High-frequency current products : Data-driven reconstructions of unsteady-Ekman

WOC UCM, Frascati, October 2022

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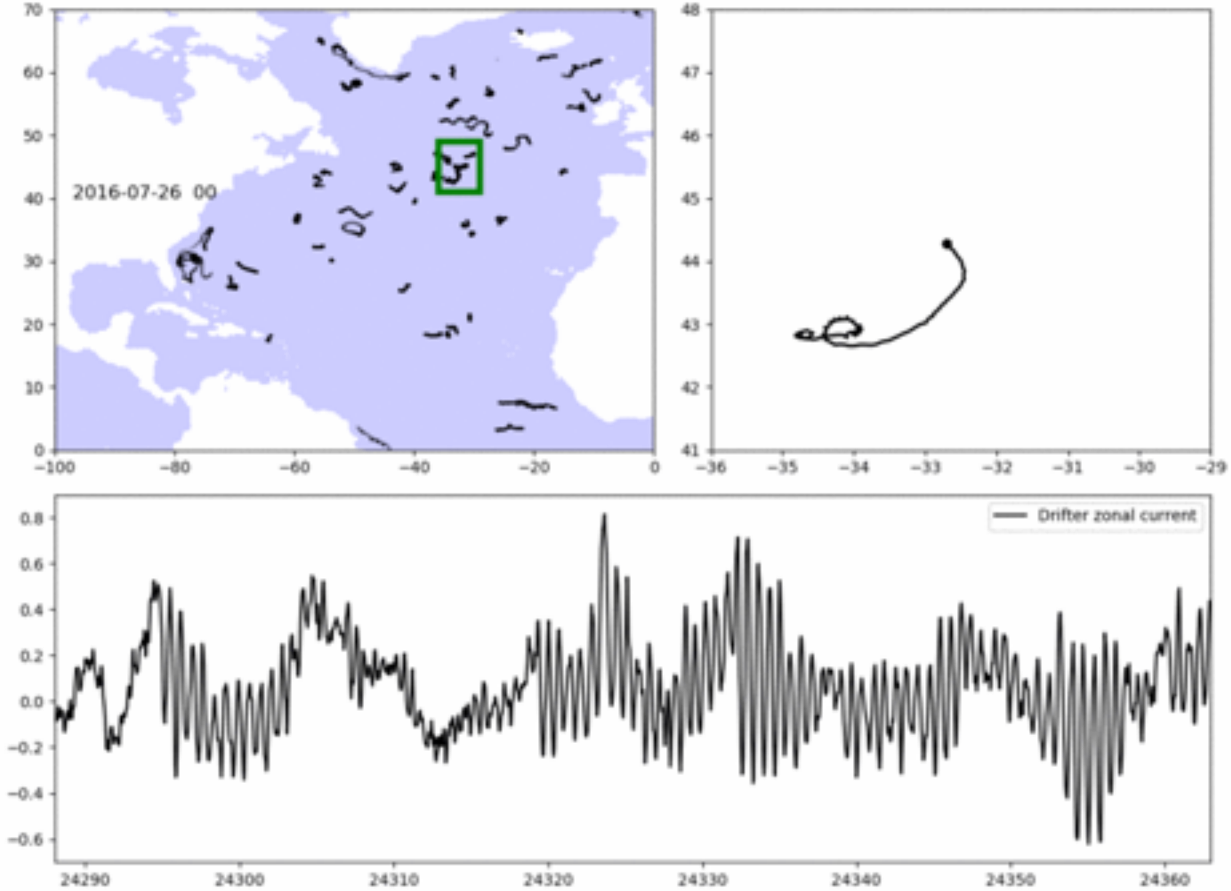
1: Datlas, Grenoble, France

- Introduction (state of the art, geostrophy, empirical Ekman estimates, …)
- An attempt to tackle Unsteady-Ekman : method, results, validation
- Beyond the product : what we can learn from the data-driven operator and science perspectives ?

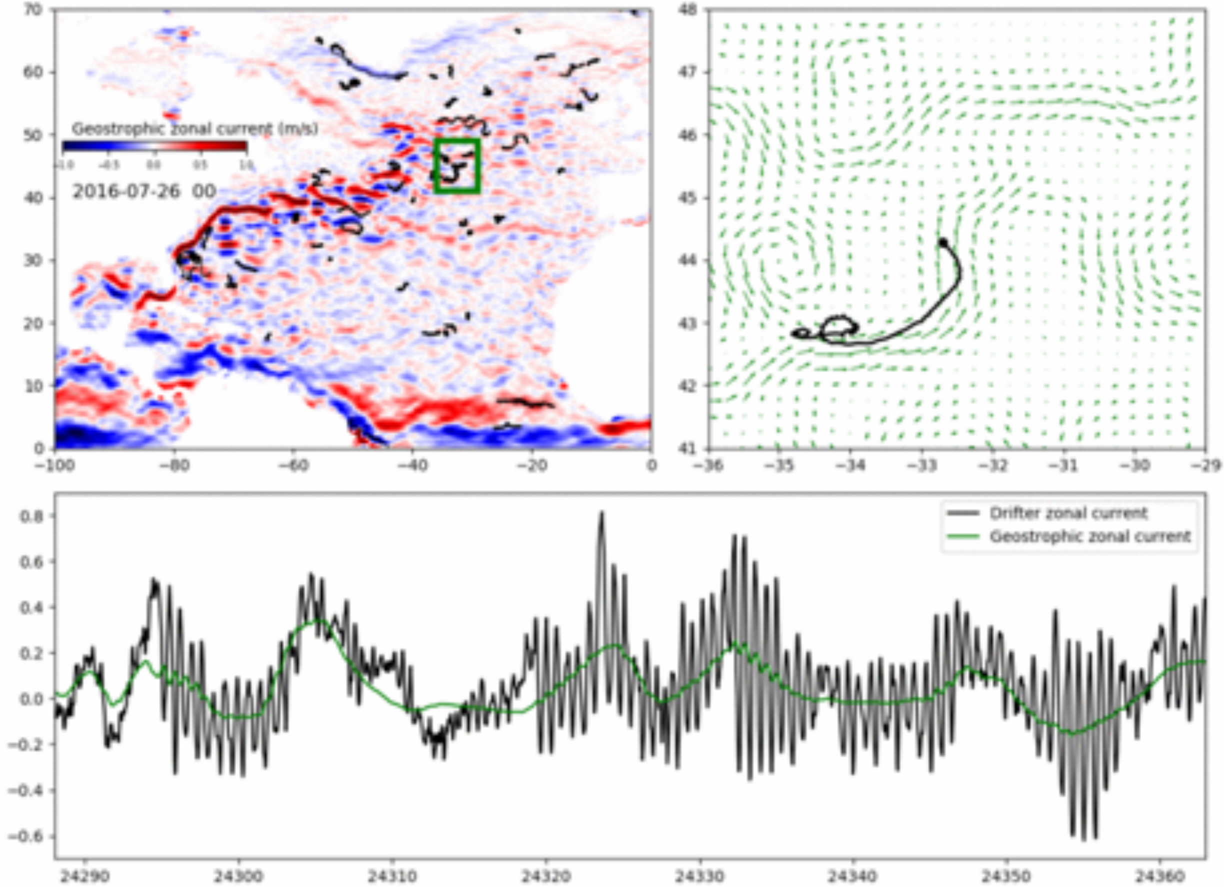
WorldOceanCirculation esa

Introduction : the drifters, some sparse but extremely useful in-situ observations of the total surface current



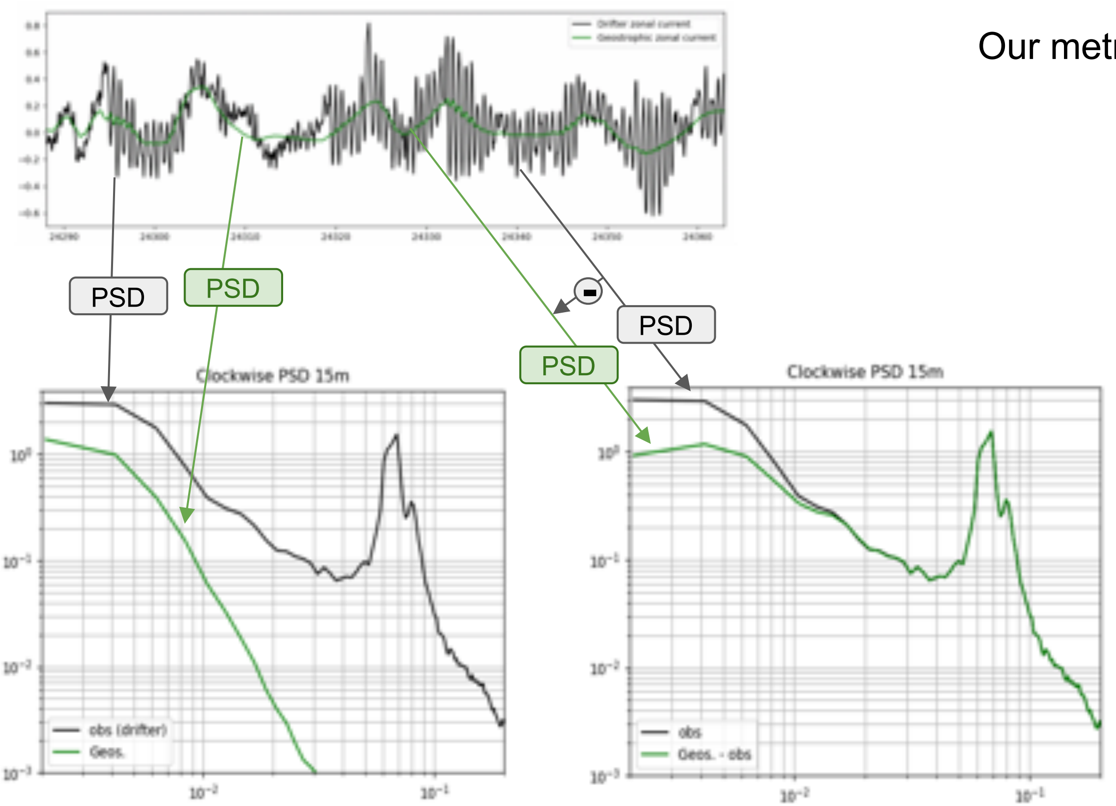
- Global Drifter AOML database blabla
- They provide local and uneven samples of surface current : **Is this current known and predictable synoptically ?**
- **If not… can we use these drifters as a training dataset ?**

Introduction : Geostrophic current from Altimetry - qualitatively…

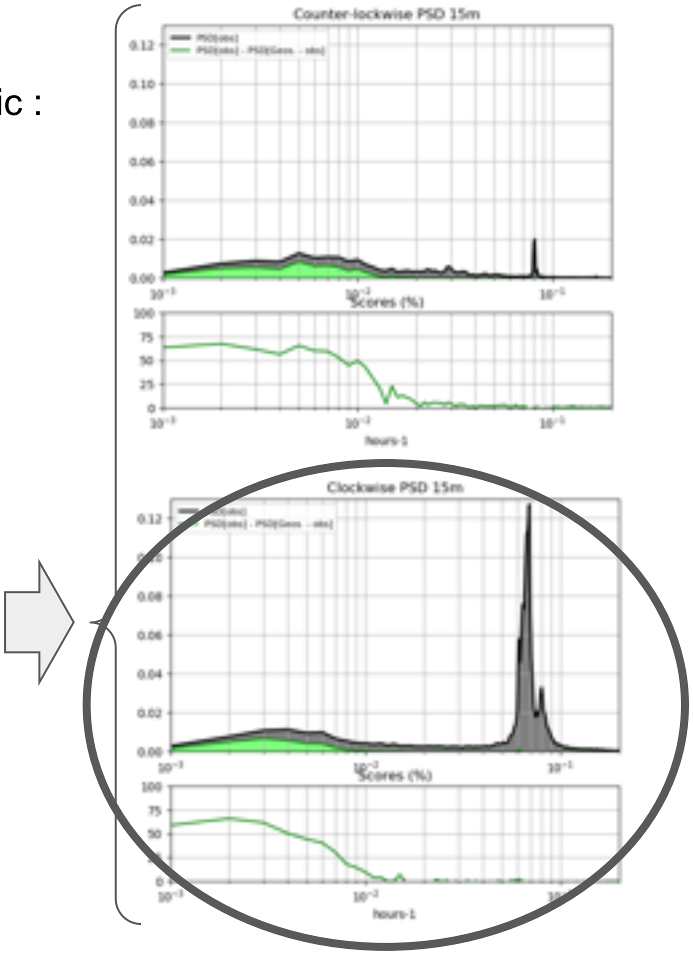


- A large part of the medium to low frequency seems explained by the geostrophy derived from Altimetry.
- Some low-frequency remains, energetic ageostrophic high-frequencies.
- A long way to go

Methodology for quantitative validation in the time-frequency domain

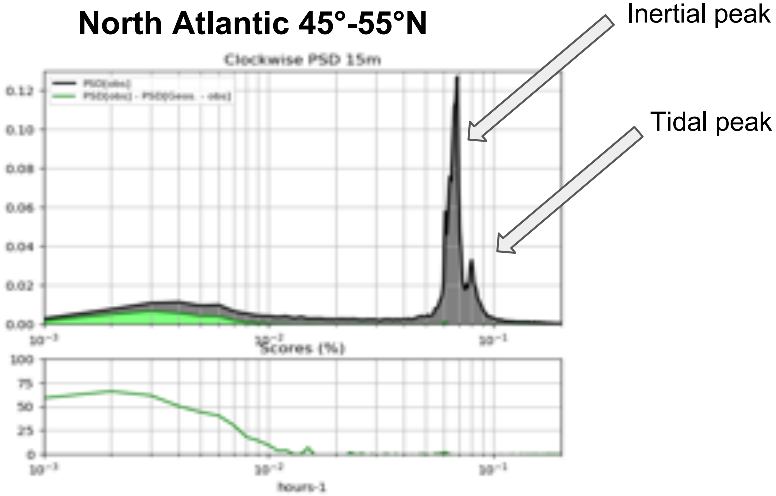


Our metric :

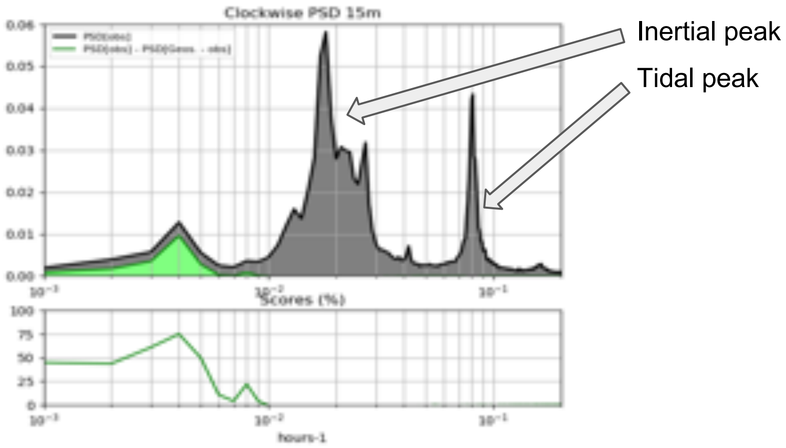


Introduction : Geostrophic current from Altimetry - quantitatively

North Atlantic 45°-55°N



subtropical Atlantic 5-20°N



- Geostrophy explains here >60% of >15days current. Similar to global Ocean estimations (Ponte et al., 2019, Etienne et al., 2019) with time/regional heterogeneities

- Nothing below 10days, as expected from the moderate resolution of Altimetry sampling.

What's missing ?

Ekman, Inertial, barotroclinic tides, unresolved geostrophy, unbalanced submesoscales, Stokes drift, interactions of all between all ...

Globcurrent

WOC-HF attempt

WOC BFN-QG, WOC SSH+SST, … improve some of these components, see other presentations

Beyond geostrophy : CMEMS Total current product (Geostrophy+Ekman)

(Globcurrent heritage)

$$\frac{\partial u}{dt} = i f_c u + \frac{\partial}{dz}(K(z))\frac{\partial u}{dz}) + \tau_{(z=0)}$$

du/dt = 0

Scalar (complex) transfer function G applied to wind stress, Rio et al., 2015

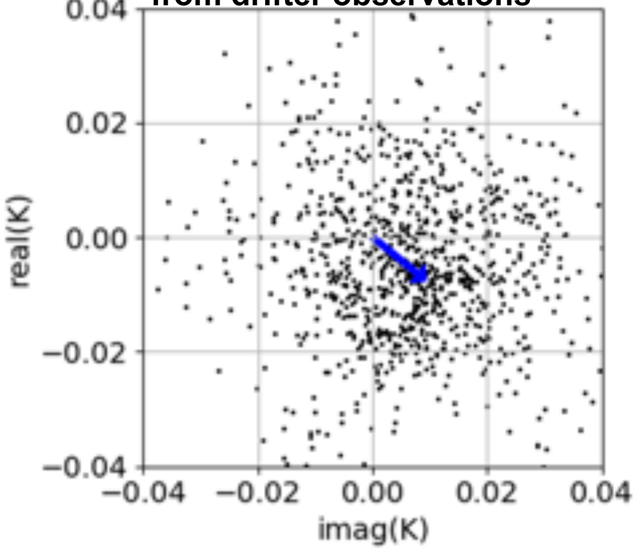
$$u(t) = G\tau(t)$$

$$\tau(t) = \tau_x(t) + i\tau_y(t)$$

$$G = A\exp(i\phi)$$

At depths 0m and 15m

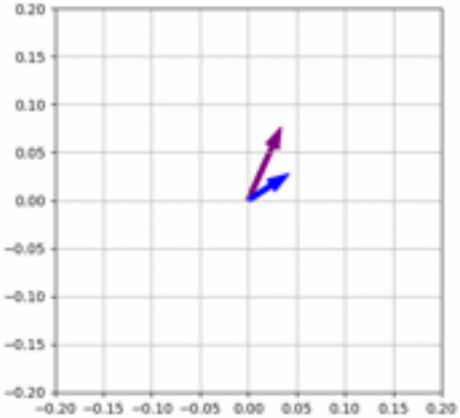
Observed transfer function **from drifter observations**



$$\boldsymbol{u} = Ae^{i\theta}\boldsymbol{\tau}$$

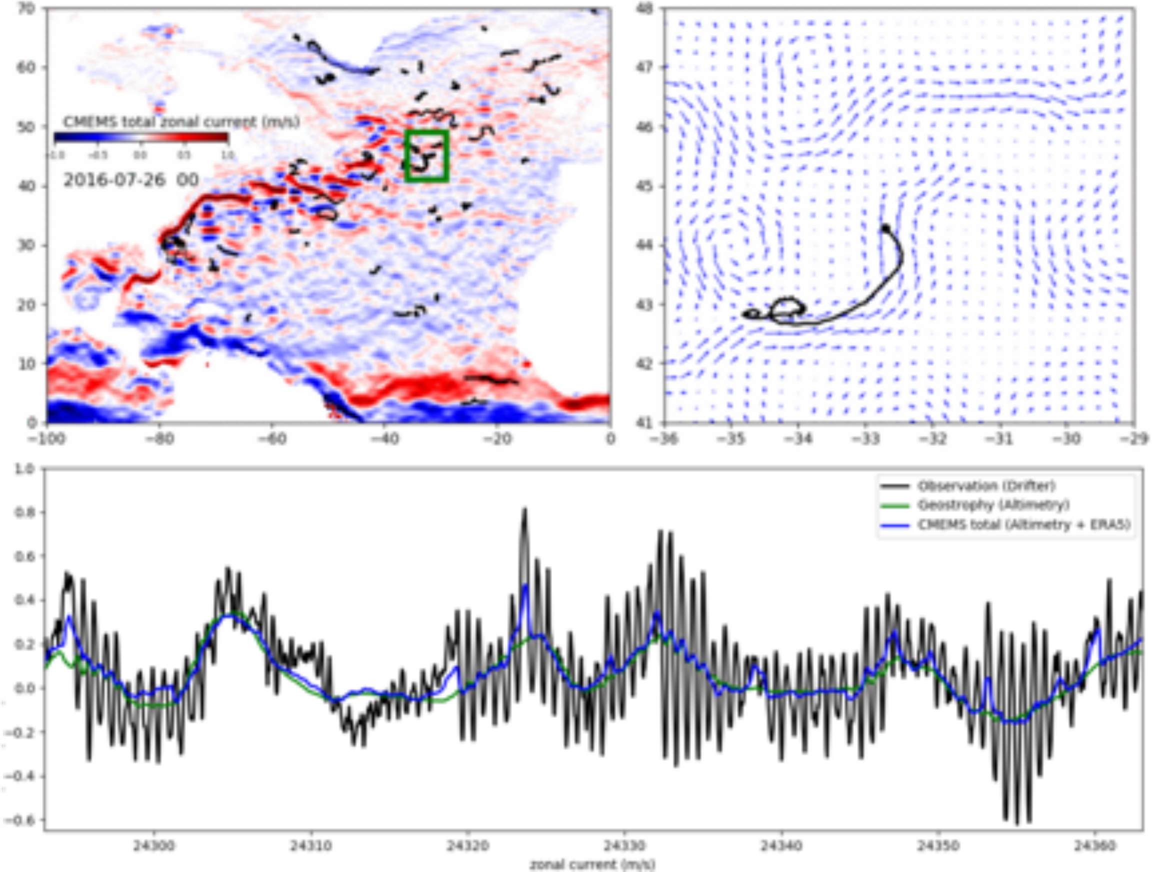
$$Ae^{i\phi} = \overline{(\frac{U_{drifter} - U_{geo}}{\tau})}$$

Stress-to-Ekman 'CMEMS-like'



Beyond geostrophy : CMEMS Total current product (Geostrophy+Ekman)

Qualitatively…

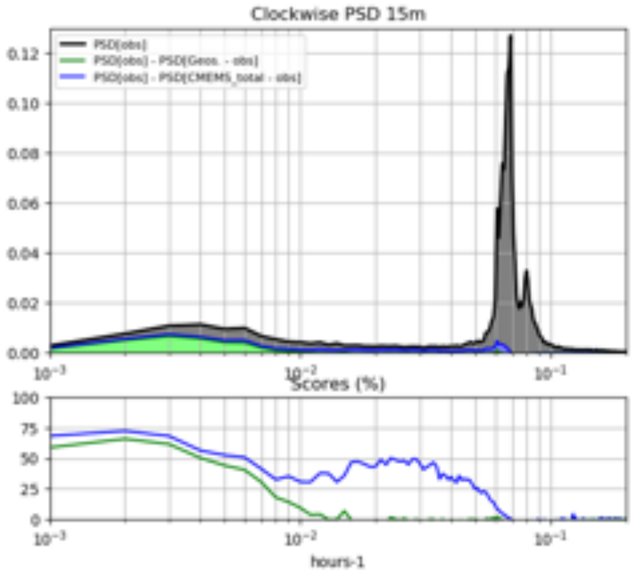


- The addition of Ekman (blue-green) is a small, but not negligible contribution (confirmed on validation next slide)
- The first kick of NIOs seems captured somehow, but without following oscillations

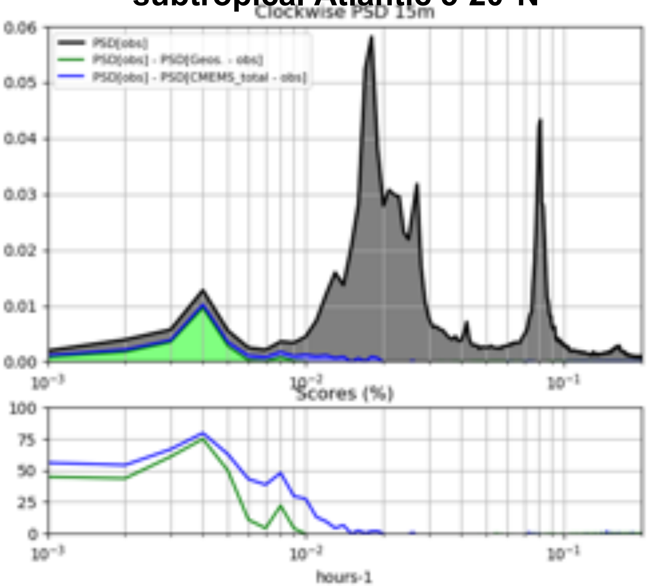
Beyond geostrophy : CMEMS Total current product (Geostrophy+Ekman)

Quantitatively…

North Atlantic 45°-55°N



subtropical Atlantic 5-20°N



- At low frequency (where geostrophy was dominant) : about 10% score gain beyond geostrophy
- In the 15day-1day range : fair contribution (30%-50% score)

An attempt to tackle unsteady-Ekman

WOC : Ageostrophic Current / Wind Stress empirical relation revisited

$$\frac{\partial u}{dt} = i f_c u + \frac{\partial}{dz}(K(z))\frac{\partial u}{dz}) + \tau_{(z=0)}$$

du/dt = 0 (Ekman only)

GlobCurrent/CMEMS : Scalar (complex) transfer function K applied to wind stress, Rio et al., 2015

$$u(t) = K\tau(t)$$

$$\tau(t) = \tau_x(t) + i\tau_y(t)$$

$$K = A\exp(i\phi)$$

At depths 0m and 15m

WOC : du/dt ≠ 0 (full unsteady Ekman)

Direct model approach :
1D vertical model forced by τ
And relying on K(z)

Pros: can be easily extended with geostrophy advection
Cons : Strong **non-linearities w.r.t. K(z)**

Convolution function approach

$$u(t) = \int_{-T}^{0} A(t')e^{i\phi(t')}\boldsymbol{\tau}(t+t')dt'$$

$$G(z, w) = A(w)\exp(i\phi(w))$$

Some theoretical background described in Elipot&Lily, 2021

Pros: fast computation, Linear problem w.r.t. G (robust), this is not a model!
Cons : Limited to 1D, coupling with geostrophic advection more difficult

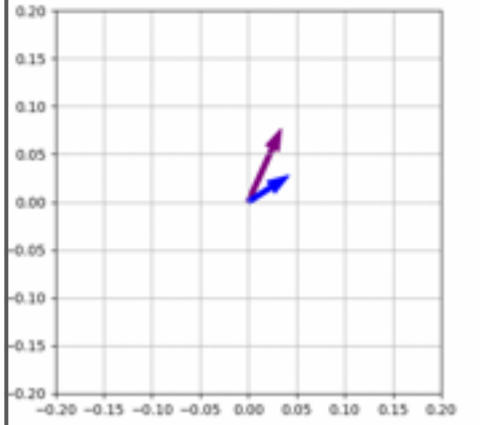
Convolution function approach : illustration of the concept

This is a natural step in the potential evolution of the CMEMS Ekman algorithm :
just a convolution instead of a scalar multiplication, to account for wind history in the Ocean response

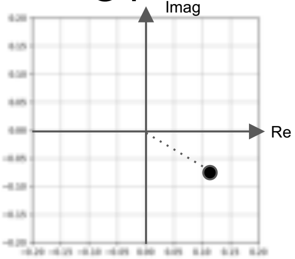
Ekman/CMEMS

$$\boldsymbol{u} = Ae^{i\theta}\boldsymbol{\tau} \;= G\boldsymbol{\tau}$$

Stress-to-current



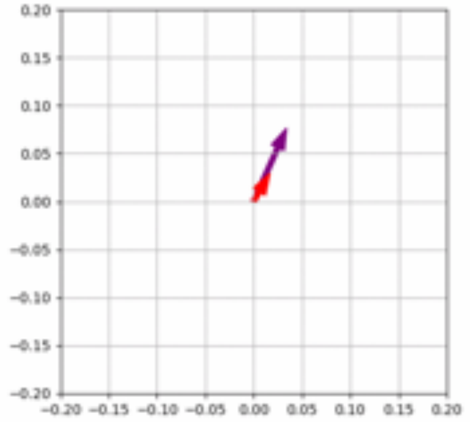
Single scalar multiplication
G :



Unsteady-Ekman WOC

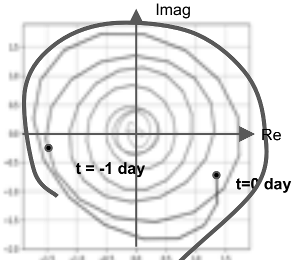
$$\boldsymbol{u} = \int_{-T}^{0} A(t')e^{i\theta(t')}\boldsymbol{\tau}(t+t')dt' \;= \int_{-T}^{0} G(t')\boldsymbol{\tau}(t+t')dt'$$

Stress-to-current



Time convolution

G(t) :

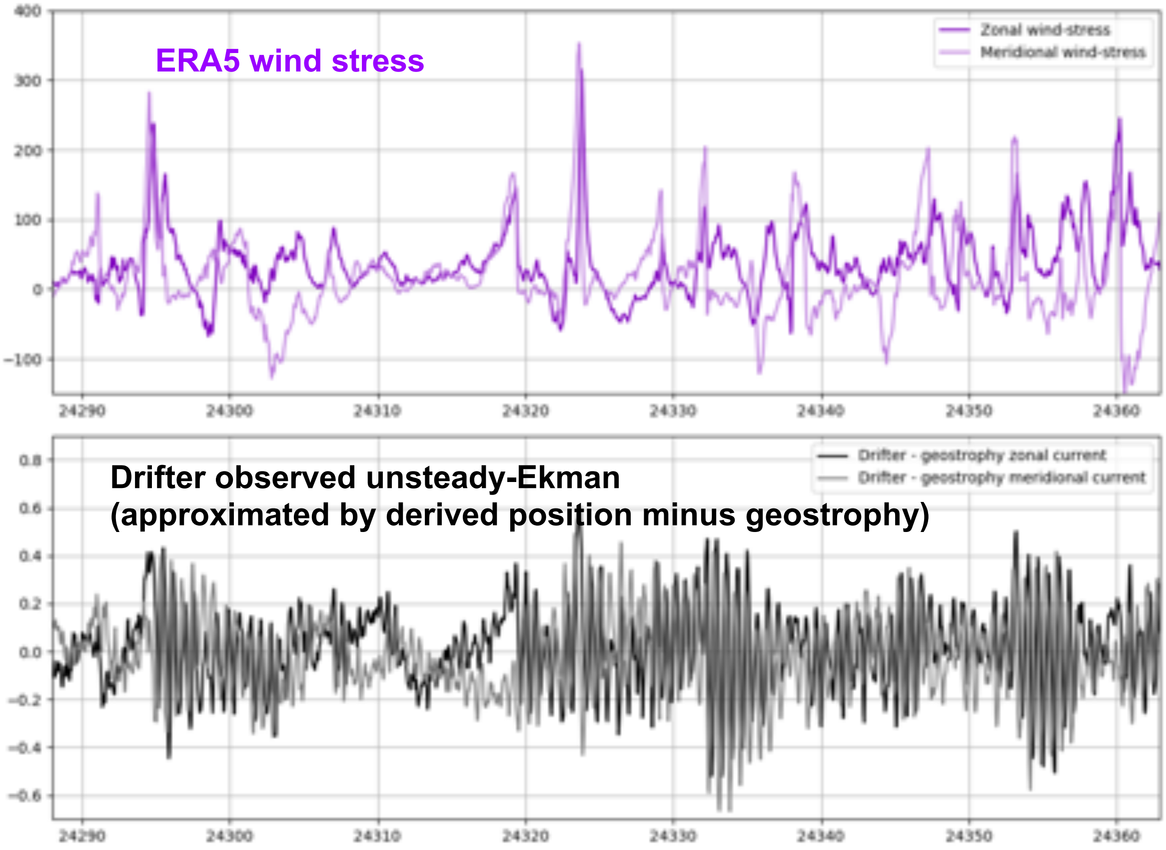


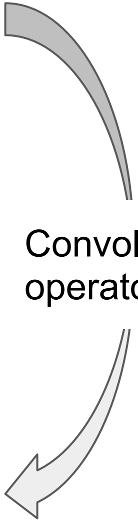
How to find this G(t)

G(t) is solved with a data-driven inverse problem :

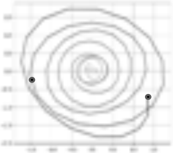
$$u_{drifter} - u_{alti} = \int_{-T}^{0} G(t')\tau_{era5}(t+t')dt' + \epsilon$$

The training dataset :





Convolution
operator G(t) ?

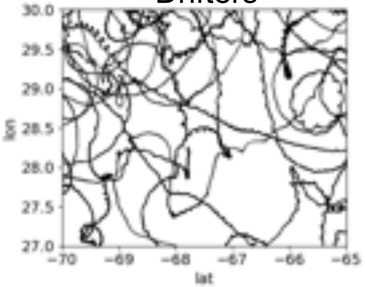


Convolution function approach : algorithm to find G

Conjugate gradient iterations to solve :

$$u_{drifter} - u_{alti} = \int_{-T}^{0} G(t')\tau_{era5}(t+t')dt' + \epsilon$$

Training Data base :
15m-drogued GPS Drifters



Remove geostrophy

Colocalisation of 7-day wind history at drifter location

ERA5 wind stress $\tau(t)$

Parameter vector **η** defining the G function over [-8,0] days
η=0 at iter 0

G=**Γ**.η

convolution

U^a

$U^o = u^o + iv^o$

M

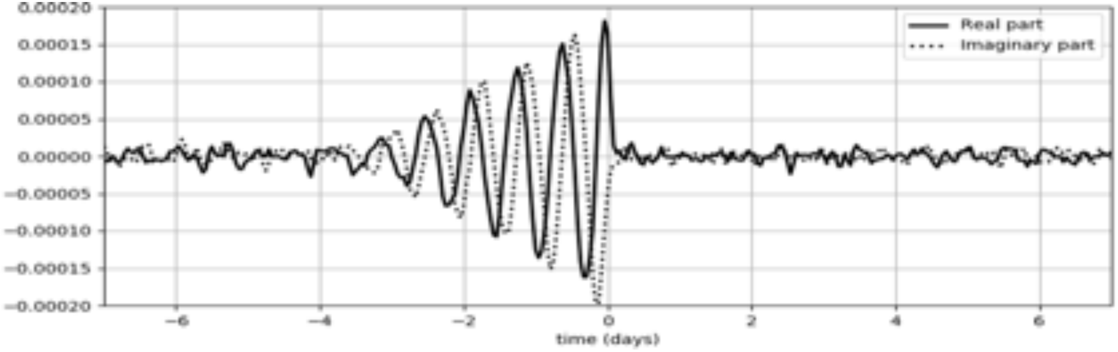
Cost function from the misfit:

$$J(\eta) = (U^a - U^o)^2$$

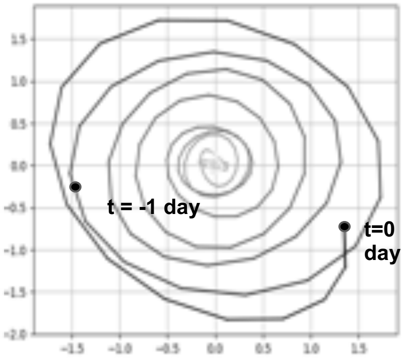
Conjugate gradients with $M^T.(U^a - U^o)$

The G function after solving the minimization with the drifter data (<u>in a particular region/season</u>)

In time, real and imag representation :



In real/imag representation

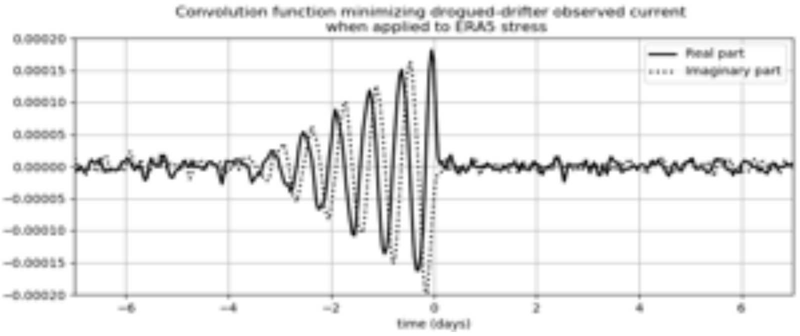


- G~0 for t’>O : the present current is statistically independent with the future wind (as expected)

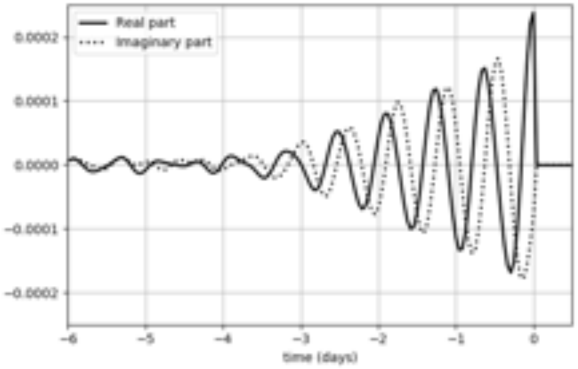
- There is a clear dependance with the wind history : here, a significant signal on [-4;0] days.

Reduction of the parameter space for G

If G is searched independently at hourly step, the vector η is of size 120 x 2



Here : 26 x 2 parameters

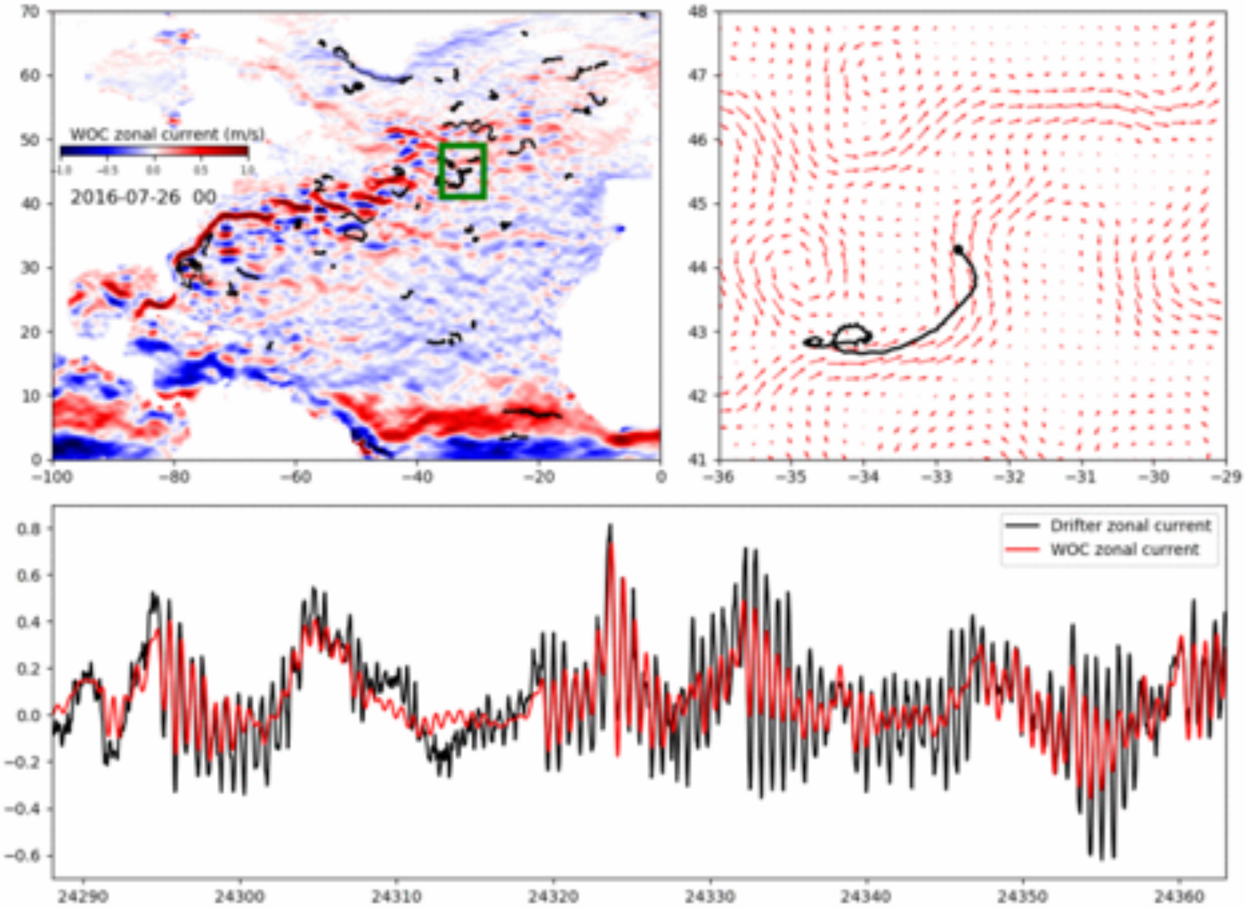


Reduction in Fourier space, allowing harmonics <1.5*fc only

Less degrees of freedom.

Implementation of seasonality (1cst + 1seasonal harmonic for each Fourier coefficient of G)

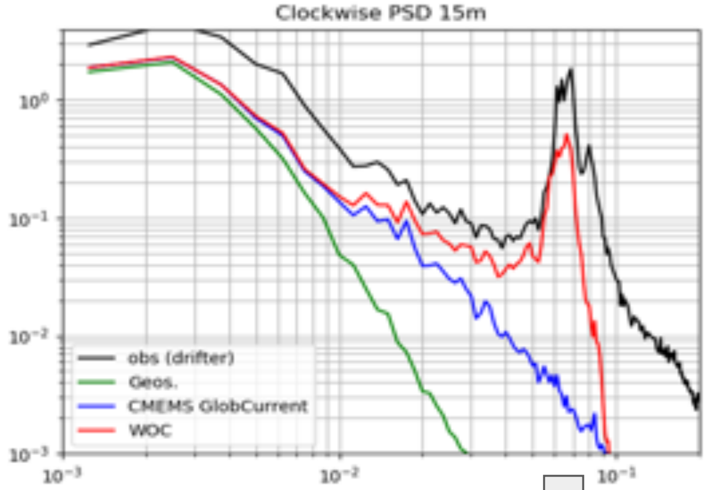
WOC TSC v2 : Applying $G \circledast \tau_{ERA5}$ over the North Atlantic bassin (G resolved at 10° x 5° resolution with 1 annual harmonic for seasonality)



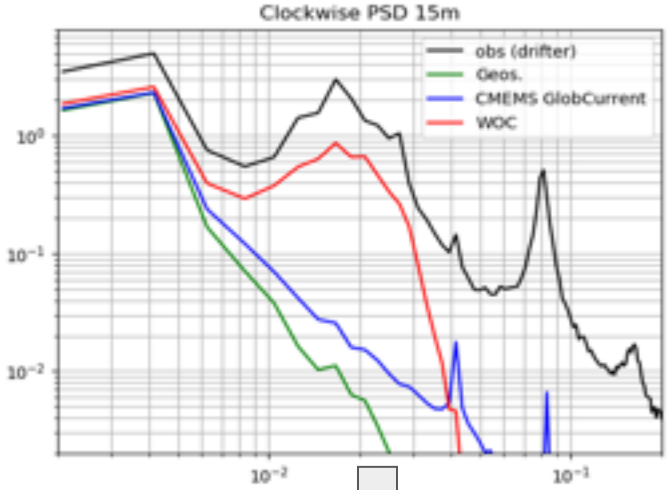
- Some high-frequencies are well captured!

WOC TSC v2 : Validation (spectra)

North Atlantic 45°-55°N



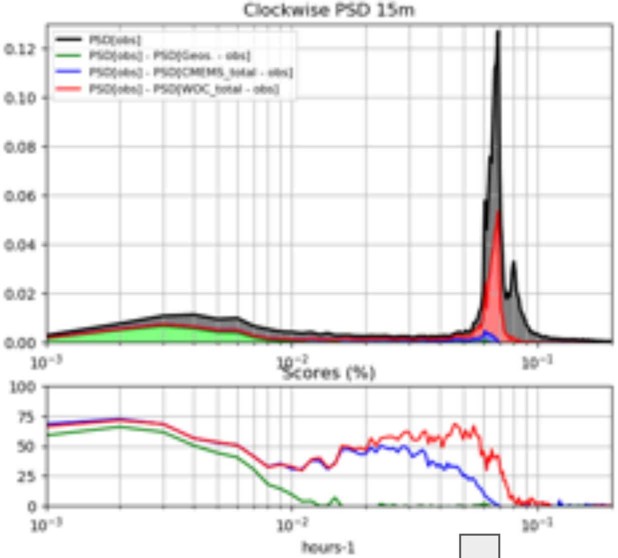
subtropical Atlantic 5-20°N



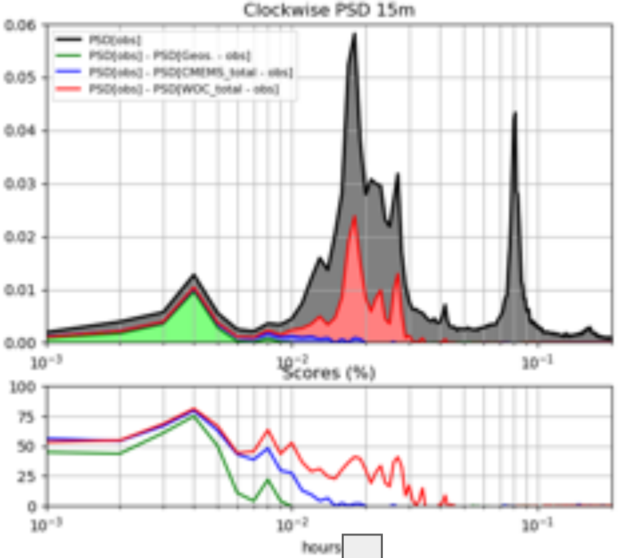
We reconstruct almost half of the energy in inertial band

WOC TSC v2 : Validation (scores)

North Atlantic 45°-55°N



subtropical Atlantic 5-20°N



And quite well in phase!

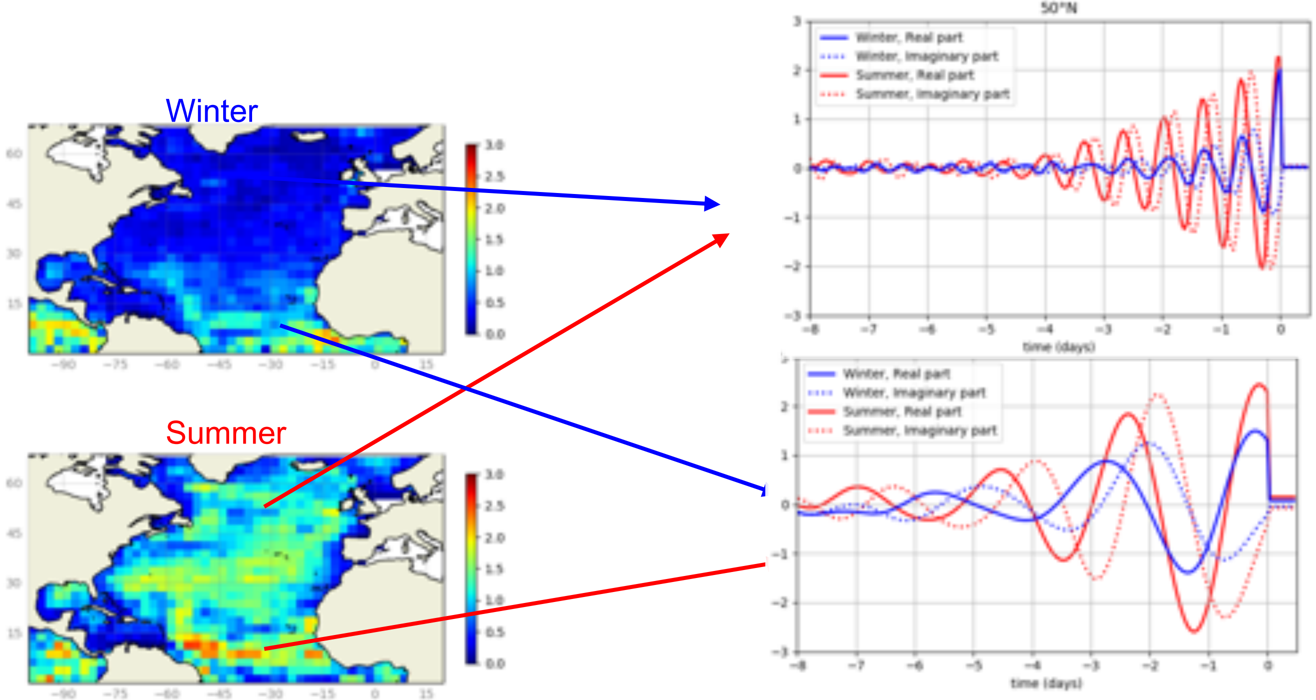
- At low frequency : from 5 days and longer, we are quite similar to the Ekman CMEMS product
- Below 100 hours, the

Analysis of the data-driven operator
(available as a WOC side-product)

And some scientific perspectives?

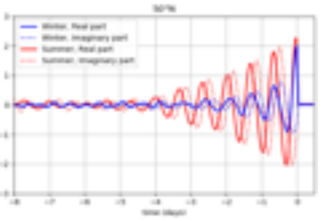
Geographical and seasonal characteristics of the data-driven transfer function G

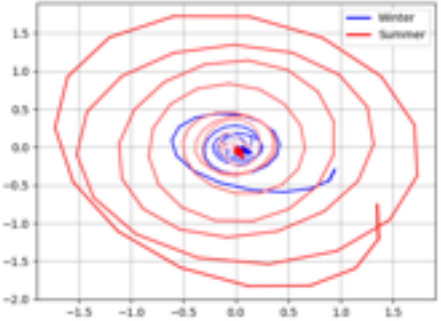
Some aspects of the Ocean seasonality are revealed (thinner layer in summer : less inertia, higher amplitude of current/wind transfer)

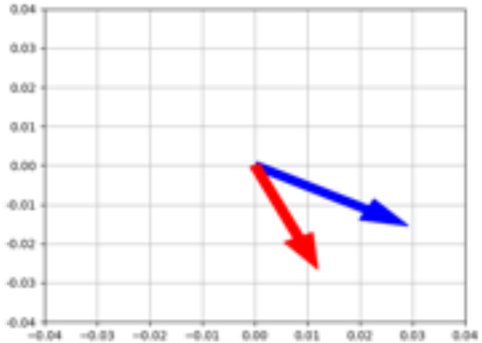


A tool to characterize the mixed layer depth ?

Theta angle at low frequency : consistent with Rio et al., 2015

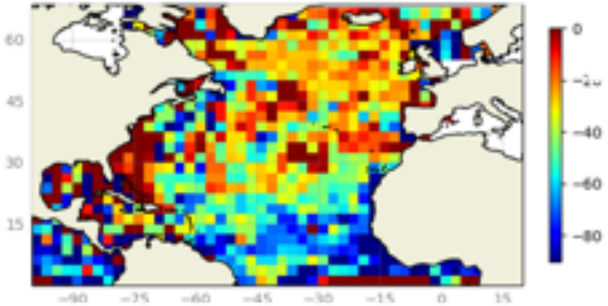


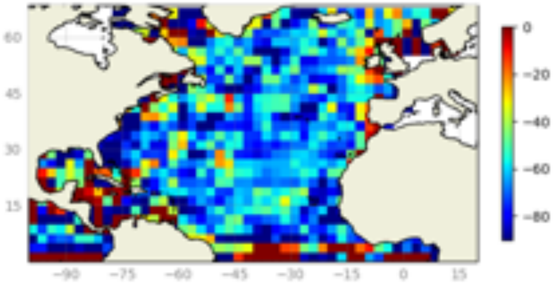




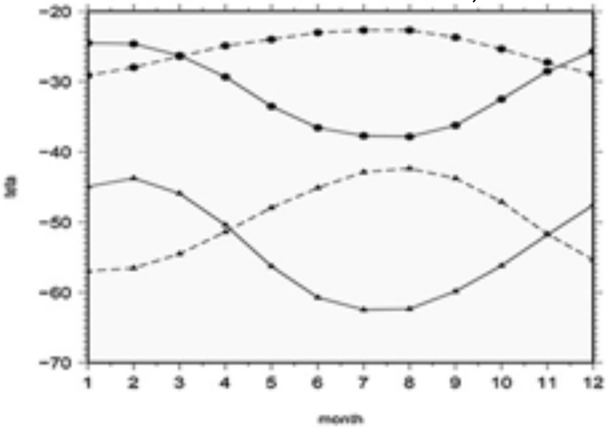
~35° right downwind in winter

~60° right downwind in summer



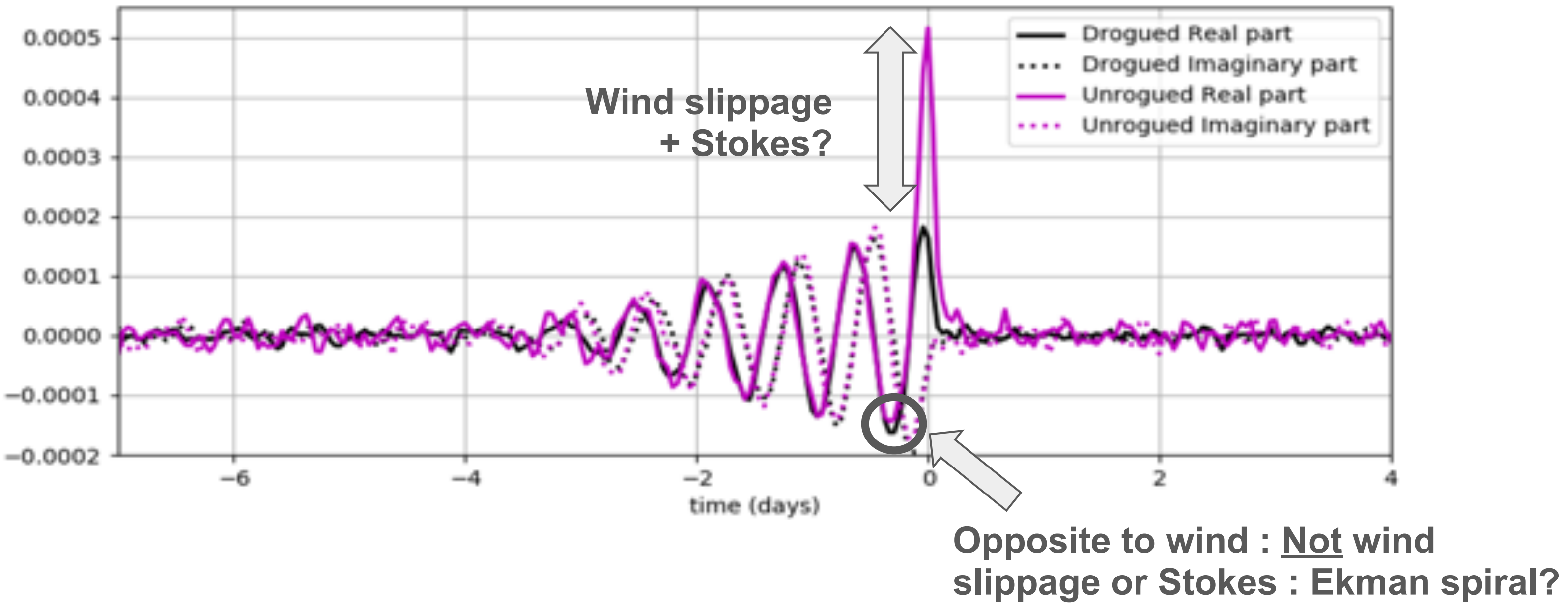


Consistent with Rio et al., 2015 :



⇨ **A tool to study the Ekman spiral ?**

About Drogued versus Undrogued drifters?



- Here : hourly (no Fourier reduction) version of the convolution function computation
- Slightly higher noise for undrogued (less data in the considered region)
- The wind slippage should be independent from Ocean dynamics, an instantaneous wind response therefore with no lagged-correlation (convolution should be zero for t≠0). An additional way to characterize wind slippage?
- Would be interesting to do the same exercise with Argo floats.
- **This could a tool to characterize different physics : Stokes, wind-slippage, drogue loss, …**

Further perspectives to characterize the Ocean response from G ?

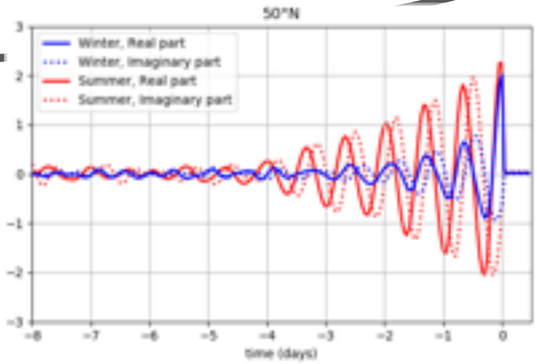
- Fit law for stress = f(wind, waves?) → **A tool to assess stress / wind empirical relations?** Under different sea state, etc… ?

- Ongoing : Test ERA5* (a better wind product should feature lower **ε** residual after the minimization) → **a tool to assess wind products?**

- Try to resolve G with additional dependances (**Waves, SLA, SST, MLD&daily cycle**, …)

- Also consider the **impact of horizontal advection terms from geostrophy** (see recent talk by Bjorn Callies here: https://drive.google.com/drive/folders/1QrOYRW79urEWOxswuc7b73K-vScC-r4H?usp=sharing) : this could be coupled to G.

→ More drifters (or a synoptic current Doppler mission!) would help all these applications!



Conclusions

On practical aspects toward a new operational product :

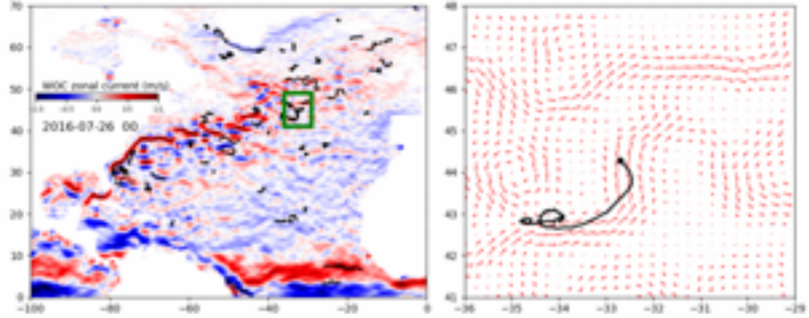
- We propose here **a simple step beyond the GlobCurrent/CMEMS Ekman product : from a multiplication to a convolution, that's it**

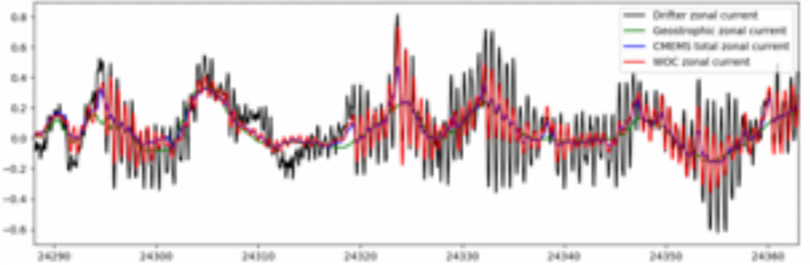
- Validation suggests improvements, more pronounced in the northern region (we would need more Equatorial drifters!)

Perspectives:

- Soon : update with ERA5* !!
- A 0m (from undrogued) product
- From North Atlantic to global coverage?
- Try NN as well?

Available :
- 2010-2020 hourly on NATL domain
- Kurushio test case
- The G ocean response operator (on demand)



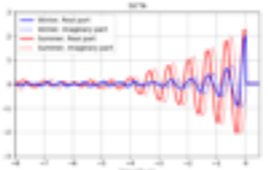


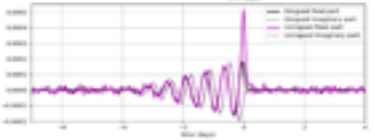
On scientific aspects :

- Better characterize undrogued-drifter physics ?

- Explore the relation between G transfer function and **surface waves, Ocean subsurface properties**, including **mesoscale interactions**

- This might help to constrain some parameterisations of diffusivity in OGCM, … ?





Knowledge gaps and priorities for next steps

This was a demonstrator of the possibility to include unsteady-Ekman in empirical operational surface current products, as the continuity of Ekman in CMEMS.

Gaps :

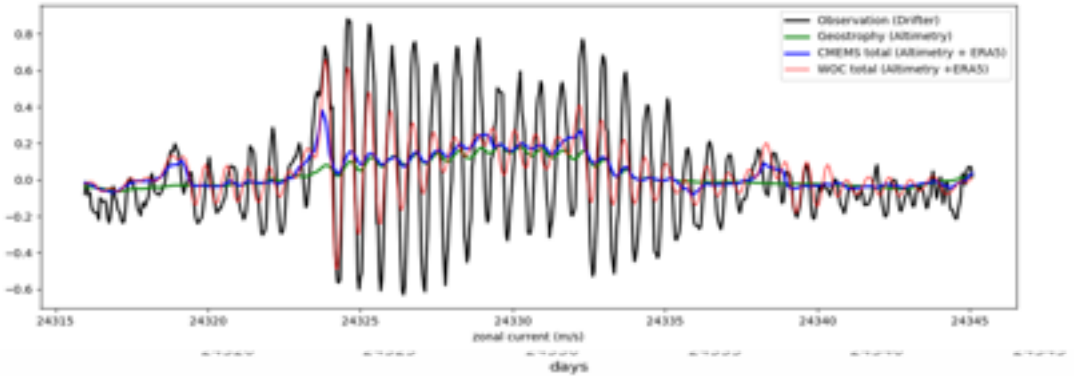
- There are complex mesoscale/unsteady-Ekman interactions that have been neglected
- The sea state (waves) certainly play a major role, not accounted so far

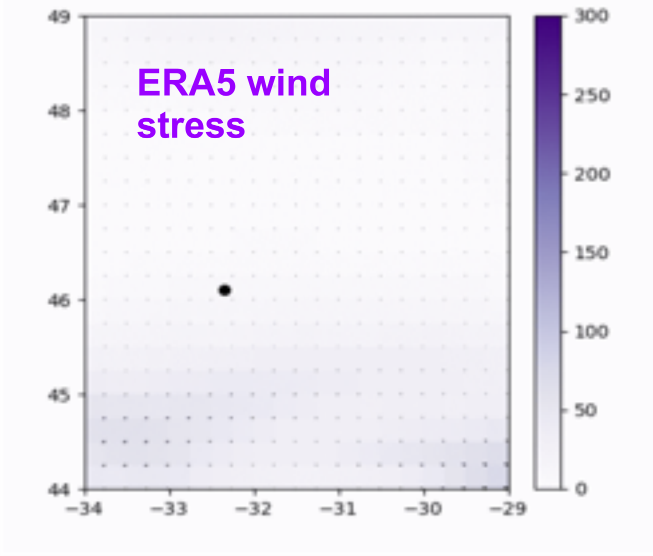
Priorities :

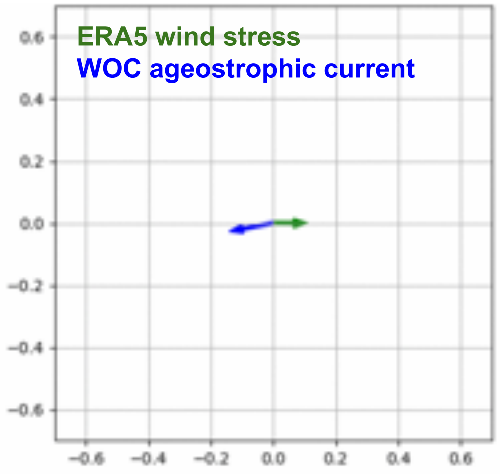
- Consolidate to present version (update with ERA5*, …) and deploy from basin to global scale (no scientific issues foreseen, could be done in an other operational context)
- Om (from undrogued) current, characterizing wind-slippage as well
- Explore the more complex dependances of G, in particular with mixed layer depth and mesoscale interactions, sea state
- Explore in parallel NN reconstructions on this problem

Backup

Little roller coaster ride : one of the biggest NIO event ever captured with Drifter **0.7m/s**

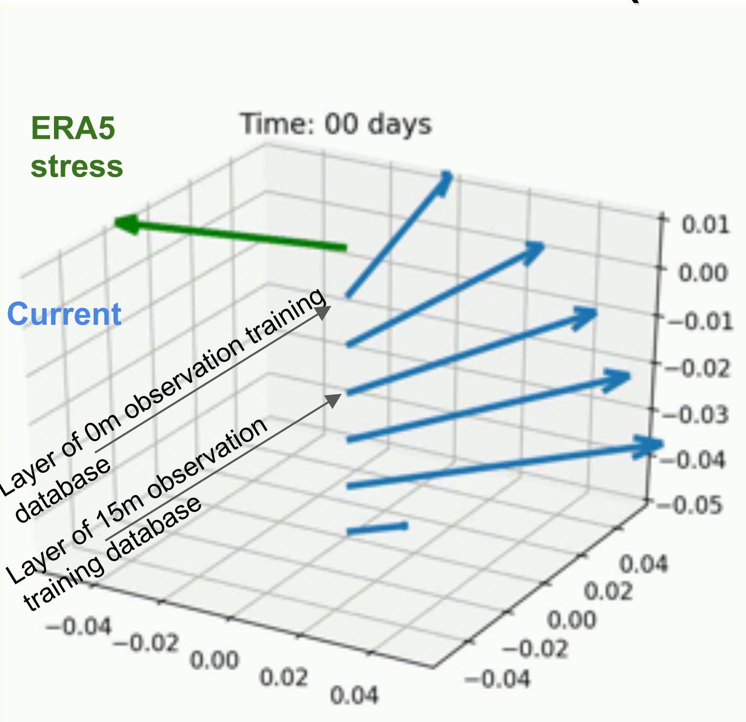






- Specific configuration where strong wind turned clockwise during several hours at a near Coriolis frequency
- ‘Lagrangian Aliasing’ (see green oscillations)
- ‘First kick’ of NIOs resolved by Ekman/CMEMS (relation applied to all frequencies)
- Shorter decrease of WOC ageos after (quasi-dirac) impulse of wind : effect of uncertainties in the data-driven algorithm based on minimized RMS… ?

1D vertical model (WOC-V1)



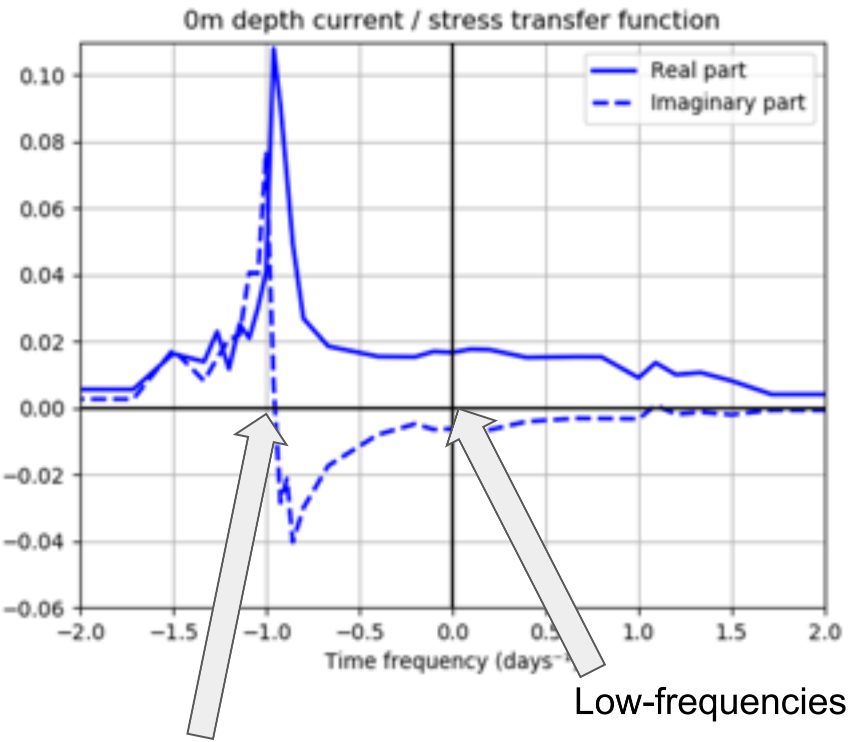
$$\frac{dU}{dt} = i f_c U + \frac{d}{dz}(K(z))\frac{dU}{dz})$$

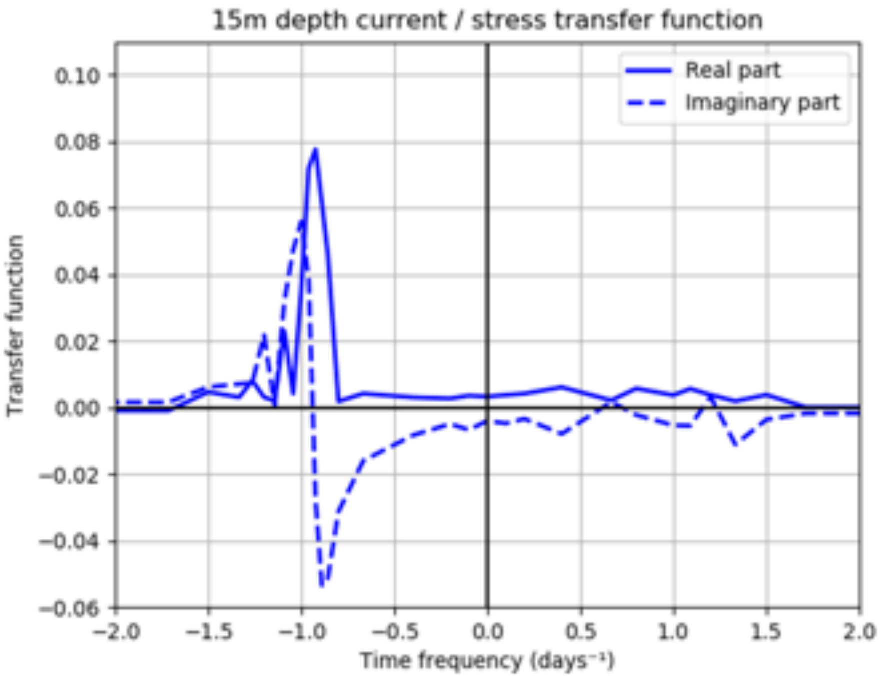
$$\frac{dU_0}{dt} = i f_c U_0 + \frac{d}{dz}(K(z))\frac{dU_0}{dz}) + f\left(|U_{era5}|\right) U_{era5}$$

- **f** and **K(z)** are adjusted from the drifter database
- No constraints on **K(z)**.
- We solve for slowly-evolving parameters in space : defined on a sub-grid of 5x10 degrees interpolated linearly. No seasonality yet.

Pros : A full 1D profile
Cons : K inversion is challenging (strong non-linearities w.r.t. K)

Spectral transfer function approach : illustration





Low-frequencies : we should retrieve CMEMS Ekman transfer-function

G is a pure real at -f : consistent with Elipot&Lily, 2021

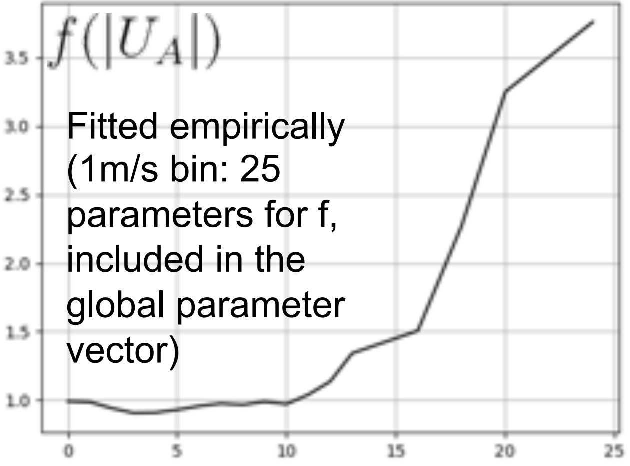
Which is promising : the results in current (not shown) seem quite similar to the direct model method cheaper and the data-driven adjustment algorithm is simpler, more robust, it would have been a better v1...

Side products? (preliminary results)

- Relation ERA5 neutral wind / stress (stress or whatever linearly related with the model input force)

$$\tau = f(|U_A|) * U_A$$

We retrieved stress-increased behaviours beyond 10m/s (rough seas)



Fitted empirically (1m/s bin: 25 parameters for f, included in the global parameter vector)

Ua (m/s)

- Look at the fitted “Stokes Drift” at 0m

- Use Lily&Elipot, 2021 to infer links between adjusted transfer function and turbulent viscosity profile

Different responses for similar wind amplitude changes

Not only the wind step matters, but it's
rotation speed w.r.t. Coriolis rotation vector