On the interest of CFOSAT/SWIM wave observations in complement to wind spaceborne observations

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CFOSAT : A China/France premiere for oceanography (launched in October 2018)

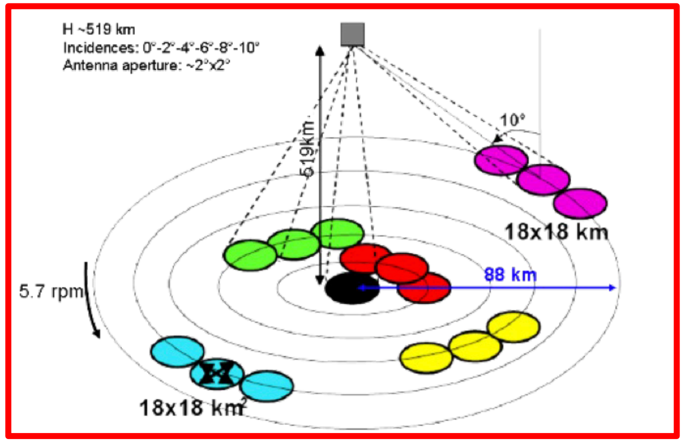
SCAT (Wind scatterometer)

- ✓Ku_band , scanning, fan beam
  - oLarge swath (~ 1000 km)
  - oRotating antenna: 3 rpm
- ✓Incidences between 26° and ~50°
- ✓Designed to measure
  - o σ0
  - o Ocean wind vectors

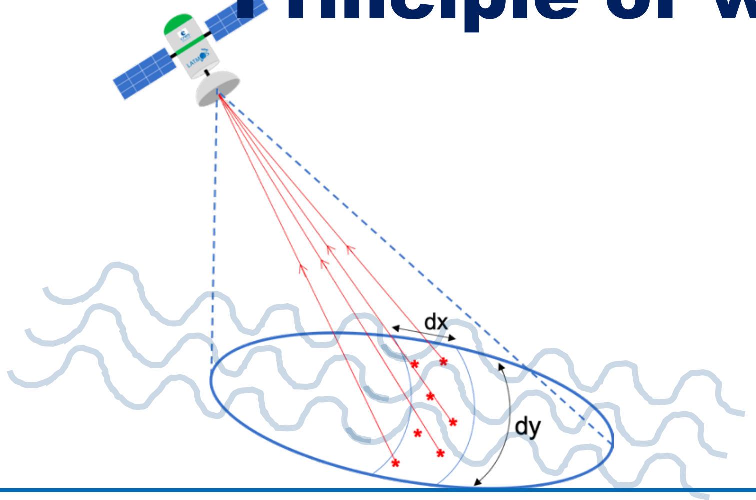
  (scale 25 km x 25 km)

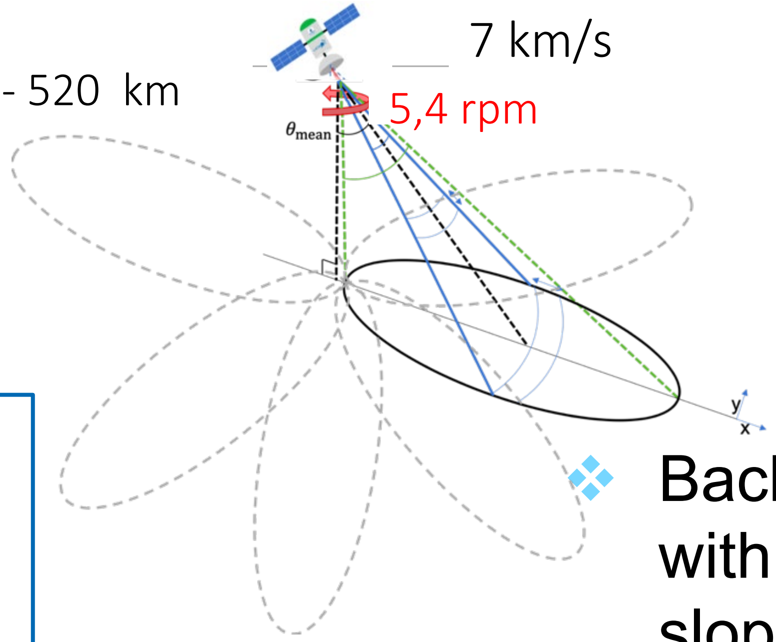
SWIM (Surface Wave investigation and Monitoring)

- ✓ Ku band real aperture radar,
- ✓ Sequential illumination with 6 incidence angles : 0 , 2°, 4°, 6°, 8°, 10°
- ✓ Rotating antenna (all azimuth direction acquisition): 5.6 rpm
- ✓ Designed to measure directional spectra of ocean waves



Principle of wave spectra measurements with SWIM





- Near-nadir incidence (≤ 10°) dominated by specular backscatter.Close to 10°incidence: almost insensitive to wind

- Large footprint in elevation and azimuth (~ 18 km) and high resolution along the look direction (~ 0.50 m, projected on the surface ~10 m)

- Backscatter modulated within the footprint by the slope of the long waves (maximum modulation maximum in the wave propagation direction)

- conical scanning in azimuth to sample all wave directions

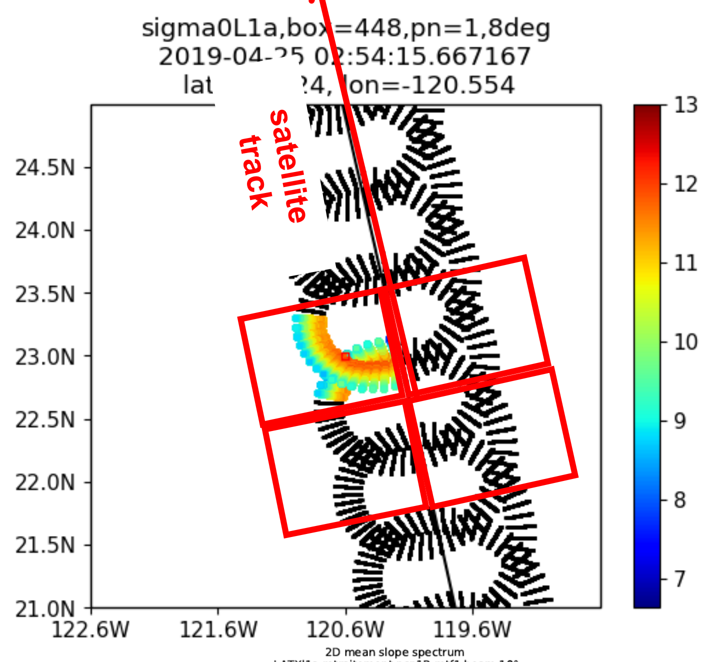
Main parameters estimated from the SWIM measurements

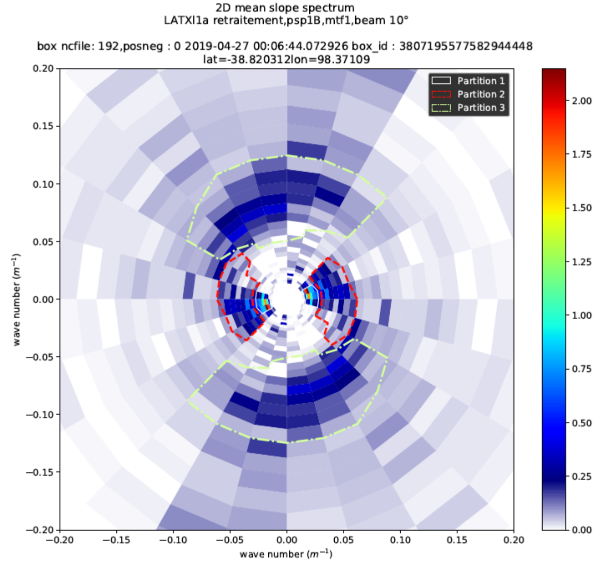
❖ **Significant wave height** (SWH) and wind speed from nadir beam, similarly to satellite altimeters:
@ 1 Hz and 5 Hz along-track

❖ In wave « cells » of about 70 km x 90 km, on each side of the nadir track, **directional spectra of the waves**

- ✓ wave height as a function of wavelengths (30 to 500 m) and direction (with 180° ambiguity)- Normalized in energy using the nadir beam SWH
- ✓ Associated wave parameters (dominant wavelength, dominant direction,…)

❖ **Normalized radar cross-sections** as a function of incidence (0-11°) and azimuth (180°), individual (L1a) or mean profiles (L2)





SWIM = complements SAR wave measurements

Pro for SWIM

- ✓ No velocity bunching effects , no azimuth cutoff => better detection of wind waves up to 30-50 m in wavelength
- ✓ Complementarity between nadir SWH and wave spectra
- ✓ Simultaneous wind field from the SCAT over same location + wind speed from nadir
- ✓ Continuous operation in wave mode

But ;

- ✓ Directional wave spectra at a scale of ~70 x 90 km (instead of 20 x 20 km for SAR)
- ✓ Currently more limited than SAR for **very** long swell detection (> 500 m in wavelength, but this may be improved in the near future)
- ✓ 180° ambiguity in direction not solved

Why and how SWIM can be useful to the IOVWST community ?

1- ocean parameter estimations

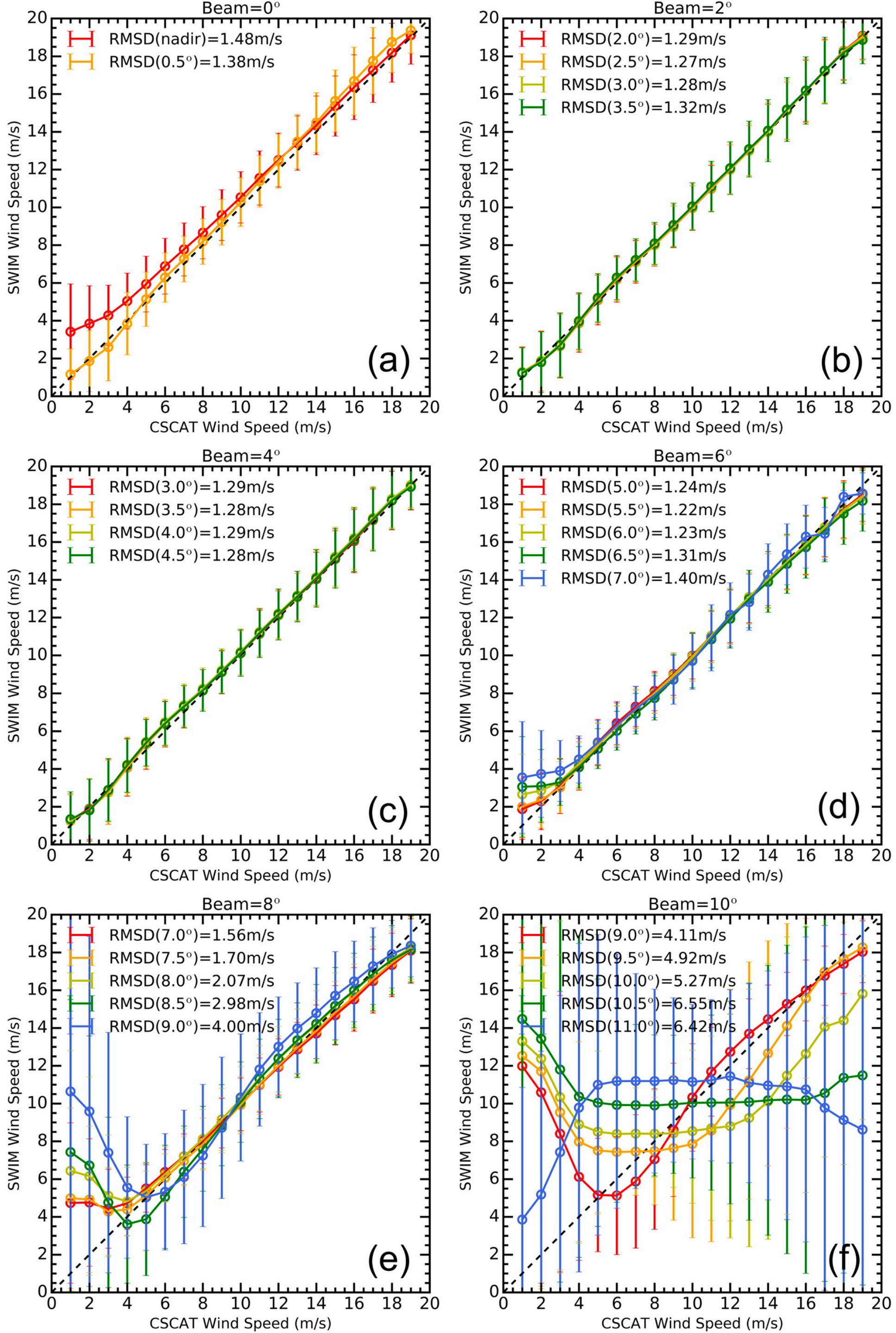
- ✓ Wind inversion from SCAT/microwave radiometers : taking into account possible effect of long waves ?

- ✓ sigma0 from SWIM sensitive to wind at low incidence up to about 8° , see illustration from **Ren Lin et al, 2021** => may help to better constrain the SCAT inversion model based on a GMF an increase swath of wind measurement, **see Alexey Mironov study**

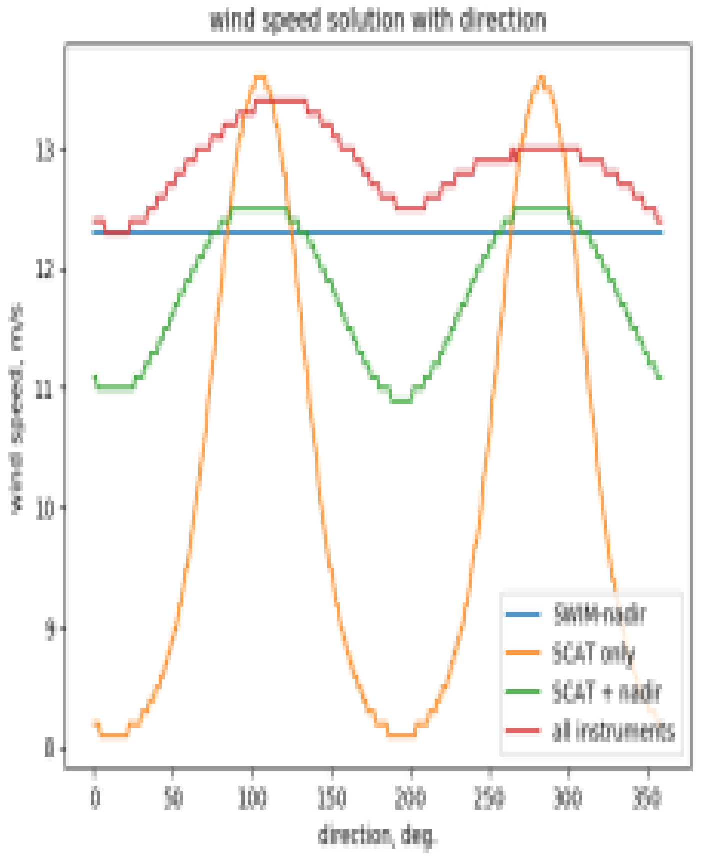
From Ren Lin et al, JGR2021

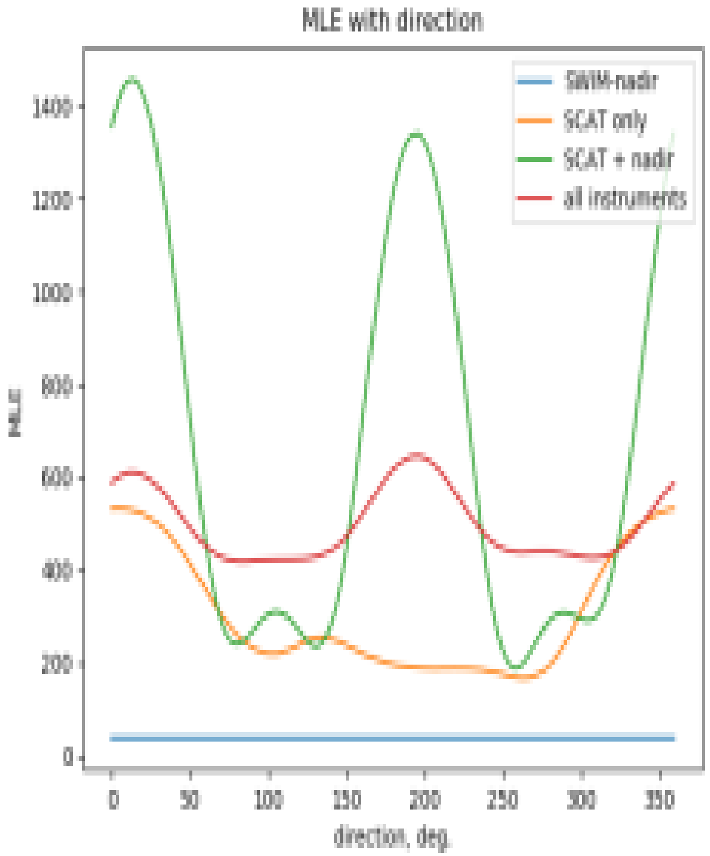
GMF developed for SWIM near nadir observations (0-10°)

Assessed by comparison with CSCAT winds



Proposed by Alexey Mironov: Using nadir σ0 to add constrain in the wind inversion algorithm





Modified MLE:

$$MLE_{SWIM/SCAT} = \frac{1}{N+1}\left(\sum_{i=1}^{N} \frac{\left(\sigma^0_{obs}(i) - \sigma^0_{GMF}(i)\right)^2}{K_{p,obs}(i)} + \frac{\left(\sigma^0_{SWIM} - \sigma^0_{GMF}\right)^2}{K_{SWIM}}\right).$$

directional MLE:
SCAT: 4 most probable solutions
SWIM + SCAT : MLE reduced to 2 most probable solutions

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- ✓ In rain conditions: wave spectra (and dominant direction, wavelength) not very much affected by rain (**see results from Xiaolu Zhao et al.**)

SWIM wave spectra not affected by rain in tropical cyclones

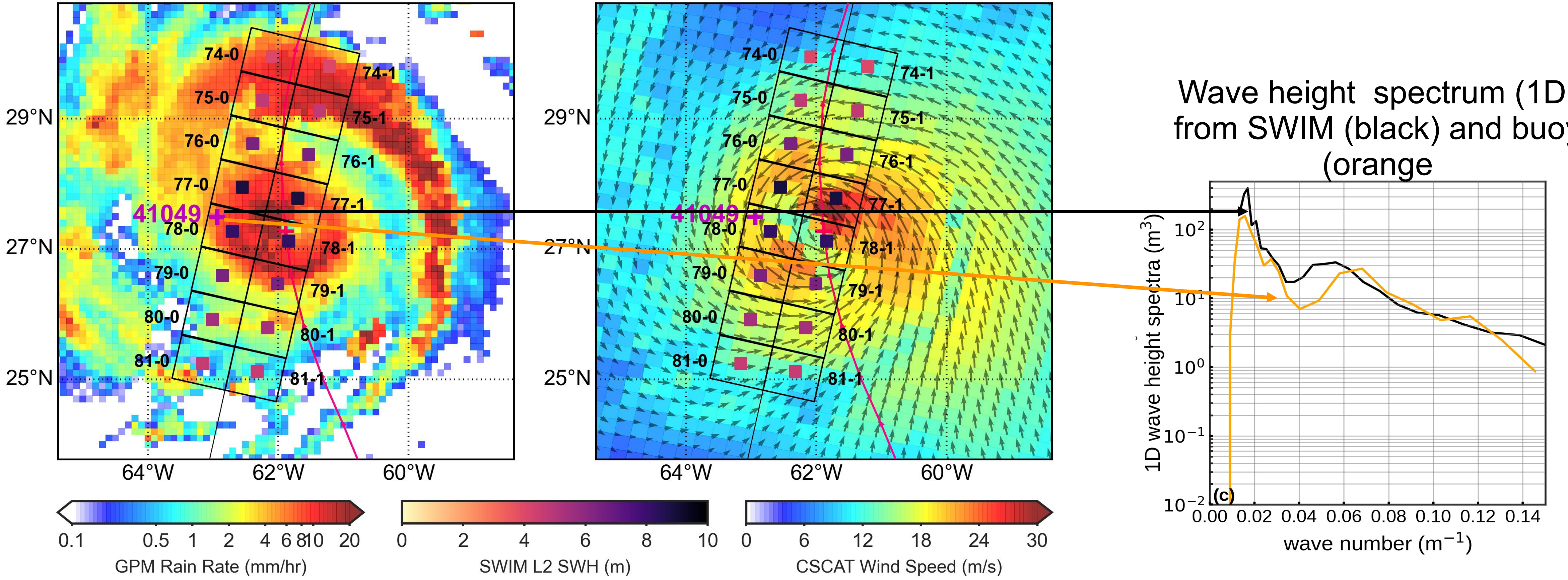
SAM hurricane (October 2021)

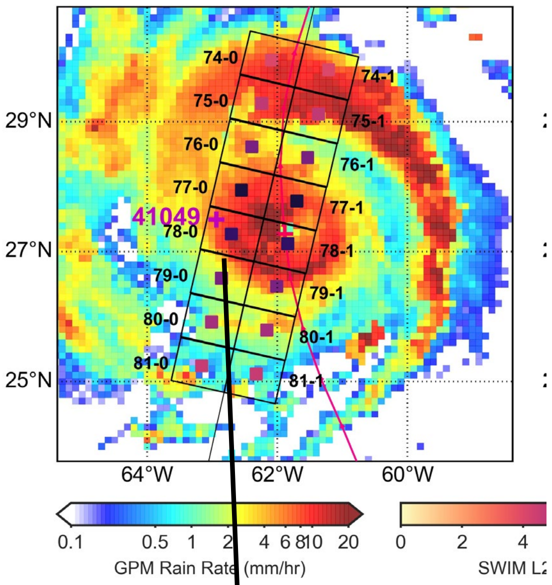
SWIM + CSCAT + GPM on 01 October 2021 ~ 11:30 UTC

Rain from GPM (11:00~11:30)

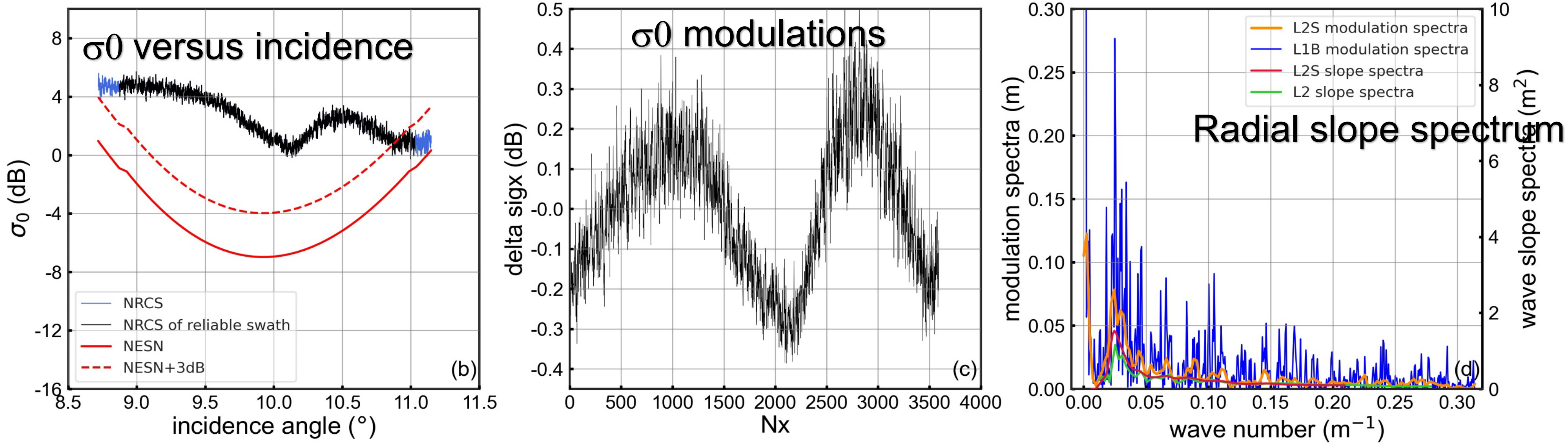
Wind from CSCAT (11:29:15~11:34:39)

Wave height spectrum (1D) from SWIM (black) and buoy (orange





Profiles in one direction within box 78-0 (R > 8 mm/h)



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1- ocean parameter estimations

- ✓ Wind inversion from SCAT/microwave radiometers : taking into account possible effect of long waves ?
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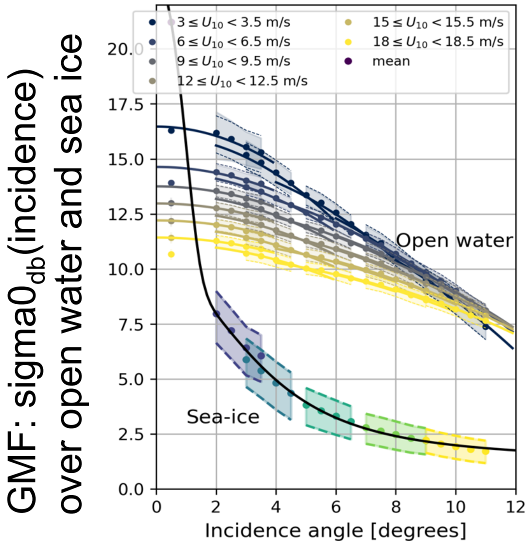
- ✓ In rain conditions: wave spectra (and dominant direction, wavelength) not very much affected by rain (**see results from Xiaolu Zhao et al.**)
- ✓ Direction of wind waves may help to solve the wind ambiguities ?
- ✓ Wind from SCAT + wave estimation => towards a better estimation of u* ??
- ✓ Sea ice detection: also possible with SWIM (**see hereafter from Peureux et al., ESS, 2022**)

Sea-ice product from CFOSAT

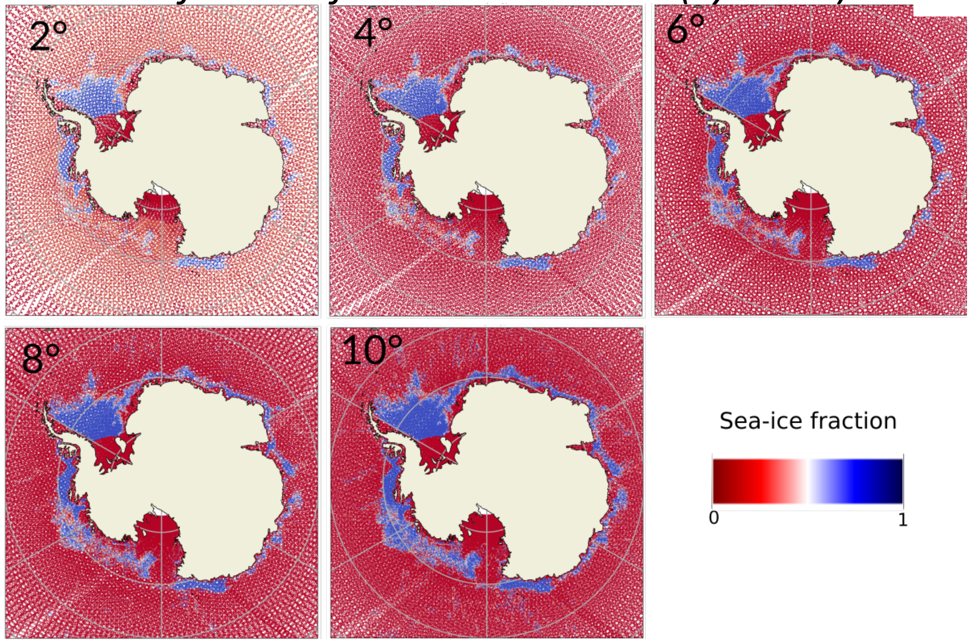
- **Sea-Ice detection algorithm from off-nadir SWIM (Ku-Band) observations**
  (Peureux et al. ESS, 2021)

- **Method:**
  - Geophysical Model Functions (GMF) : dependence of sigma0 with incidence, wind, sea-ice, established independently over open water and sea-ice areas
  - Bayesian scheme applied on the measured sigma0 => probability of sea-ice presence
  - Validated against sea- ice OSI-SAF products



=> Prototype sea-ice product (flag and sea-ice fraction) available for use (AVISO+ data server)

Sea-ice fraction from SWIM beams (cycle 63,



Why and how SWIM can be useful to the IOVWST community ?

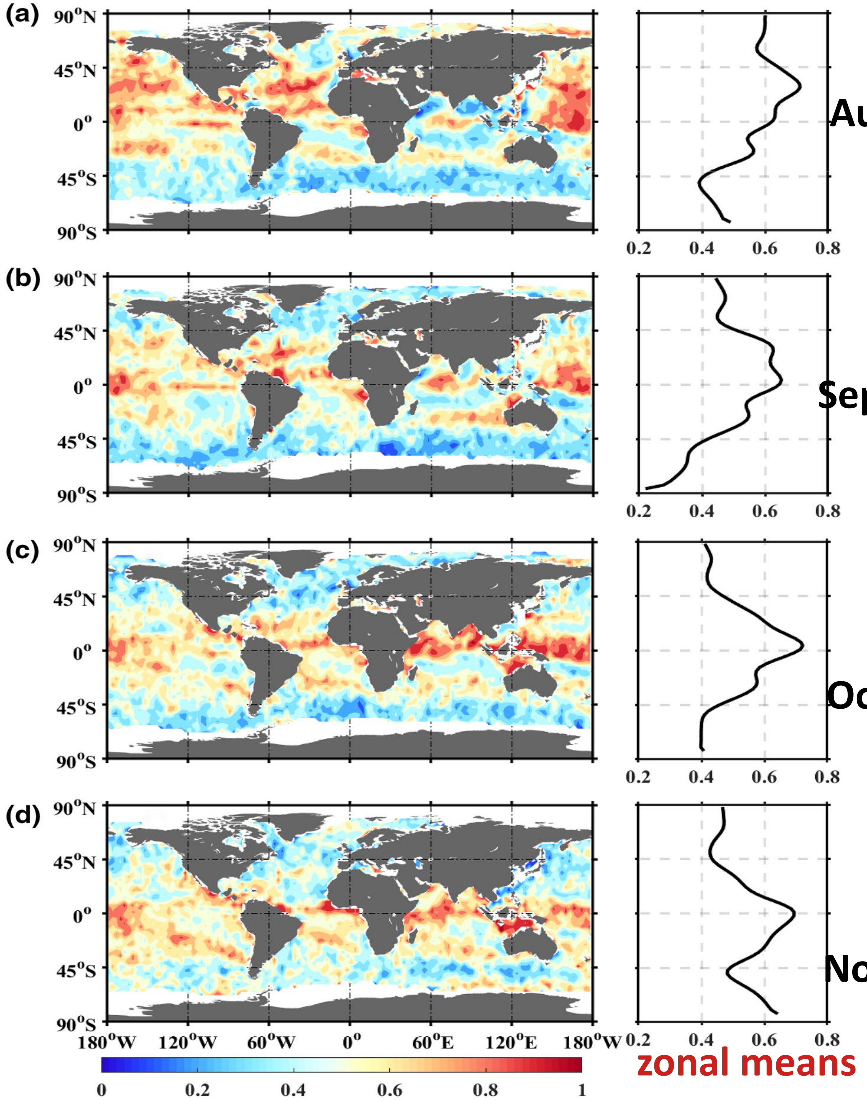
2- Coupled processes involving Wind, Wave, Surface current

- ✓ Estimation and analysis of wind stress modulated by waves => see hereafter, from **Chen et al, 2020**

Wave-induced stress over the global ocean

(Chen et al, J.Geophys. Res., 2020)

Monthly averaged values of the percentage of wave energy from swell



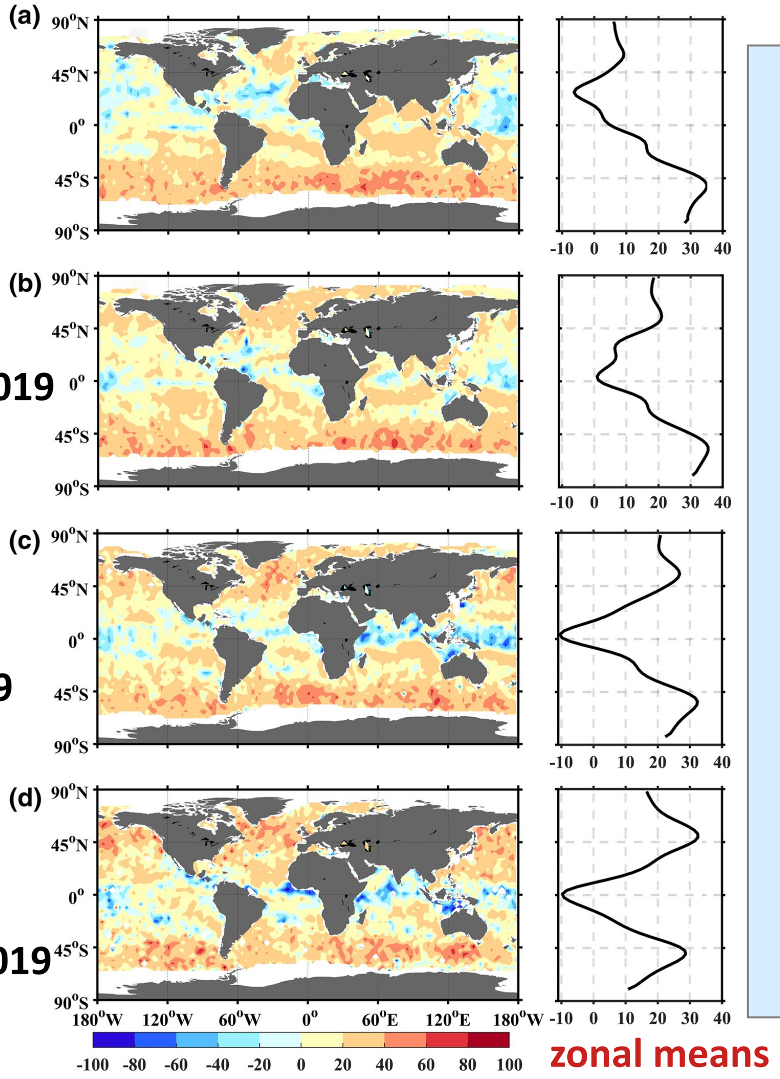
August 2019

September 2019

October 2019

November 2019

Monthly averaged values of wave contribution to the total stress (in %)



- ➔ Method :
  - ✓ combines observations of CSCAT and SWIM to separate swell and wind sea (left plot) + wave-induced stress estimated through empirical dependent on sea-state (wind sea or swell)- right plot
- ➔ Result
  - ✓ first evaluation from observations of seasonal and geographical variations of the influence of waves on the atmospheric stress at the air/sea interface

Why and how SWIM can be useful to the IOVWST community ?

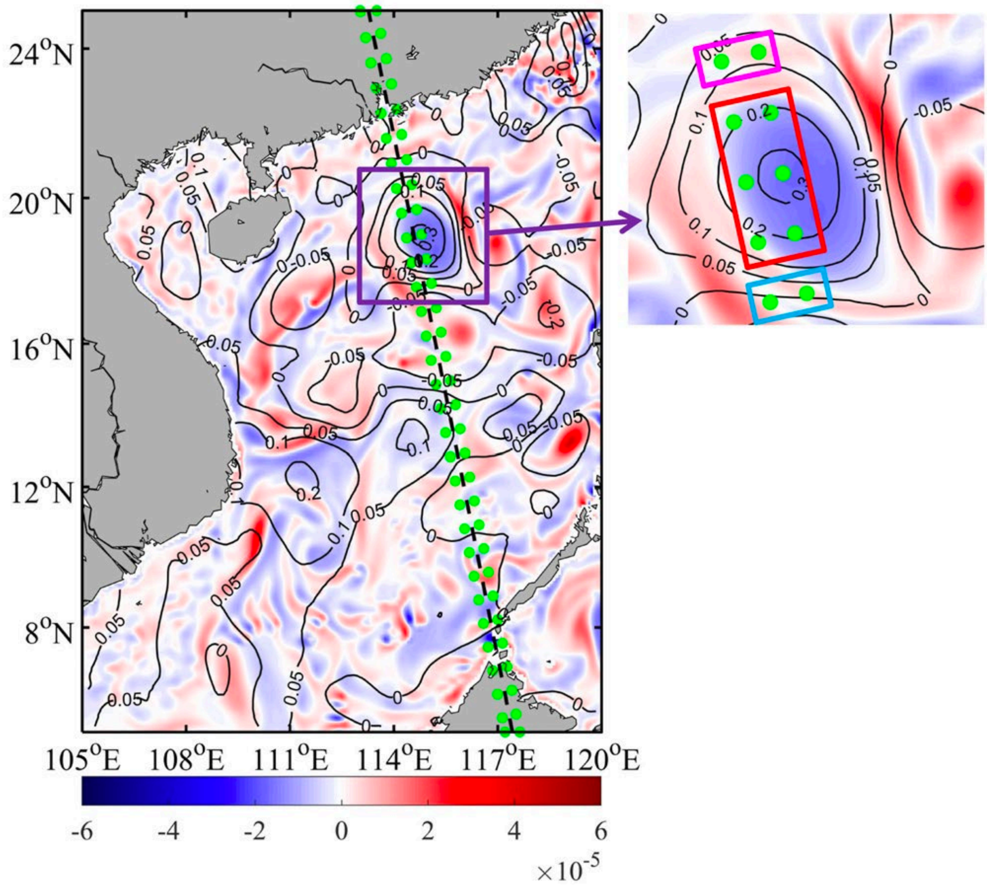
2- Coupled processes involving Wind, Wave, Surface current

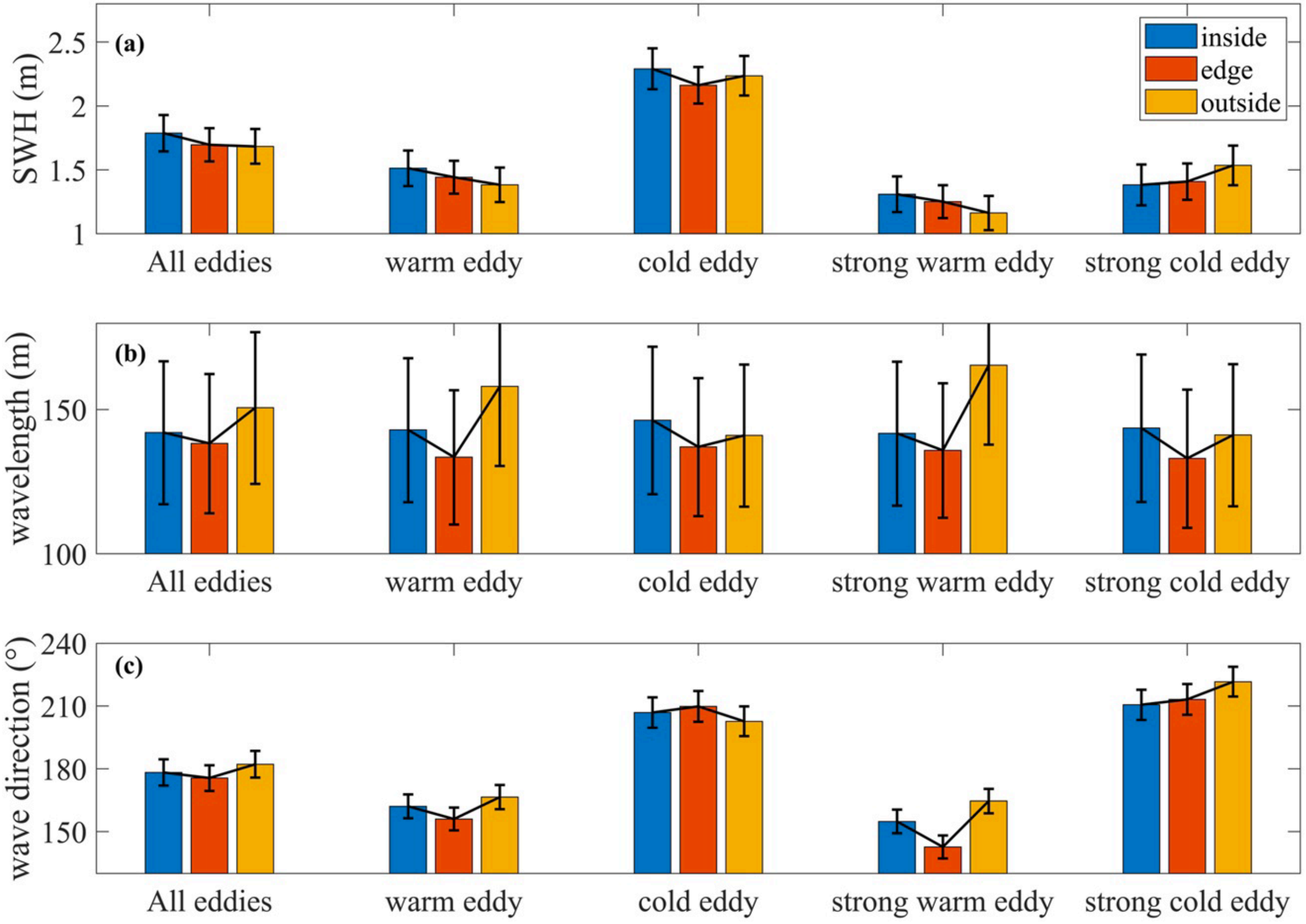
- ✓ Estimation and analysis of wind stress modulated by waves => see hereafter, from **Chen et al, 2020**

- ✓ Impact wind and wave response to eddies, need to separate effect of wind modulations du to current, from wave/current interactions (see hereafter from **Tan et al, 2022**)

Tan et al, JGr 2023: « Modulation Effects of Mesoscale Eddies on Sea Surface Wave Fields in the South China Sea Derived From a Wave Spectrometer Onboard the China-France Ocean Satellite »

SWIM data over 33 mesoscale eddies regions





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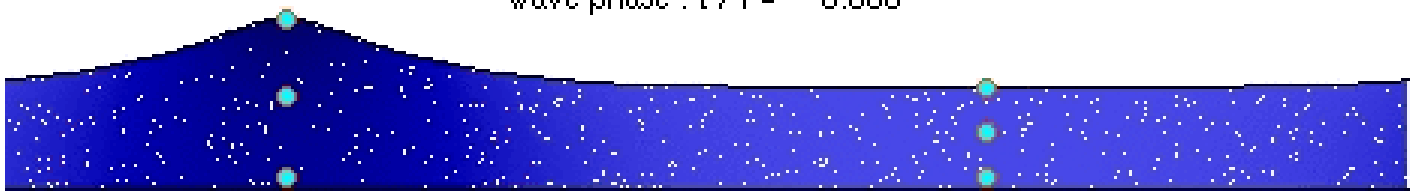
- ✓ Stokes drift may be estimated from SWIM (**see hereafter from Peureux et al.**). Stokes drift governed by intermediate and short waves.

Stokes drift estimation from SWIM

Stokes drift due to waves; one component of the surface current which impacts, processes in the lower atmosphere and upper ocean, and affects the Doppler measurement. Mainly givverned by the wind wave contributions.

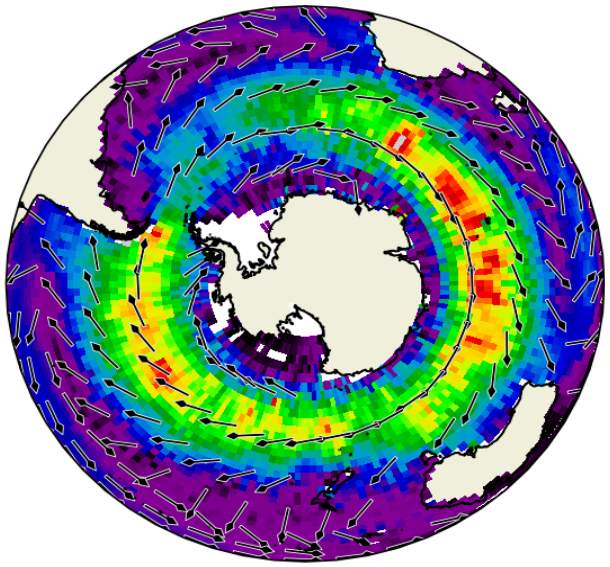
Stokes drift estimated from the SWIM wave spectra



$$u_{s,1d} = \int_0^{2\pi/30\,\mathrm{m}} dk\, V(k)$$

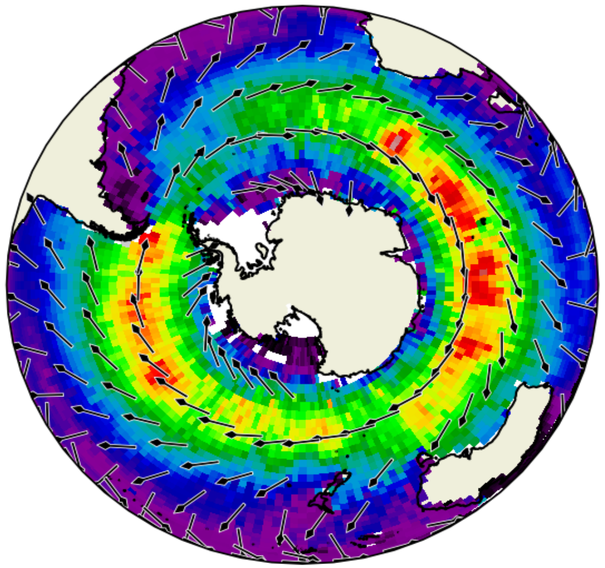
$$V(k) = 2\sqrt{g}k^{1.5}E(k)$$

SWIM (beam 10°)



MODEL

(MF-WAM) depth= 15m)



Stokes drift from SWIM, estimated over wavelengths larger than 30 m) => representative of Stokes drift at 15 m depth

By extrapolating the wave spectrum for waves shorter than 30m, surface Stokes drift can also be estimated

Why and how SWIM can be useful to the IOVWST community ?

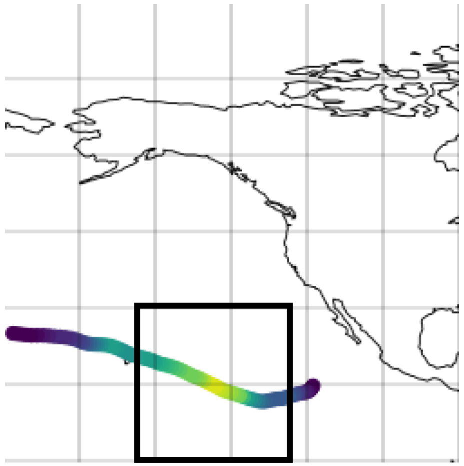
3- Wind and waves in extreme events

- ✓ Tropical cyclones and mid-latitude storms (**see e.g Le Merle et al, 2021 Yurovskaya et al, et, 2022, Cheshm Siyahi et al, 2023): ** characterization, devolopment of parametric models

- ✓ Extra-tropical storm characherization from wave measurements **(see study by Husson et al)**

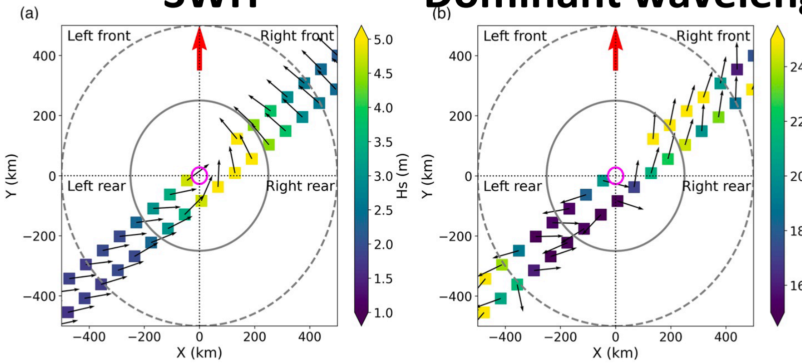
Wave spectra analysis in cyclone conditions
Le Merle et al. (JGR 2022)

Example of Hurricane Douglas on july 2020



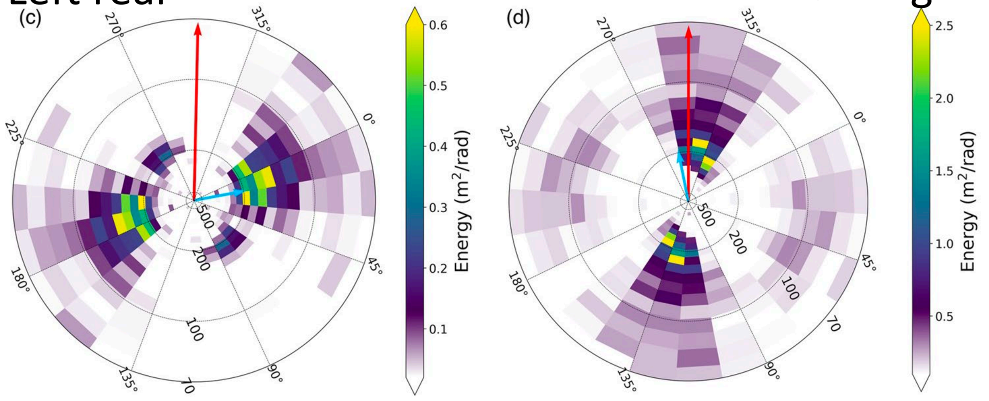
In the reference frame of the cyclone

SWH | Dominant wavelength



SWIM directional spectra

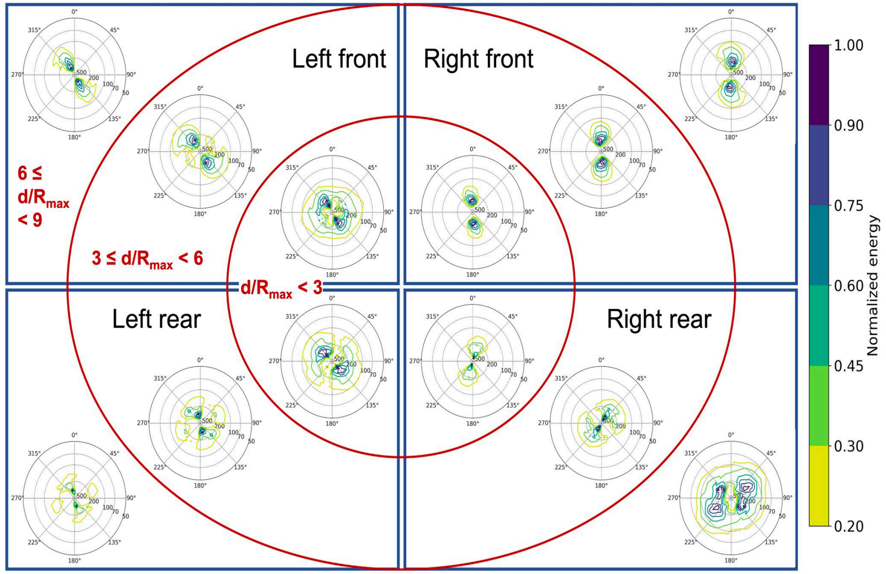
Left rear | Front right



Detailed analysis based on SWIM spectra in 64 cyclones of the Northern Hemisphere (May 2019-Septembre 2022)

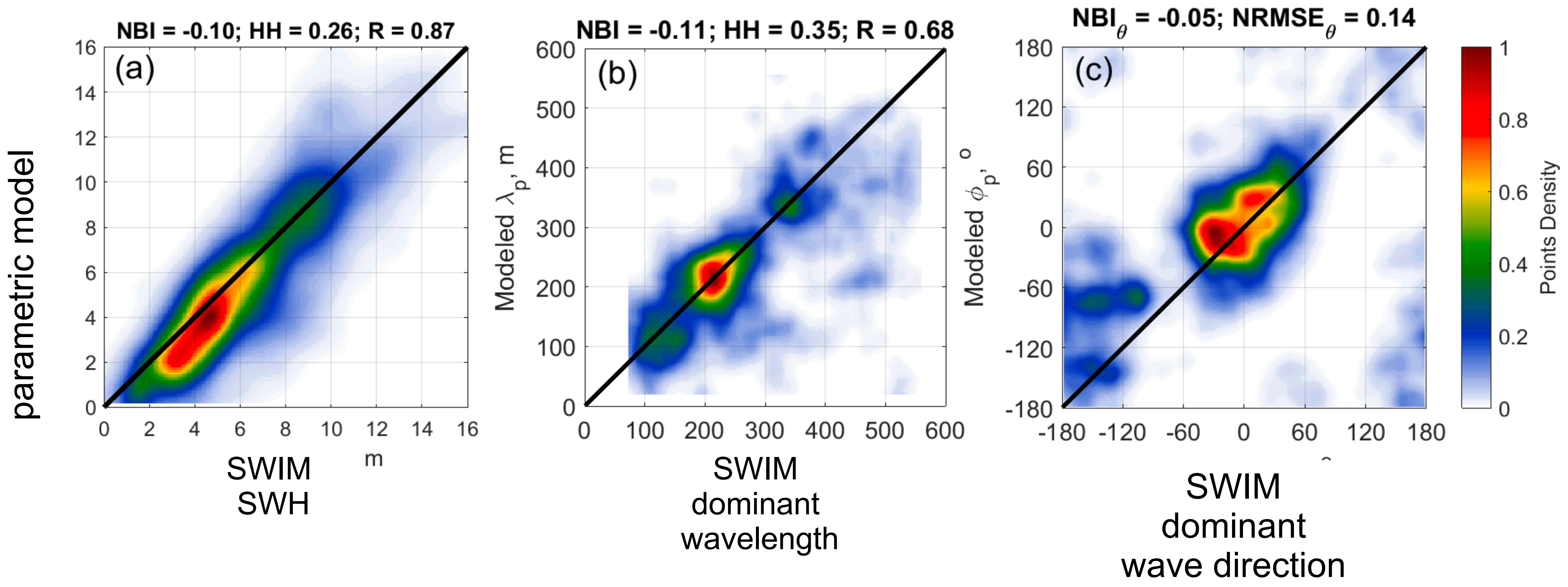
- ➔ Mono-modal only in the front-right quadrant
- ➔ Complex spectra in other quadrants
- ➔ Dominant waves never aligned with wind
- ➔ 1D spectra close to Jonwsap spectral shape only in the front right sector or very close to the center

Mean spectra for cyclones of moderate speed



Cheshm Siyahi et al, Remote Sensing 2023

Establishment and validation (below) of a wave prediction parametric model (along wave rays) applicable for intense and rapidly moving storms



Tracking swell from storm sources observed By SWIM (Guitton & Collard, ODL)

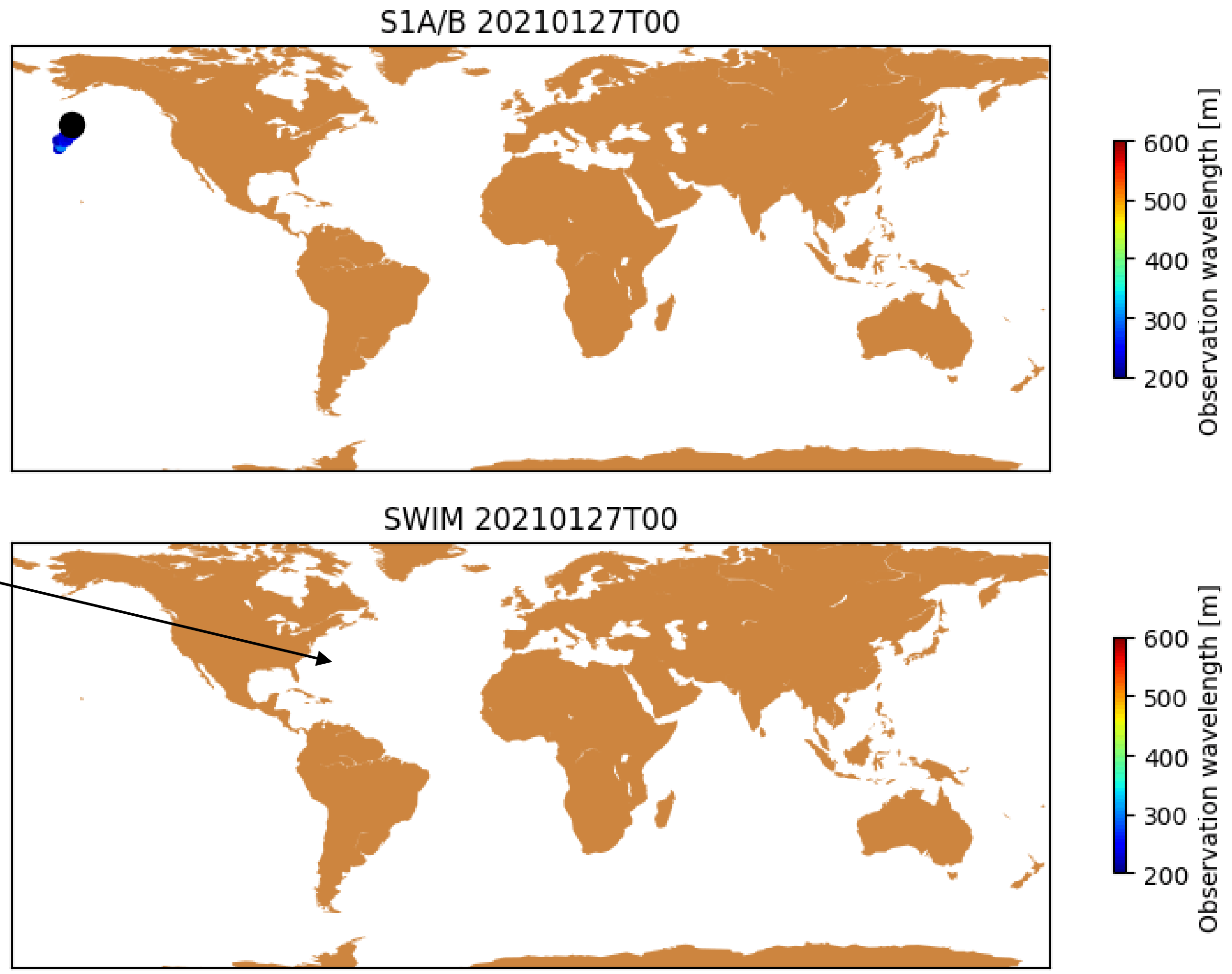
Swell tracking generating from storms sources observed by SWIM and generated by a propagation model

CFOSAT ensures swell tracking in North-East Atlantic, not covered By Sentinel-1.
Complementarity to Sentinel-1

S1A&1B

SWIM

Fireworks from L2S products (Ifremer)



4- Assimilation of wave spectra in wave models

=> impacts not only SWH, but also direction and dominant period, and on the whole wave spectrum

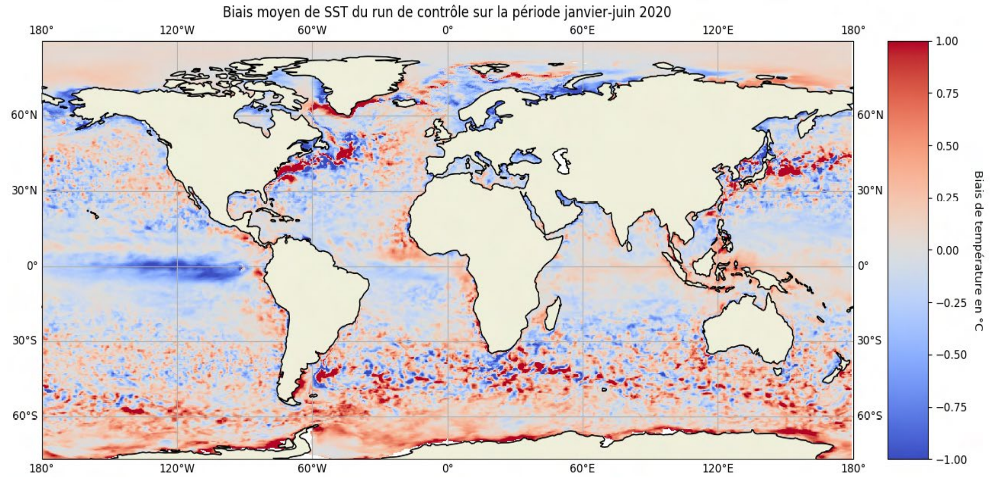
=> impacts the wave age, may impact wind correction in the coupled wave/atmospheric model (e.g; ECMWF, MFWAM,..)

Impacts Stokes drift => impact the ocean surface responses (SST, surface current, mixed depth layer) in the coupled wave/ocean models

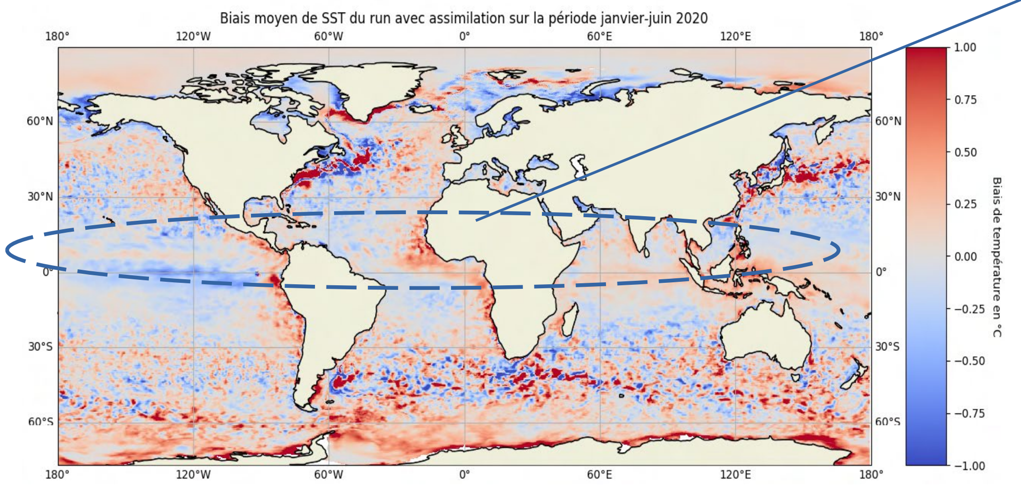
See **illustrations by Lotfi Aouf here after**

Improved wave/ocean coupling : thanks to DA of CFOSAT

Bias of SST without wave coupling

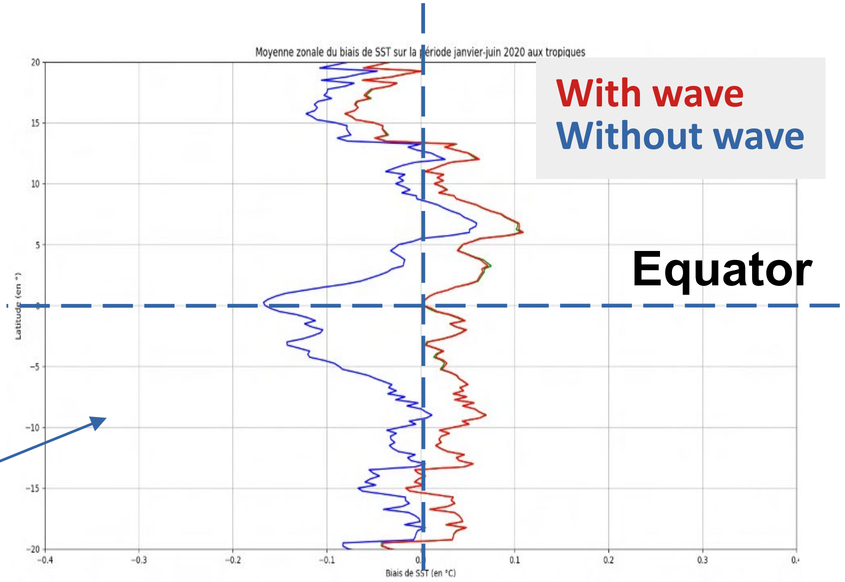


Bias of SST with wave coupling (DA CFOSAT)



Validation with SST from L4 OSTIA January-June 2020

Zonal mean of SST in the tropics (20°S-20°N)



Significant reduction of SST bias in the Tropics and in strong currents ocean regions

In summary

- CFOSAT provides not only wind from CSCAT but also useful wave information
- IOVWST community should be interested in this information !
- Easy access to CFOSAT data (AVISO website): https://www.aviso.altimetry.fr
  - SWIM Near-real time wave products (complete and simplified)
  - SWIM Reprocessed wave products (OP06)
  - SWIM Ice product
  - Stokes drift product coming soon
  - SCAT products (until antenna stop event)

- Systematic distribution of L2 SWIM products to EU Copernicus Marine Service (CMEMS)

- Operational assimilation of SWIM products in Météo-France wave prediction model (model fields also provided to CMEMS)

- Coming soon : distribution by WMO in NRT

Any questions?
Email to
cedric.tourain@cnes.fr,
lotfi.aouf@meteo.fr or
daniele.hauser@latmos.ipsl.fr

SWIM-SAR complementarity : comparison with WAM

Large Swells, wind waves

CFOSAT is better capturing variability in SO and mid lats than S1

Classe of wavelength (200m<wl<500m)

ween 200 and 500m,

eas with swell

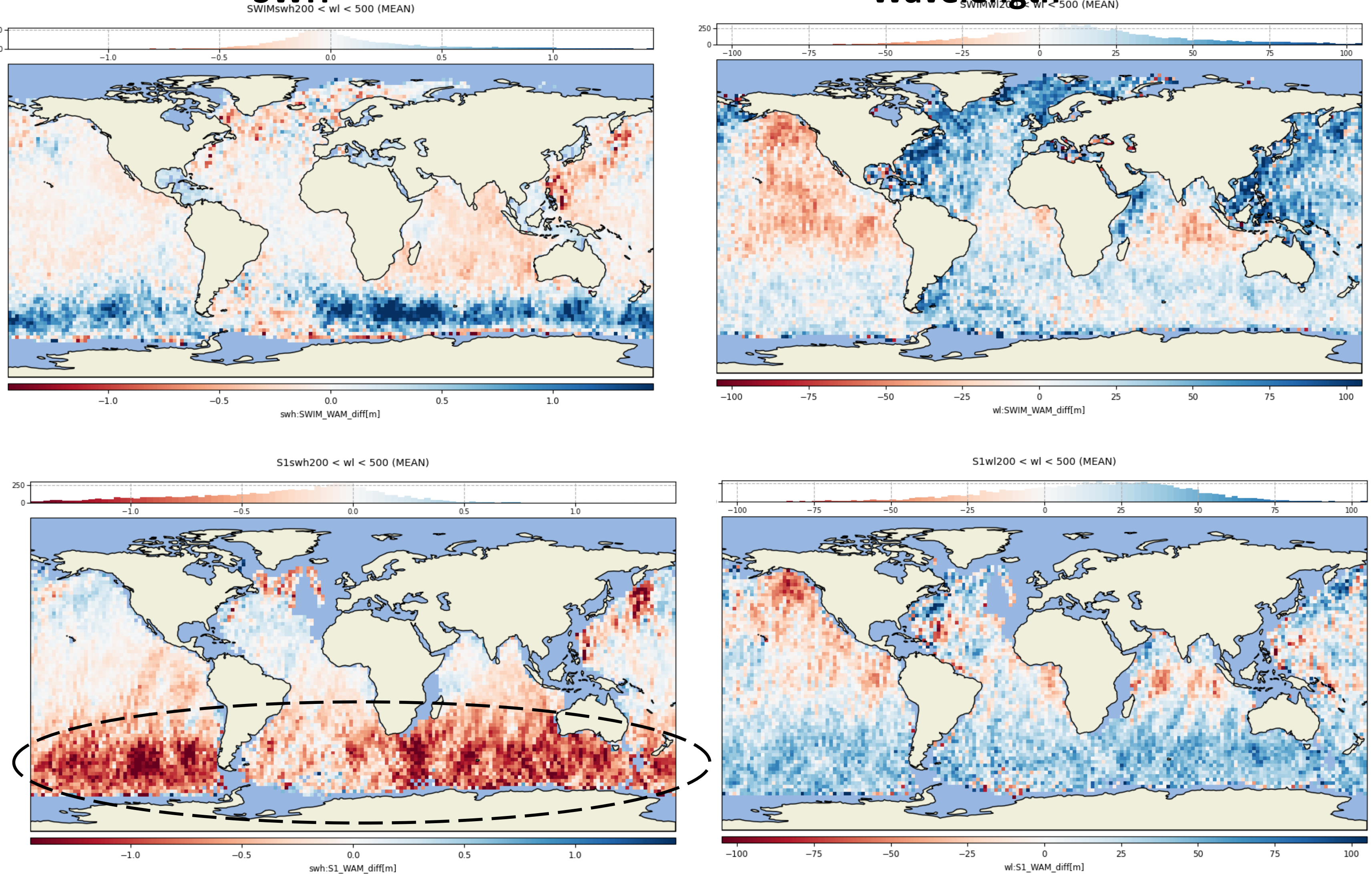
Occurrence w.r.t WAM : 10%-60%

SWH

Wavelength

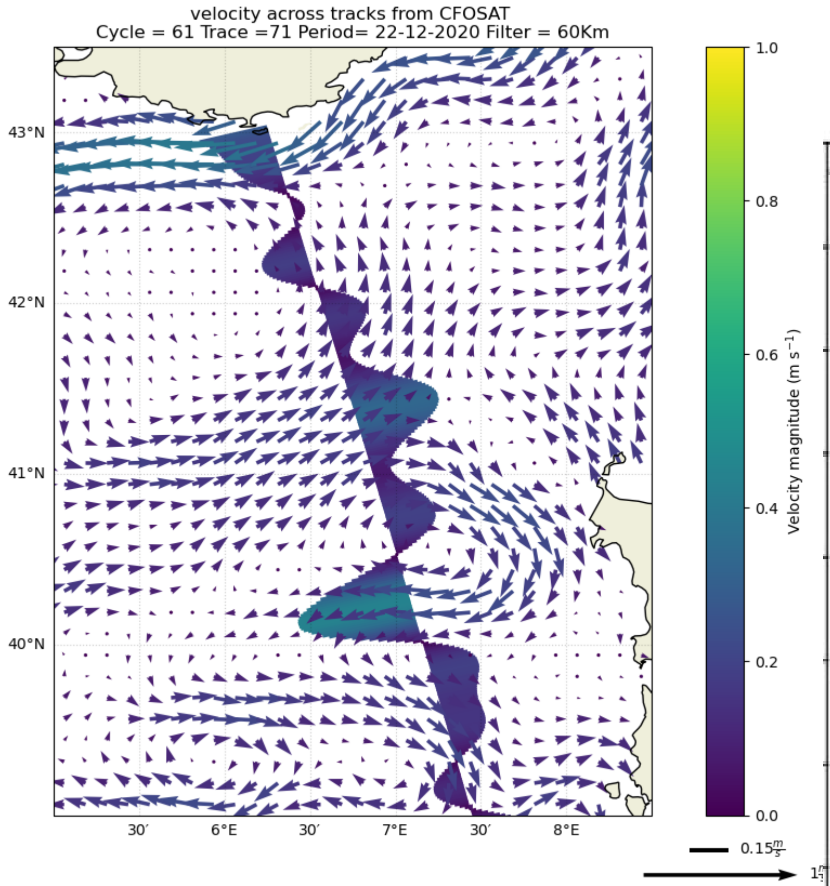
SWIM - WAM

S1 - WAM

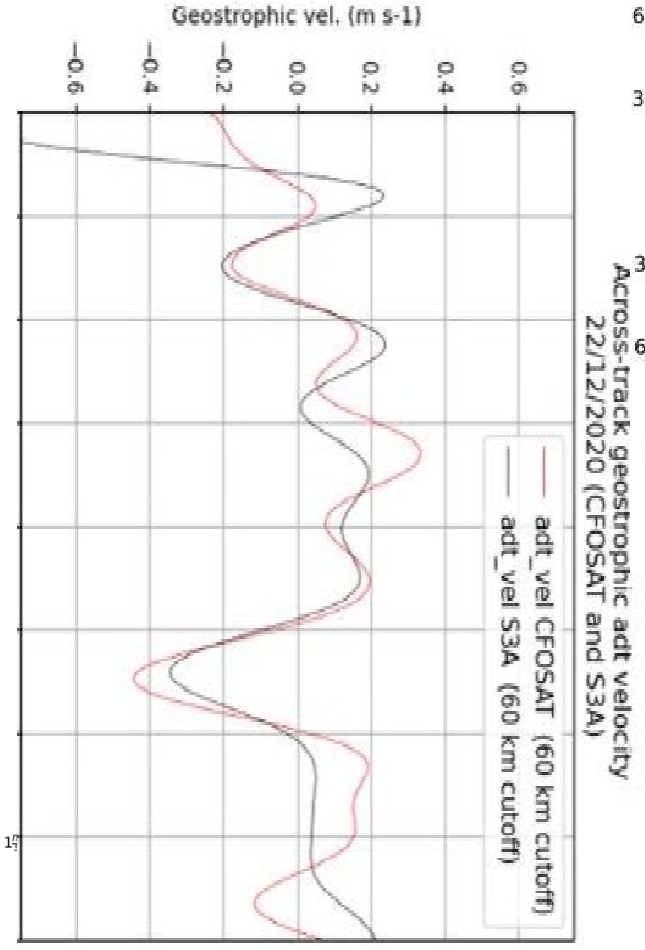


Contribution of CFOSAT in altimetric SLA multi-missions Products : geostrophic velocity (Faugere et al. OSTST 2022)

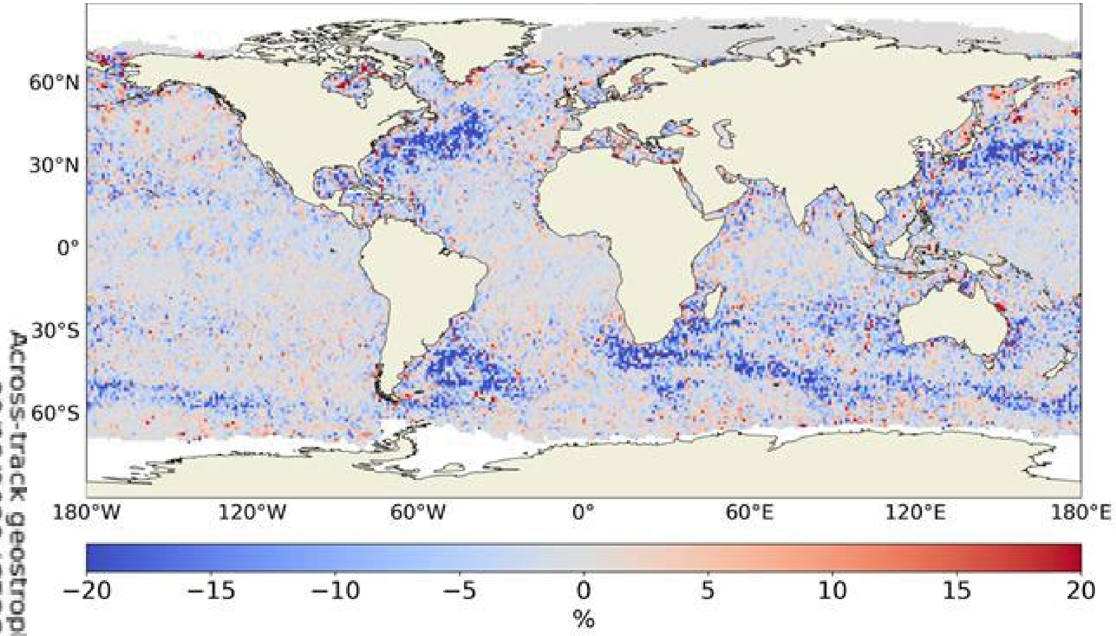
Geostrophic currents from CFOSAT at Porquerolles In Mediterranean Sea



CFOSAT S3A



Error reduction (%) of multi-missions including CFOSAT : April-0ctober 2021. comparison with independent altimetric data



Blue color indicates improved mesoscale description