Ocean waves from space: what is new with the CFOSAT mission ?"

Danièle HAUSER, LATMOS-IPSL (CNRS, Univ. Versaillles St Quentin, Univ. Paris Saclay)- PI CFOSAT

Lotfi Aouf (Meteo-France) - Co-PI CFOSAT

Cedric Tourain (CNES) – CNES mission scientist

Contributions from A. Dalphinet, G. Marechal, F, Ardhuin , C. Peureux, …

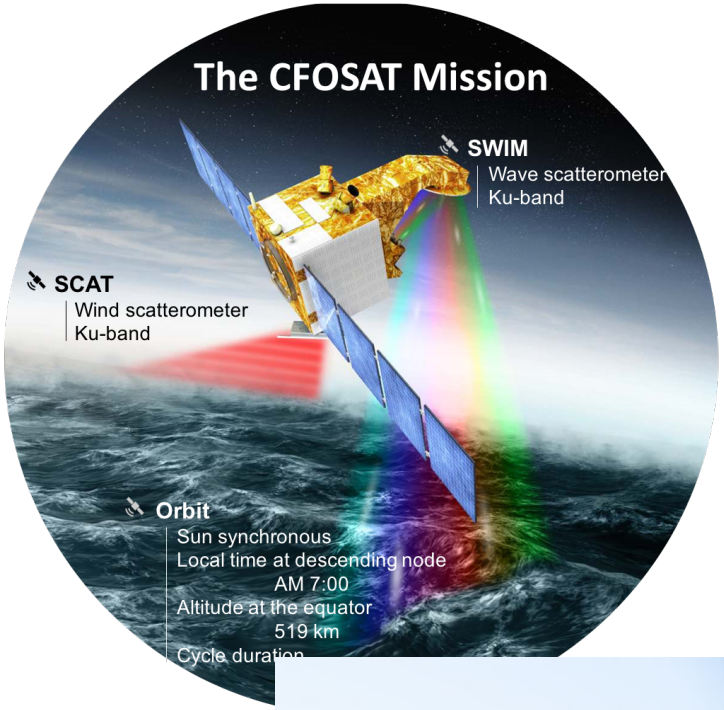
Sea-State CCI User meeting, March 2021

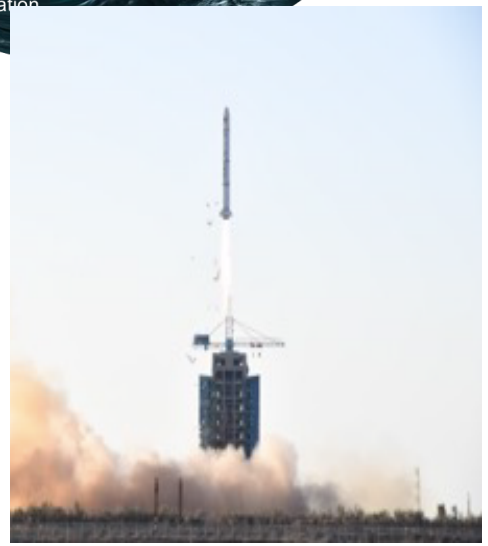
Outline

- Specificity, originality of CFOSAT
- First results
- Perspectives

Specificity, originality of CFOSAT

- **Two instruments on the same platform** for measuring wind and waves simultaneously
- **Two new instrumental concepts**
  - ✓ CSCAT: a wind scatterometer with a fan beam antenna at medium incidence (20-50°) AND scanning over 360° **=> first time in orbit for this configuration**
  - ✓ SWIM: a « wave scatterometer » + altimeter mode looking at low incidence (0-10°) and scanning over 360° => directional wave spectra + wind speed and significant wave height (from altimeter mode) – **Concept entirely new for space observations**
- **First scientific French-Chinese cooperation in the space domain**
- Polar Orbit, ~ 520 km, sun-synchronous, 13-day orbital cycle
- Carried by a Chinese platform
- Launched from China on October 29th, 2018

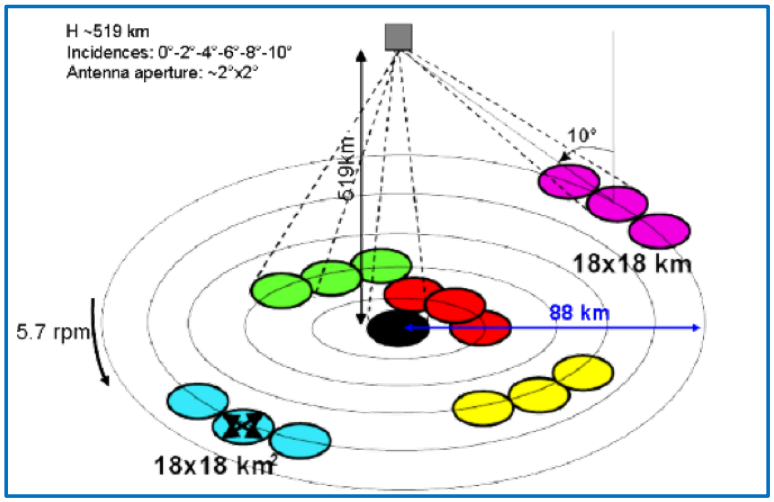




Payload: two radar instruments

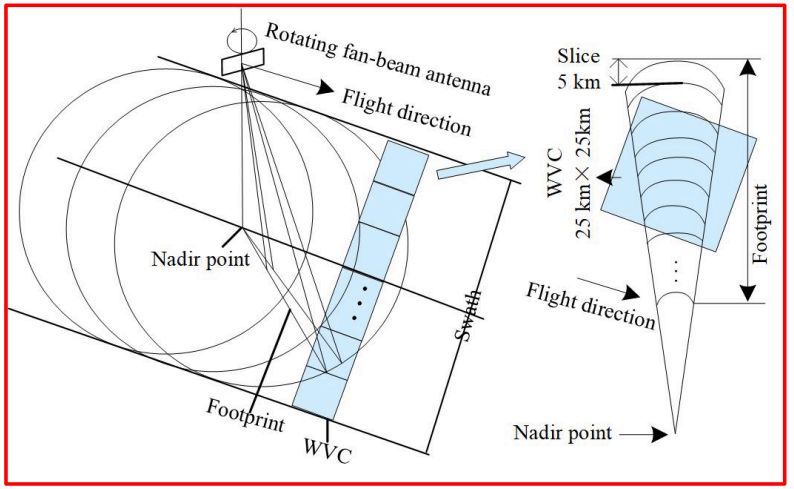
❖**SWIM** (Surface Waves Investigation and Monitoring) designed and manufacture by France (CNES/Thales Alenia Space)

- ✓ Ku-Band Radar (~13.5 GHz)
- ✓ nadir (like standard altimeters)
- ✓ off-nadir illumination (from 2° to 10°)
- ✓ antenna beams scan in azimuth and illuminate successively the surface
- ✓ beam spot at the surface ~18 km in diameter
- ✓ full scan ~90 km in radius



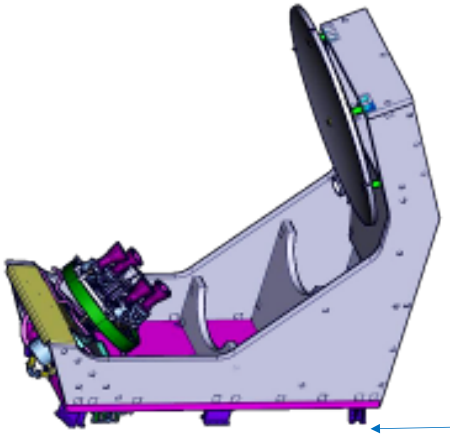
❖**CSCAT** (Cfosat SCATterometer) designed and manufactured by China

- ✓ Ku-Band Radar (~13.5 GHz)
- ✓ Incidence 28°to 51° , scanning in azimuth
- ✓ Wide swath at the surface (~1000 km)

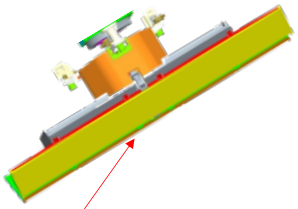


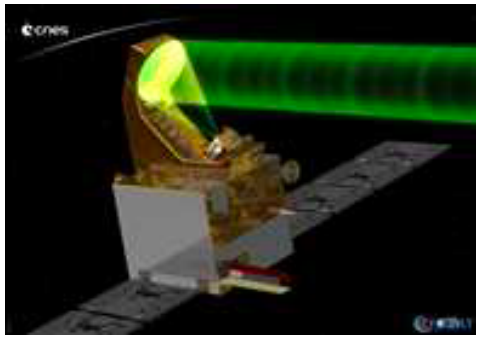
SWIM antenna system

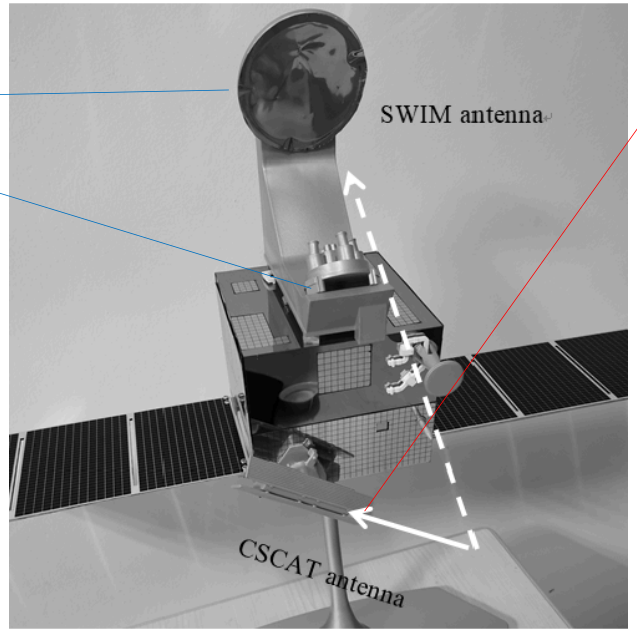
SCAT antenna system

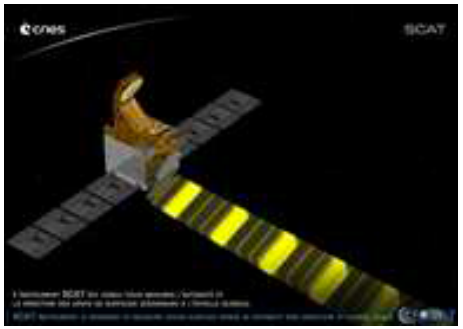


2 m



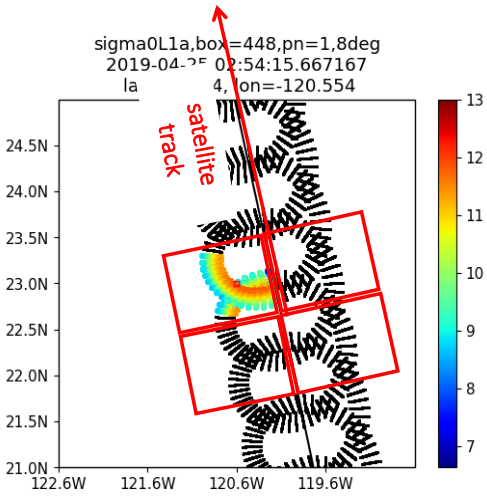




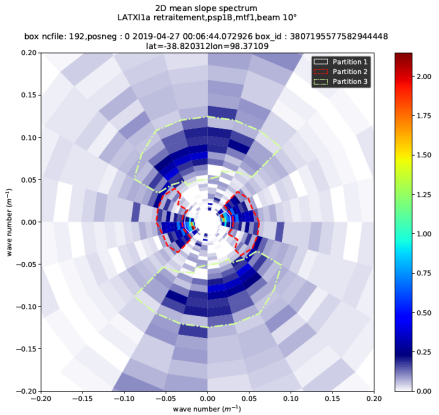


Main parameters estimated from the **SWIM** measurements

- Significant wave heights and wind speed along track, from nadir beam (similarly to other missions in satellite altimetry)



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

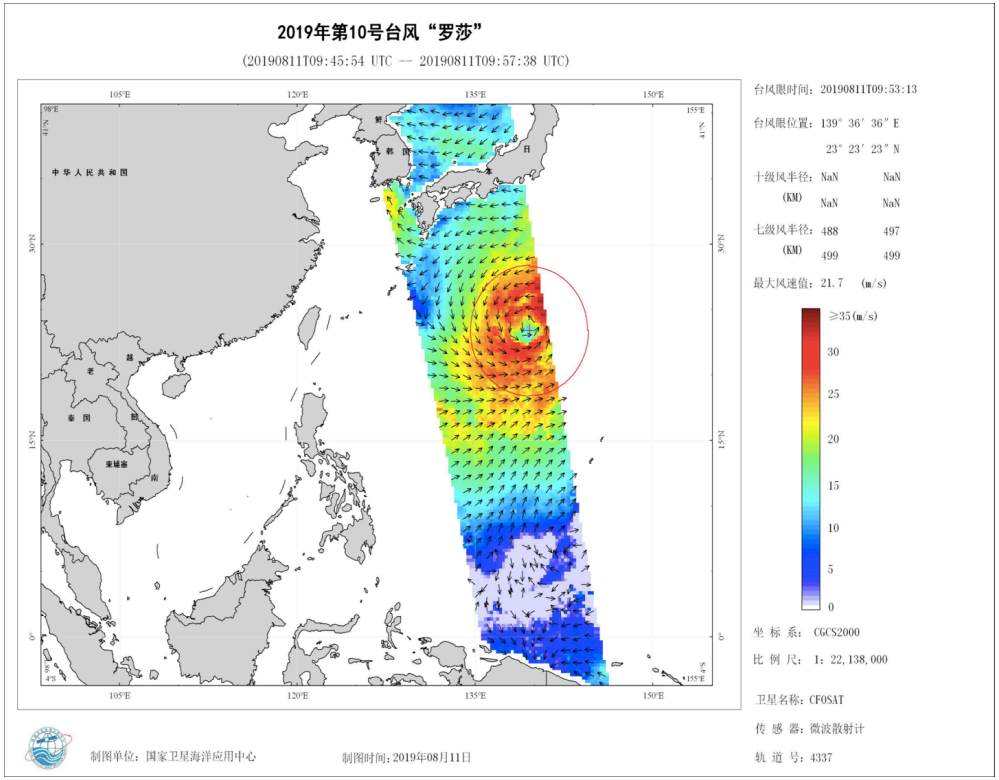


  - ✓ wave height as a function of wavelengths (70 to 500 m) and direction (with 180° ambiguity)
  - ✓ estimated using the linear theoretical which relates modulations of the backscattered signal to slopes at the surface
  - ✓ main challenge: elimination of speckle noise

- Normalized radar cross-sections

Main parameters from the SCAT measurements

11 August 2019, wind along an orbit pass

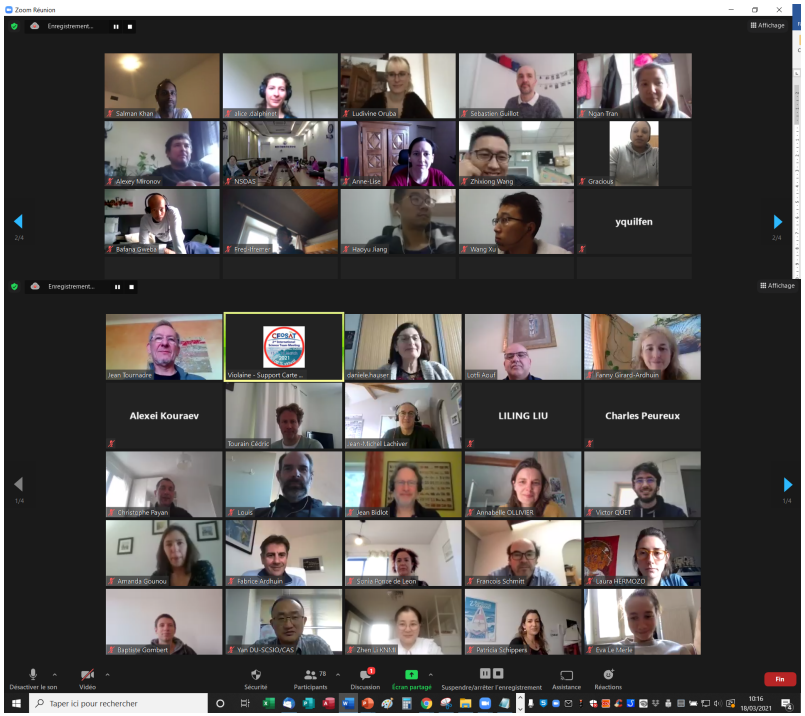


Over a swath of ~1000 km perpendicularly to the satellite track

- ✓ wind speed and wind direction in wind cells of about 25 km x 25 km
- ✓ estimation using a “geophysical model function” (empirical model between normalized radar cross-section and wind , established from data of previous scatterometer missions)
- ✓ normalized radar cross-section σ_0

First results from the Science Team CoIs: a selection

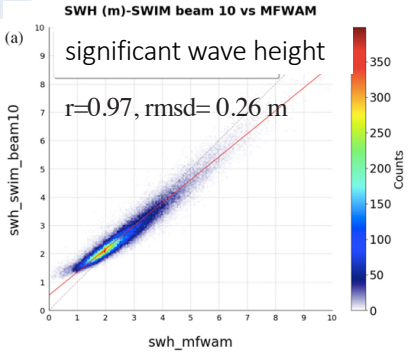
Nanjing meeting 2019

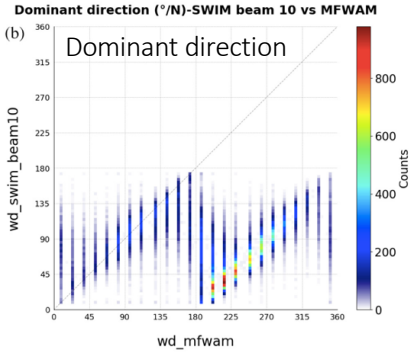


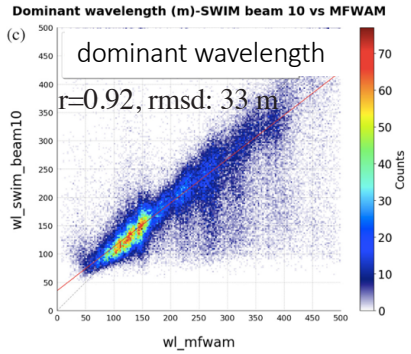
Online meeting 2021

~25 publications in 2020-2021, more coming soon

First step for SWIM : validate the observations, improve the inversion methods, provide new data sets, *Hauser et al (TGRS, 2021)*

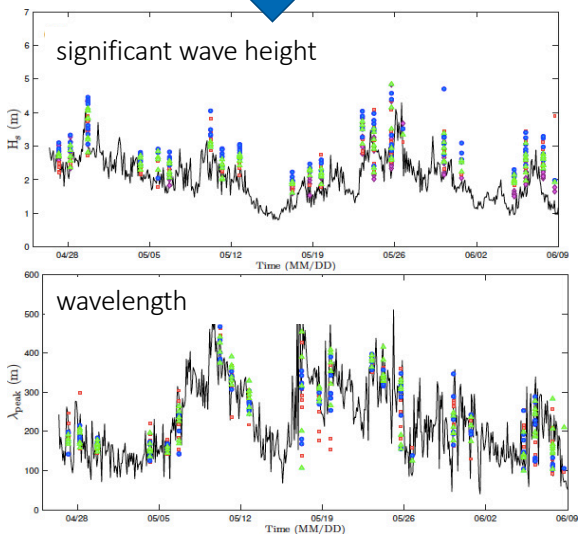






Global validation using numerical wave model (MFWAM) for comparisons

Local validation using long-time series of in situ data (here in the Pacific)

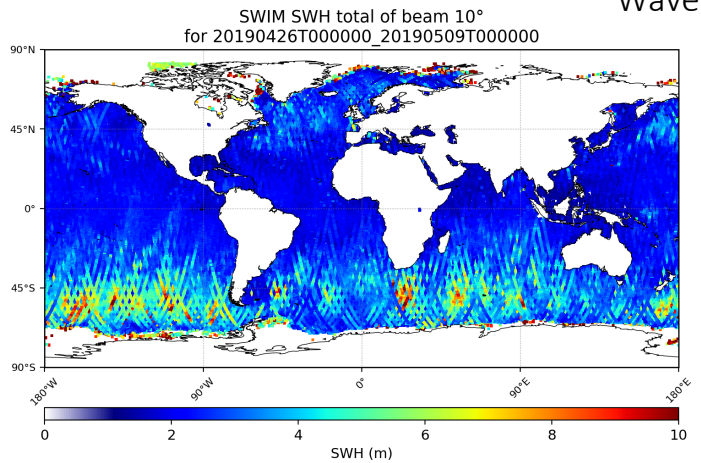


Main conclusions

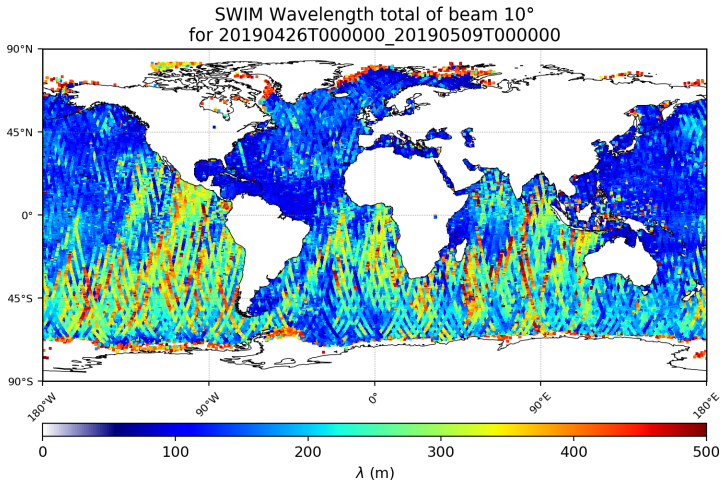
- Overall good consistency of wave parameters
- Waves detected in the [50-500m] wavelength range
- Some limitations when waves of low energy propagate along track

For the first time: continuous maps (global coverage) of wave height, wavelength and wave direction observed from satellite

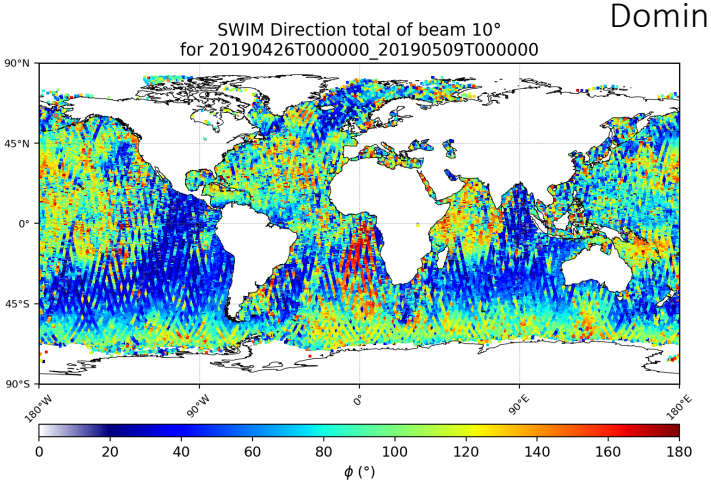
Wave height



Dominant wavelength



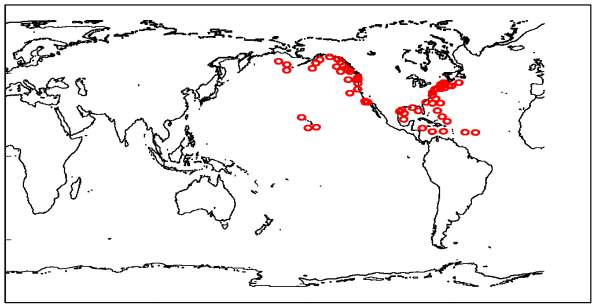
Dominant direction



Recent improvements in the SWIM processing chains

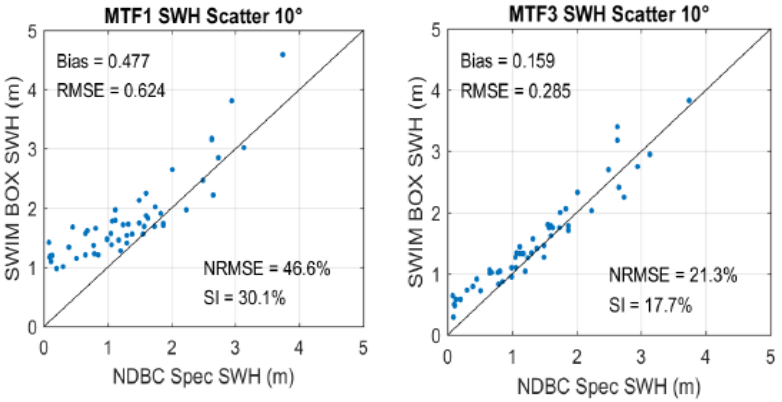
Most recent products with new processing options (v5.1 since October 2020): no more bias in Hs (normalization using nadir value)

Comparsion to NDBC buoys network



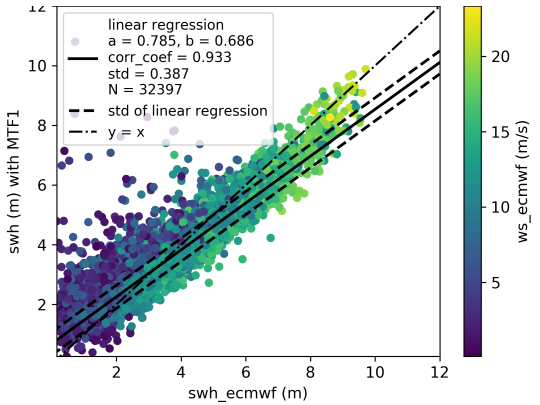
SWH from SWIM wave spectra vs NDBC buoys for beam 10°

MTF1 (previous version) MTF3 (new)

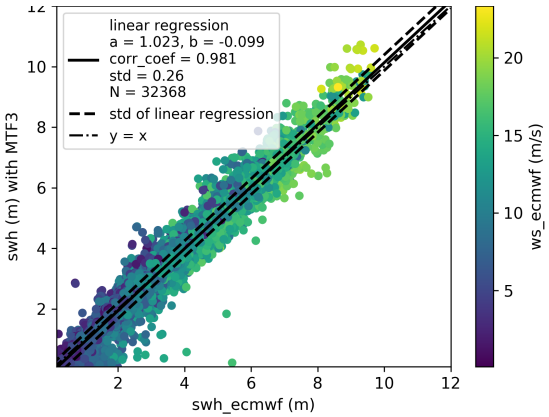


SWH from SWIM wave spectra vs ECMWF for beam 10°

MTF1 (previous version)

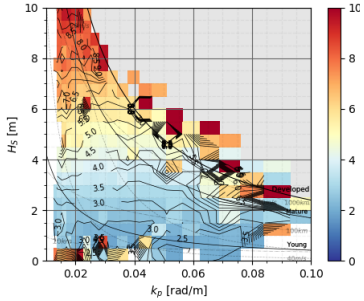


MTF3 (new version)

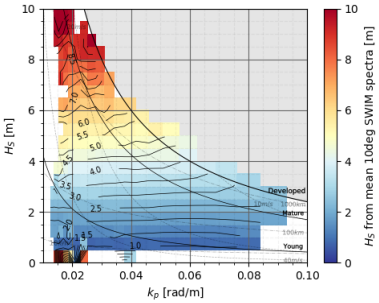


SWH/peak wavenumber relationship (for beam 10°, over 1 month)

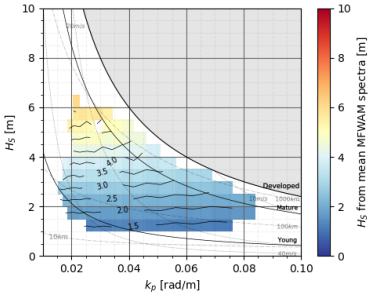
MTF1 (previous)



MTF3 (new)

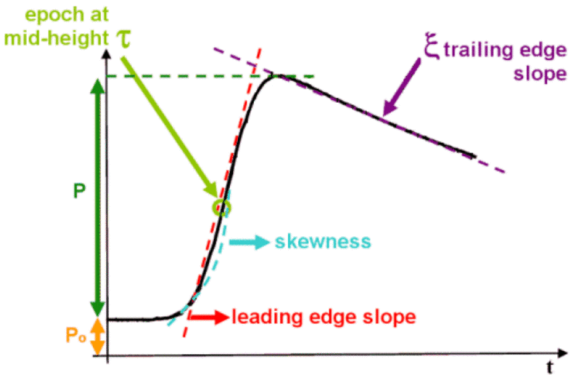


model MFWAM



Improved information from nadir observations with respect to classical method employed on altimeter missions, *Tourain et al, 2021, TGRS in press*

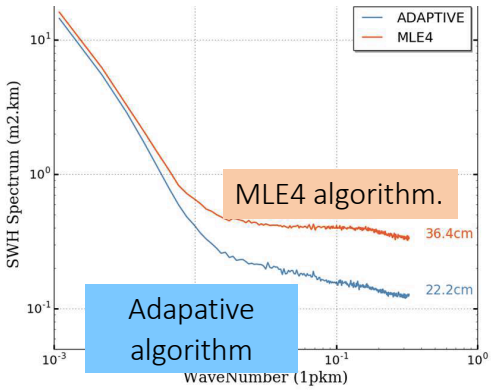
- With CFOSAT/SWIM, the opportunity was taken to develop and validate an improved method to analyze the echo (the "Adaptive retracking method")
  - ✓ significant wave height (leading edge slope)
  - ✓ backscattering coefficient
  - ✓ wind speed

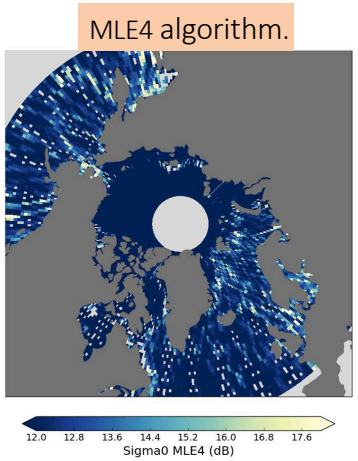


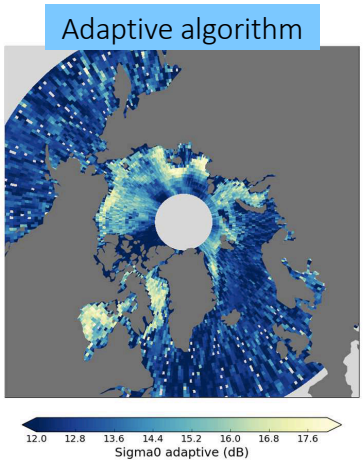
Results compared to the classical MLE4 retracking algorithm

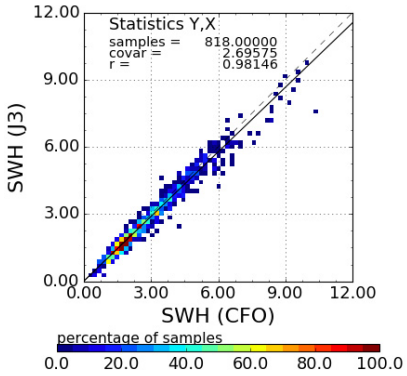
- less noise in the estimation of along-track variations of Hs (and sigma0)
- better identification of sea ice and sea-ice nature variations
- In spite of lower sampling, similar performances as other altimeter for Hs retrieval

density spectrum of Hs fluctuations along-track









SWIM- Some remarkable results

1- assimilation study in a wave prediction model, with spectral information *(Aouf et al. 2021, GRL)*

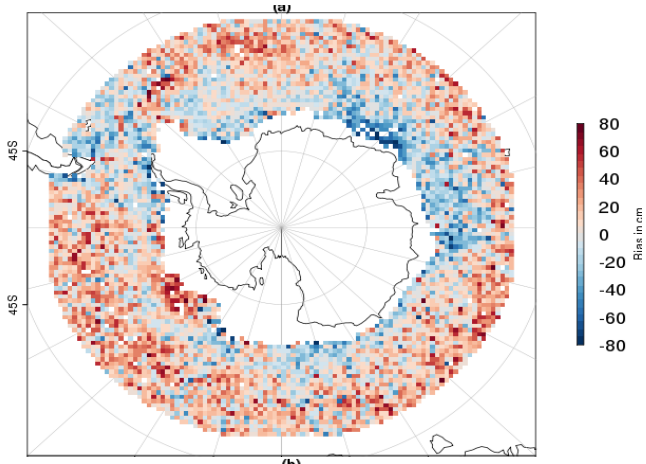
- Assimilation : constrain numerical prediction model results by observations
- Here: assimilation of spectral information, i.e. wavelength and direction of wave partitions, in addition to wave height
- Southern Ocean case study (high wind and waves)

Results

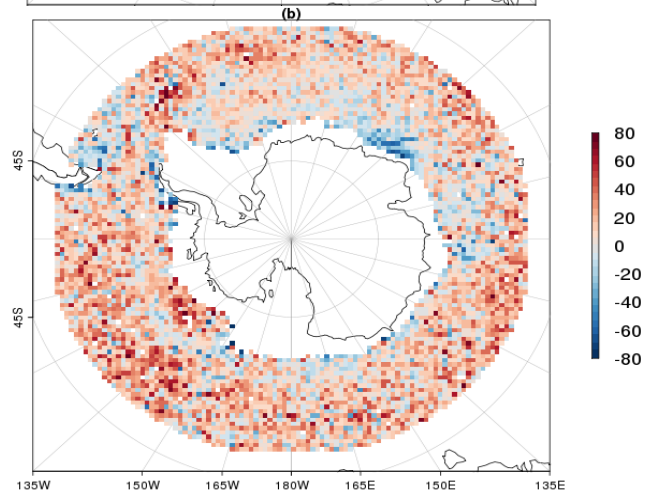
- Only the assimilation of spectral information (wavelength and direction of the waves) corrects at an appropriate level the bias in wave height of the model prediction
- In these cases strongly forced by the wind, the models tends to maintain wave growth for a too long time
- Important for coupled wave/ocean models because the state of wave development stage governs the turbulence intensity in the mixed oceanic layer

Bias on the modeled significant wave height compared to altimeter data (26 April – 1st June 2019).

assimilation of wavelength and wave direction



assimilation of significant wave height only



SWIM- Some remarkable results

2- assimilation of spectral information (Hs and wavenumbers of partitions) in a wave prediction mode (MF-WAM)

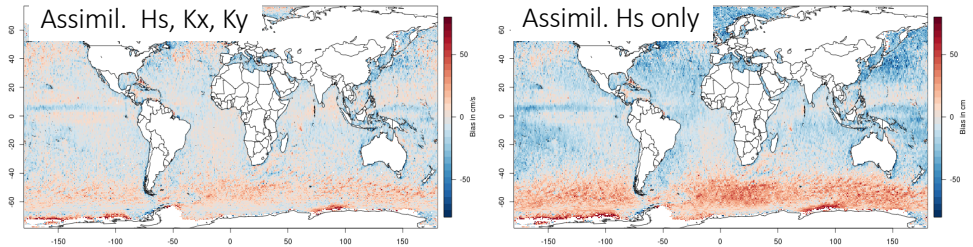
- Impact studied over 3 months
- operational since February 2nd, 2021

Lotfi Aouf , communication during the CFOSAT ST meeting, 14-18 March 2021

Performance of the assimilation of wavenumbers kx-ky and off-nadir SWH : Jan-Feb-March 2020

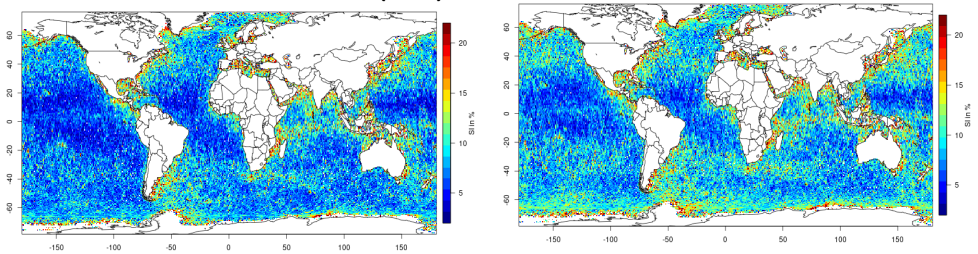
Significant bias reduction of SWH In all regions, particularly in SO

Bias maps (maximum 50 cm)



SI maps (%)

Remarkable SI after the assimilation (7-9%)

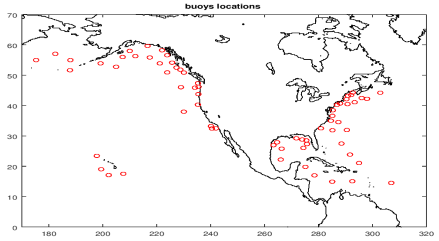


Validation with Jason-3, Sral and S3A-3B

Significant impact on bias and SI reduction on SWH (Altimeter used as reference, J3, Saral, S-3A, S-3B)

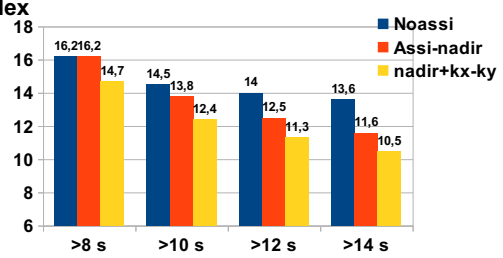
Validation with NDBC buoys data : Peak period Jul-Dec 2019

Buoys locations (data from LC-WFV, thanks to J. Bidlot)



Using directional wavenumber removes the bias on Tp (0.01 sec) in Comparison with runs of assimilation of SWH only (0.26s) and without assimilation (-0.28s)

Scatter index of Tp



Assimilation of kx-ky induces a Significant impact on Tp. For waves With Tp greater than 10 sec, the impact is ~3 times larger than using SWH-only

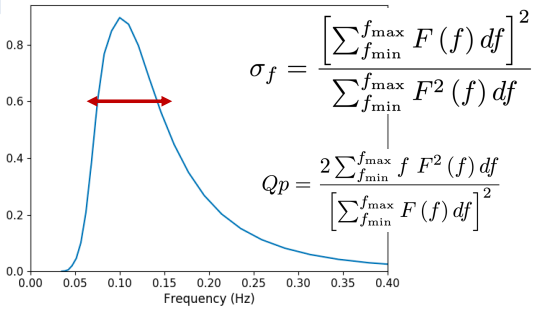
The validation with buoys indicates the uniqueness of directional wave observations to improve significantly peak period (by more ~20% for waves with wavelength greater 150m)

SWIM- Some remarkable results

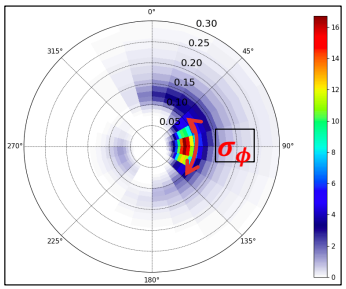
3- Wave spectra properties (frequency and directional distribution)

(Le Merle, Hauser, et al, in revision, J. Geophys. Res)

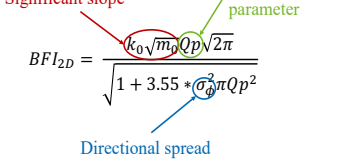
Frequency spread (two parameters)



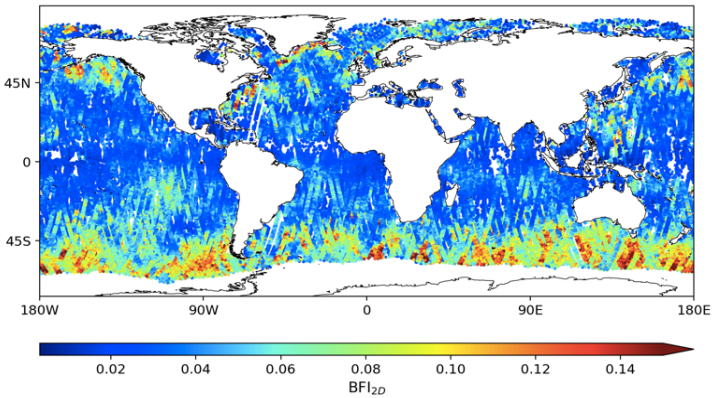
Directional spread



Benjamin-Feir index (BFI)



first global map of BFI from observations

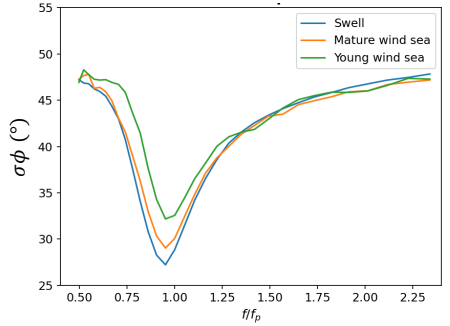


For the first time from space, global characterization of the frequency and directional spread of wave energy. Very innovative to:

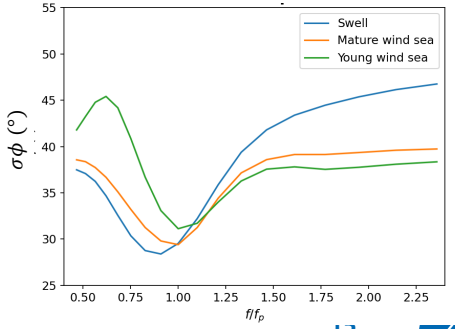
- better understand limits of the numerical models (in particular representation of the non linear interactions between waves)
- provide indexes which characterize the probability of freak waves (Benjamin-Feir index)
- identify and study regions of wave/current interactions

angular spread versus the normalized wave frequency for different sea-state conditions

SWIM



model (MFWAM)

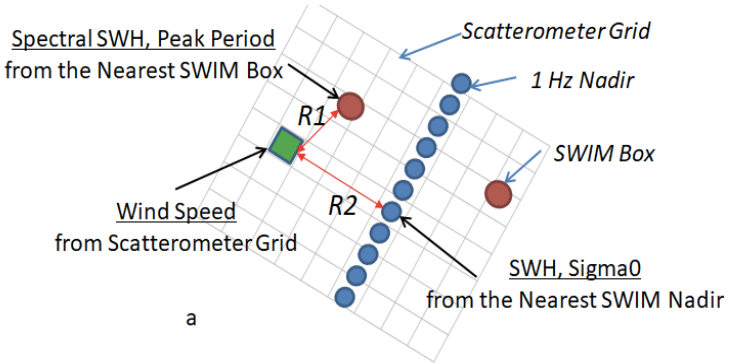


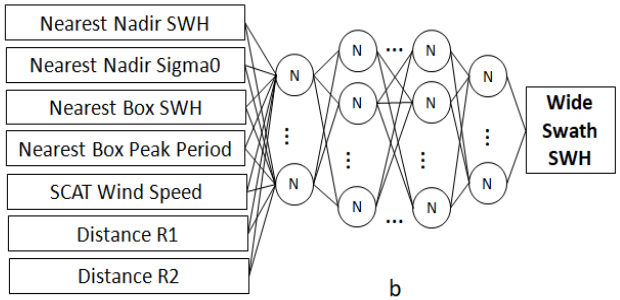
SWIM/SCAT – Some remarkable results

4- Deep learning method proposed and validated to extend the wave height estimate over a "wide" swath

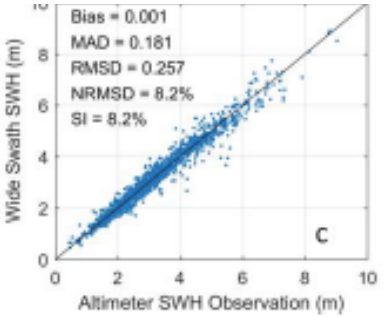
(Wang et al, Geophys.Res Letters, 2021)

- Combines nadir and non-nadir observations from SWIM (σ0, wave height, wave period) and the CSCAT observations (wind speed and wind direction)





Extended Hs compared to cross-over altimeters



Results

- Hs over an extended area ~200 km from nadir - validated by comparisons with altimeter crossing points and buoy observations
- Increased positive impact in the wave model results when these extended observations are assimilated compared to the case where only nadir wave heights are assimilated
- Interesting perspectives for other satellite missions with combined wind/wave measurement or wide swath geometry (HY2B, SWOT..)

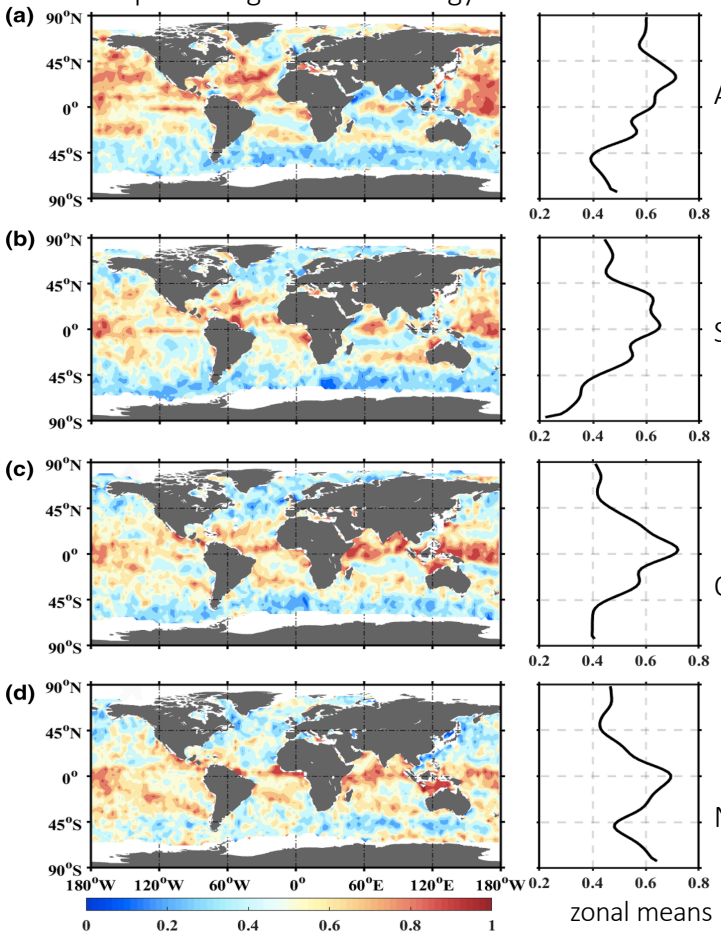
Hs compared to buoy observations

Assimilated Data	Biais (m)	standard deviation of difference (m)	NRMSD (%)	SI (%)
Wide Swath SWH, Nadir SWH	-0.044	0.299	17.85	17.65
Nadir SWH only	-0.038	0.317	18.88	18.74

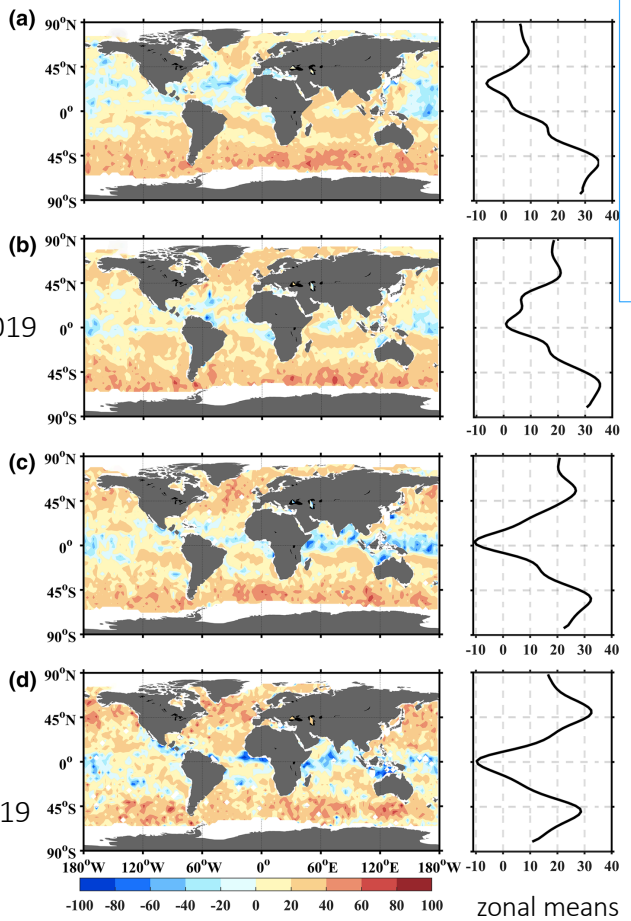
SWIM/SCAT - Some remarkable results

5- Wave-induced stress over the global ocean, *(Chen et al, J.Geophys. Res., 2021)*

Monthly averaged values
of the percentage of wave energy from swell



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



❖ Method :

- ✓ combined observations of CSCAT and SWIM (separation of swell and wind sea) + empirical model of wave-induced stress , depending on sea-state (wind sea or swell)

Result

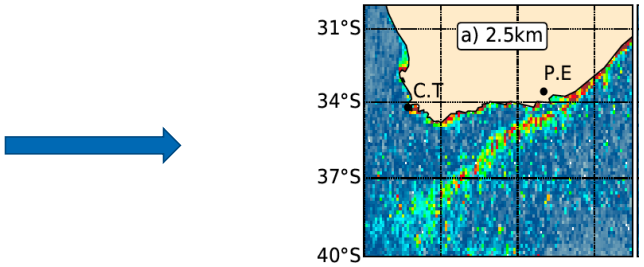
first evaluation from observations of seasonal and geographical variations of the influence of waves on the atmospheric stress at the air/sea interface

New perspectives

Wave-current interactions

From Marechal and Ardhuin, JGR2021

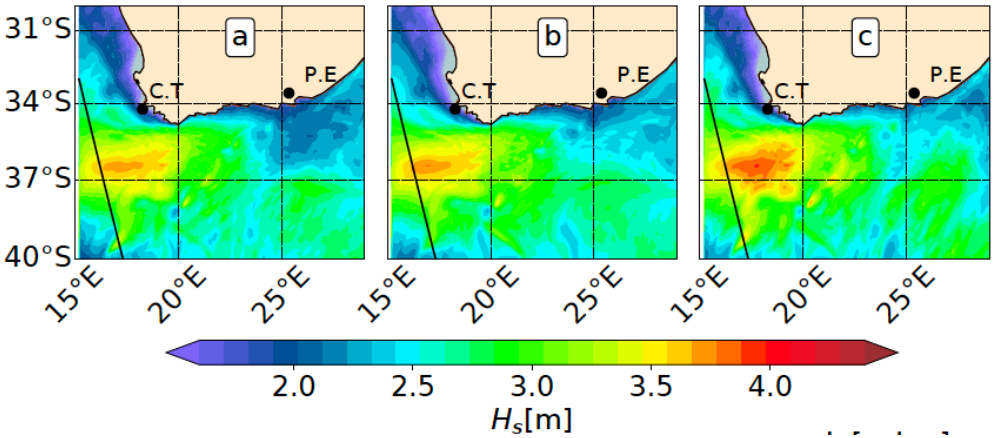
Mean Gradient of Hs (2014-2016) across the Agulhas current from WW3 model and altimetry



WW3 with current at 2.5 km resolution

WW3 without current

altimetry

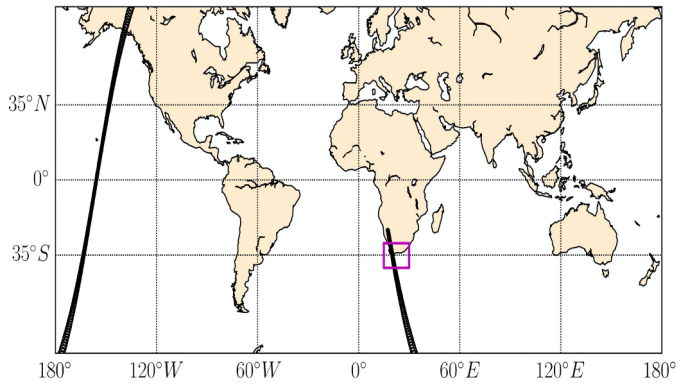


From model : Sensitivity of Hs field in current areas to the directional spread (standard, increased or reduced) of the incident waves

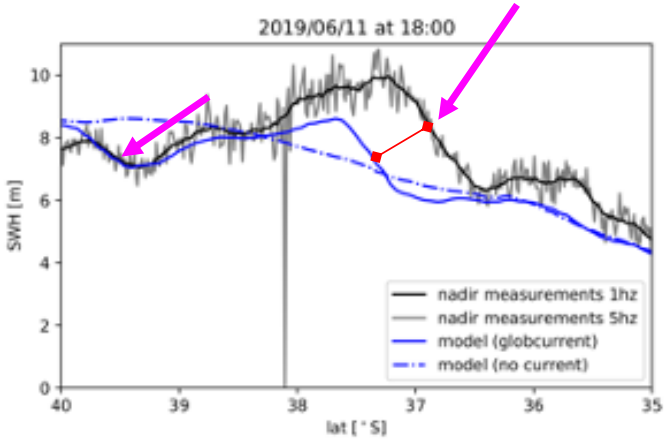
Promising results on one case study (Agulhas current): Hs gradients and wave turning due to focusing/refraction

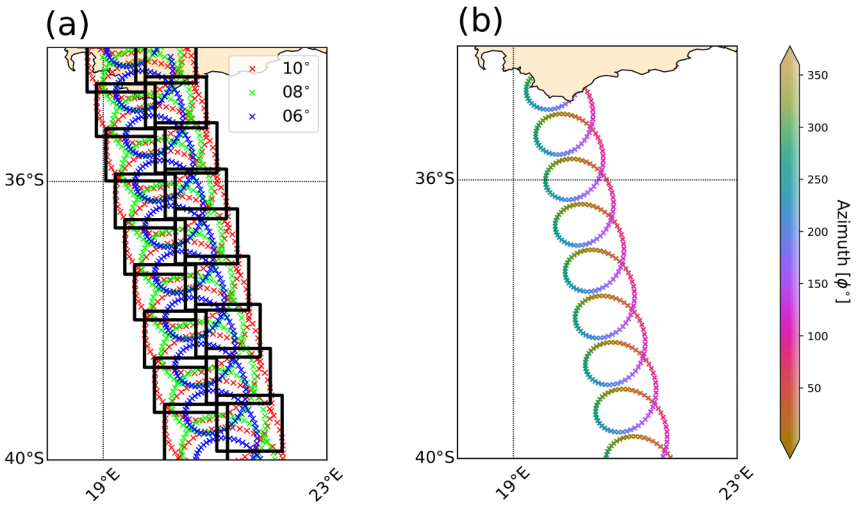
From Marechal and Ardhuin, communication during the CFOSAT ST meeting, 14-18 March 2021

11th June 2019

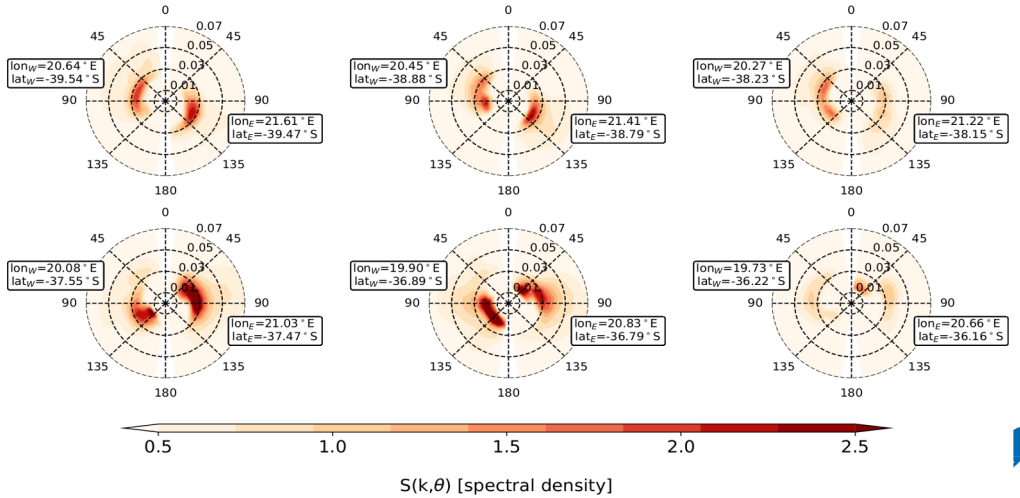


Hs gradients near frontal discontinuities





SWIM 2d spectra across the current (From South to North



New perspectives

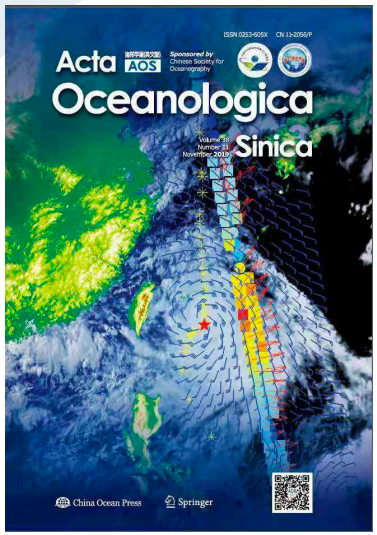
Wave-current interactions

Open perspectives

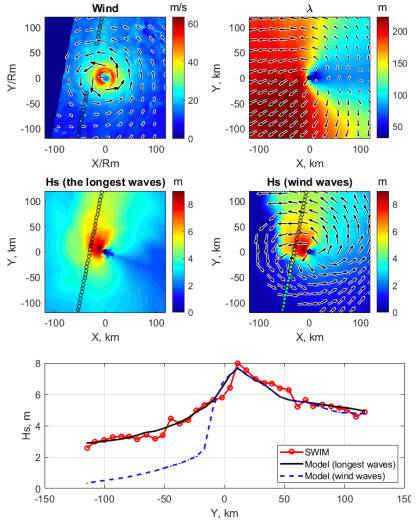
- characterize globally with observations, wave/current interactions in terms of wavelength and direction in addition to Hs,
- better constrain wave models and ocean/wave coupled models with observations of mean direction and directional spread
- use wave modulation signature as a proxy for surface current ?

New perspectives

Wind and waves in tropical cyclones

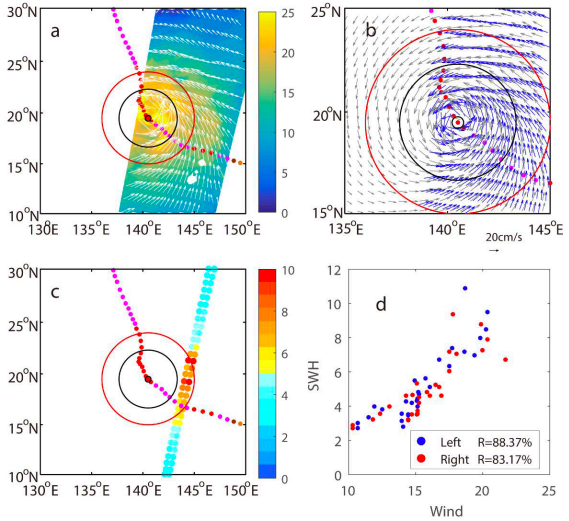


Xu Ying et al, 2019



Yurovskaya et al, communication during the CFOSAT ST meeting, 14-18 March 2021

Super typhoon Hagibis, Oct 2019



Shi Yanping et al, communication during the CFOSAT ST meeting, 14-18 March 2021

Results

Better characterization of waves generated by tropical cyclones, confirmation of phenomenological schemes, and numerical model results behaviour

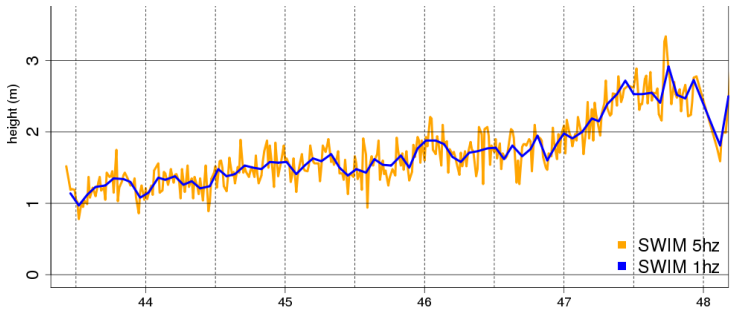
Asymmetry of the wave height field (and wind speed) => in the Northern hemisphere, on the right-hand side of the TC propagation: higher wave heights, longer wavelengths, wind and waves non aligned

Validation of a simplified parametric model to explain and predict waves in cyclones (function on cyclone intensity, diameter, propagation speed)

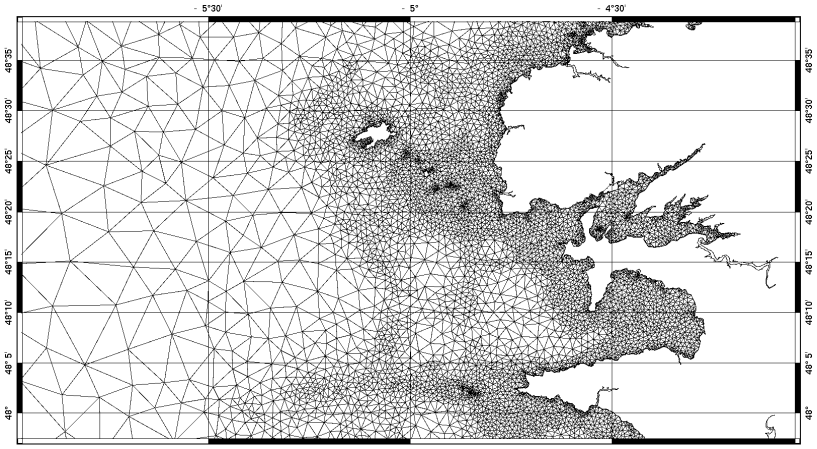
New perspectives

Waves in coastal regions: take benefit of the good quality of 5 Hz resolution (~1.4 km) nadir SWH

DALPHINET Alice, NIGOU Adrien, AOUF Lotfi, WANG Jiuke, *communication during the CFOSAT ST meeting, 14-18 March 2021*



Example of SWIM nadir wave height in m
The 19/11/2019 in Bay of Biscay near France
Blue : 1 Hz data
Orange : 5 Hz data



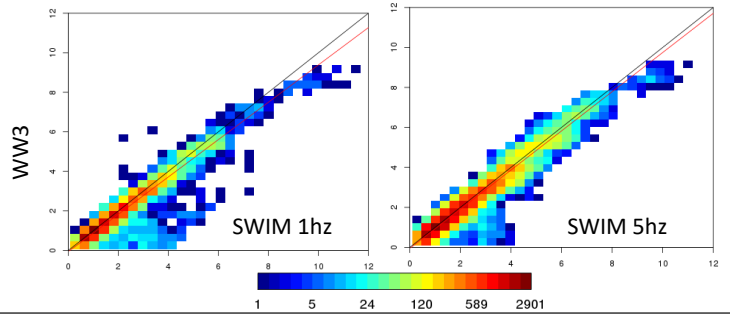
Main results

- Good agreement of 5Hz SWIM data with HR coastal model, in shallow water and high currents area
- Slight but positive impact of the assimilation of high resolution data rather than 1hz data in regional wave model (0,05° and less)- not illustrated here

Comparison of nadir data against WW3

from August to December 2019

	population	WW3 bias (m)	RMSE (m)	SI (%)	Corrélation (%)
1Hz	5900	-0,18	0,59	25,2	93,2
5Hz	27987	-0,1	0,39	17,2	96,8



Better slope with 5hz data
SI : 25,2% → 17,2% !

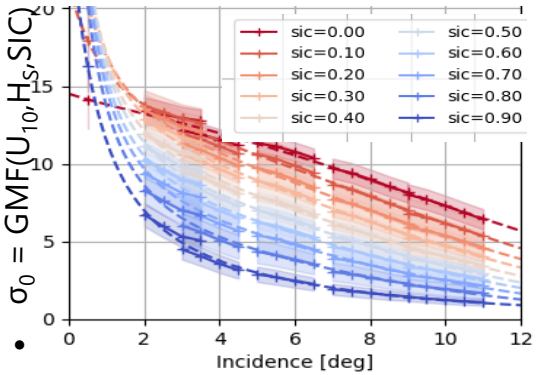
WW3 is closer to 5hz data than 1hz
Better representation of the waves-current interaction by 5hz

New perspectives

SWIM- Sea-ice signature from off-nadir (near-nadir) echoes

C. Peureux, N. Longépé, A. Mouche, C. Tison, C. Tourain, J.-M. Lachiver, in preparation ESS , 2021

Bayesian method



Fully analytical relationship

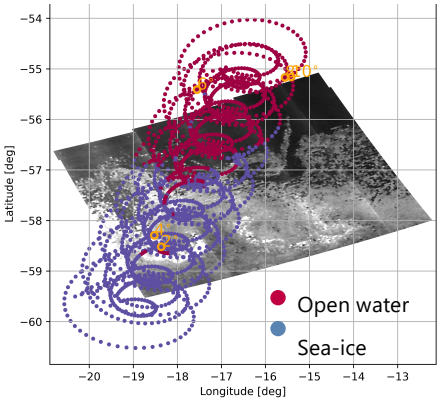
$\sigma_0 = GMF(U_{10},H_S,SIC)$

- Open water σ_0 (SIC=0)
- SWIM σ_0
- Sea-ice σ_0 (SIC=1)

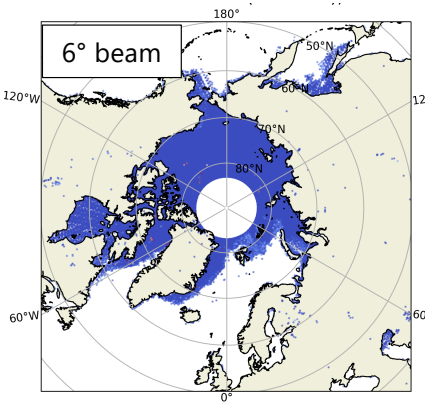
→ Sea-ice likelihood

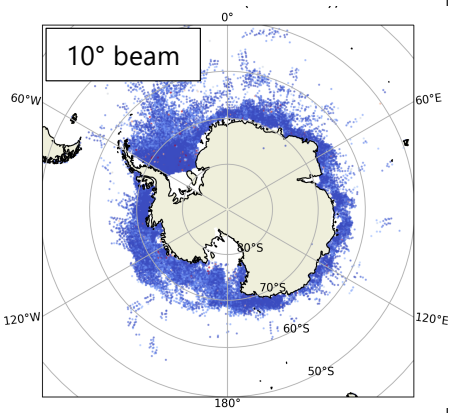
Example outputs

- L1 to L2 flag
- Colocations with Sentinel-1
- Further characterization (concentration) possible



SWIM/S1 colocation





L2 Sea-ice flag (01/2021)

Further details and comparisons to be published

New perspectives
and for wave climate studies ?

- Complement classical altimeter missions in terms of Hs and wind speed measurement.

- Exploit information on directions and wavelengths (of the full spectrum or of partitions)

  - separate wind-generated waves from swell and subsequently their respective contribution to the wave-induced stress, to the turbulence generated in the mixed layer, Stokes drift, ..
  - through assimilation, better characterize potential limits of numerical model, improve forecast, hindcasts
  - better characterize wave properties arriving at the coast for coastal studies

- Exploit more information from the wave spectra:
  - directional spread of wave energy
  - frequency bandwidth or peakedness
  - Indexes related to these spectral properties (Benjamin-Feir or equivalent), which govern the non-Gaussian nature of the height pdf (kurtosis) and hence the probability of occurrence of extreme waves
  - Stokes drift

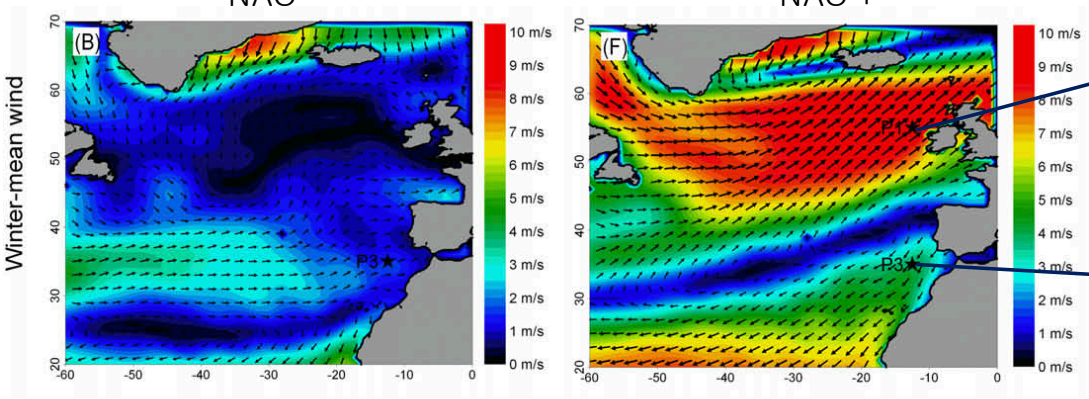
Variability and trends of wave spectral parameters

IPCC AR6 notes “only few studies focused on wave direction change, which is important for shoreline response” and that “there is still limited knowledge on projected wave period and direction” .

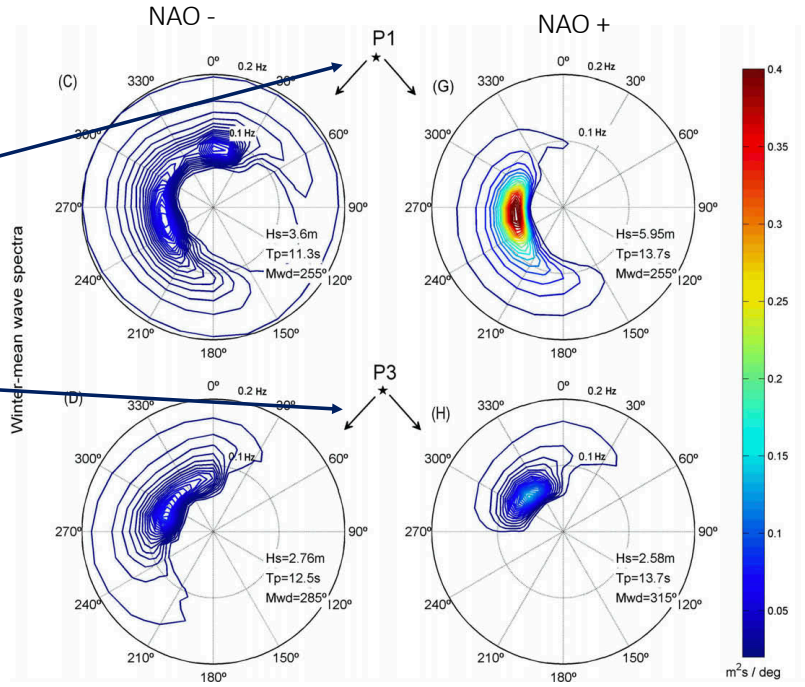
Dodet et al, Ocean Modelling, 2010 => modelling studies (WW3)

=> Important spatial differences of variability and trends in the North Atlantic , not only Hs but also in wave spectra

Mean winds in 1969 (NAO-) and 1989 (NAO+)



Mean wave spectra of winter 1969 (NAO-) and 1989 (NAO+)

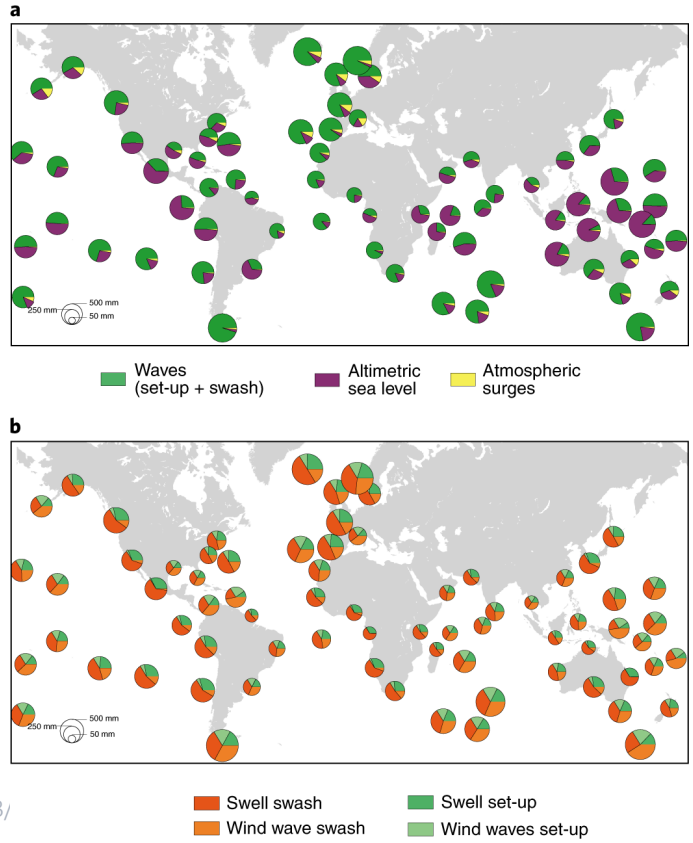


Contribution of waves in variability and trend of water-level in coastal areas

Waves contribute to sea- level variability and sea level rise at the coast (wave set-up, wave swash).

Wave setup and wave swash depend on deep-water wave height and wavelength (and on wave directionality)

From Melet et al, in Nature Climate Change (2017)



From models + altimeter data

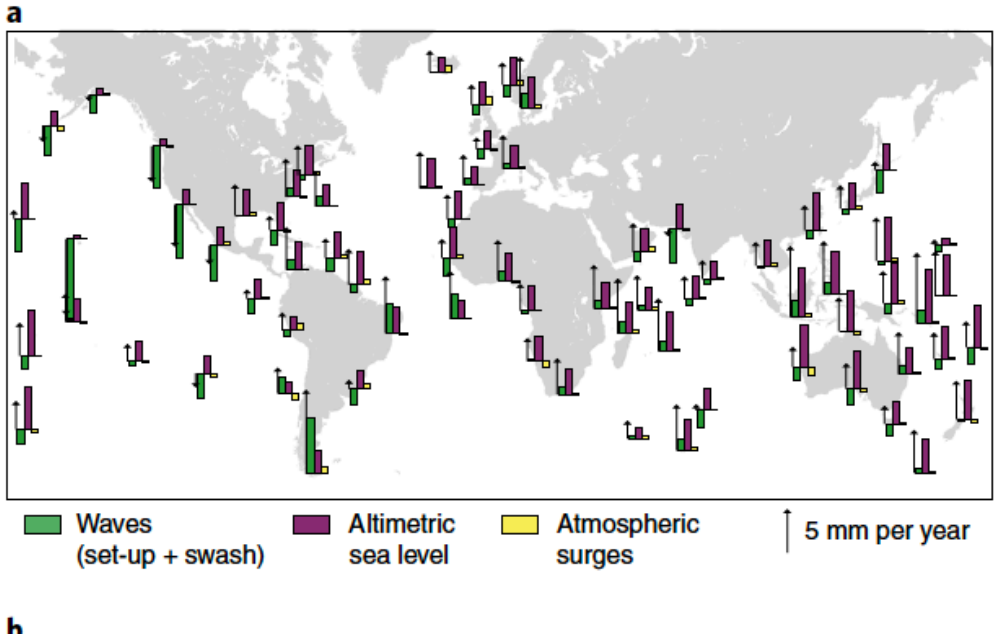
Relative contribution to the total water-level variations at the interannual-to-multidecadal scale (1993–2015)

- wave setup (green),
- altimetric sea level (violet)
- atmospheric surge (yellow)

=> median contribution of waves to total water-level variations at the interannual-to-multidecadal scale=> across the 153 studied sites = 58% (but also important geographical variations)

=> Swell (orange) contribute more than wind sea (green) to this water level variations

From Melet et al, in Nature Climate Change (2017)



water-level trends over 1993–2015 in coastal regions

- green: wave contribution
- Violet: mean sea level (from altimetry)
- Yellow: atmospheric effect

In some regions, the wave contribution may dominate the mean water-level trends.

Conclusions, Perspectives

- CFOSAT is an innovative satellite mission
  - ✓ the first mission entirely dedicated to wind and waves at the surface
  - ✓ novel instrumental concepts
  - ✓ first China-France cooperation in space science
- Already scientific breakthrough results in the first ~ 2.5 years
- Very promising results which open new perspectives
- Data widely accessible (see last slide)

❖ Perspectives

- ✓ Further improve the inversion algorithms
- ✓ Further develop methods and analysis to increase the benefit of the joint observations of wind and waves
- ✓ Combine CFOSAT data with other data sets (e.g. Sentinel missions, ..)
- ✓ Incite additional operational entities to include CFOSAT data in their assimilation/forecast systems
- ✓ Expected original contributions on
  - role of waves in the coupled atmosphere/ocean system , extreme events, wave/current and wave/ice interactions
  - feeding long series of observations for climate studies
  - Experience gained from SWIM other new mission concepts (SKIM-like concept to measure surface currents and waves) and/or CFOSAT follow-on projects (China, Europe ??)

❖Data available to users:

- ✓ Latest version of the SWIM processing (v5.1) for both near-real time processed data and data re-processed from April 25 2019 through AVISO+ data center (CNES) , after registration
  - Direct access via ftp: ftp-access.aviso.altimetry.fr/cfosat (SWM only)
  - More products (including SWIM-L1A and CSCAT), on https://aviso-data-center.cnes.fr/

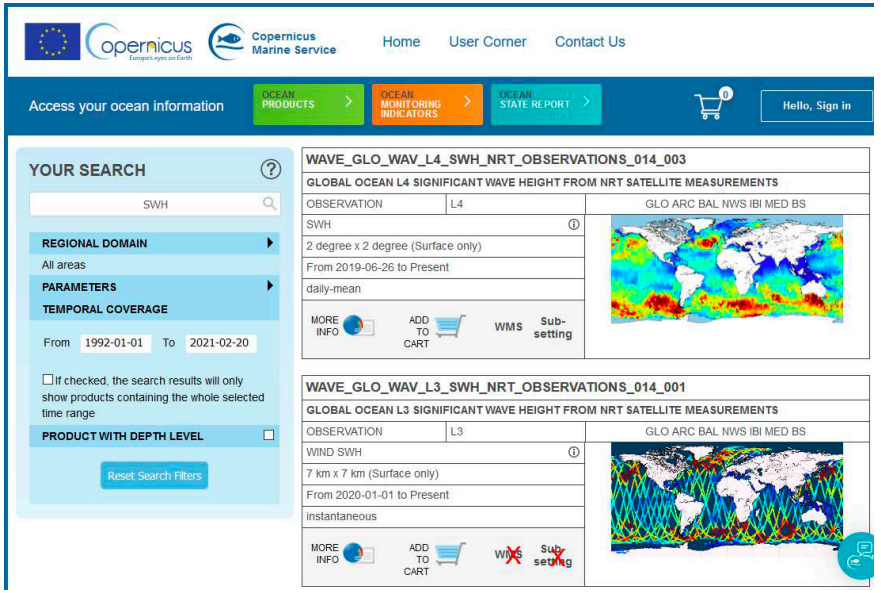
`

❖Also distributed by CNES to

- ✓ EUMETSAT => accessible to Member states via EUMETCast (SWIM only until now)

- ✓ CMEMS => accessible to Waves-TAC : SWIM –L2P – nadir and coming soon wave spectra => https://resources.marine.copernicus.eu/

  => see Annabelle Ollivier presentation for more details on CMEMS products

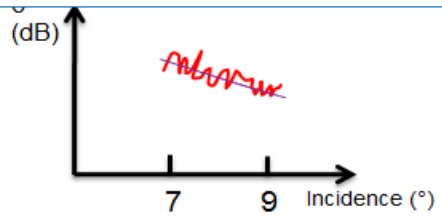


Thank you for your attention

Backup slides

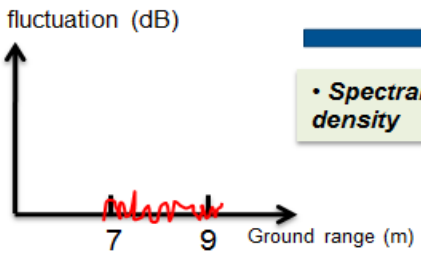
Principle of wave spectra retrieval

1- normalized backscattered coeff over a 18 km-footprint in elevation



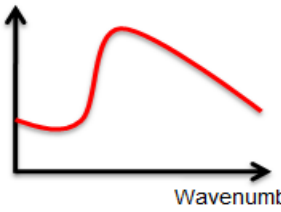
2- fluctuations in the ground geometry

- ***Mean trend suppression***
- ***Ground projection***



3- fluctuation spectrum

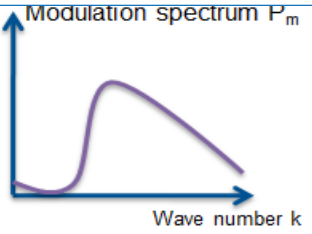
- ***Spectral density***



$P_{\sigma 0} = P_{IR}.P_m + P_{sp}$

- ***Speckle + IR correction***

4- fluctuation spectrum corrected from speckle effects



$P_w = P_m/MTF$

- ***Transfer function estimation and wave slope spectrum computation***
- ***15°-azimuth averaging***
- ***Partitioning and physical parameter computation***

5- smoothing averages in the spectral domain and building a directional (2D) spectrum, estimating main parameters