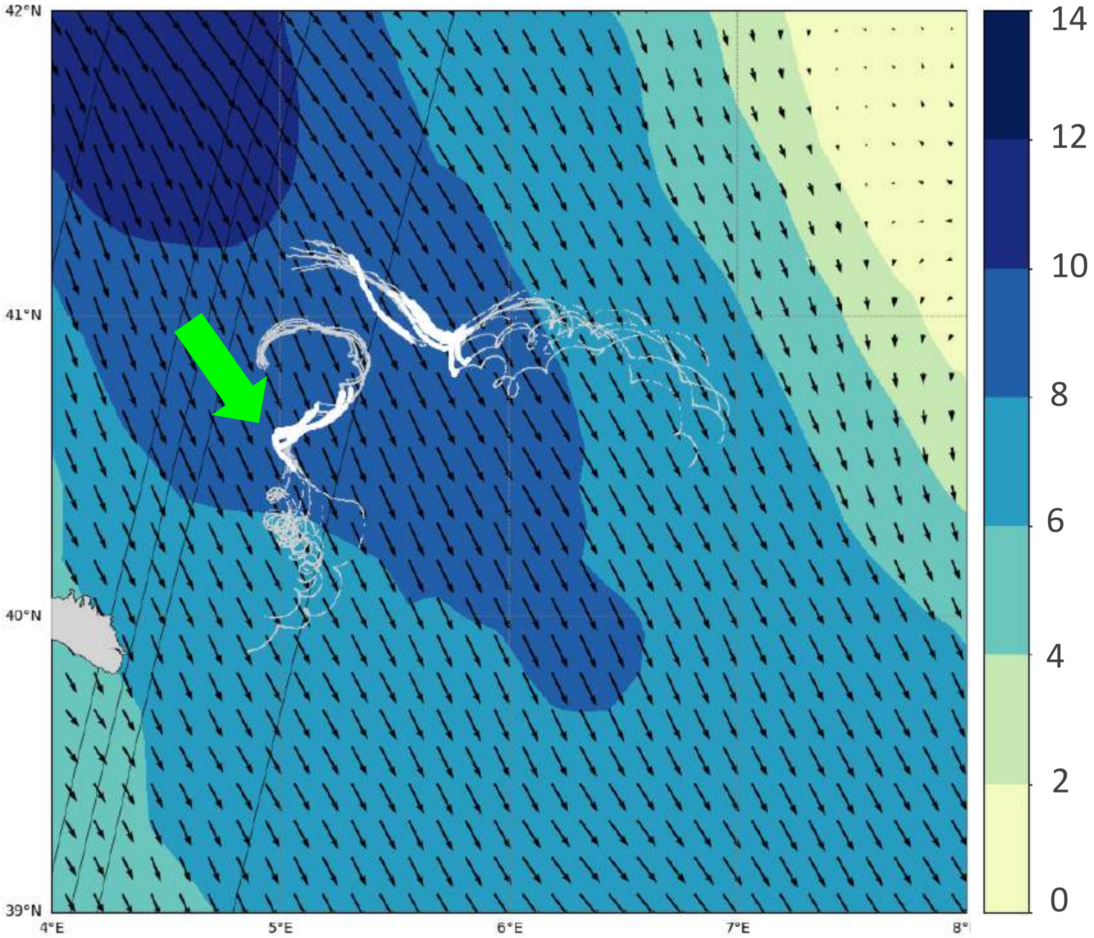
- moderate wind: 2-6 m/s

May 8 afternoon:

- Mistral event: **> 14m/s**

4. Influence of the wind: friction

May 8 - Wind velocities (m/s)
1-m drifters trajectories



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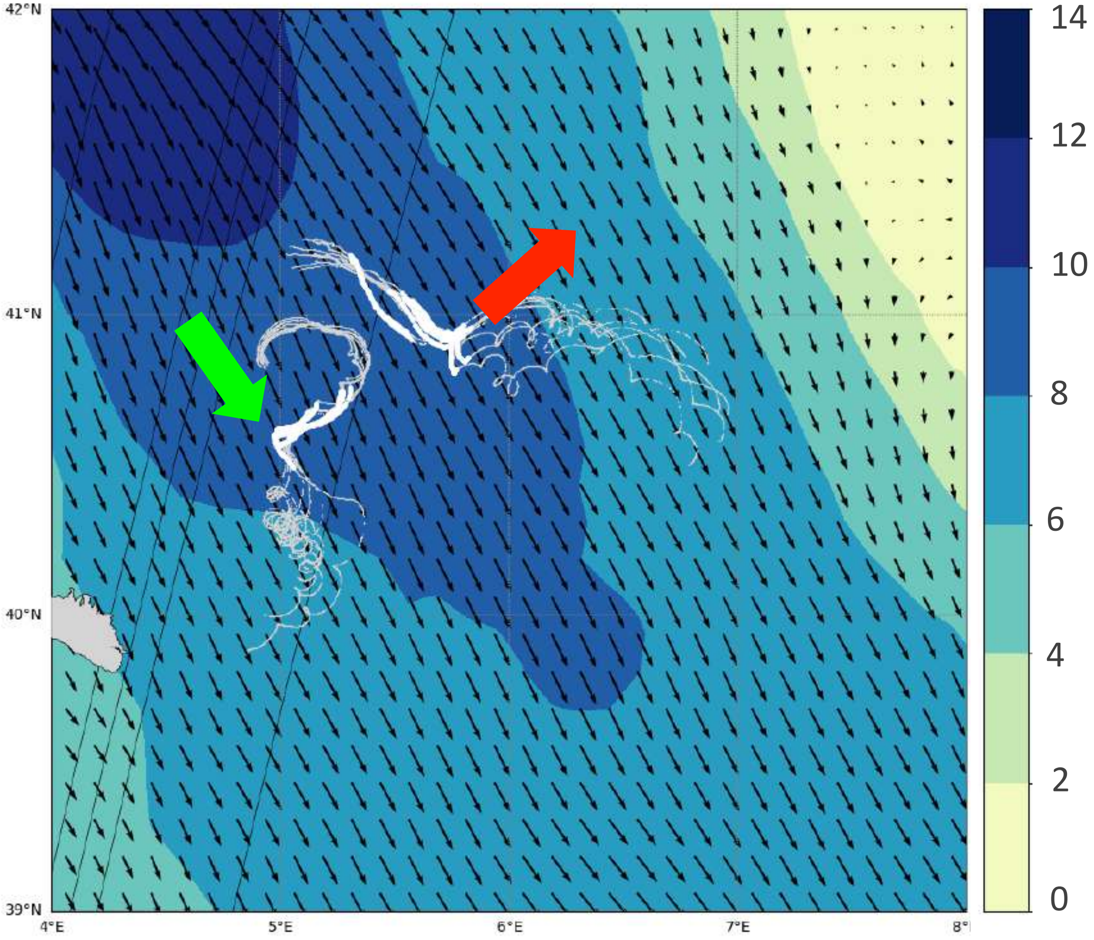


May 7:

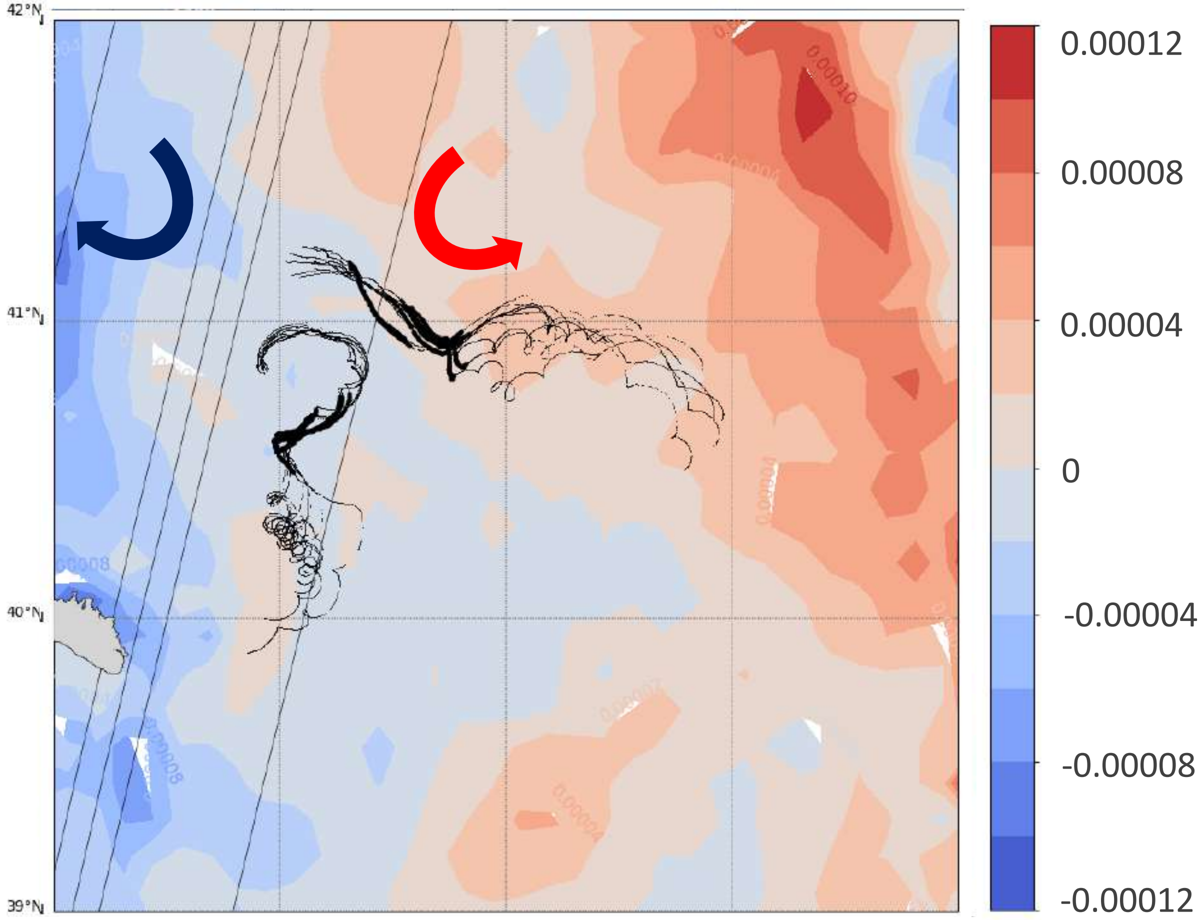
- moderate wind: 2-6 m/s

May 8 afternoon:

- Mistral event: **> 14m/s**
- **1-m drifters:**
  - **in eddy: ejected toward SE (as wind)**
  - in front: drifters toward NE. Why???

4. Influence of the wind: vorticity

May 8 - Wind curl (m^{-1})
1-m drifters trajectories



Before May 8:

- Negative vorticity in drifter's area

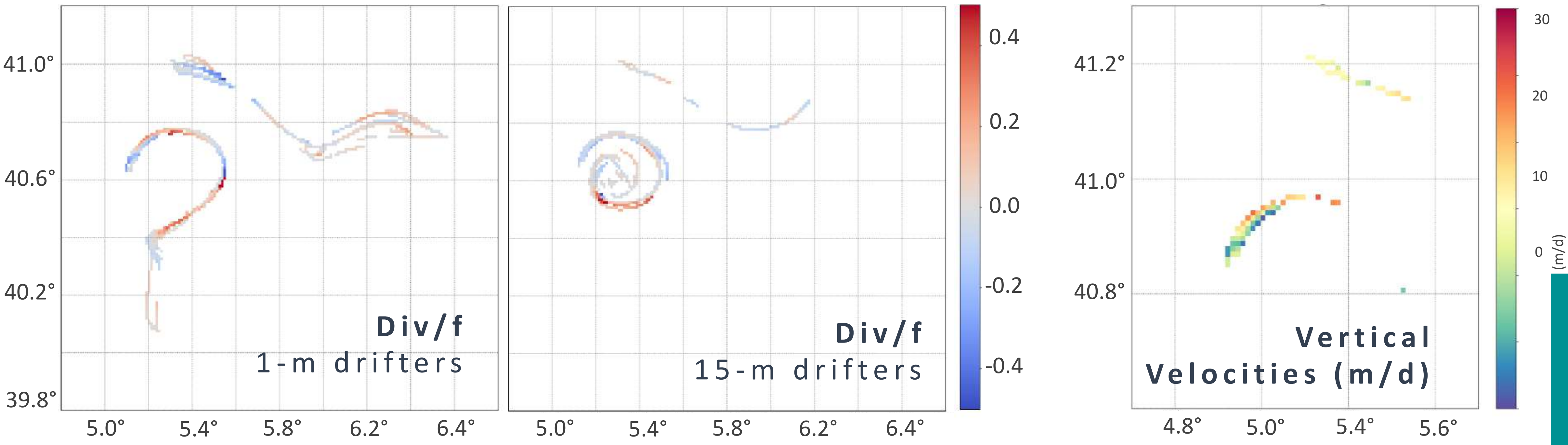
May 8:

- Shift from negative to positive vorticity coinciding with shift in 1-m drifters trajectories and vorticity

4. NIOs filtering and new Lagrangian diag.

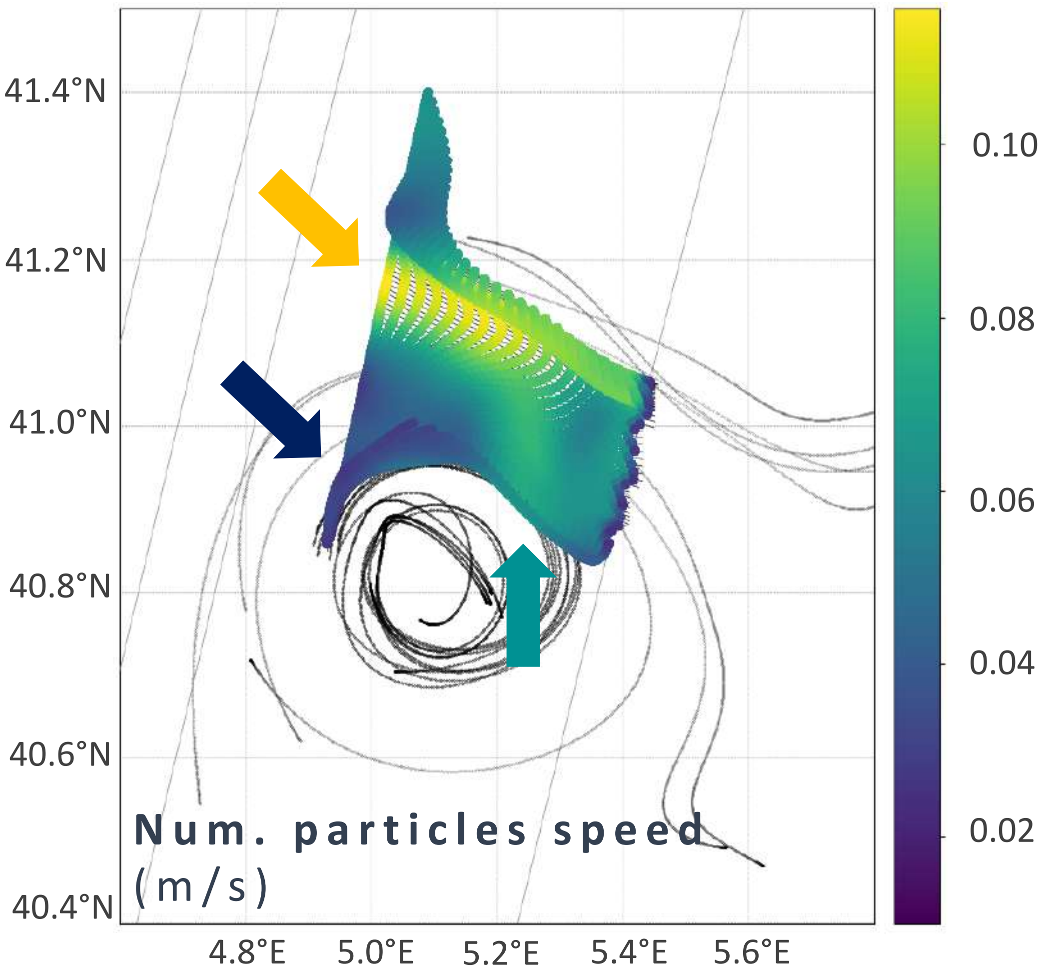
Low-pass Butterworth filter (order = 4, period = 24h)

FILTERED TRAJECTORIES:



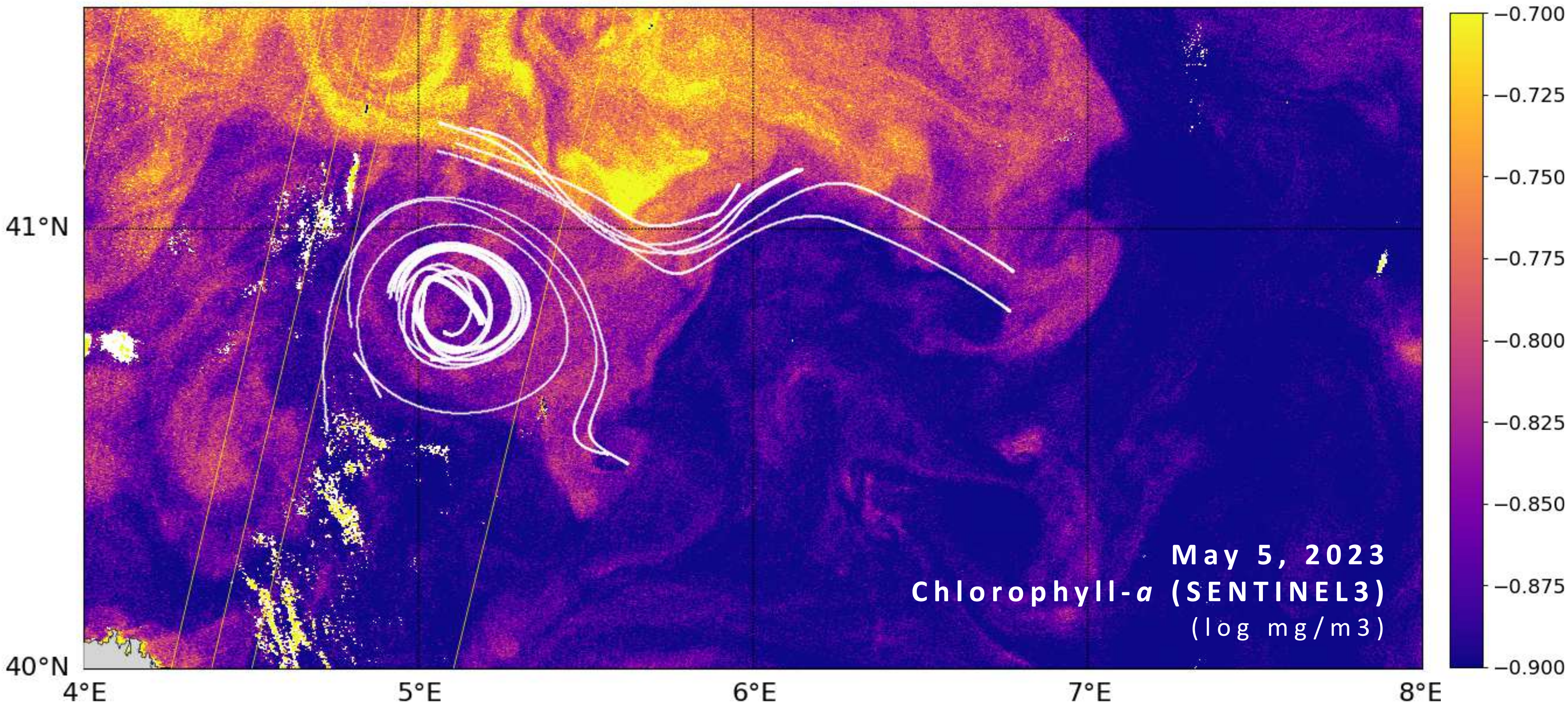
- Secondary vertical ageostrophic circulation (Tarry et al. 2021, 2022, Esposito et al. 2023)
- **Interaction between the eddy and the front?**

4. Interactions eddy / front: LAMTA simulations



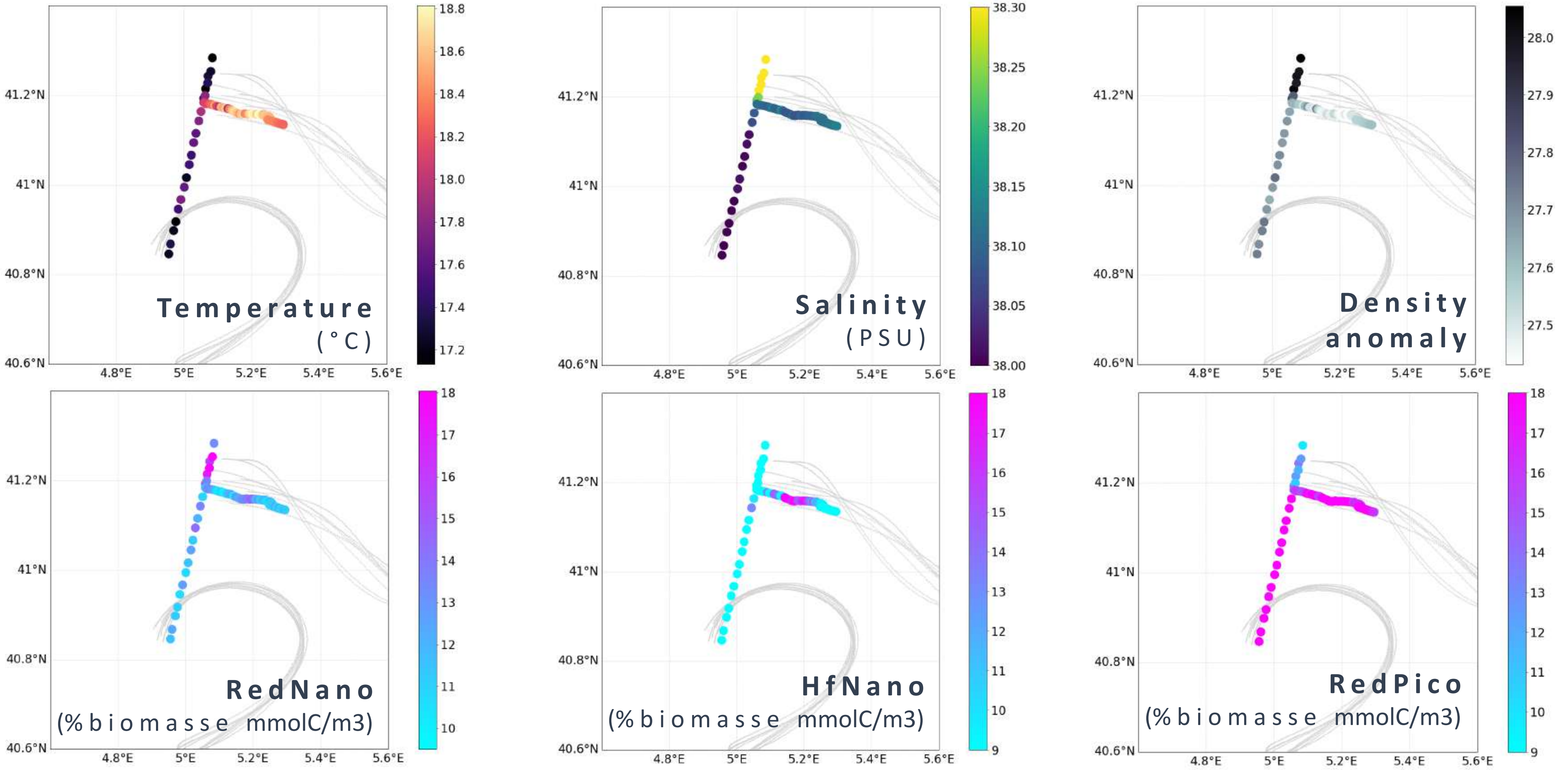
- **3-days simulation: May 6 to 8**
- 60 particles initialized on an array on the drifter deployment's locations in the eddy to the front
- **Day 1**: strong contrasted velocities between the front (> 0.1 m/s) and the anticyclone (0.02-0.03 m/s)
- **Days 2-3**: **homogeneous velocities** (0.07-0.08 m/s)
- Interactions between the two fine-scale features

5. Coupling physics - biogeochemistry



5. Coupling physics – biology

(TSG - cytometry data: courtesy of L. Oms and G. Grégori)



5. Conclusion and perspectives

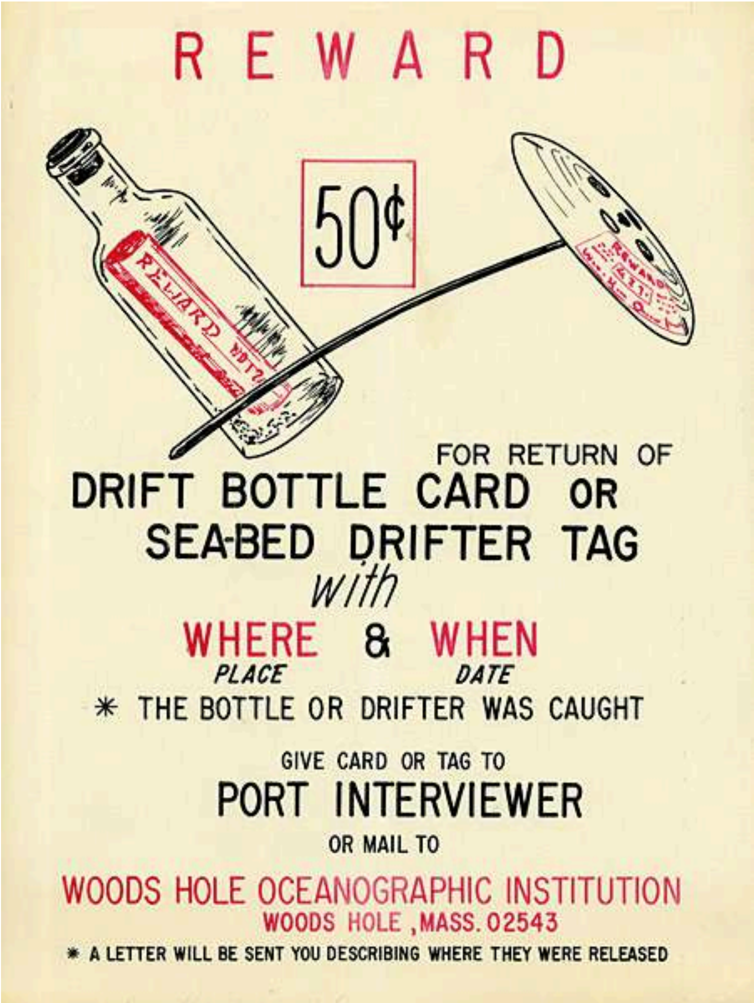
- **Fine-scale features and circulation** & **Lagrangian diagnostics tools**: in-situ & remote sensing data + numerical tool;
- **Estimation of Lagrangian properties (divergence, w) for BioSWOT-Med** in conformity with literature;
- **Original results** on interactions between two fine-scale features;
- **Perspectives:** 3-D exploration of the impact of physical characteristics over biogeochemical processes;

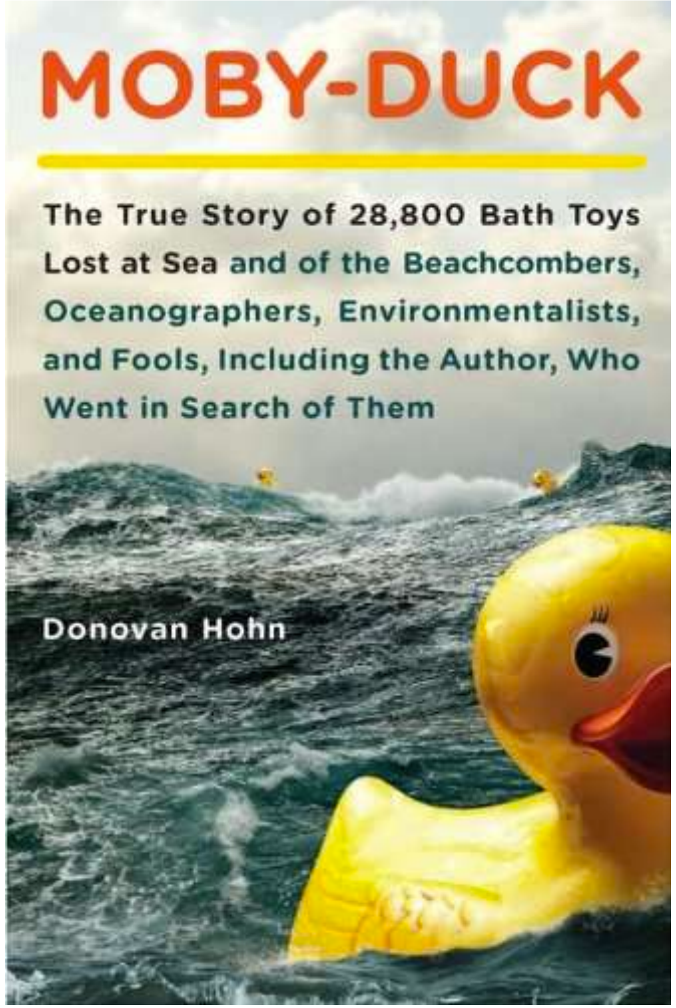
+ Contribution to EGU 2024 abstract and poster (Martelucci et al.) and publication (Demol et al., in prep) on drifter datasets.

(not)
the end...

HISTORY OF DRIFTERS

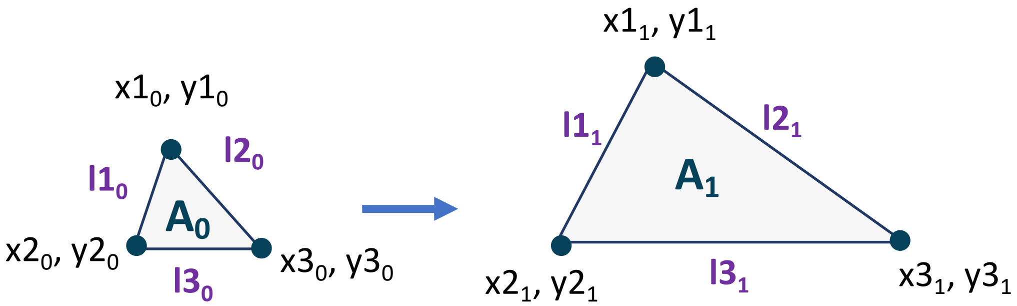
- 18th cent. Franklin / Lagrange
- **1980s**: Coastal Oceanic drifter experience (CODE, Davis et al., 1985)
- **1990s:** Surface Velocity Program (SVP)
- 1992: Friendly Floatees





AREA RATE OF CHANGE Molinari et Kirwan. (1975)

$$D = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \rightarrow \frac{1}{A}\frac{dA}{dt}$$



D > 0 → divergence
D < 0 → convergence

Heron's formula for A_0 / A_1: $\sqrt{(c.(c-l1).(c-l2)(c-L3))}$
with c = half-perimeter

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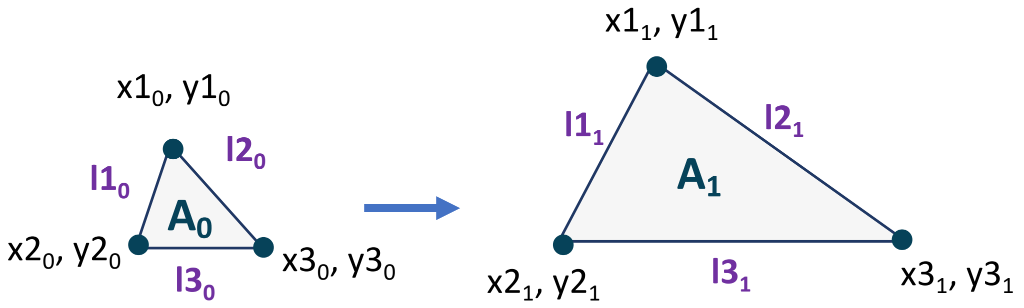
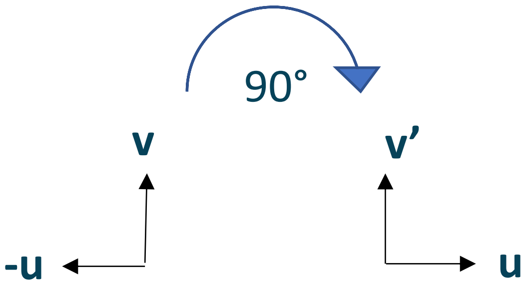
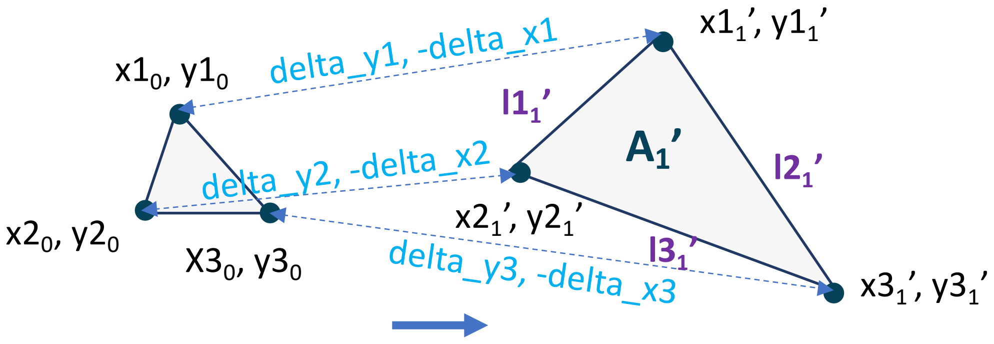


D > 0 → divergence
D < 0 → convergence

Heron's formula for A_0 / A_1: √(c.(c-l1).(c-l2)(c-L3))
with c = half-perimeter

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \frac{\partial u'}{\partial x} + \frac{\partial v'}{\partial y} \rightarrow \frac{1}{A'}\frac{dA'}{dt}$$





$x1_1'$, $y1_1'$ = $x1_0$, $y1_0$, $delta\_y_1$, $-delta\_x_1$

ζ > 0 → cyclonique
ζ < 0 → anticyclonique

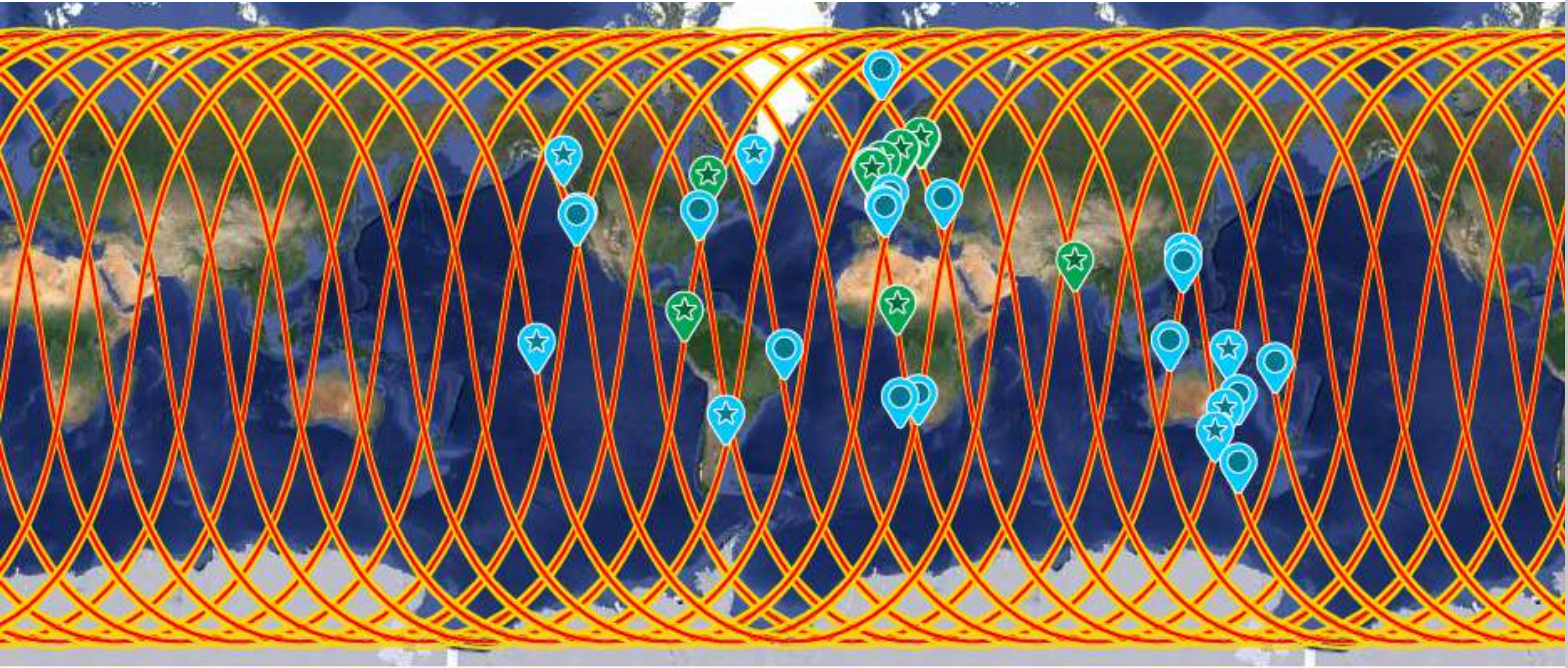
AREA RATE OF CHANGE Molinari et Kirwan. (1975)

$$N_{st} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} = \frac{\partial u''}{\partial x} + \frac{\partial v''}{\partial y} \rightarrow \frac{1}{A''}\frac{dA''}{dt}$$

$$Strain = \sqrt{N_{st}^2 + S_{st}^2}$$

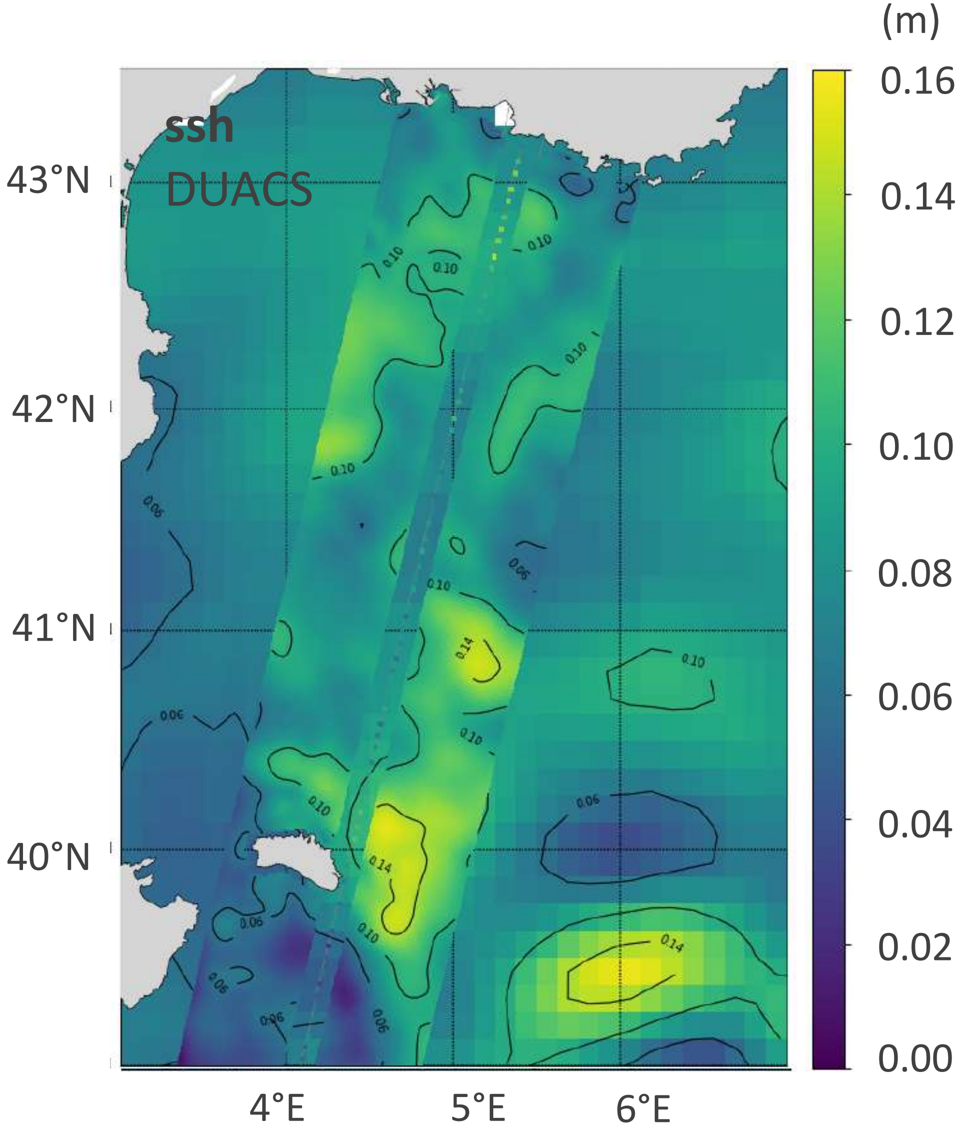
$$S_{st} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} = \frac{\partial u'''}{\partial x} + \frac{\partial v'''}{\partial y} \rightarrow \frac{1}{A'''}\frac{dA'''}{dt}$$

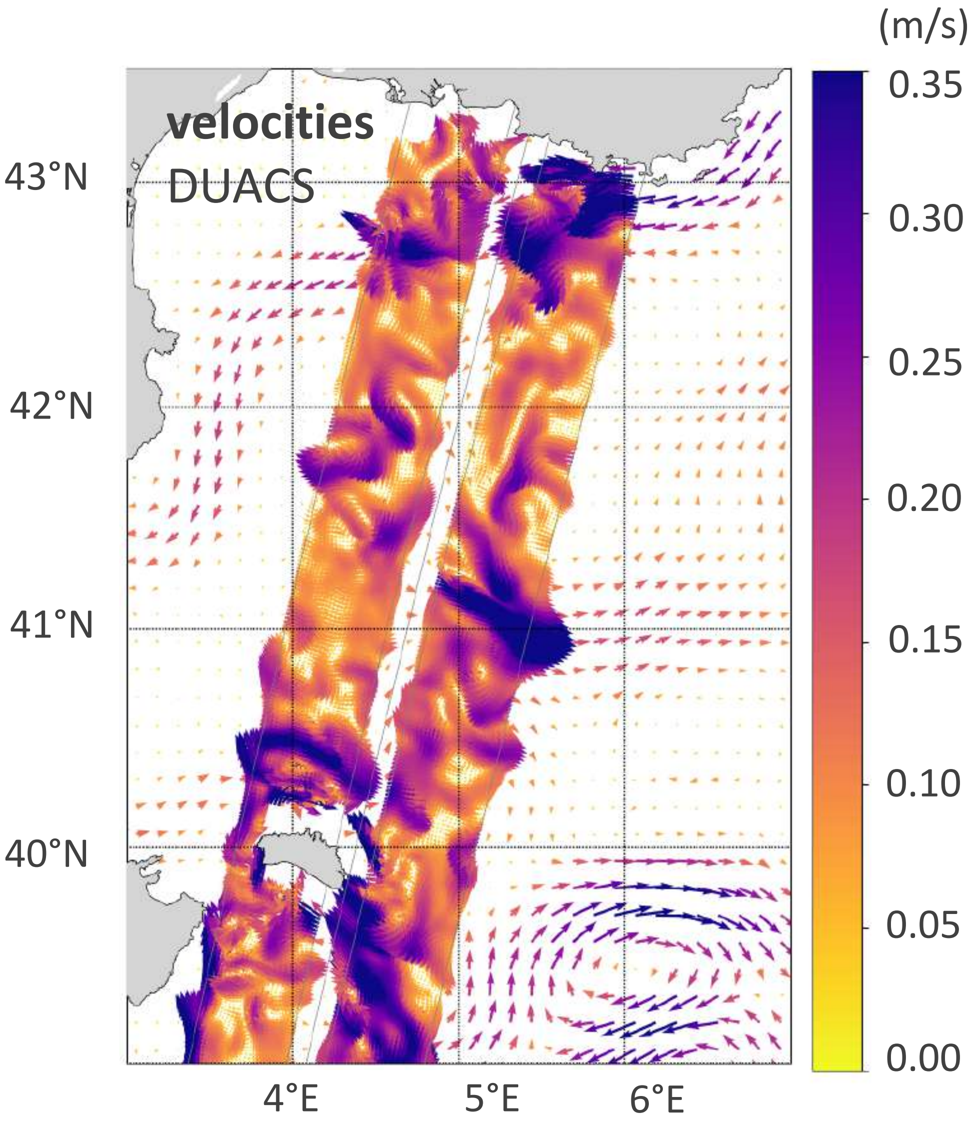
SWOT vs DUACS



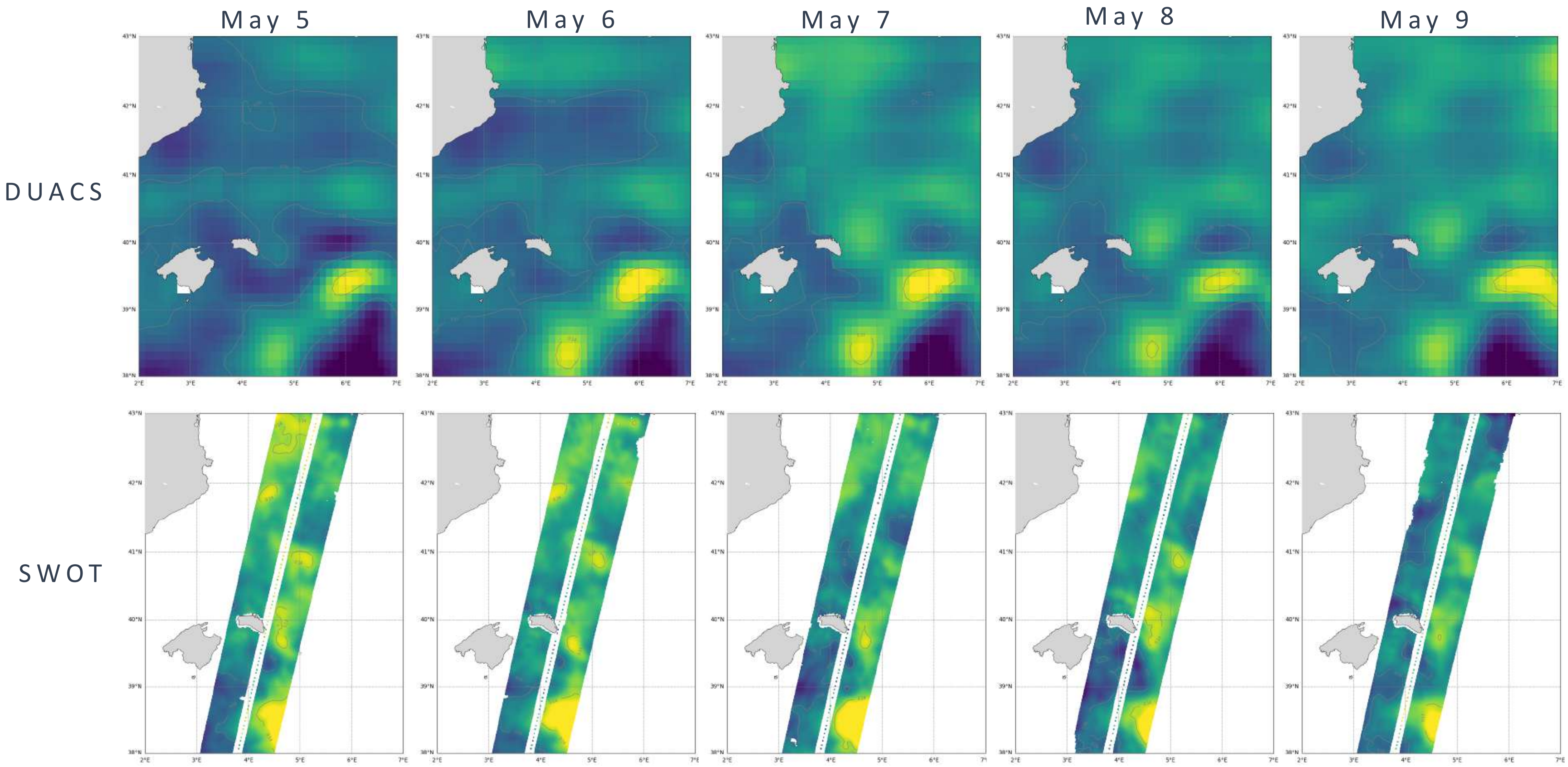
Source: SWOT-AdAc

SWOT vs DUACS





OCEANIC VARIABILITY SEEN BY DUACS / SWOT

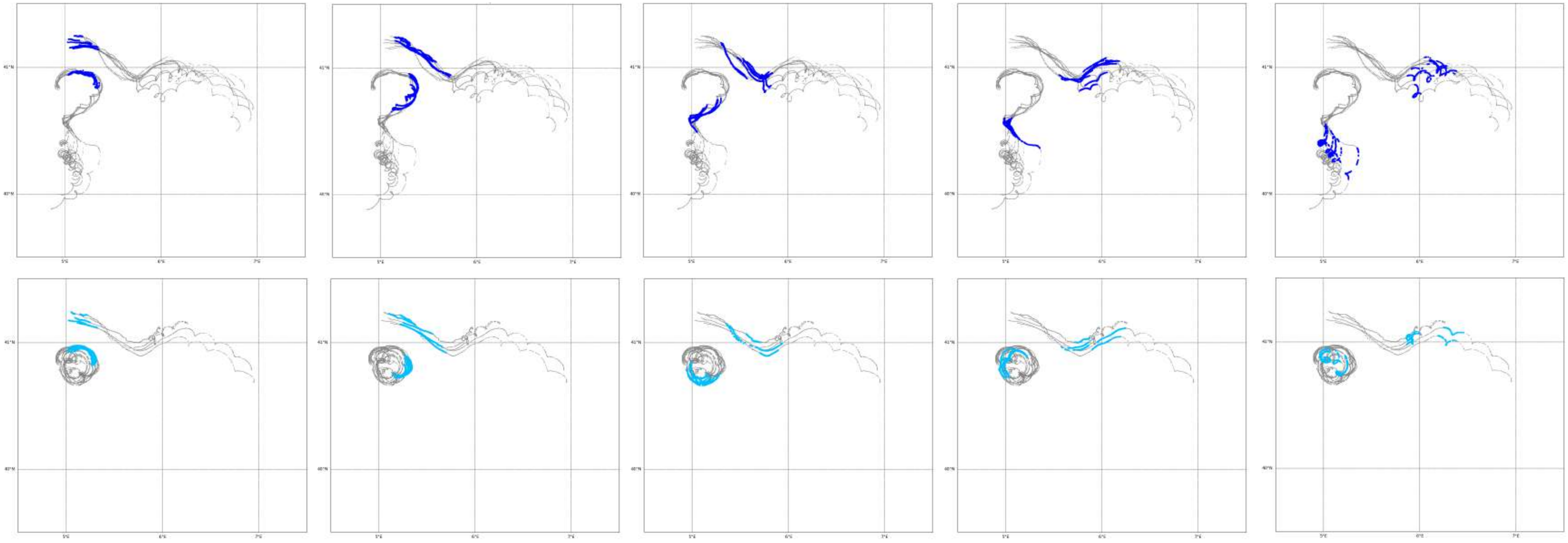


DRIFTER’S TRAJECTORIES

May 6 | May 7 | May 8 | May 9 | May 10

1 m

15 m



VERTICAL VELOCITY w (1/2)

Assumption of an incompressible fluid

Equation of continuity : $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad => \quad -\frac{\partial w}{\partial z} = D$

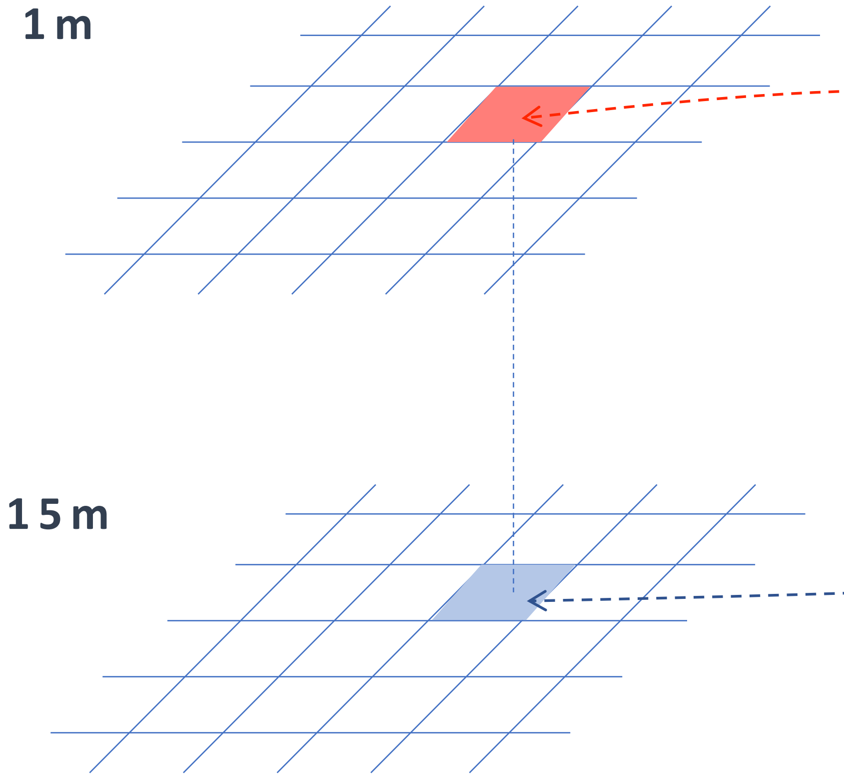
$$=> \int_{-15m}^{0m} -\frac{\partial w}{\partial z}\, dz = \int_{-15m}^{0m} D\, dz \quad => \quad [-w]_{-15m}^{0m} = D \int_{-15m}^{0m} dz$$

$$=> -w_{0m} - (-w_{-15m}) = D \quad [z]_{-15m}^{0m}$$

= 0

$$=> w_{-15m} = D \; z_{-15m}$$

VERTICAL VELOCITY *w* (2/2)



Grid resolution: 1 km x 1km, per day
In each bin:

$$D = \frac{D_{mean0m} + D_{mean15m}}{2}$$

→ ***w***: smaller value at 15m
most conservative method of estimati

GEOSTROPHIC VELOCITY (1/2)

$$Navier - Stokes\ equations: \frac{d\vec{v}}{dt} = -\frac{1}{\rho}\vec{\Delta}p + \vec{g} - 2\Omega\vec{v} + v\vec{\Delta}^2\vec{v}$$

X X

X Neglected: stationary fluid, no friction

☐ Geostrophic approximation (pressure, gravitational & Coriolis forces

$$v = \frac{1}{f\rho}\frac{\partial p}{\partial x} \qquad u = -\frac{1}{f\rho}\frac{\partial p}{\partial y} \qquad \frac{\partial p}{\partial z} = -\rho g \quad (\acute{e}q.\ hydrostatique)$$

GEOSTROPHIC VELOCITY (2/2)

$$=> \int_{-z_0}^{\eta} dp = -\rho_0 g \int_{-z_0}^{\eta} dz \quad (\eta = sea - surface\ height)$$

$$=> [p]_{-z_0}^{\eta} = -\rho_0 g\, [z]_{-z_0}^{\eta} \qquad => \quad p_\eta - p_{-z_0} = -\rho_0 g(\eta + z_0)$$

$$=> \quad p_{-z_0} = p_\eta + \rho_0 g(\eta + z_0) \quad (p_\eta = pression\ atm.)$$

$$=> \quad v = \frac{1}{f\rho}\frac{\partial(\rho_0 g(\eta + z_0))}{\partial x} \qquad u = -\frac{1}{f\rho}\frac{\partial(\rho_0 g(\eta + z_0))}{\partial y}$$

$$=> \quad v = \frac{g}{f}\frac{\partial \eta}{\partial x} \qquad u = -\frac{g}{f}\frac{\partial \eta}{\partial y}$$

η = ssh measured by satellite

SATELLITE ALTIMETRY

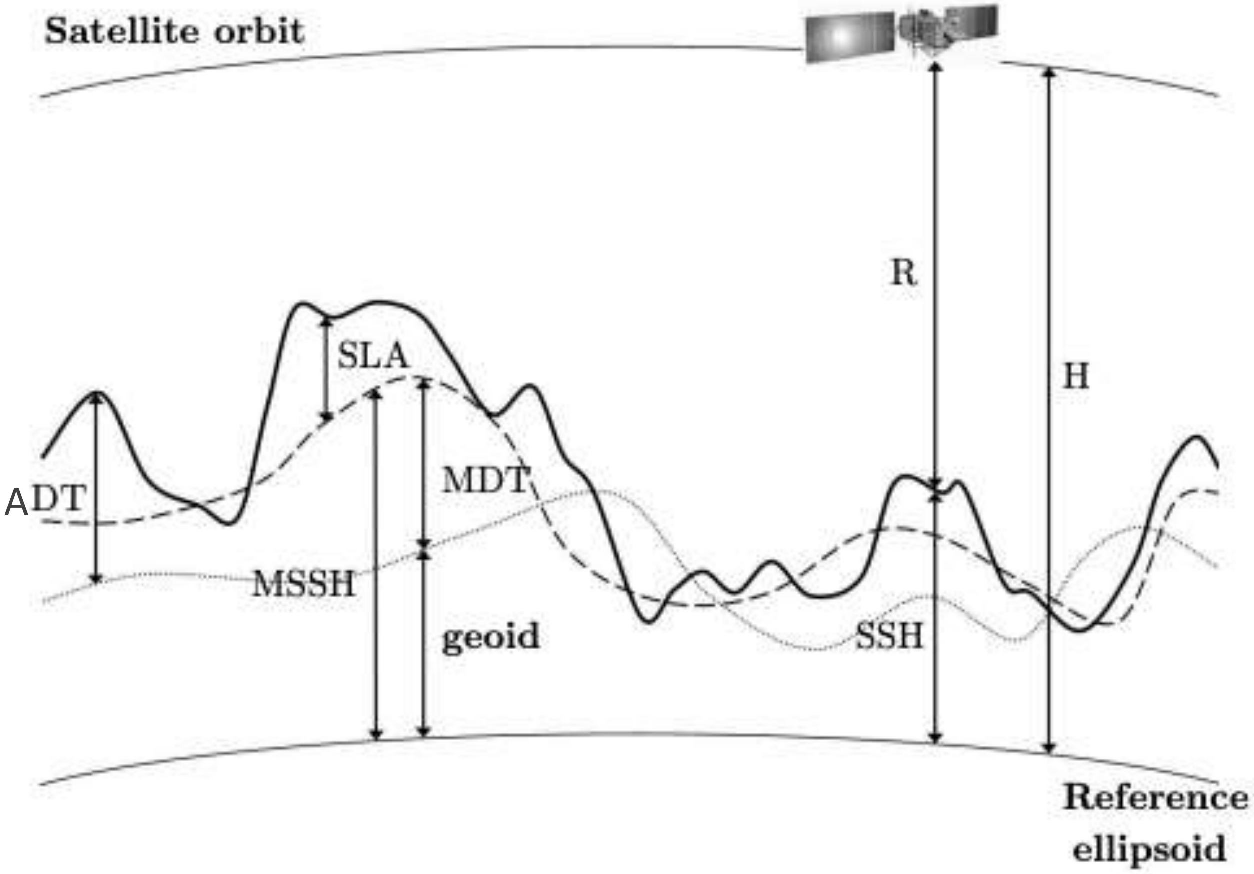


FIG. 1.1 – *Principe de la mesure altimétrique. D'après Castruccio (2006).*

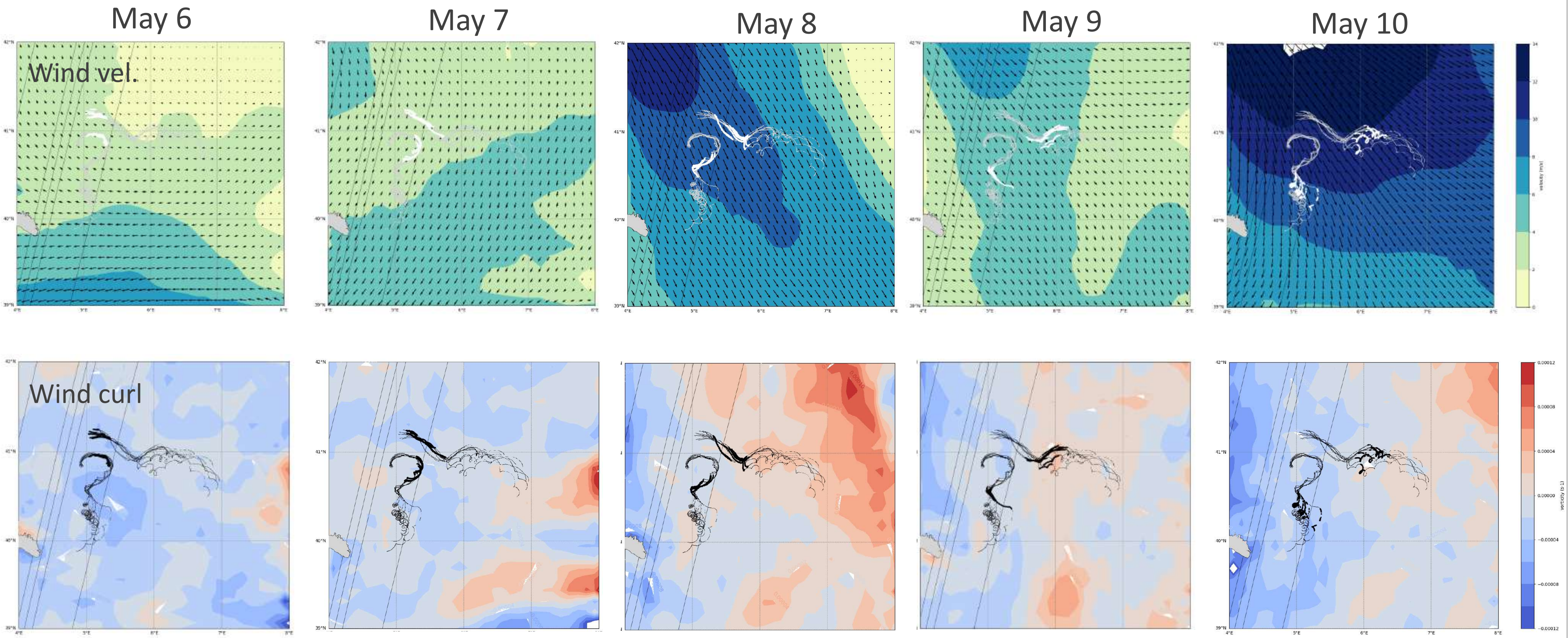
THESE Clément Ubelmann. Etude de scénarios d'altimétrie satellitaire pour le contrôle de la circulation océanique dans l'océan Atlantique tropical par assimilation de données. Océan, attmosphère. Université Joseph-Fourier - Grenoble I, 2009. Français. ffNNT : ff. fftel-00408763f

- **Géoïde** = surface équipotentielle du champ de gravité terrestre
- **Ellipsoïde de référence** = approximation du géoïde
- **H** = distance satellite – ellipsoïde
- **R** = distance satellite – surface de l'eau
- **SSH** (Sea Surface High) = H – R.

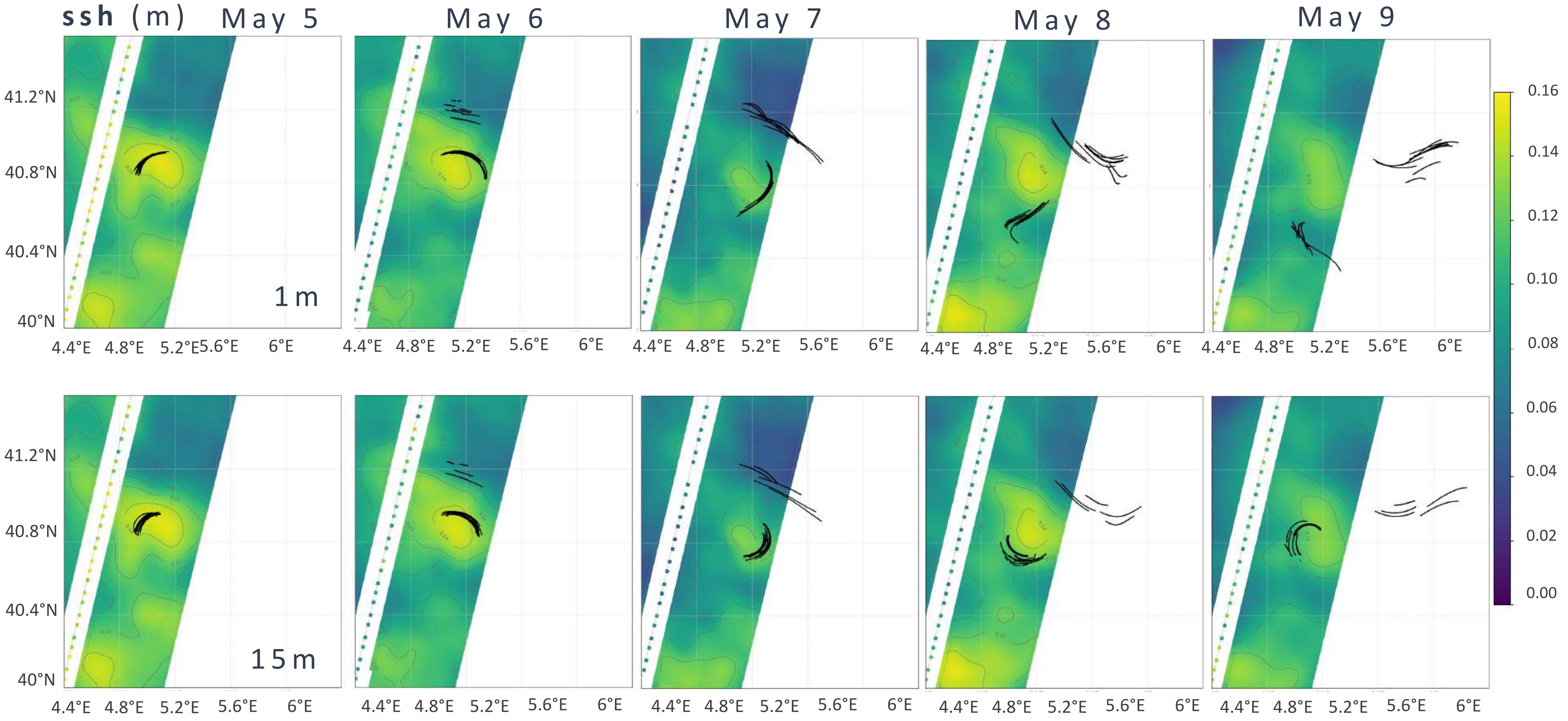
La SSH a deux composantes :

- **MSSH** = Mean SSH (SSH moyenne sur un temps long)
- **SLA** (Sea Level anomaly, due à la circulation océanique) = SSH – MSSH
- **ADT** (Absolute dynamique topographie, circulation océanique variable en fonction du géoïde) = SLA + MDT
- **MDT** = MSSH – geoïde

WIND FIELDS: May 06 to 10



INFLUENCE OF ssh



LAMTA – METHODE NUM. RUNGE-KUTTA ORDRE 4

Solving Ordinary Differential Equations (ODE):

$\frac{dy}{dt} = f(t, y)$

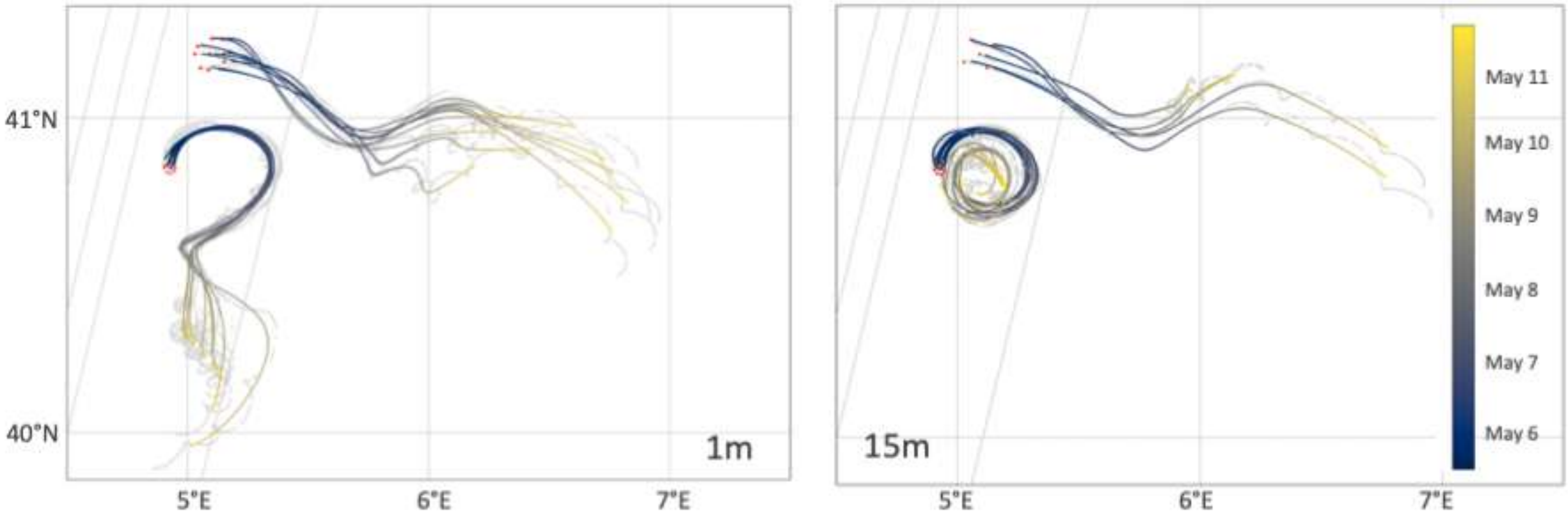
avec une condition initiale $y(t_0) = y_0$.

$$Y_{n+1} = Y_n + \frac{h}{6}(K_1 + 2K_2 + 2K_3 + K_4)$$

$$\begin{aligned} K_1 &= f\left(x_n, Y_n\right) \\ K_2 &= f\left(x_n + \tfrac{h}{2}, Y_n + \tfrac{h}{2}K_1\right) \\ K_3 &= f\left(x_n + \tfrac{h}{2}, Y_n + \tfrac{h}{2}K_2\right) \\ K_4 &= f\left(x_n + h, Y_n + hK_3\right) \end{aligned}$$

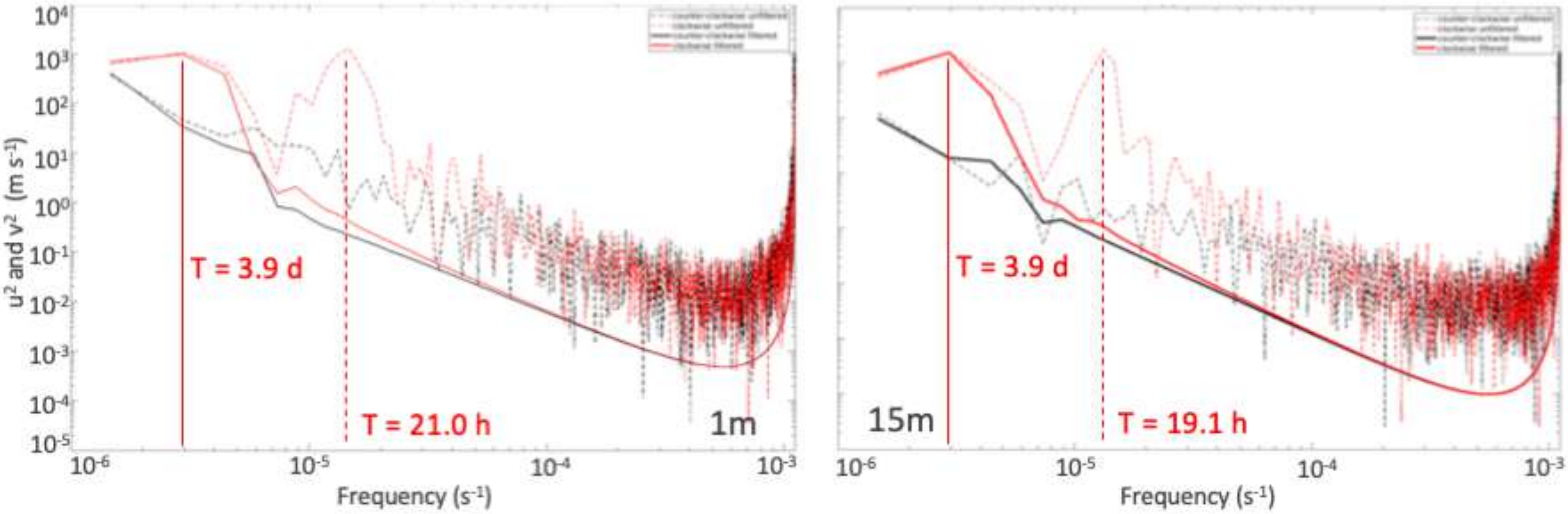
$$\begin{array}{c|cccc} 0 & & & & \\ \frac{1}{2} & \frac{1}{2} & & & \\ \frac{1}{2} & 0 & \frac{1}{2} & & \\ 1 & 0 & 0 & 1 & \\ \hline & \frac{1}{6} & \frac{1}{3} & \frac{1}{3} & \frac{1}{6} \end{array}$$

BUTTERWORTH FILTER

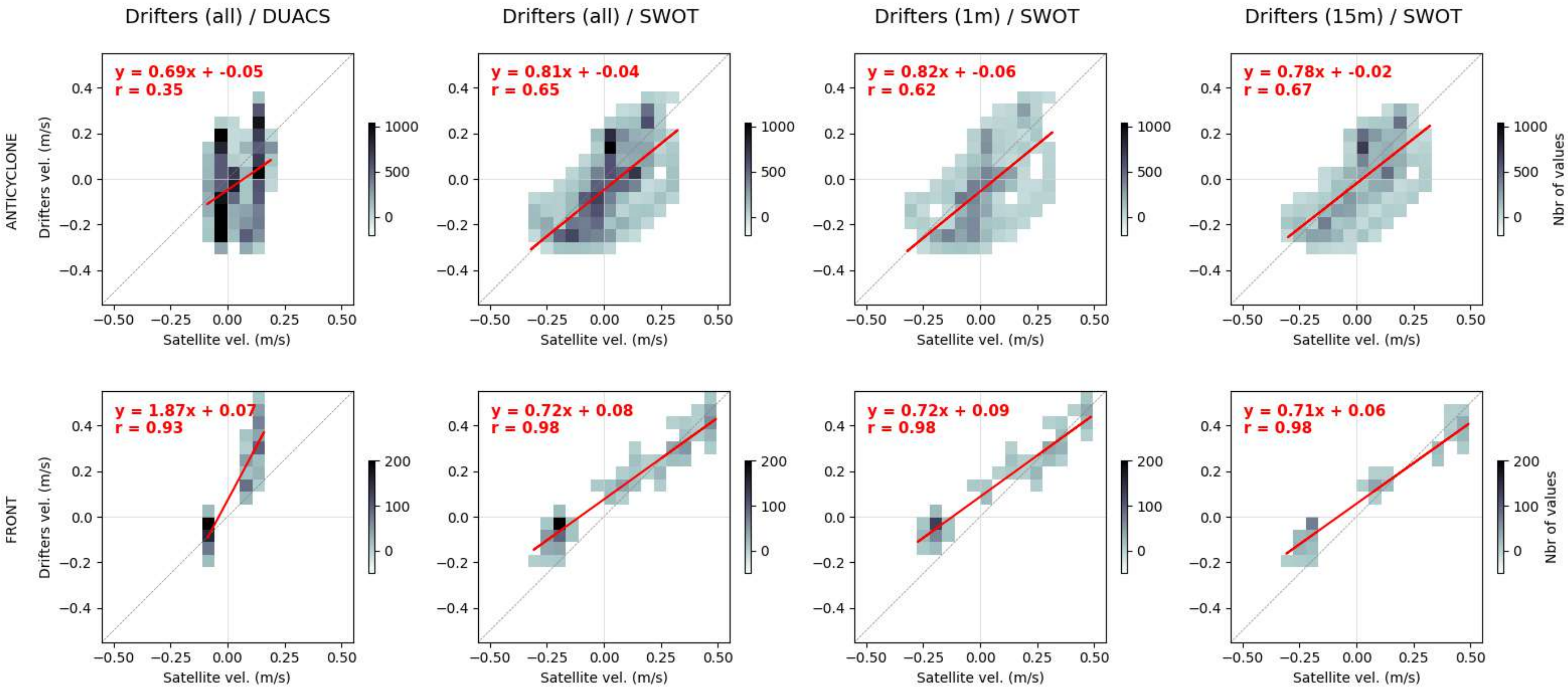


$$|H(\omega)| = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}}}$$

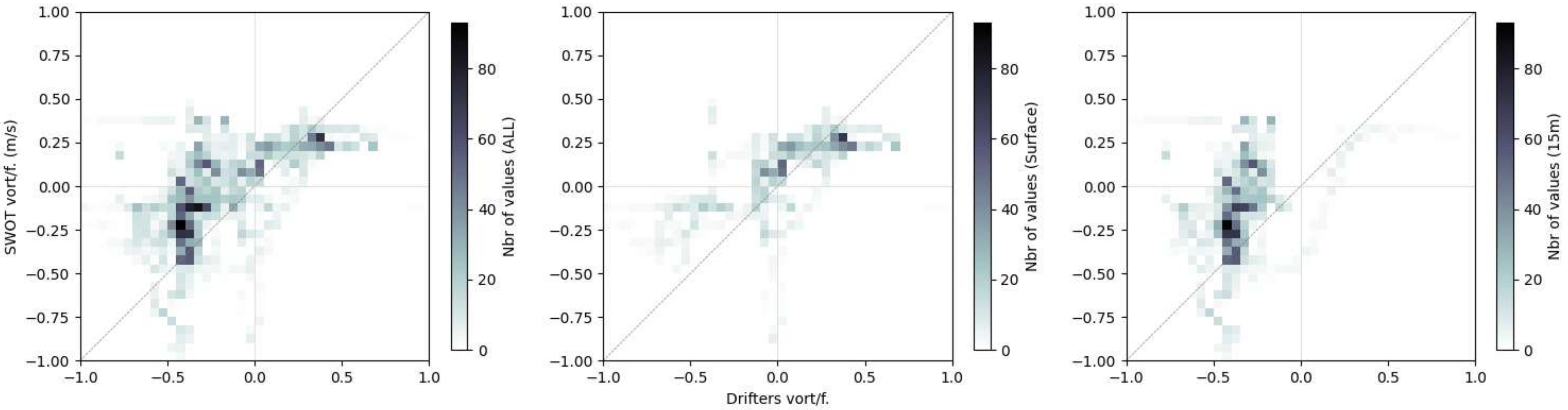
ROTARY SPECTRA



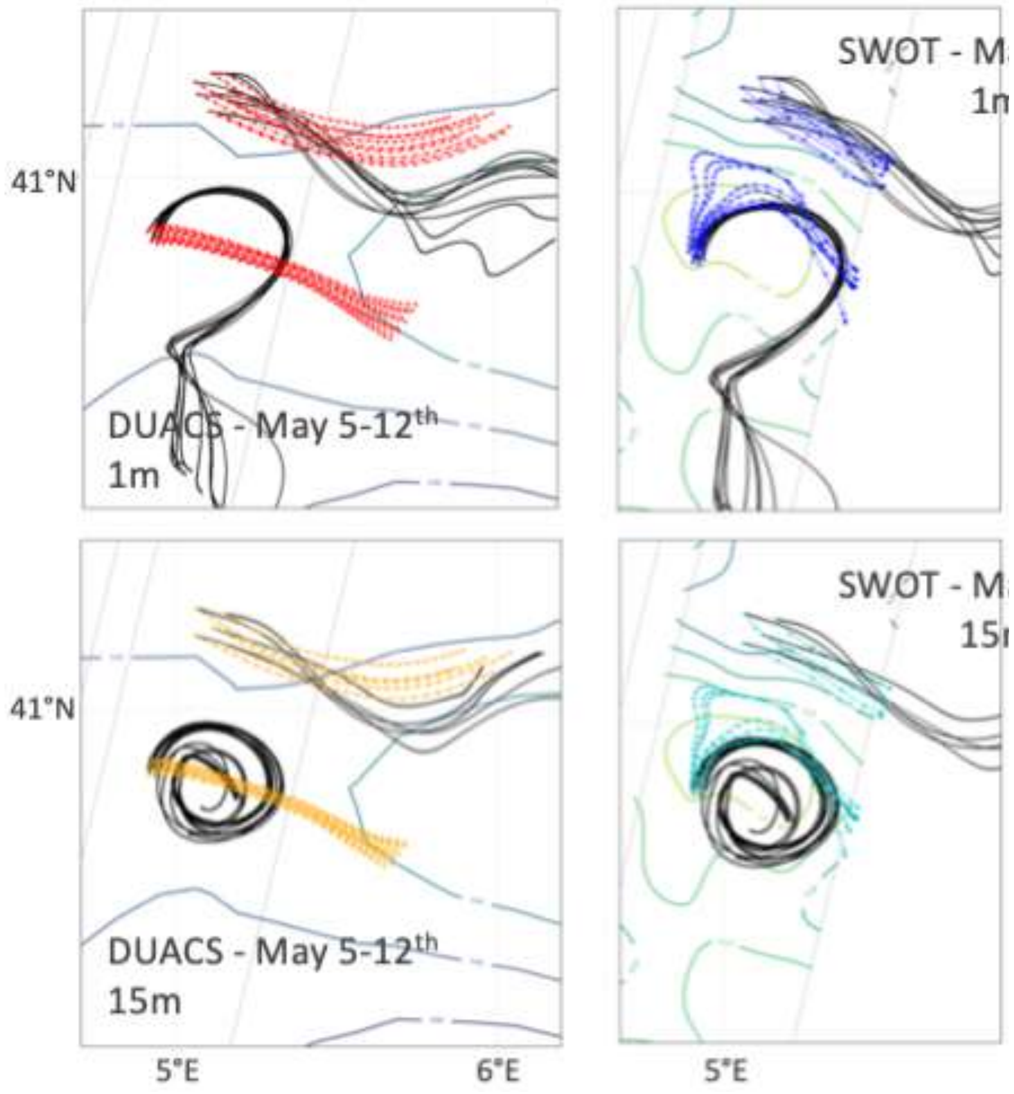
COMPARISON DUACS / SWOT / DRIFTERS



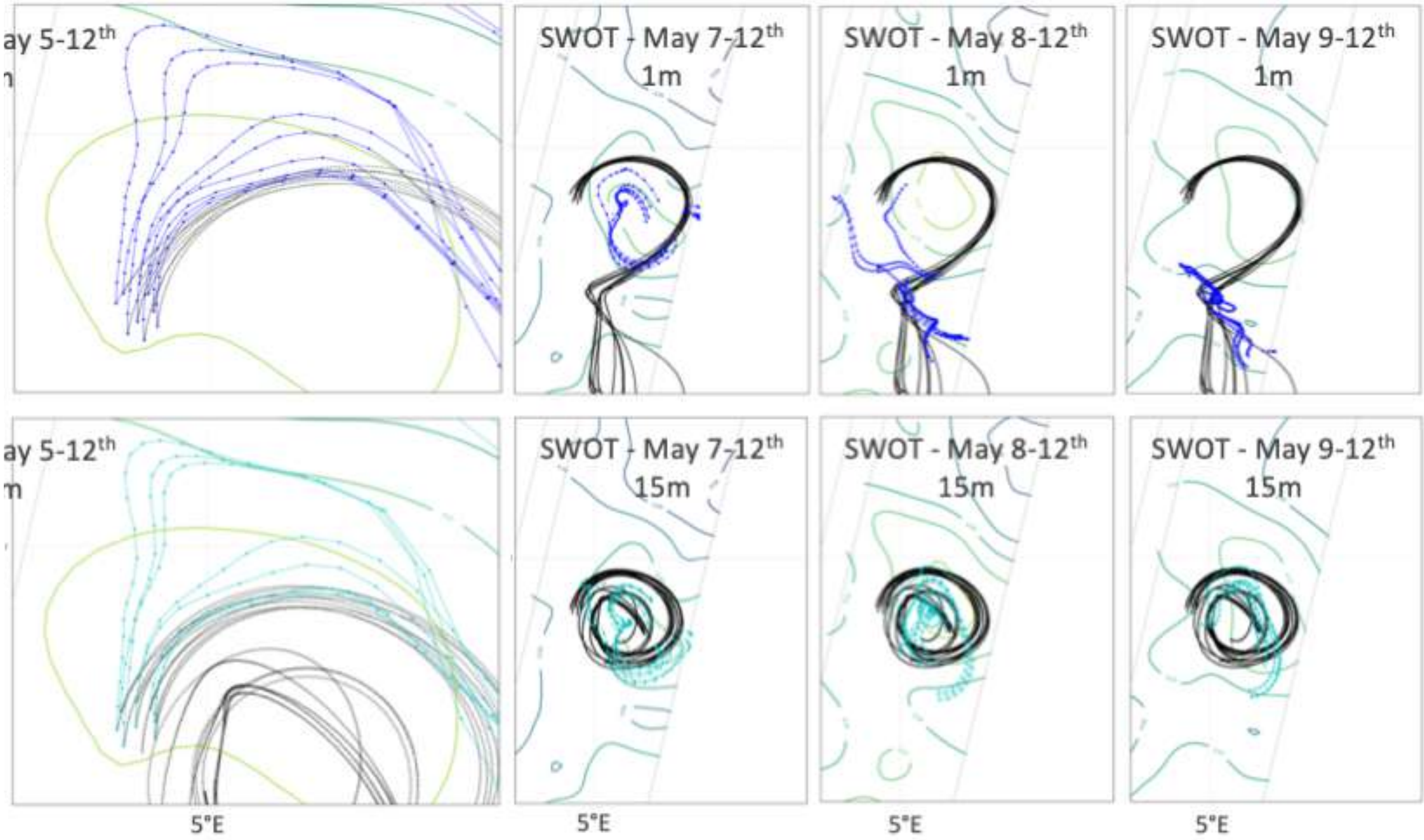
COMPARISON DUACS / SWOT / DRIFTERS



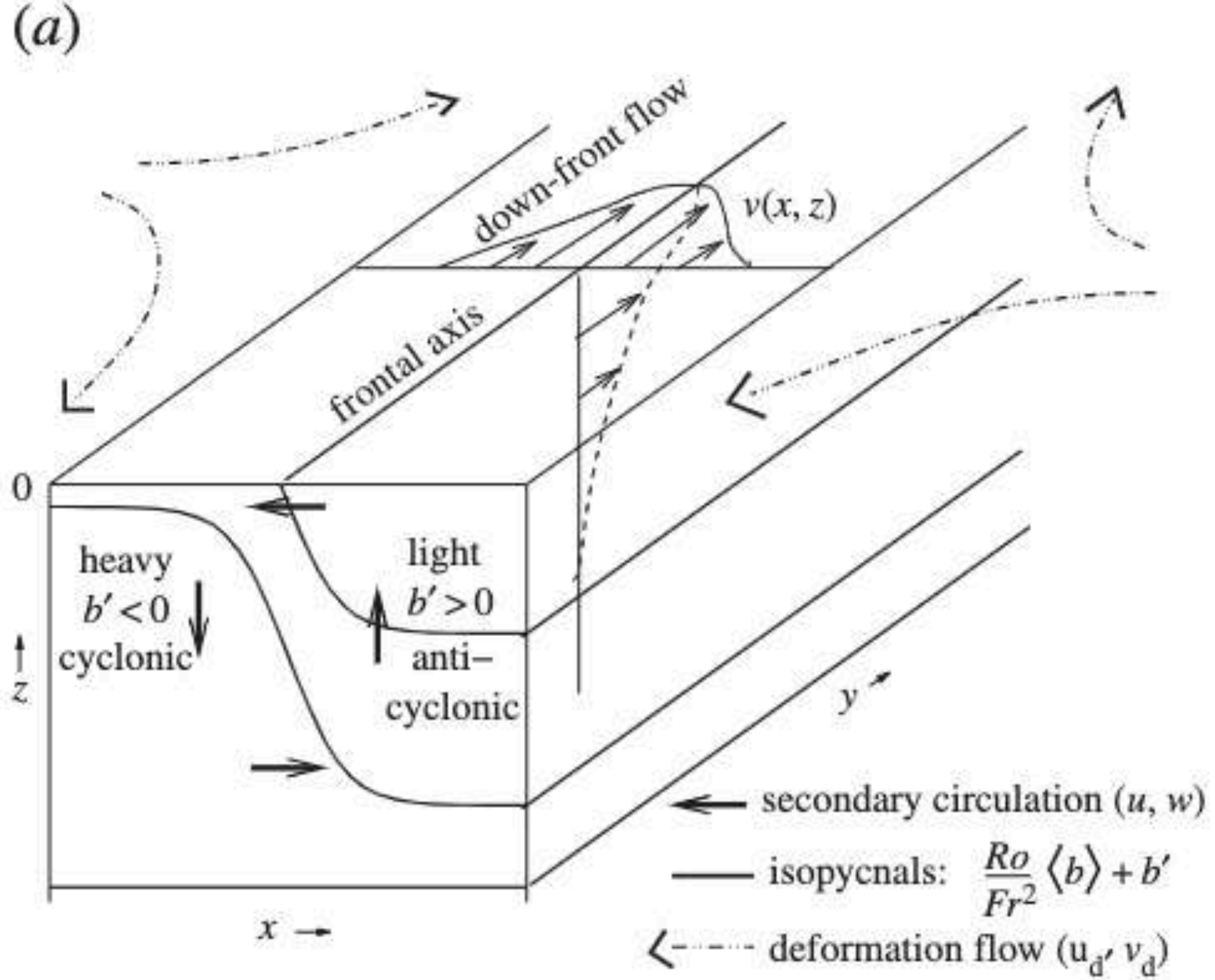
COMPARISON DUACS / SWOT / DRIFTERS



COMPARISON DUACS / SWOT / DRIFTERS

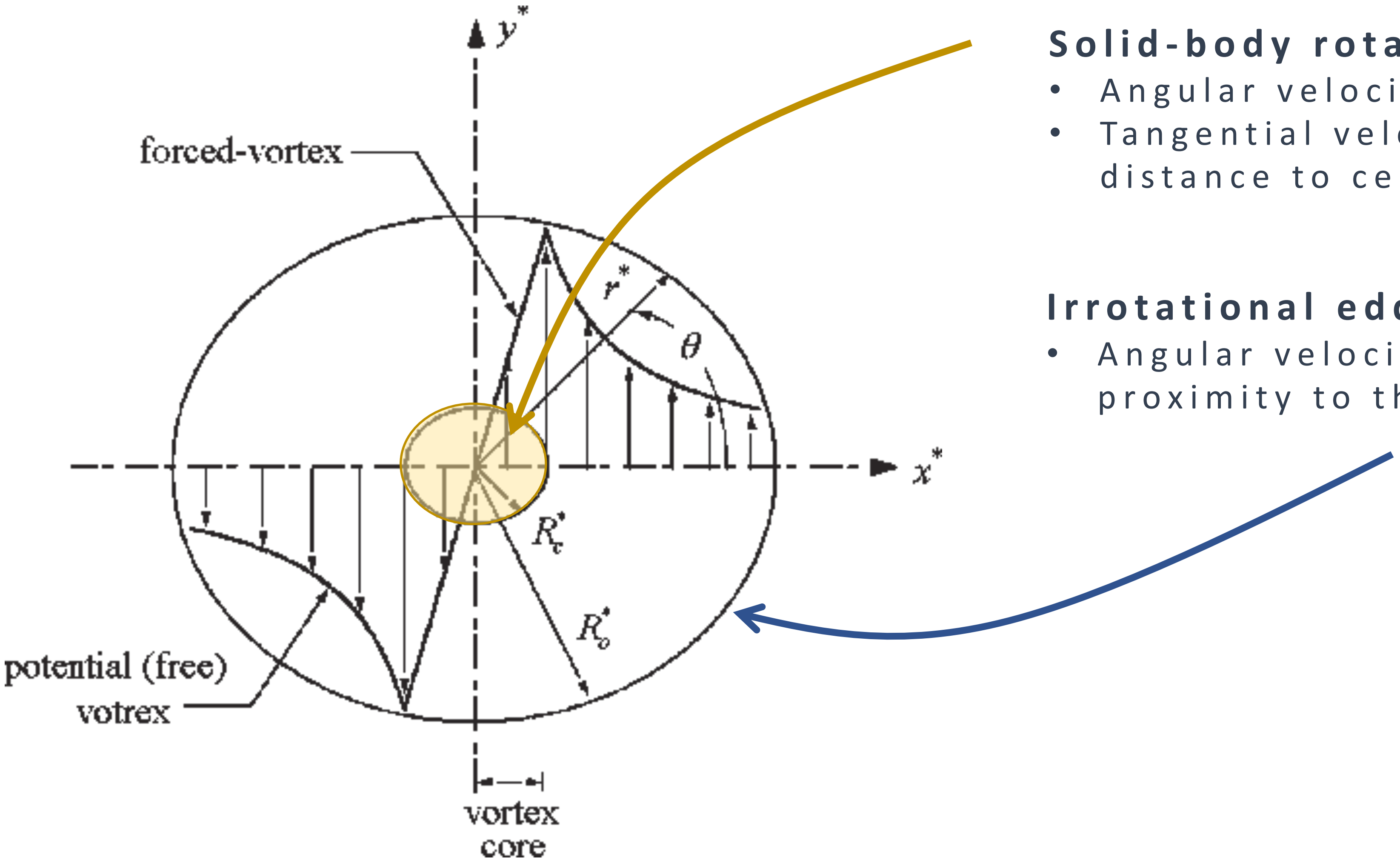


SECONDARY VERTICAL AGEOSTROPHIC CIRCULATION



McWilliams, 2016

RANKINE MODEL



Solid-body rotation

- Angular velocity: constant
- Tangential velocity: increase with distance to center

Irrotational eddy

- Angular velocity: increase with proximity to the center) constant

Aboelkassem et al. (2005)
DOI 10.1007/s10409-005-0073-3

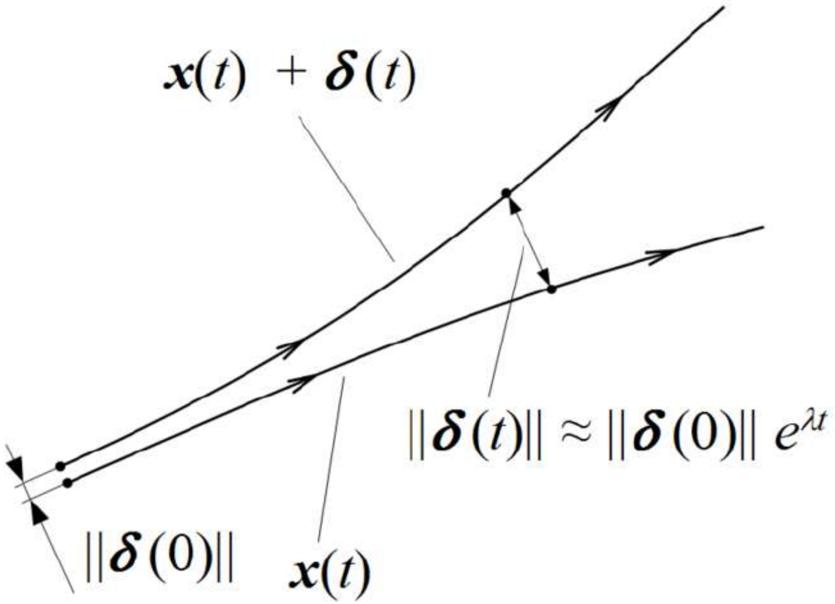
FINITE-TIME LYAPUNOV EXPONENT (FTLE)

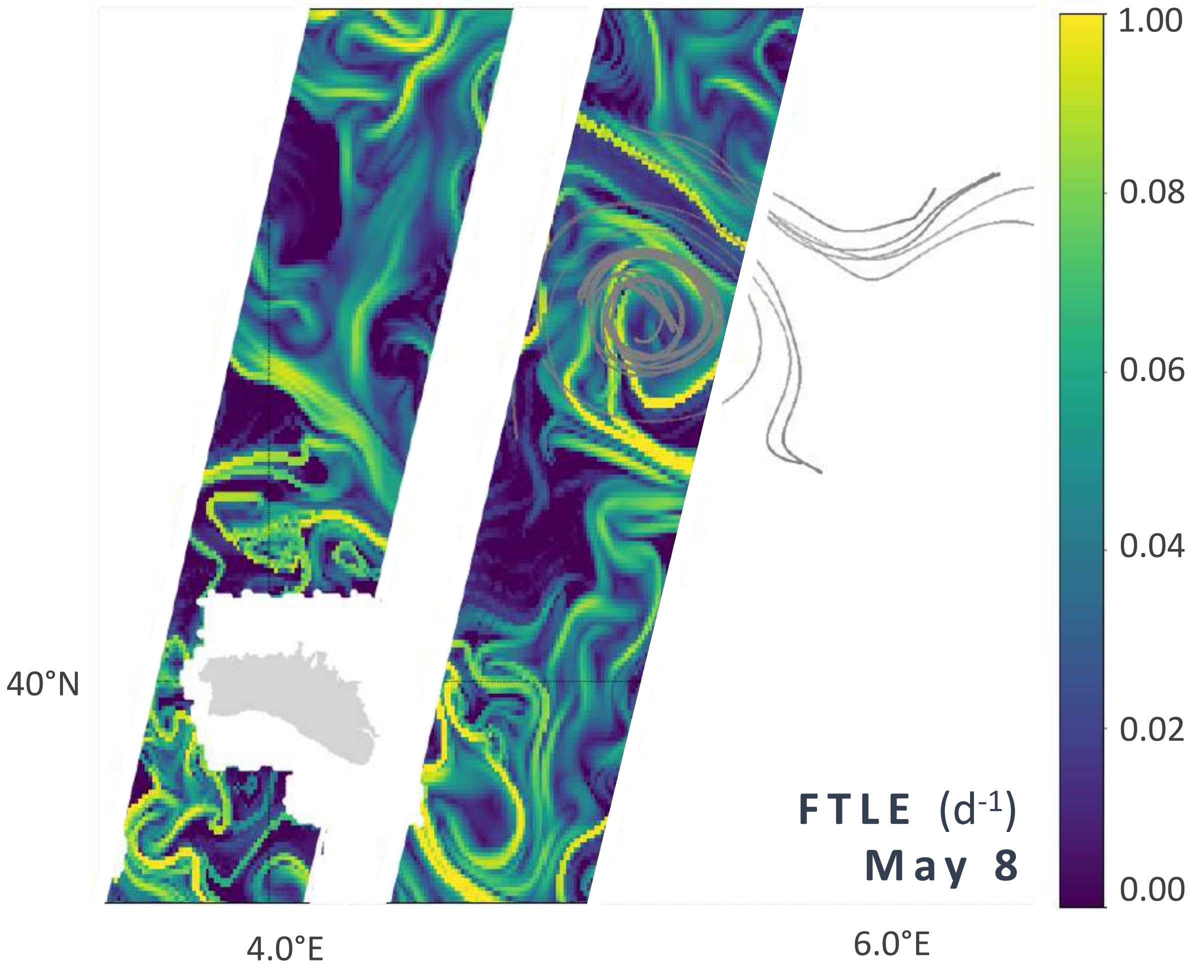
$$\lambda(t) = \lim_{\delta(0)\to 0} \frac{1}{t} \ln \frac{\|\delta(t)\|}{\|\delta(0)\|}$$

in s^{-1}

δ(0) initial distance between 2 particles

δ(t) final distance after time t





CHL-*a* SENTINEL 3 – May 5