ESTIMATING UNCERTAINTY OF SEA STATE OBSERVATIONS USING HIGH-RESOLUTION NADIR ALTIMETRY AND MULTI-SENSOR REMOTE SENSING SYNERGIES

NIGOU Adrien, OLLIVIER Annabelle, DE CARLO Marine, AVERSENG Matthias, MOLERO Beatriz, PEUREUX Charles, HUSSON Romain (CLS)

ARDHUIN Fabrice, DODET Guillaume, POSTEC Taïna (LOPS, IFREMER)

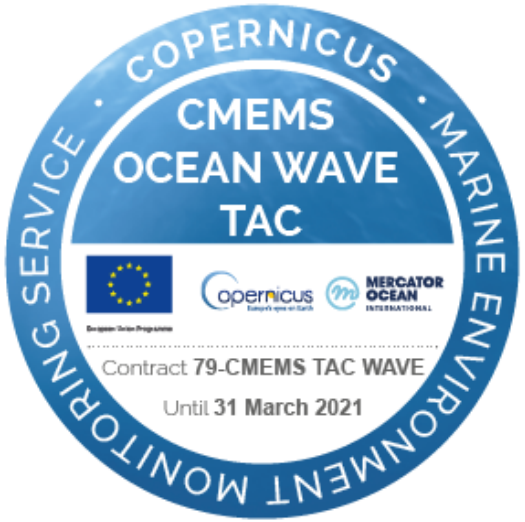
DIBARBOURE Gerald, TOURAIN Cedric (CNES)

AOUF Lotfi (Météo-France)

Satisfy user needs

CMS Wave-TAC User Survey 2023 :

3 main needs identified for operationnal data



1 - 91% **Additionnal variables** from **wave spectra** (direction and period)

2 - 79% **Increase the resolution** for along track products near coasts and high variability areas

3 - 79% **Uncertainty metrics** associated to data

Altimeter response to different sea states

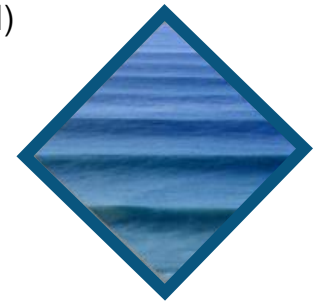
For both scenes Hs = 3 m

A)

Wind sea (Elfouhaily spectrum)

B)

200m Swell with strong spectral peakedness (reduced frequency & directional spread)



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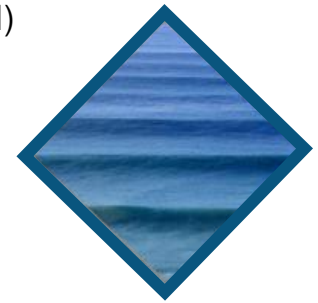
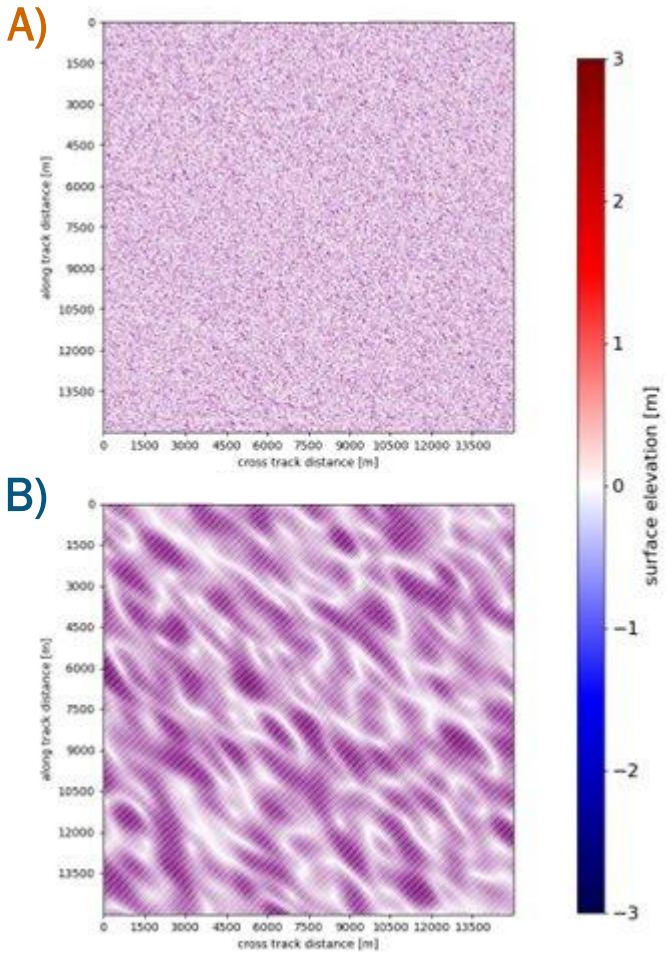


Oceanic surface simulated



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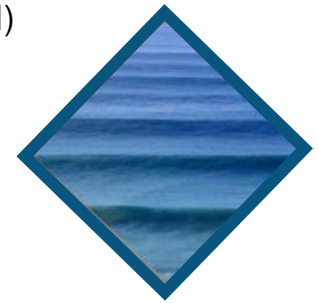

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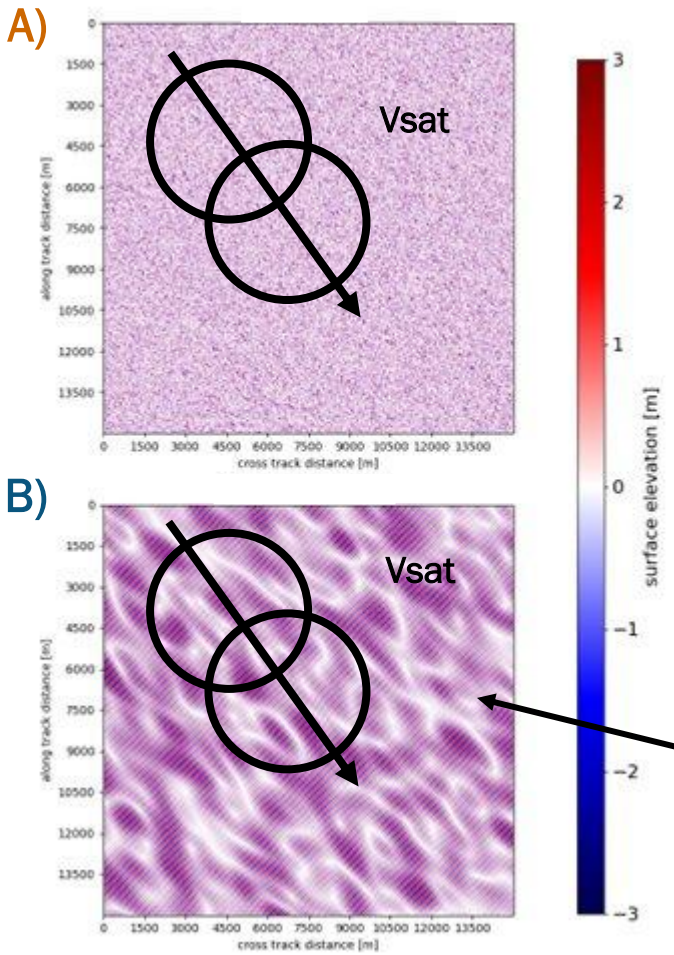

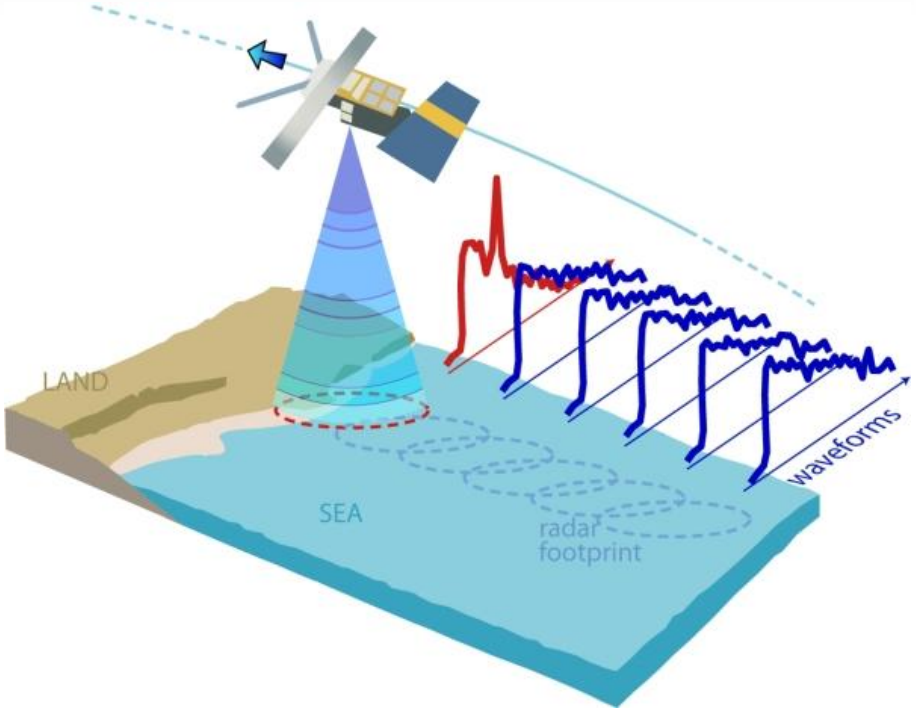

Wave groups is one of the uncertainty source in altimetry

Wave groups increase SWH estimates variability

For both scenes Hs = 3 m

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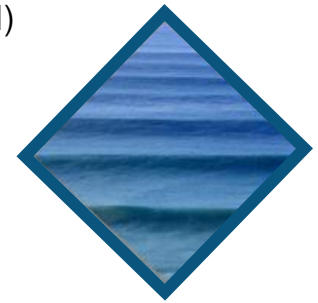

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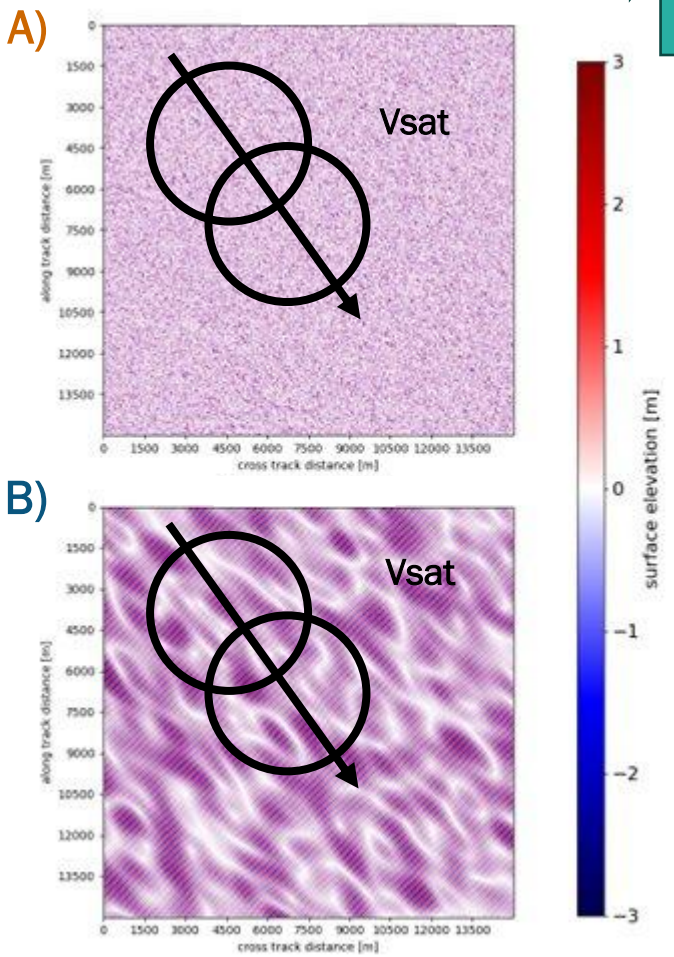
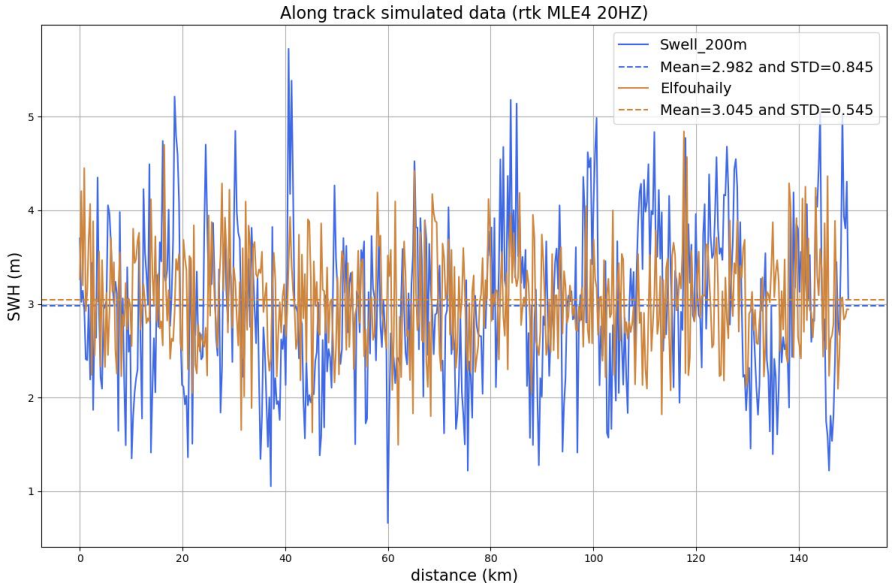


Altimeter simulation

Estimated SWH



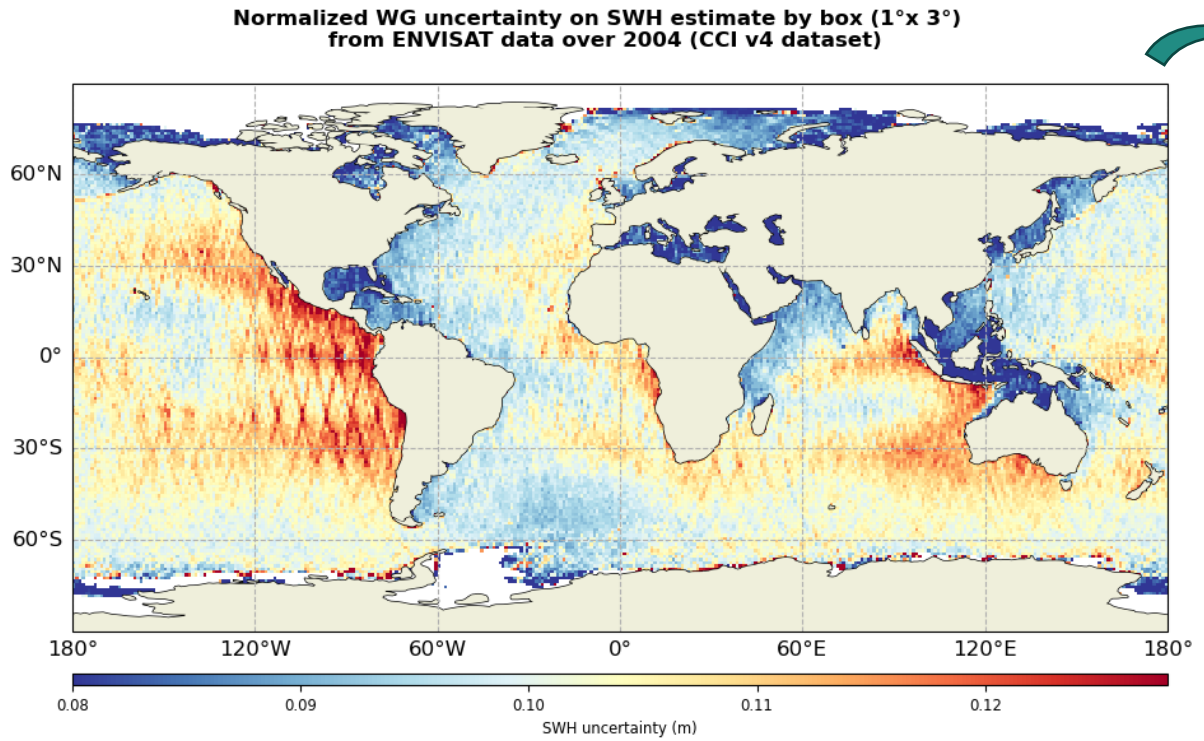
A) std = 0,545m

B) std = 0,845m

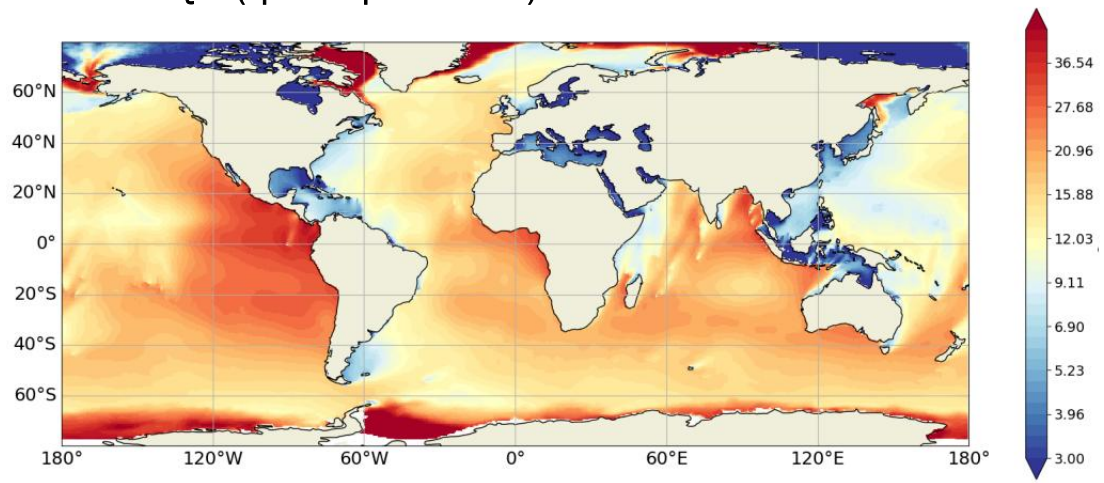
+50% std

Deriving SWH uncertainty from SWH estimates variability

- This pollution of altimetric data can be isolated in an **uncertainty field** thanks to **EMD filtering** method (Quilfen et al 2021).
- This variability acts like a **correlated noise** and was shown to be **directly related** to the spectral peakedness **Qkk** (De Carlo et al 2023).



Closely linked



Multi sensor synergies to bridge wave groups uncertainty and sea state

2 main objectives reached

2 - 79% ***Increase the resolution*** *for along track products near coasts and high variability areas*

3 - 79% **Uncertainty metrics** associated to data

Provide users with a clean high-resolution along-track SWH product, denoised from sea state variability

Provide an uncertainty field that brings additional info about sea state

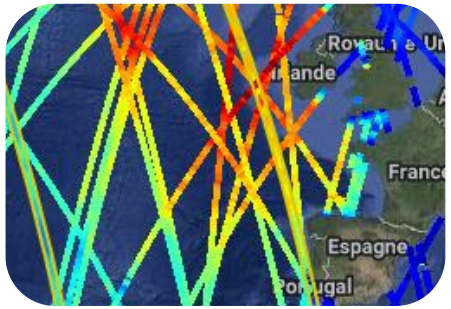
Better sea state characterization !

- Our SWH uncertainty field brings additional information about sea state in nadir SWH products
- Nadir altimetry is not only Hs for waves !
- Recent missions (Sentinel-1, CFOSAT, SWOT) provide a 2D spectral view of sea state, offering new opportunities to link uncertainties with sea states observed by different sensors.

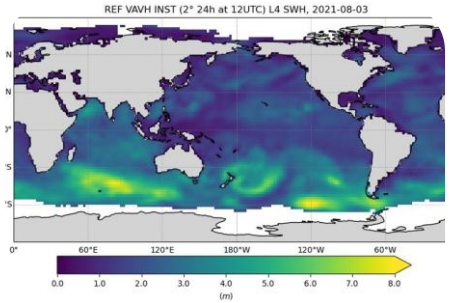
Multi sensor synergies

A variety of complementary products

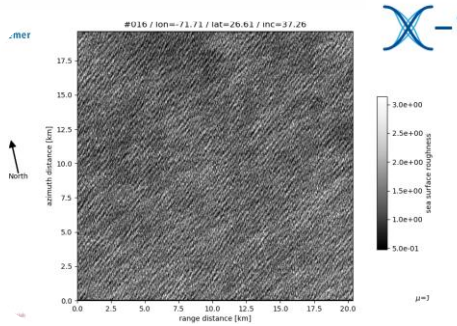
https://ovl.oceandatalab.com/



Nadir L3 along track products



L4 maps

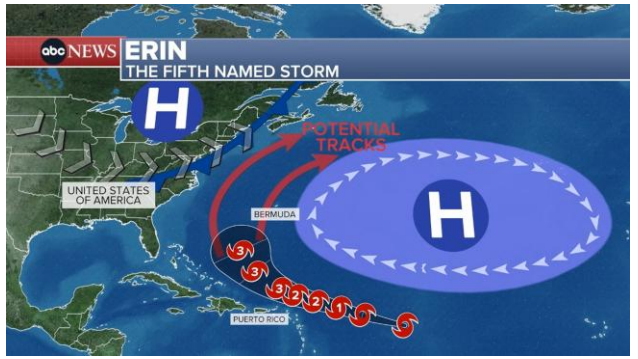


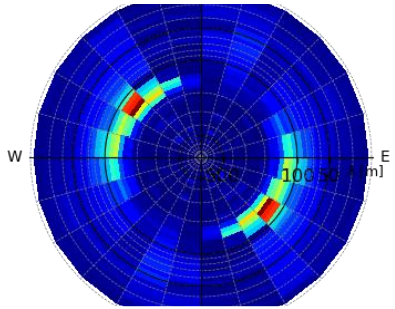
X-waves

Copernicus Marine Service

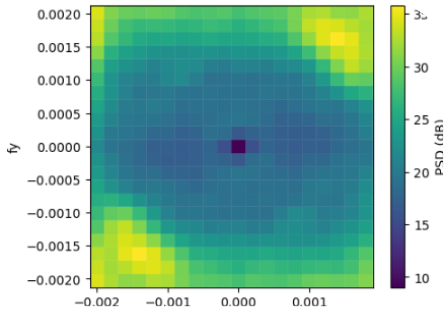
Sentinel-1 WV images

Multi sensor synergies : Erin usecase

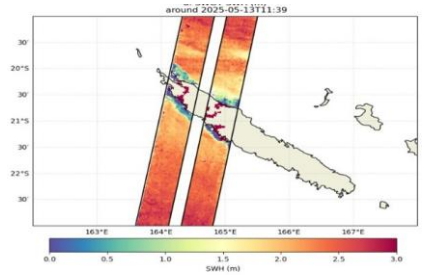




SWIM L2P BOX



SWOT L3 WW



SWH 2D KaRIn

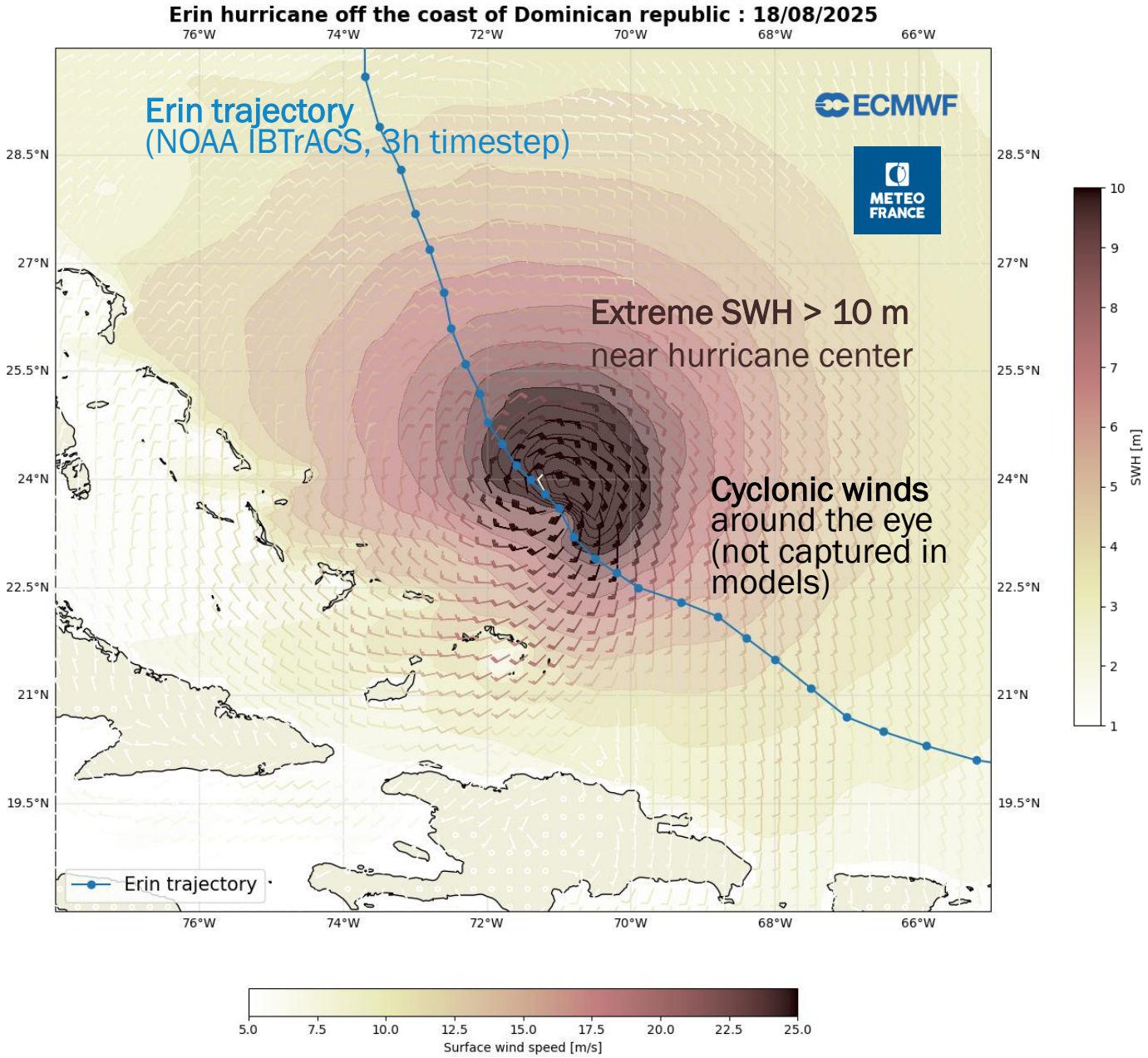
AVISO+ Satellite Altimetry Data

cnes

Start with model maps

Focus on :

1 / the **peak intensity of the hurricane** off the coast of Dominican Republic on August 18, 2025 with extreme high waves.



MFWAM SWH & ECMWF wind models
18 Aug 2025, 21:00 UTC

SWIM brings crucial insights

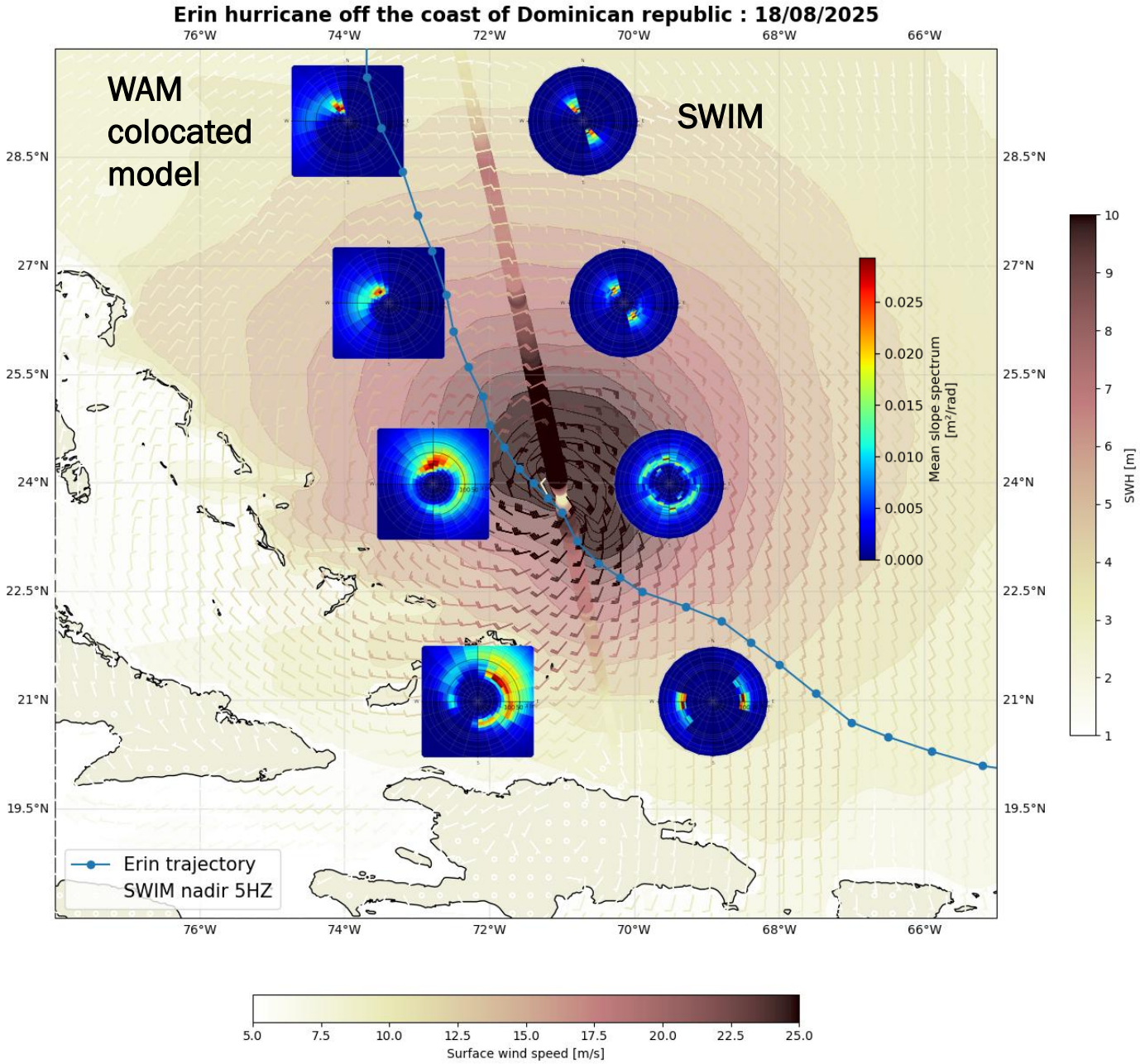
2D ocean wave spectra (3° lat bins along track):

Main insights :

- Different sea states along hurricane track
  South: complex sea after cyclone passage
  North: strong swell generated by the hurricane and propagating following its trajectory

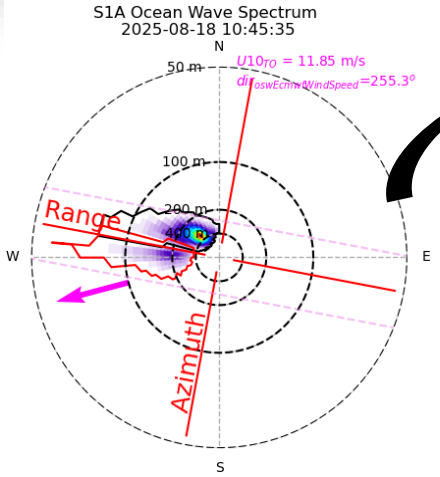
- Swirling winds in hurricane core

MFWAM SWH & ECMWF wind models
18 Aug 2025, 21:00 UTC
CFOSAT pass
18 Aug 2025, 22:30 UTC



S1 makes it visible

SAR Sentinel-1 WV images
High-resolution sea state view
(20 km × 20 km)
**Here, image size has been deliberately enlarged for better visualization*

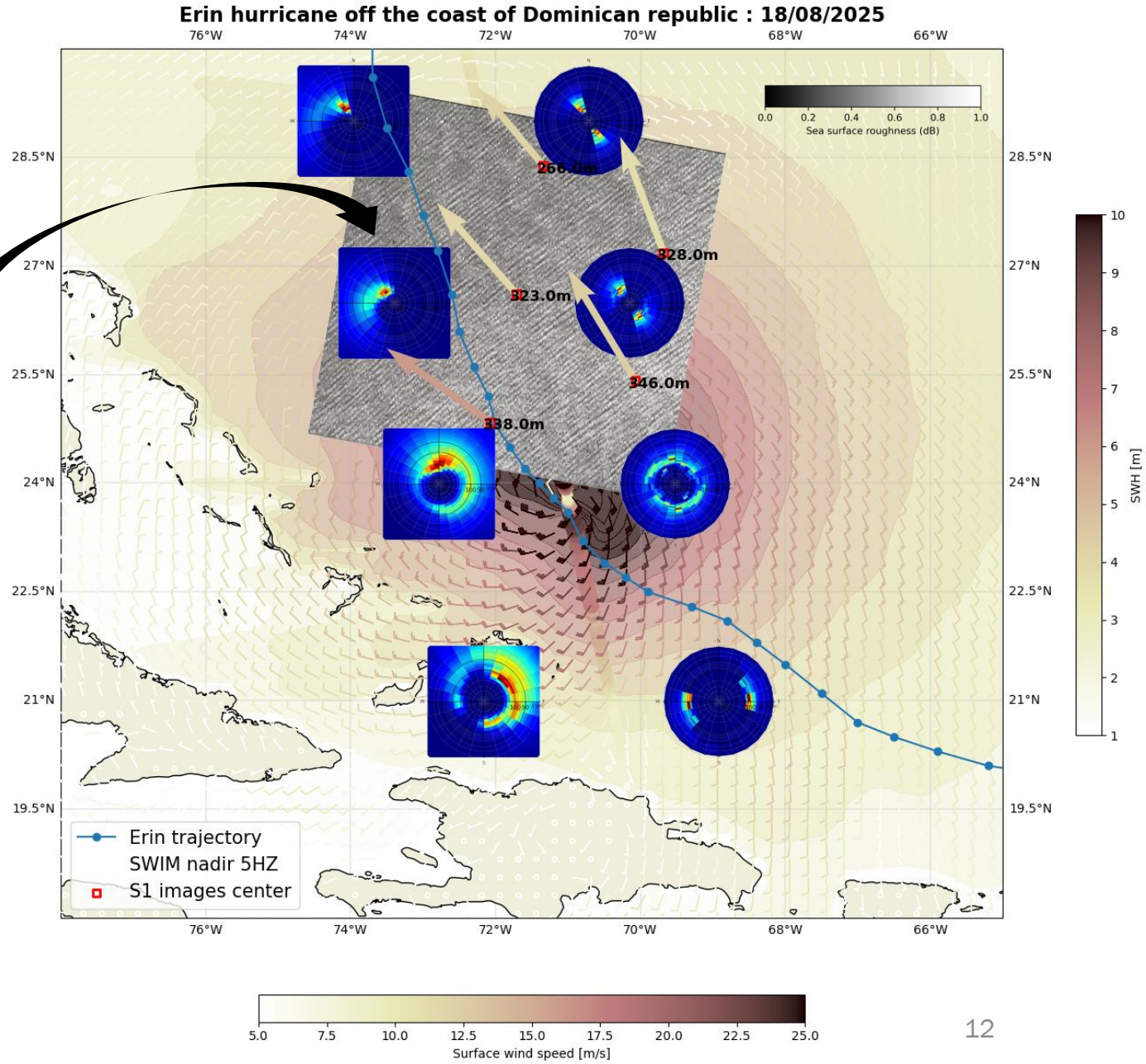


https://xwaves.ifremer.fr/

S1 WV Wave spectra can be derived from the images

The swell train generated by Erin is clearly visible on S1 images

S1 overpass around 11:00 ⟶ >10 h before SWIM.
This explains the small SWH offset between model, SWIM, and S1



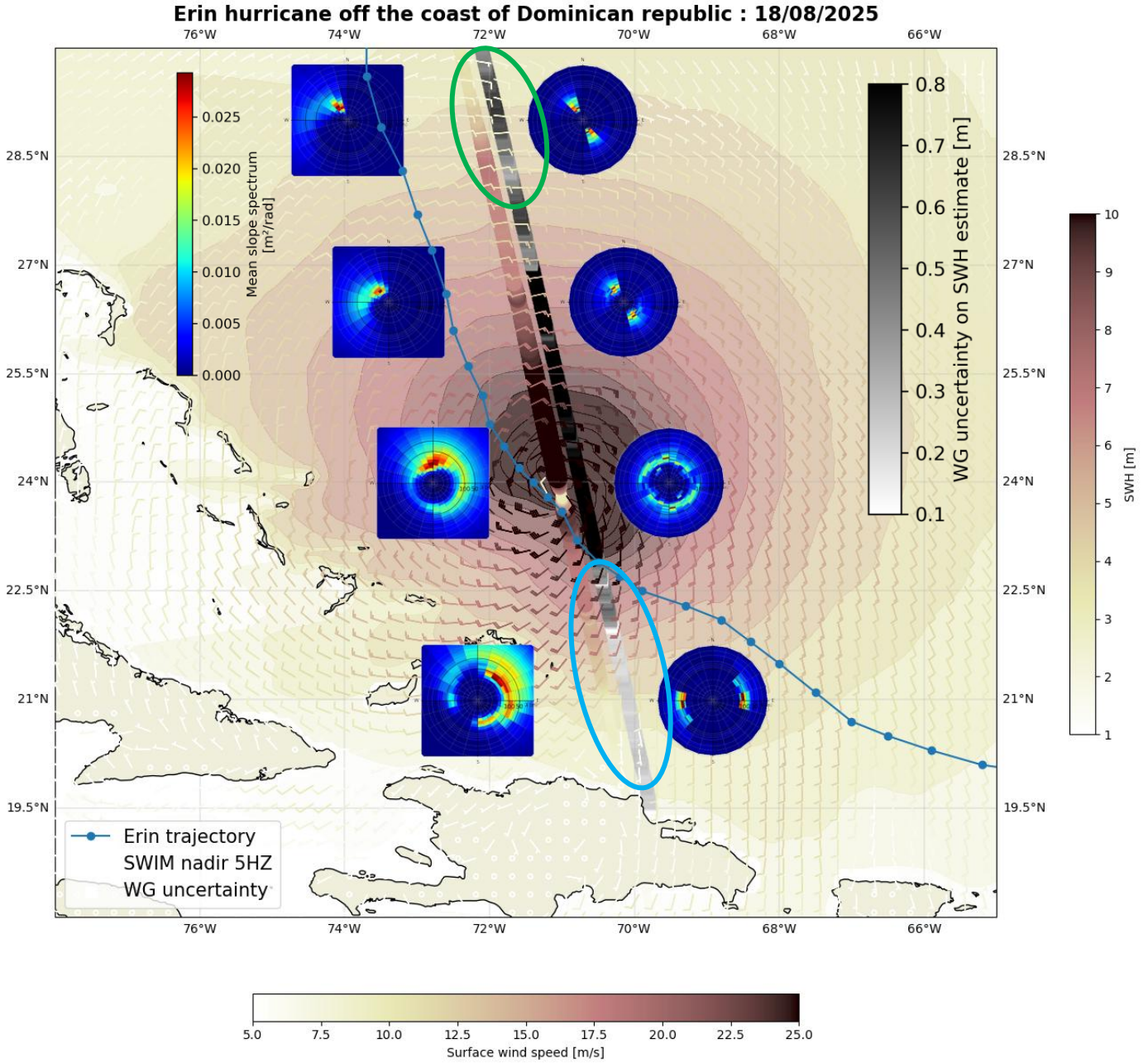
Bridge WG uncertainty & sea state

WG Uncertainty field estimation
From along-track variability of residual (raw vs. denoised 5Hz SWH)

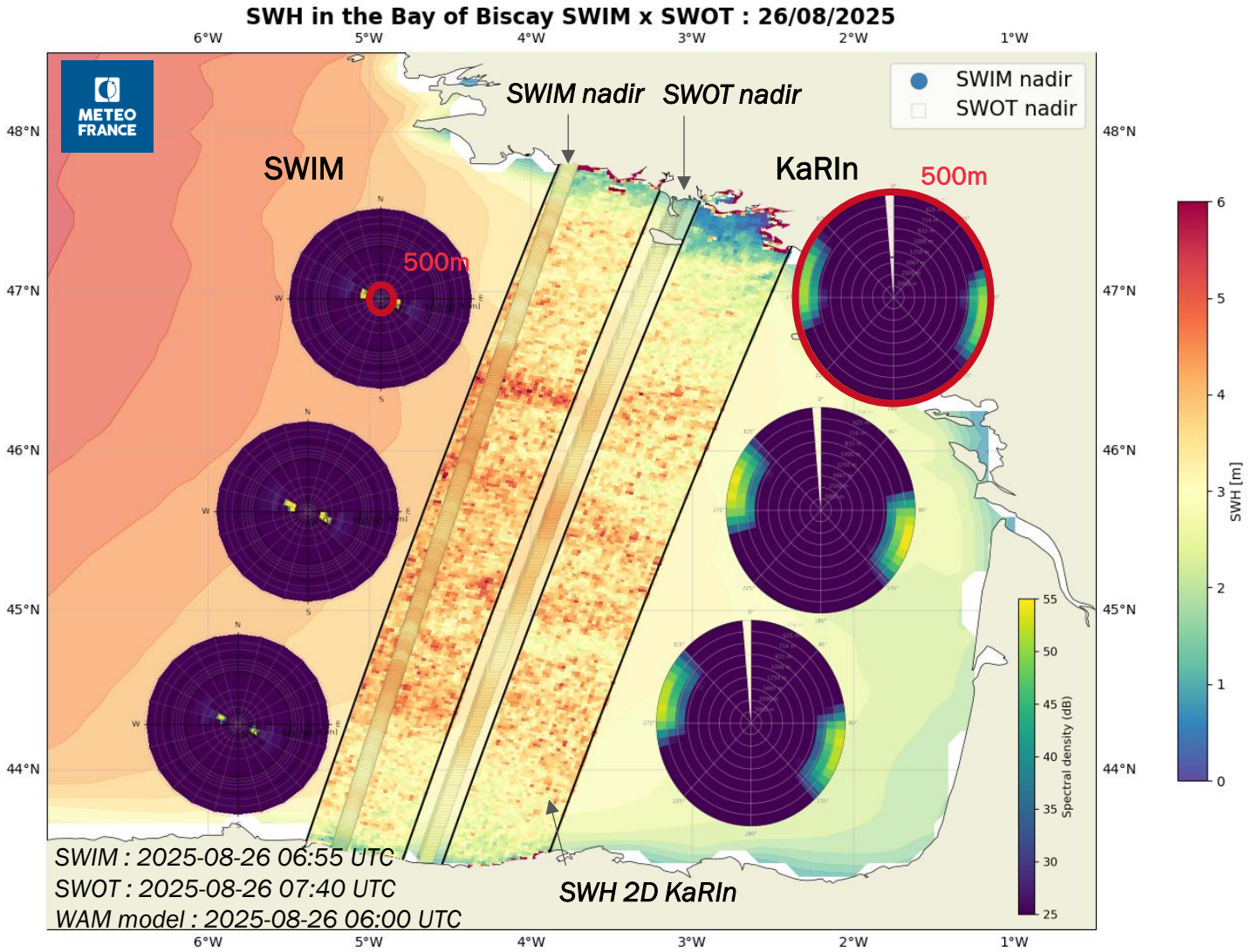
Main insights :
- Highlights presence of **wave groups**

Case study
Blue & Green areas → similar SWH
…but higher uncertainty in green vs. blue

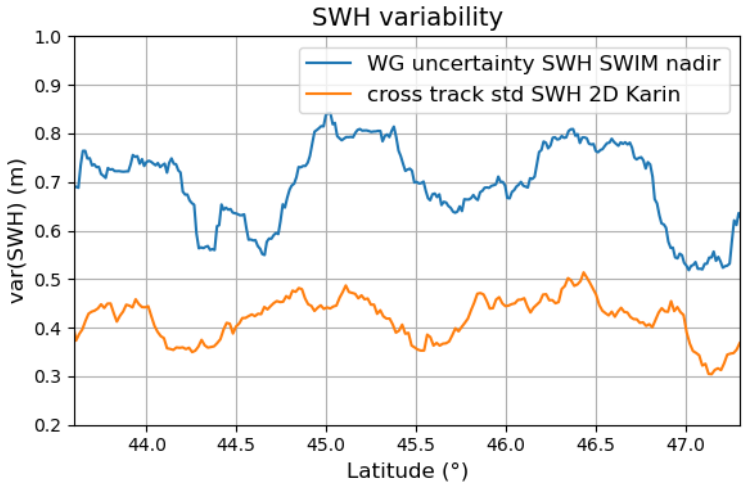
Blue = swell dominated area (strong Qkk)
Green = more complex wind driven sea



Observing Erin's cyclonic swell through SWOT–SWIM synergy



- 2D ocean wave spectra (1.5° latitude bins along track)
- A long swell ($\lambda_p \approx 500$ m) from the East is consistently observed by SWIM and the KaRIn_L3_LR_WW product derived from 250 m SSHA (Ardhuin et al., 2024)
- KaRIn SWH can also be impacted by WG (Villas Bôas et al., 2025)



KaRin cross track std seems correlated with SWIM along track wave groups uncertainty

Multi Sensor Synergy : Advancing sea state characterization

- **Complementarity across missions and observing systems** is essential for an improved description and understanding of **sea state, wave dynamics, and extreme events.**

- Nadir altimetry is **not only Hs** ! It can bring crucial **information about sea state**

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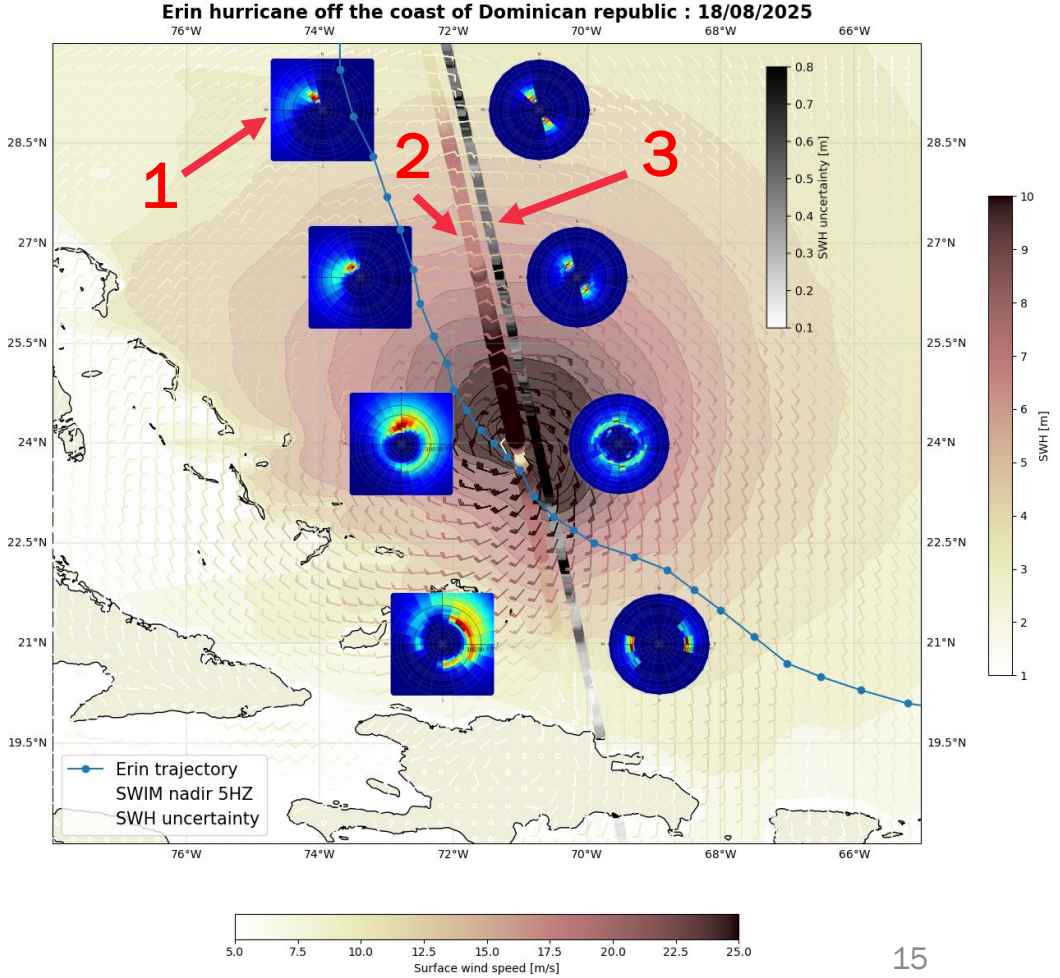

Thank you for your attention !

1 year of data available here : https://www.aviso.altimetry.fr/en/data/products/windwave-products/wave-experimental-products.html

Contact : anigou@groupcls.com