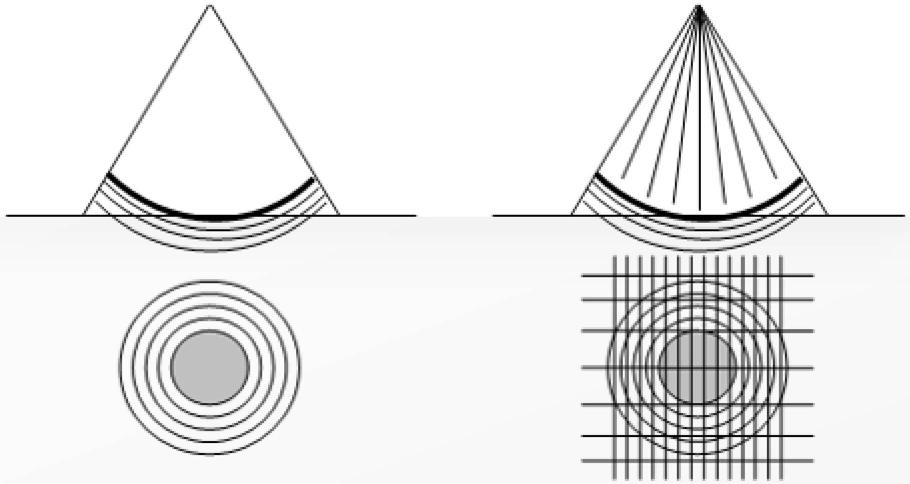
Leveraging Delay-Doppler altimetry for Enhanced Sea-State Characterization

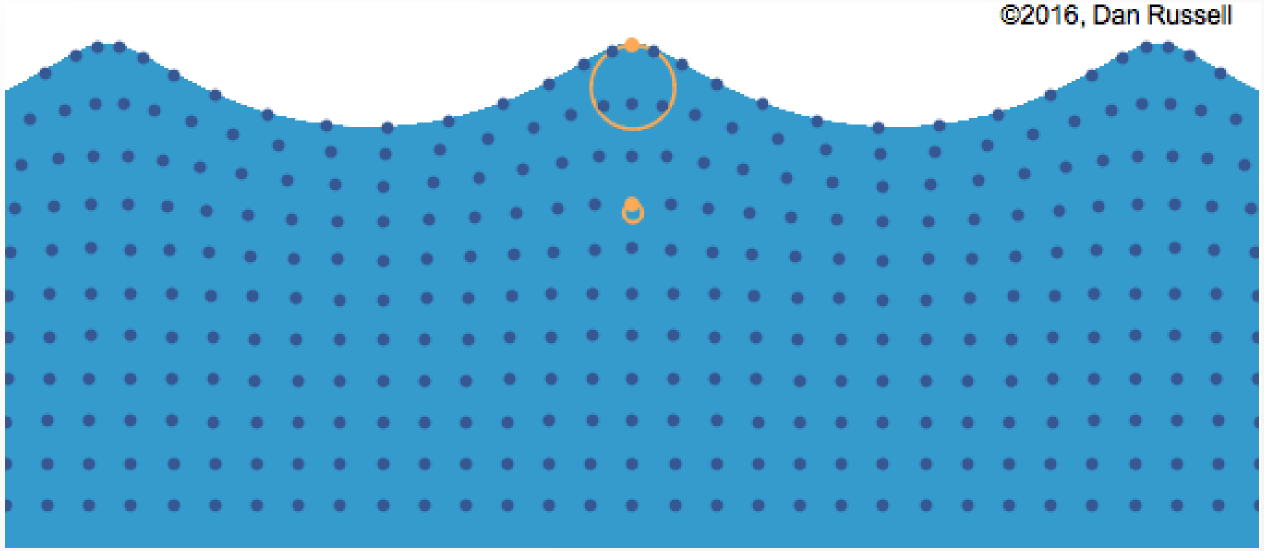
L. Rodet[1], M. Pommier[1], E. Mazaleyrat[1], A. Ollivier[1], T. Moreau[1], S. Daniel[1], C. Maraldi[2], F. Bignalet-Cazalet[2], F. Ehlers[1], C. Buchhaupt[3], L. Marié[4], B. Chapron[4], P. Dubois[1], L. Zawadzki[2], N. Picot[2]

[1]CLS, France
[2]CNES, France
[3]University of Maryland, USA
[4]IFREMER, France

Delay-Doppler: Limitations so far



Since the Delay-Doppler uses the Doppler effect to locate the signal along-track, it is impacted by the ocean dynamics, and **particularly the waves and their wind-driven contribution**.



Noise? Or new sea state variable!

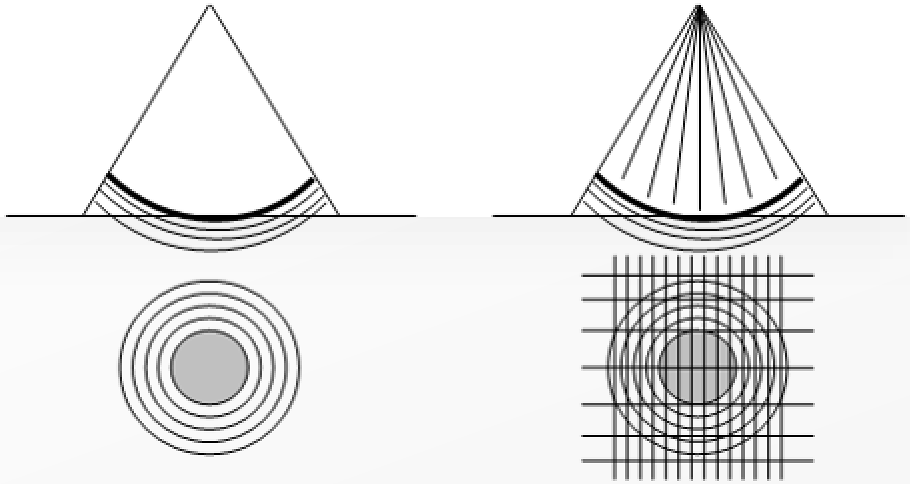
The bigger impact is due to **the variation of the vertical component of the waves velocity weighted with radiometry** over the footprint. This quantity can be directly linked to the waves second momentum:

$$\boxed{\sigma_v^2 = m_2 = \int_0^{+\infty} \omega^2 \, S(\omega) \, d\omega}$$

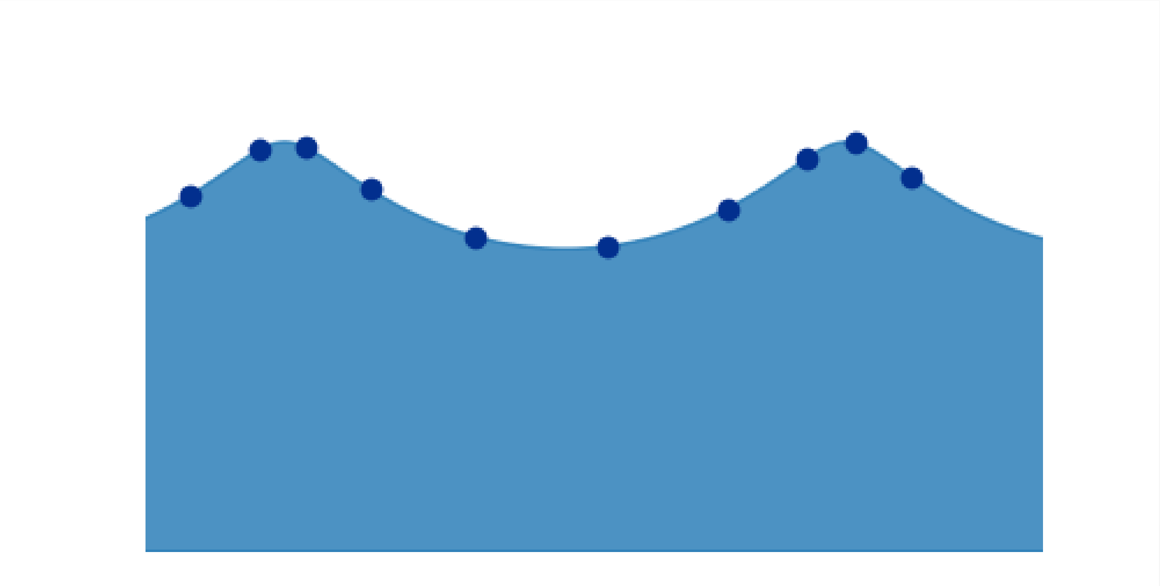
where $S(\omega)$ is the power density spectra of the sampled ocean area. Using the standard SWH and mean zero-crossing wave period T_{02}, it can be rewritten as:

$$\boxed{\sigma_v = \frac{\pi}{2} \frac{SWH}{T_{02}}}$$

Delay-Doppler: Limitations so far



Since the Delay-Doppler uses the Doppler effect to locate the signal along-track, it is impacted by the ocean dynamics, and **particularly the waves and their wind-driven contribution.**



Another impact is due to the Doppler due to horizontal wave-facets motions weighted by their radiometry**.** This can be written as **the along-track projection of the Stokes drift**, weighted by the mean square slope (MSS):

$$\boxed{u_x \sim \frac{U_{Stokes}}{2\ MSS} \cos(\phi_{Stokes} - \phi_{sat})}$$

Taking advantage of the wind dependency of the Stokes drift and MSS, it can be fitted with the following formula:

$$\boxed{u_x \sim A(U_{10}) \cos(\phi_{wind} - \phi_{sat}) + B(U_{10})}$$

Noise? Or another sea state variable!

Transforming noise into wind and waves variables

Presenting our new Sentinel-6HR 5-parameter product!
January—June 2022 and January—June 2024

- **Removing the major sea-state-dependent biases**
  Aligning Delay-Doppler with Low Resolution Mode (LRM) altimetry
  without Look-Up Table or ERA5 inputs

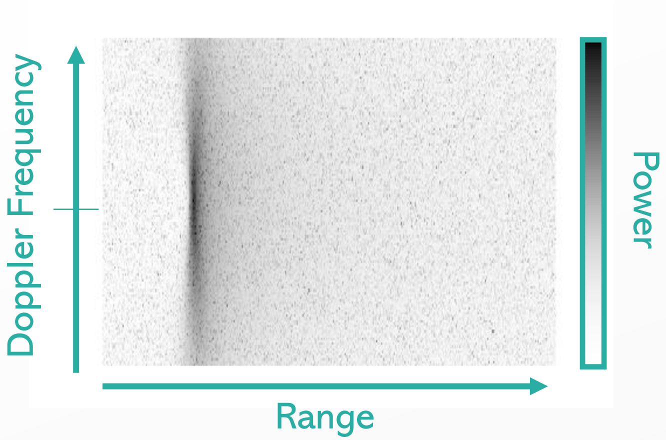
- **High-Resolution (~ 300 m) along-track**
  For coastal areas, extreme events or wave-topography disentanglement

- **Offering two new sea-state variables**
  Related to wave period and wind speed

- **Soon (by summer 2026) available on Aviso!**

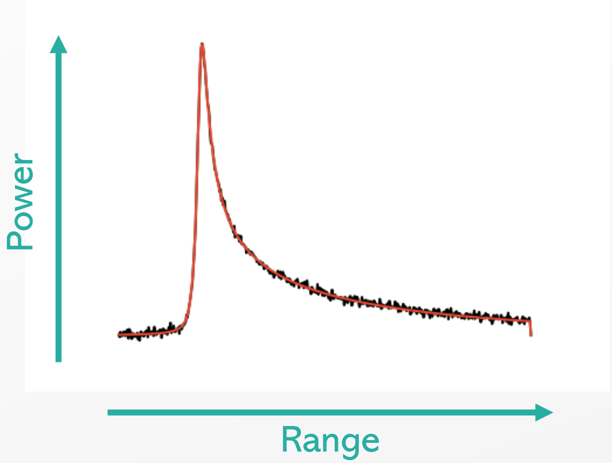
Leveraging Delay-Doppler altimetry

After the L1B processing and range migration correction, for each ground point, we get a “stack” of Doppler looks:



Currently not directly used

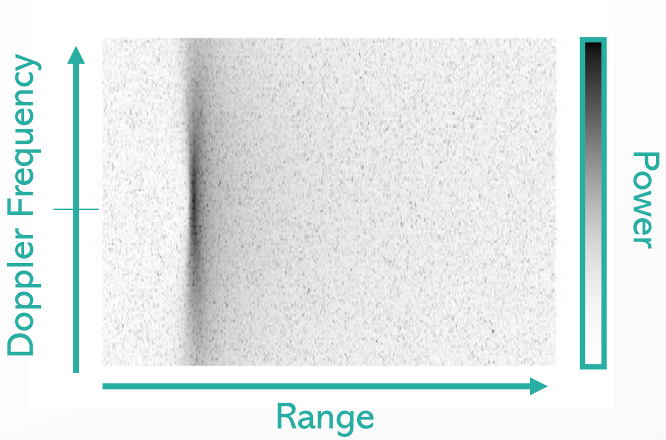
In the current operational chain, the Doppler looks are summed to get the multilook waveform, which is then retracked:



Numerical retracking: using the real Point Target Response
3 parameters : Epoch, Amplitude and SWH

Leveraging Delay-Doppler altimetry : “2-Dimensional retracking”

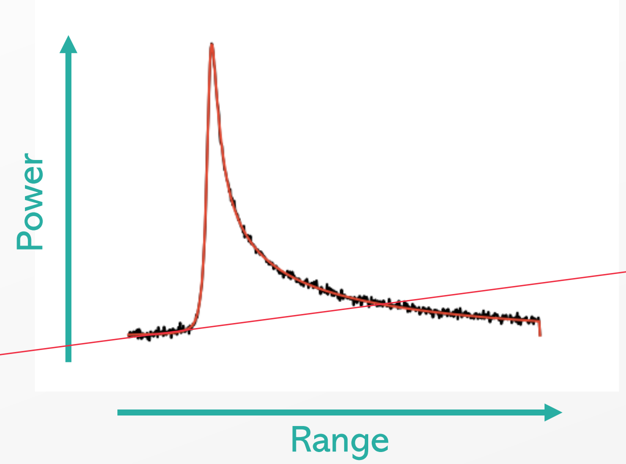
After the L1B processing and range migration correction, for each ground point, we get a “stack” of Doppler looks:



Numerical “2-Dimensional” retracking: using the real Point Target Response
5 parameters : Epoch, Amplitude, SWH, σ_v and u_x

Now using all available information

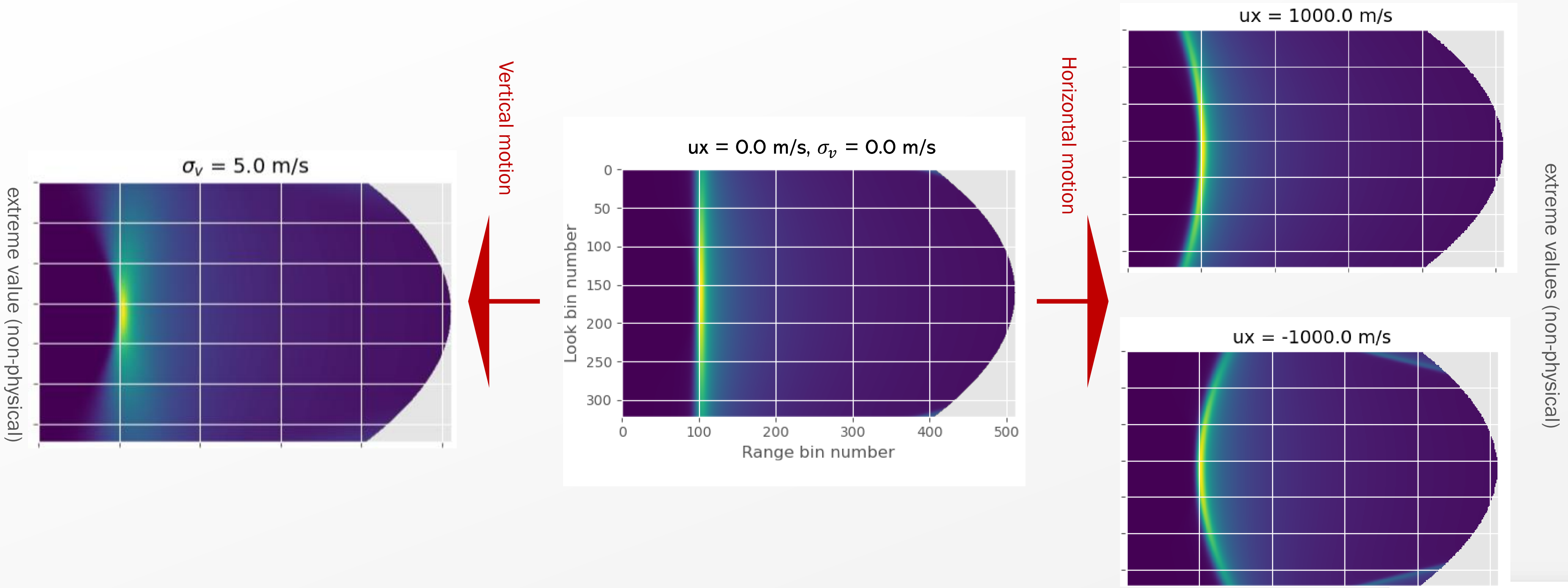
In the current operational chain, the Doppler looks are summed to get the multilooked waveform, which is then retracked:



~~Numerical retracking: using the real Point Target Response~~
~~3 parameters : Epoch, Amplitude and SWH~~

Leveraging Delay-Doppler altimetry : “2-Dimensional retracking”

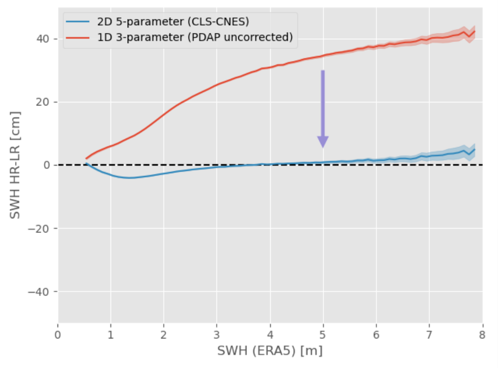
Retracking the full stack instead of the multilook allows us to constrain the surface motion:

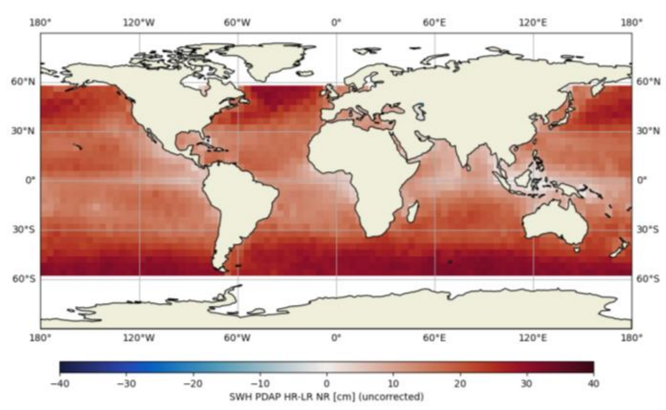


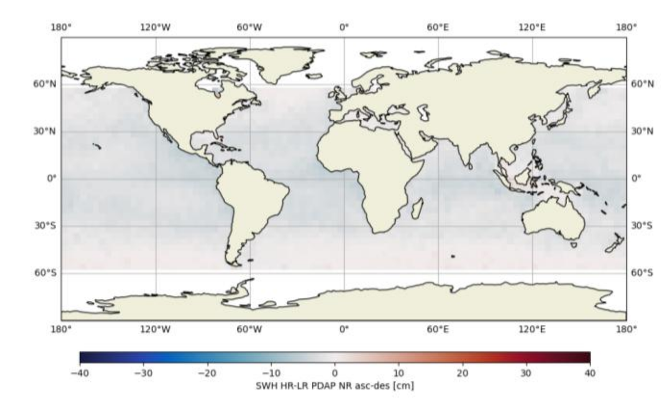
(Buchhaupt 2020—2023, Marié et al. 2024)

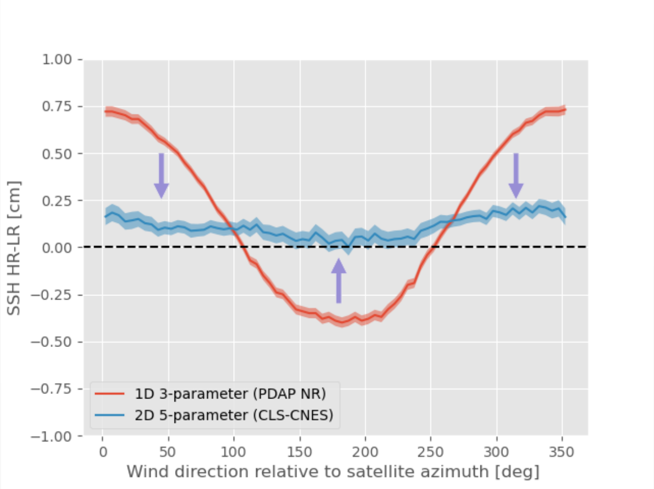
Resolving the biases: alignment with LRM without any Look Up table

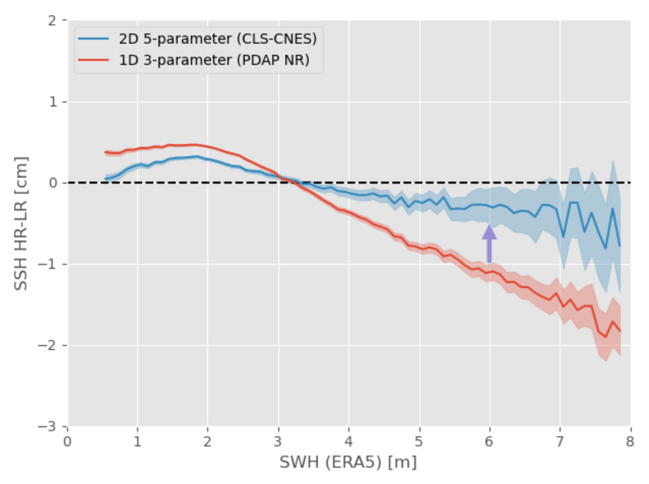
Removing the overestimation of the waves heights









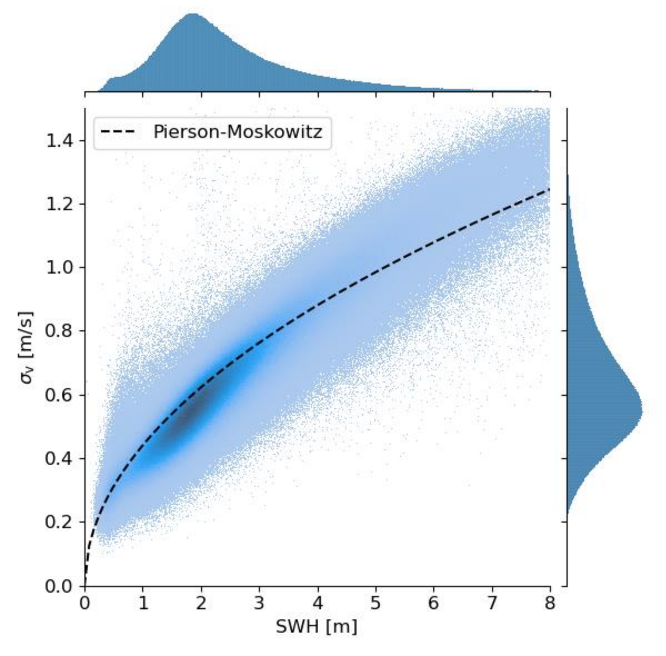


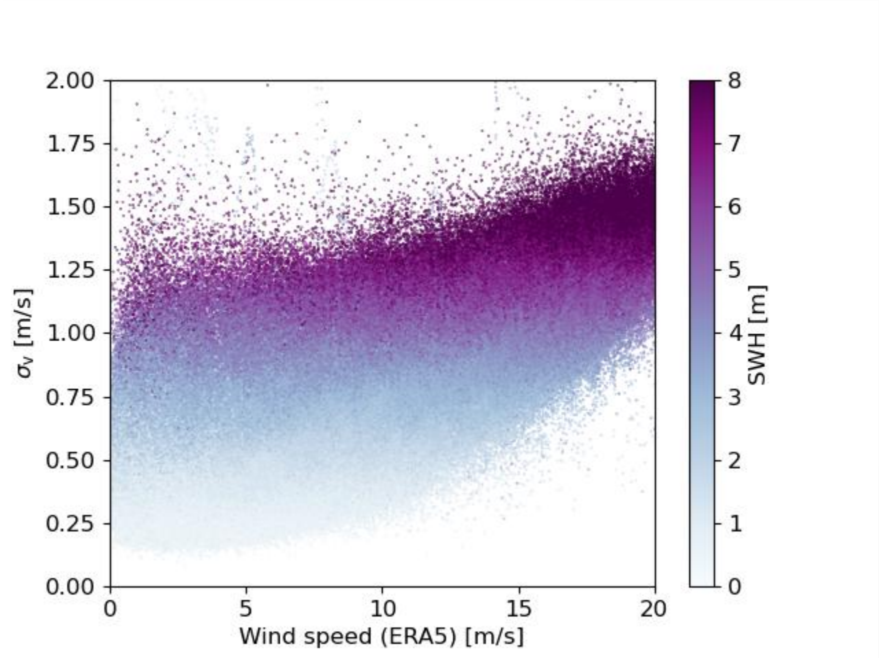
Removing the wind (and wave)-dependent SSH bias

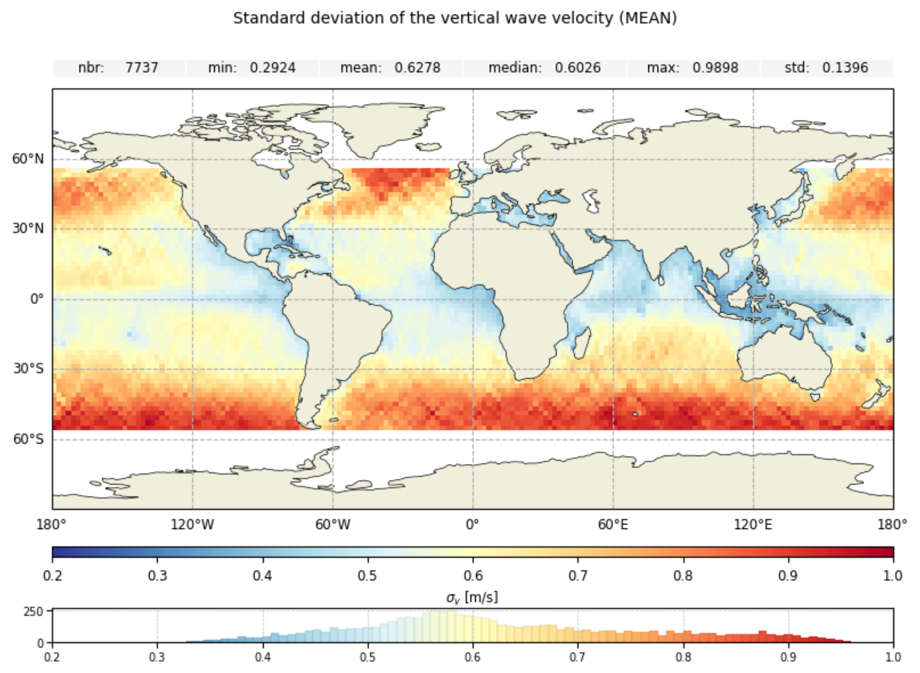
Sentinel-6 PDAP LR NR, HR NR, HR MLE4 or CLS product, January-June 2022

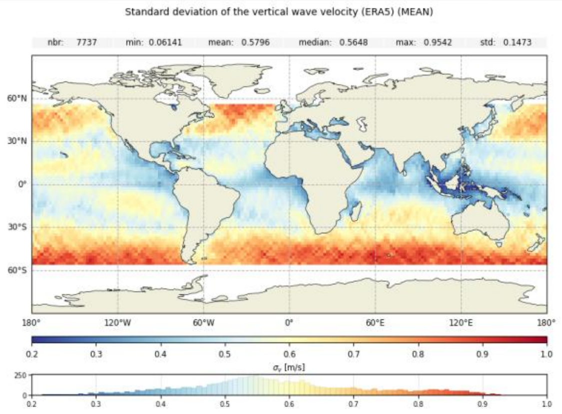
Retrieving new variables: characterizing ocean dynamics

Wave vertical velocity standard deviation σ_v









CLS/CNES

ERA5

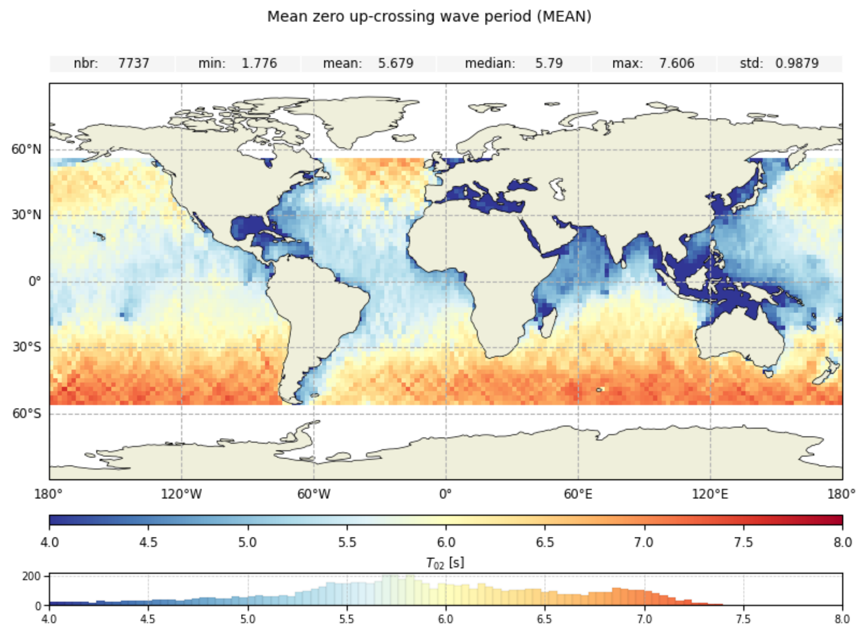
The vertical velocity variance is **correlated to both the significant wave height and wind speed**, roughly as expected by the theoretical wave spectrum models for a fully-developped sea

Sentinel-6 CLS product, January-June 2022

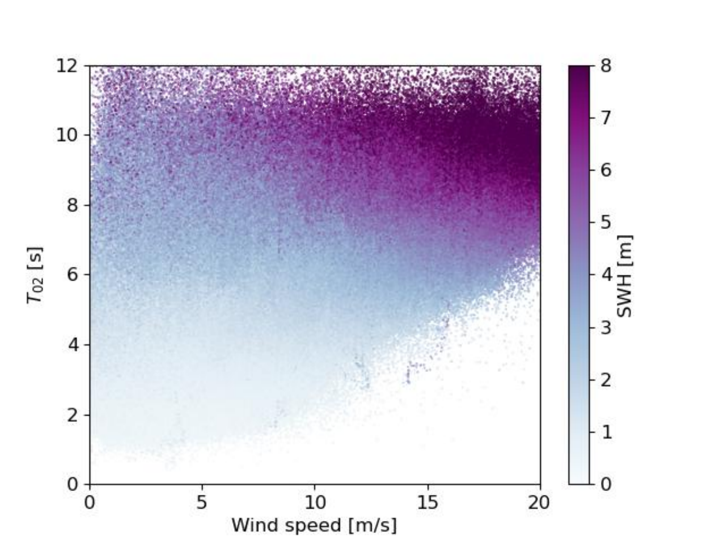
Retrieving new variables: characterizing ocean dynamics

Wave vertical velocity standard deviation σ_v

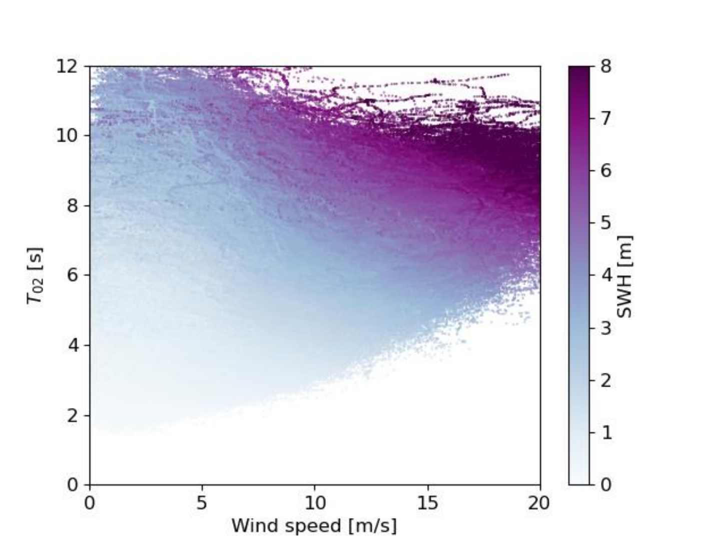
→ Retrieving the mean zero-upcrossing period $T_{02} = \frac{\pi}{2}\frac{SWH}{\sigma_v}$



T_{02} is an integrated parameter that gives more weight to the higher frequencies of the wave spectrum, i.e. wind waves. It is used to estimate the average period of the zero-crossing waves in a sea state.



CLS/CNES



ERA5

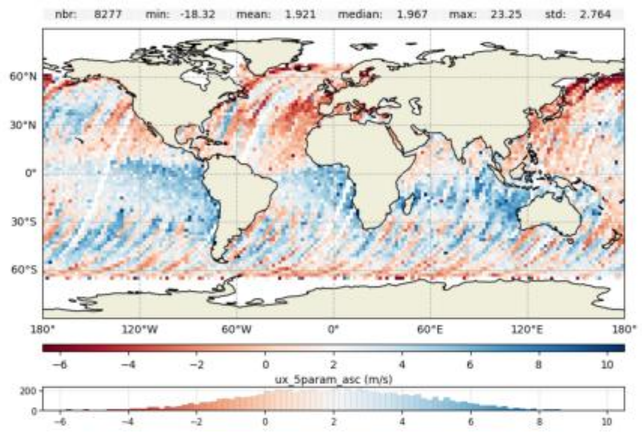
L. Rodet (CLS) et al., OSTST 2026

cnes CLS COLLECTE LOCALISATION SATELLITES

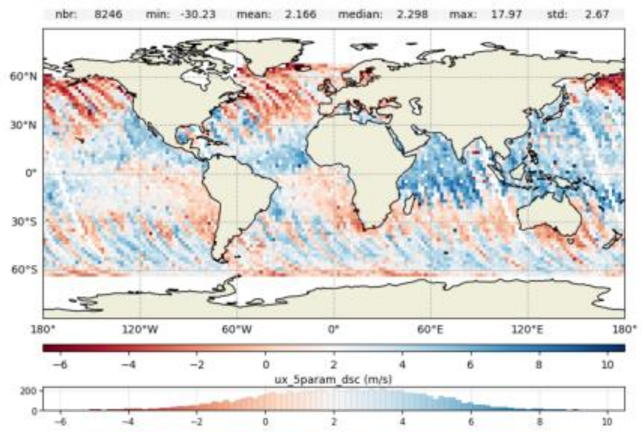
Retrieving new variables: characterizing ocean dynamics

Effective along-track surface velocity u_x

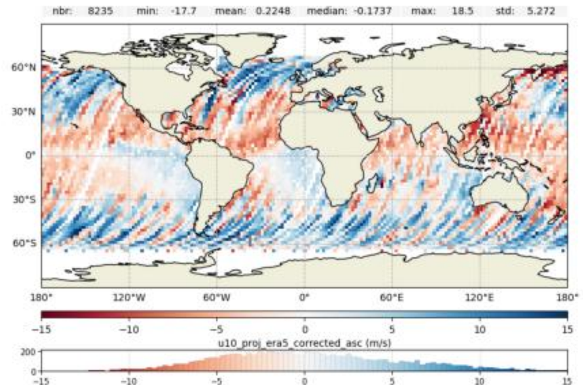
Ascending



Descending

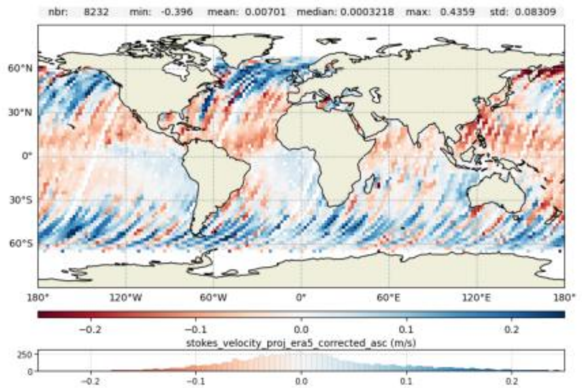


Ascending



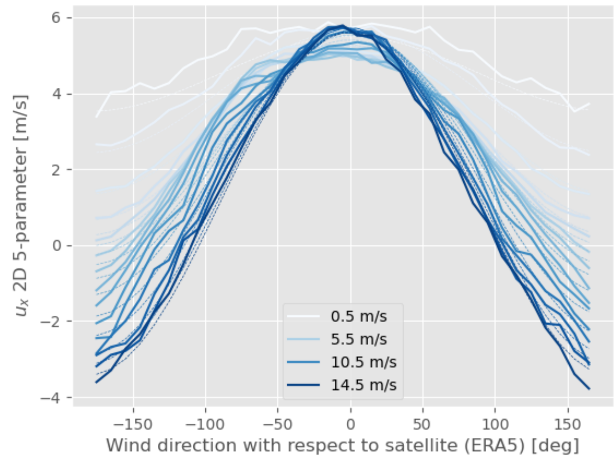
Projected wind speed

Ascending



Projected Stokes drift

January-June 2026



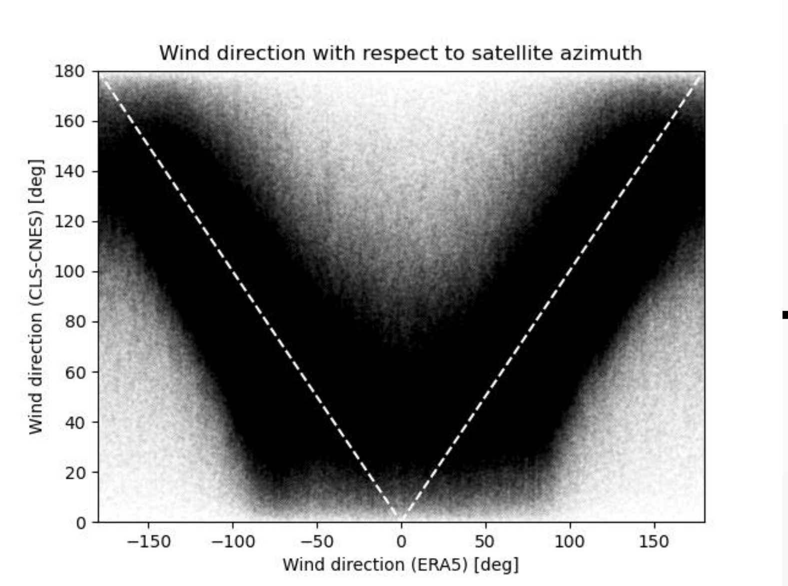
L. Rodet (CLS) et al., OSTST 2026

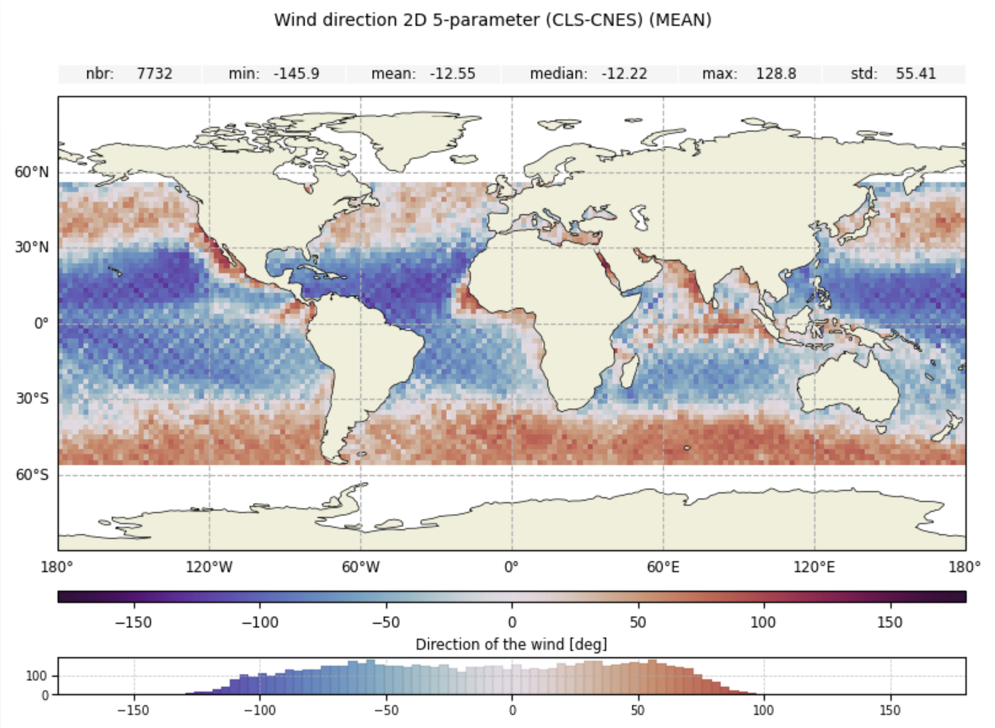
Sentinel-6 CLS-CNES product, Cycle 45

Retrieving new variables: characterizing ocean dynamics

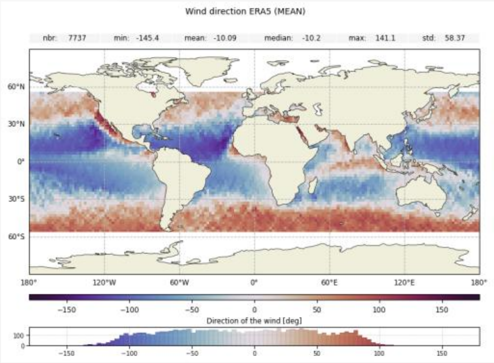
Effective along-track surface velocity u_x
⟶ Perspective: Retrieving the wind direction

(Further validation is needed on this retrieval)





ERA5



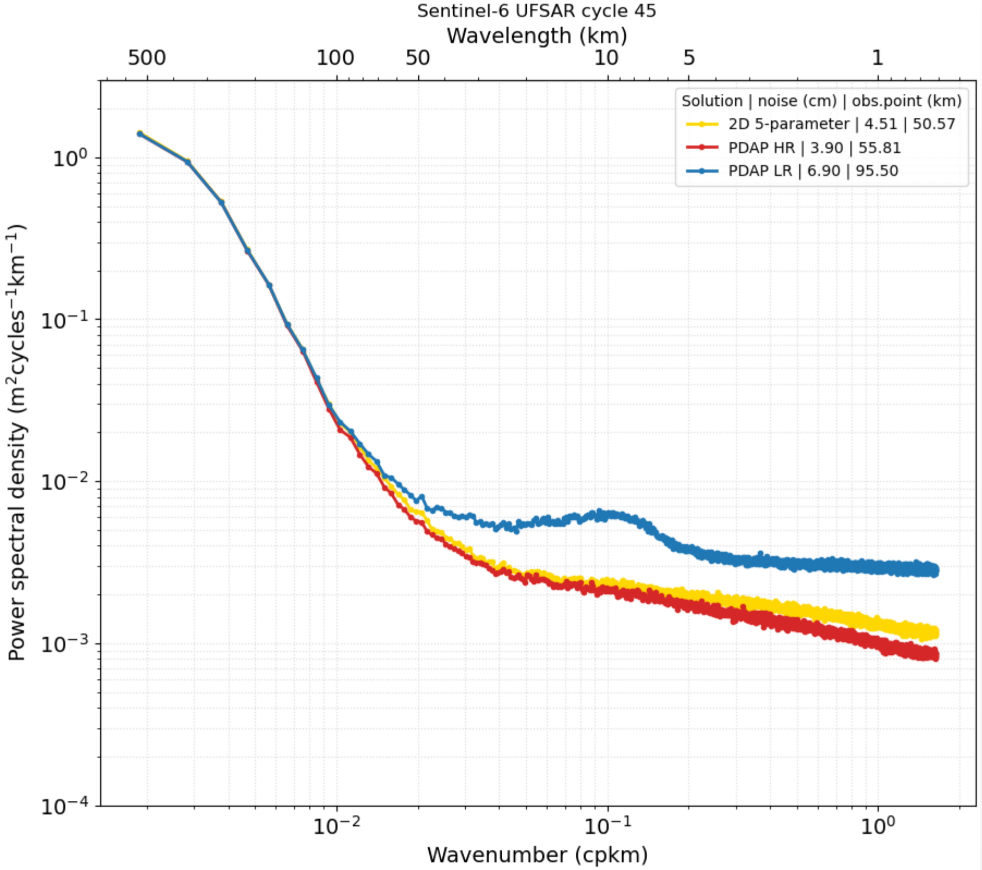
Using ERA5 to calibrate the wind dependency and to remove the left-right ambiguity

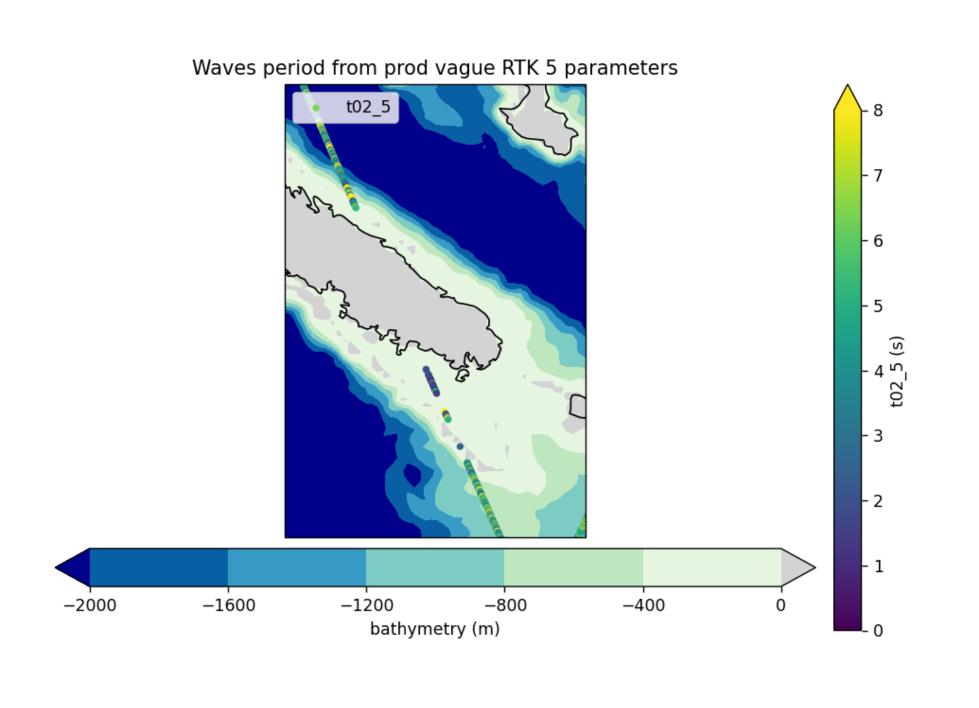
L. Rodet (CLS) et al., OSTST 2026

Sentinel-6 CLS-CNES product, January-June 2022

Keeping the Delay-Doppler improved along-track resolution

The high along-track resolution can be used to study coastal areas, extreme events or wave-topography disentanglement





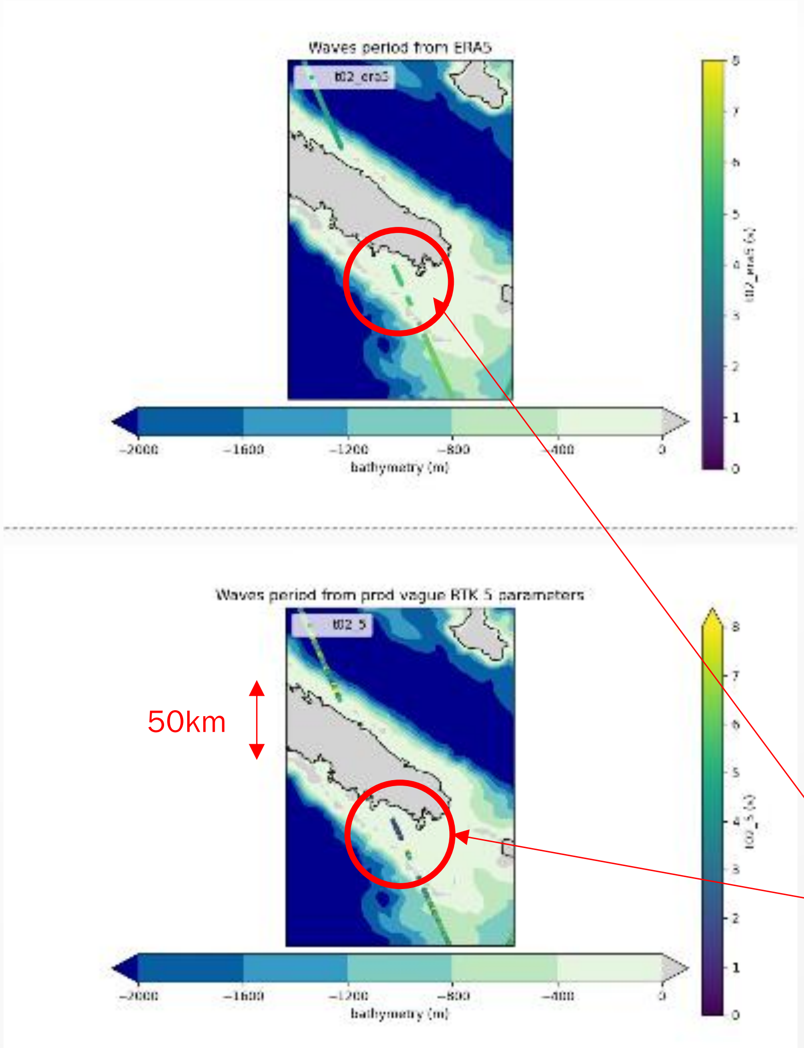
Retracked wave period when entering the lagoon of New Caledonia

L. Rodet (CLS) et al., OSTST 2026

Sentinel-6 CNES-CLS product, cycle 45

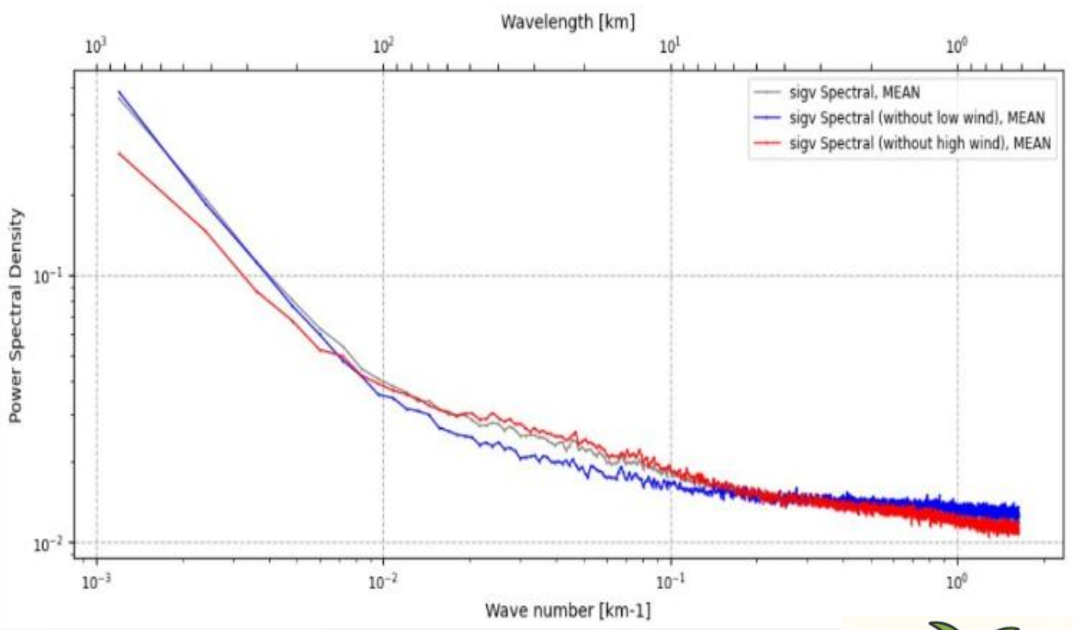
Example of applications: reduction of swell inside a lagoon

New Caledonia



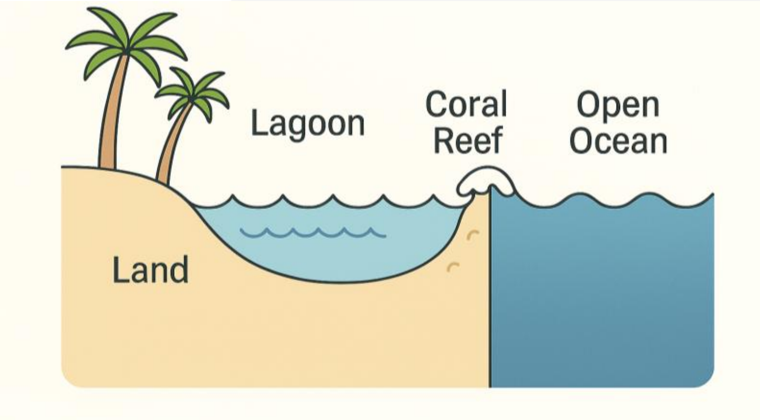
sigv Spectral

	nbr	min	mean	median	max	std
sigv Spectral, MEAN	1361	0.001294	0.01466	0.01332	0.4555	0.01371
sigv Spectral (without low wind), MEAN	1361	0.001291	0.01474	0.01372	0.4813	0.01407
sigv Spectral (without high wind), MEAN	1361	0.0009596	0.01388	0.01257	0.2839	0.009247



The removal of low winds area reduces the spectral slope, illustrating the impact of **wind/waves interactions or uncertainty** to be studied with such products

The reduced period inside the lagoon is observed with the data whereas the model misses this variation



Thank you for your listening!

→ Contact: lrodet@groupcls.com

Be ready for the incoming product on Aviso by mid-July!

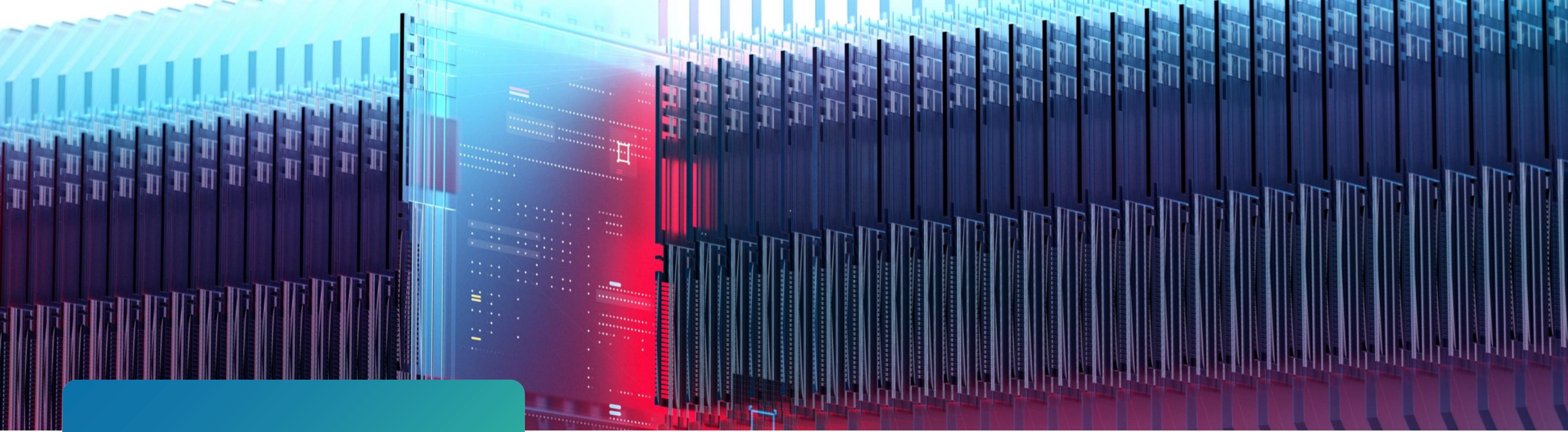
DOI: **10.24400/527896/AVISO-2026.008**

New wind and wave variables to assimilate!

Higher resolution without the associated biases!

→ Prospects for the present and future SAR altimetry missions (CRISTAL, S3NG-T, S6NG)

This work was supported by CNES in the frame of the CNES/ESTEC agreement



Supplementary material

Leveraging Delay-Doppler altimetry

We made use of Christopher Buchhaupt's model (Egido and Smith 2017, Bucchaupt 2020—2023):

$$\text{Model} = \frac{P_u}{2F_s}\,\text{IFFT}\left(\frac{1}{N_{looks}}\sum_\eta \mathrm{PDF_r} \times \mathrm{PDF_{az}} \times \mathrm{PTR_r} \times \mathrm{PTR_{az}} \times \mathrm{FSSR} \times e^{-\frac{2i\pi\eta f_d}{1+\frac{u_x}{v_{sat}}}}\right) + \frac{t_n}{N_{looks}}$$

Adding a new term in the physical model to account for vertical surface motion:

$$\mathrm{PDF}_{az} = \mathrm{e}^{-\frac{4\pi^2 a_v \sigma_v^2 \eta^2}{\lambda_c^2}}$$

Modifying the iDFT to account for horizontal surface motion

→ Direct theoretical dependency in σ_v^2 and u_x, without model input!

Similar approach: Louis Marié et al 2024

Product content

“Attenuated” σ_v

Straight from the retracker:	Range,	SWH,	σ_0,	$\widetilde{\sigma_v}$,	u_x
Slightly-processed variables:	SSH,		T_{02},	σ_v	
ERA5-interpolated variables?	u10, v10				
Advanced variables:	SSHA,	U10,		ϕ_{wind}	

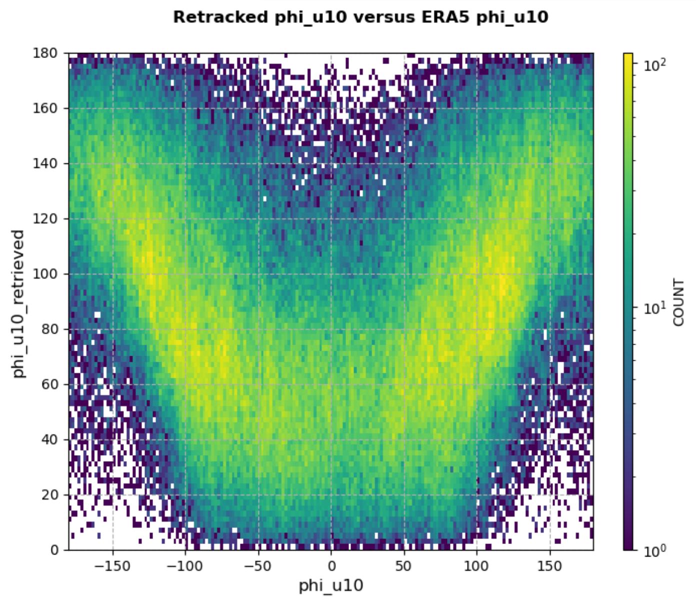
Deriving SSHA from SSH: Using geophysical corrections

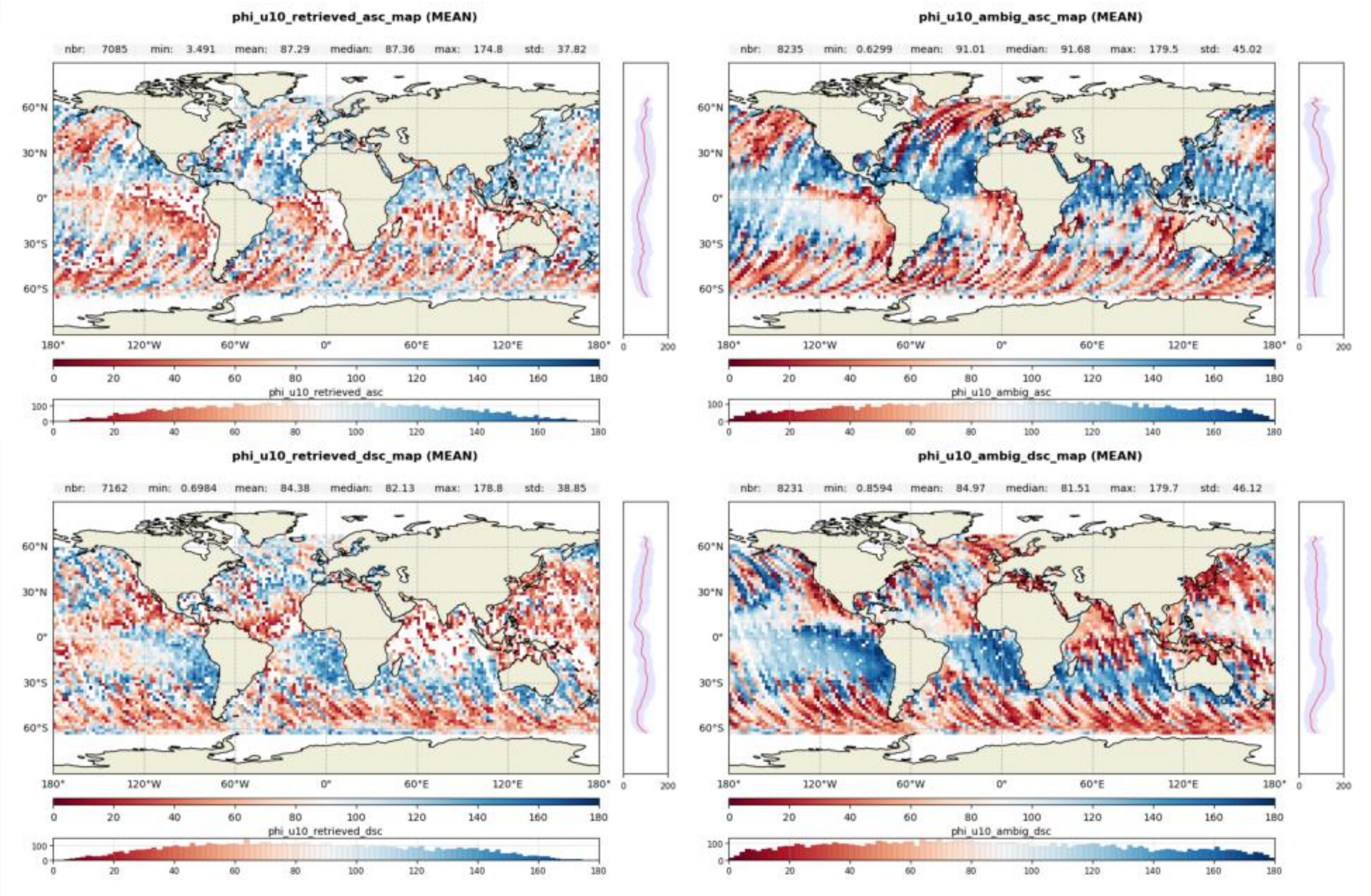
Deriving U10 from $\boldsymbol{\sigma_0}$: Using Collard et al., neural network prediction calibrated with model and altimetry data

Deriving $\boldsymbol{\phi_{\text{wind}}}$ from $\boldsymbol{u_x}$: Using $u_x = A(U_{10})\cos(\phi_{\text{wind}} - \phi_{\text{sat}}) + B(U_{10})$, with $A(U_{10})$ and $B(U_{10})$ calibrated with model and altimetry data. U_{10} can be the altimeter wind speed or the model wind speed. Finally, a model must be used to remove the left-right ambiguity associated with the cosinus.

Retrieving new variables: characterizing ocean dynamics

Effective along-track surface velocity u_x
⟶ Retrieving the wind direction





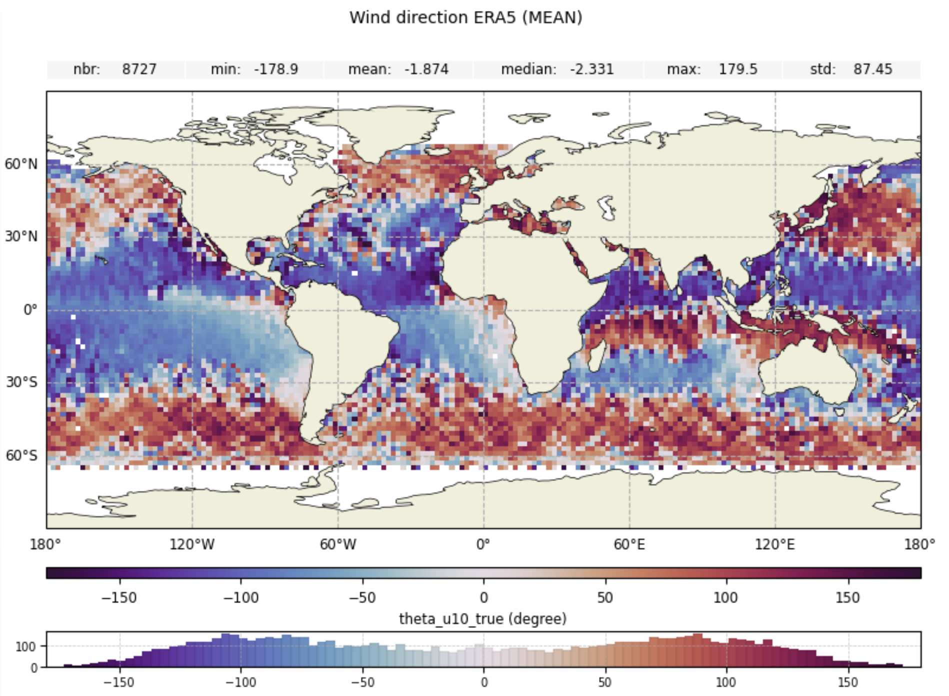
Perspective: Using models or cross-overs to remove the left-right ambiguity

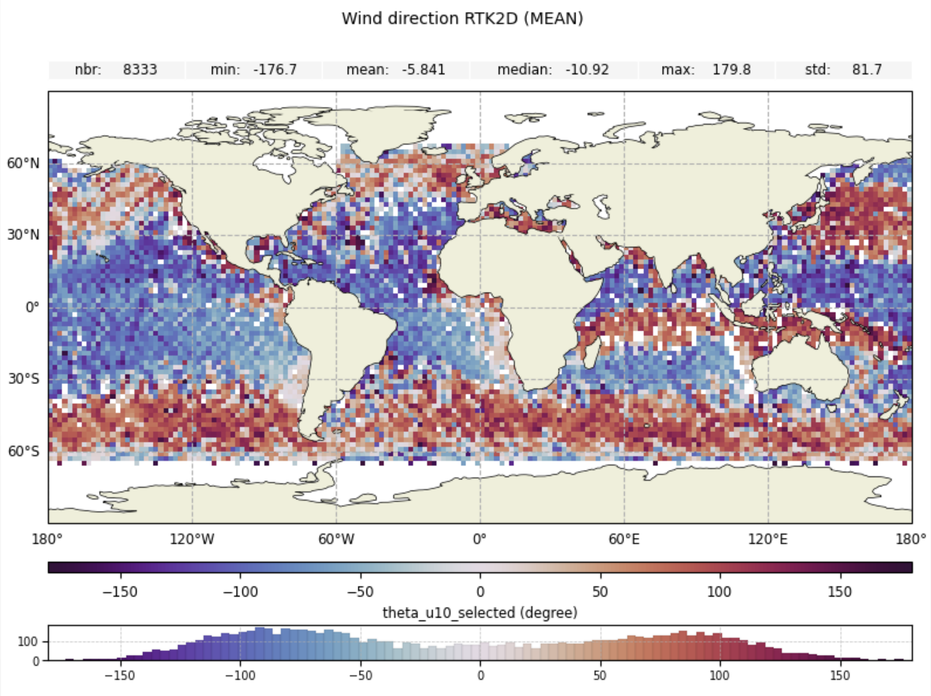
L. Rodet (CLS) et al., OSTST 2026

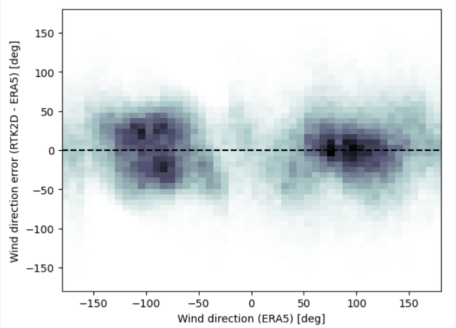
Sentinel-6 CLS product, cycle 45

Retrieving new variables: characterizing ocean dynamics

Effective along-track surface velocity u_x
⟶ Retrieving the wind direction, removing the left-right ambiguity using the ERA5 model





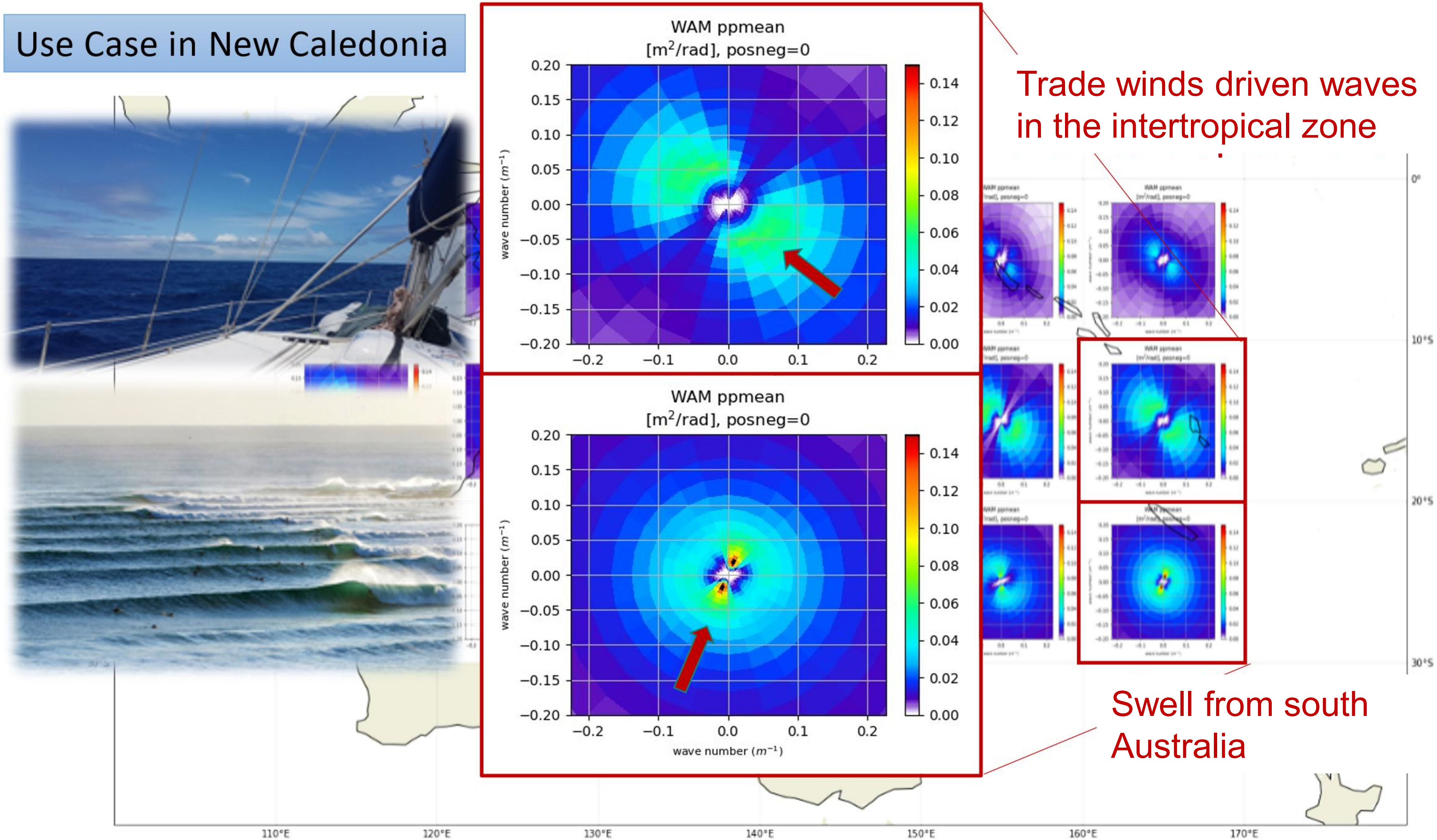


L. Rodet (CLS) et al., OSTST 2026

Sentinel-6 CLS product, cycle 45

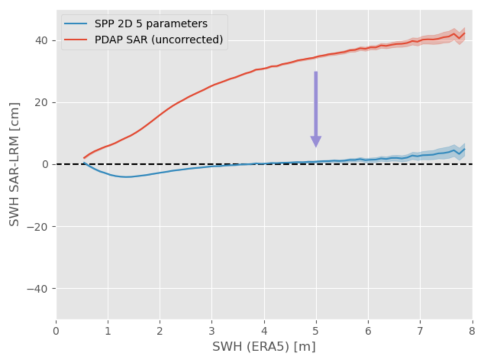
CFOSAT spectral data

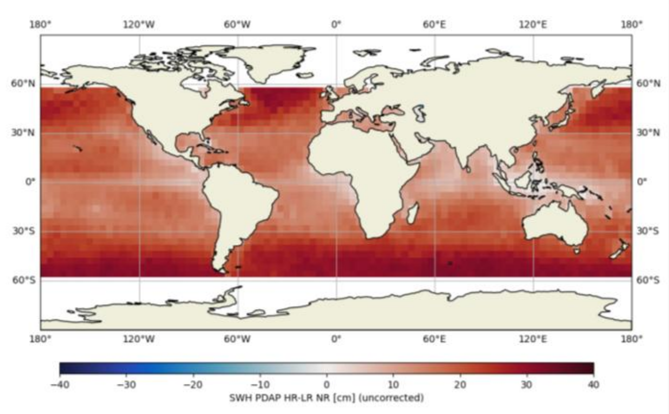
Use Case in New Caledonia

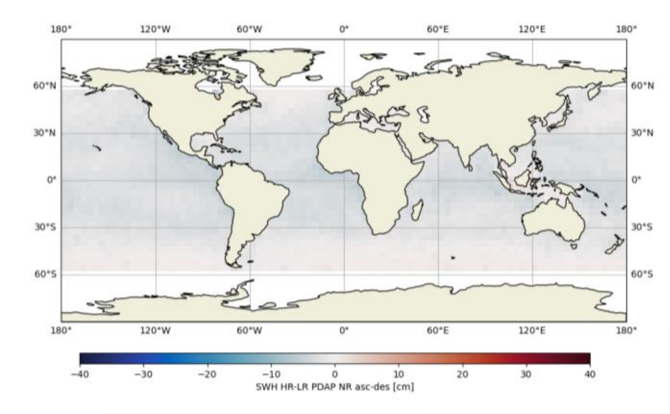


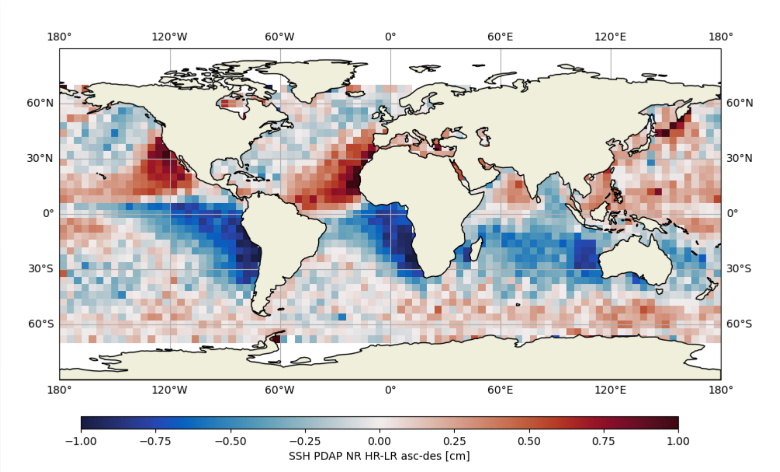
Resolving the biases: alignment with LRM without any Look Up table

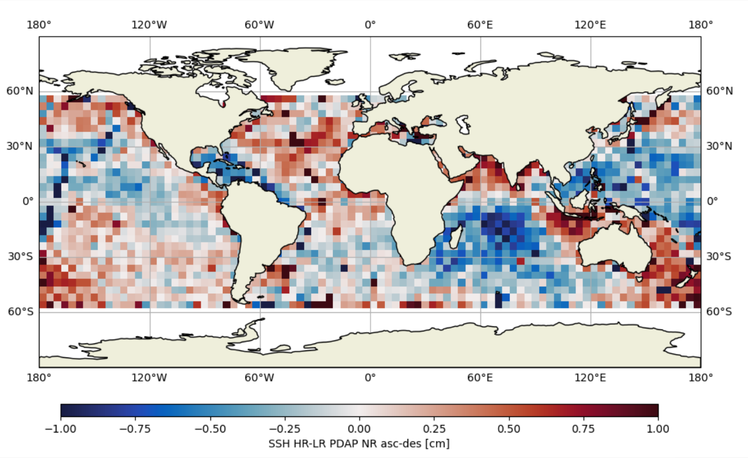
Removing the overestimation of the waves heights



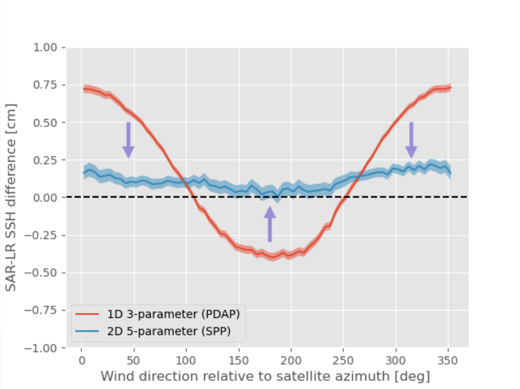








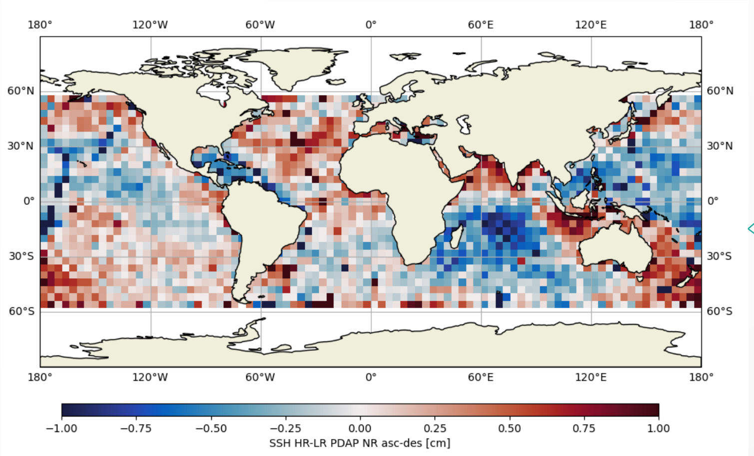
Removing the wind-dependent SSH bias



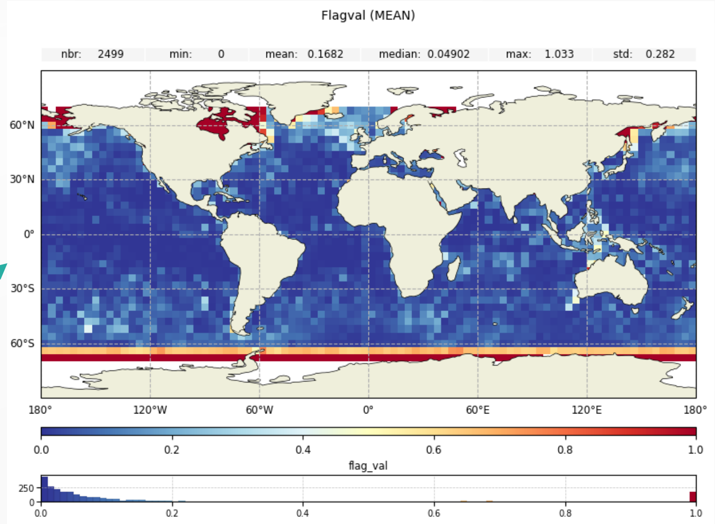
Sentinel-6 PDAP LR NR, HR NR, or CLS product, January-June 2022

Editing questions

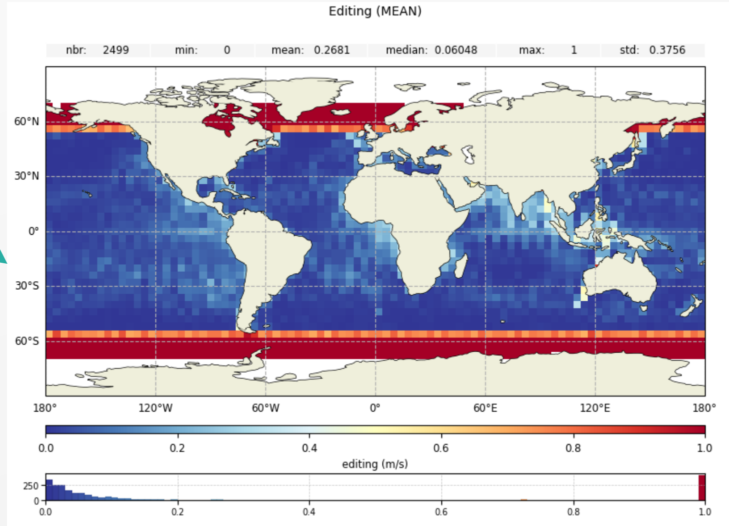
Cycle 45

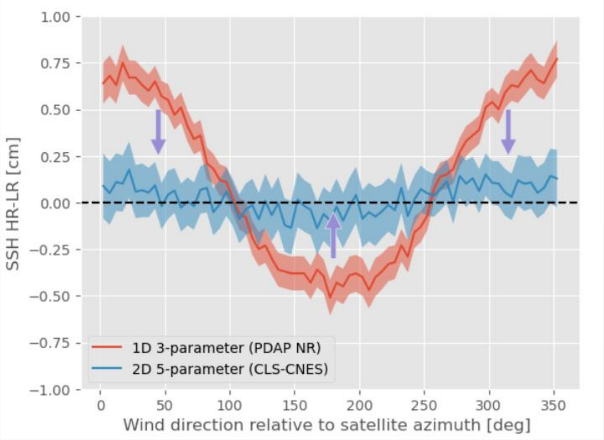


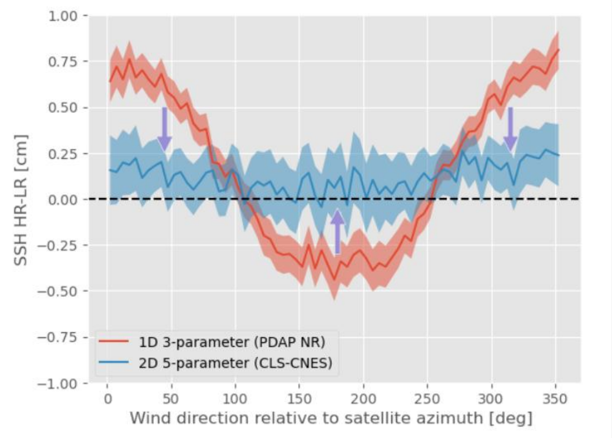
Flagval
(SSHA)



Custom editing:
|Lat| < 55°
0 m < SWH < 20 m
-130 m < SSH < 100 m
$0 < \sigma_v < 2$ m/s
$|u_x| < 60$ m/s







Sentinel-6 PDAP LR NR, HR NR, or CLS product, January-June 2022