CFOSAT

Four years of scientific results (2018-2022) based on the CFOSAT Science Team results and the CAL/VAL expert group activity

December the 7th, 2022

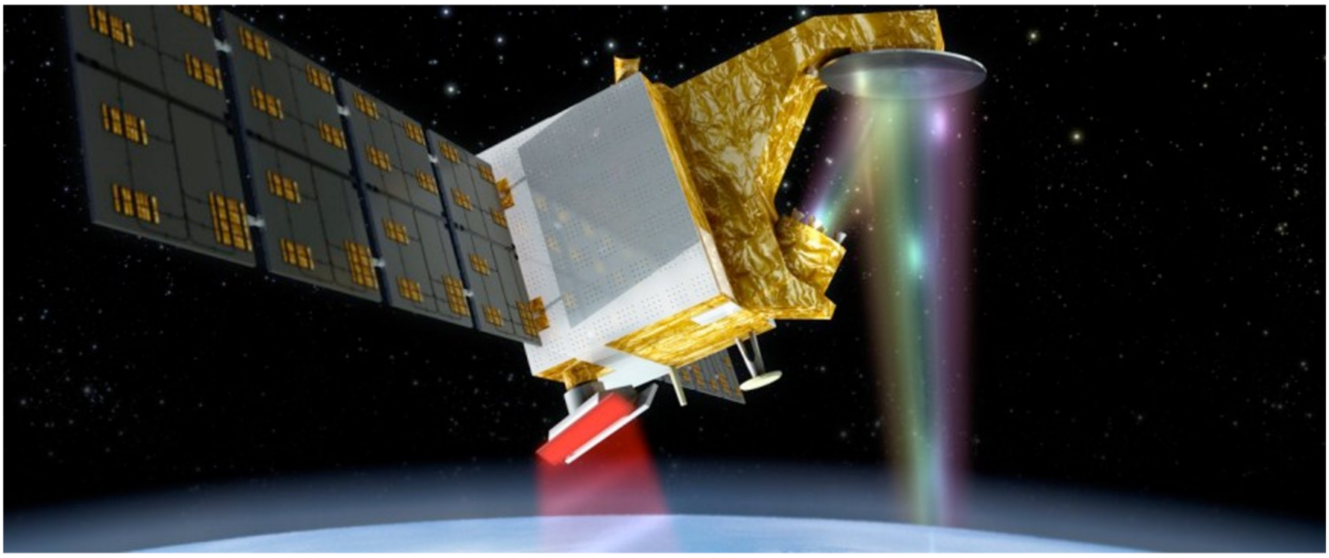

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TABLE OF CONTENT

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1. INTRODUCTION

It is first recalled that CFOSAT (China France Oceanography SAtellite) was launched on October 29, 2018, that the commissioning phase took place until June 2019 and that the intensive geophysical validation phase before opening the data continued until September 2019.

CFOSAT is an original mission, which embarks two instruments whose concepts are new. On the one hand the SWIM radar, dedicated to the measurement of the wave spectrum (designed and produced by France) and on the other hand the CSCAT wind scatterometer (designed and produced by China).

The scientific objectives of CFOSAT are related with the facts that wind and waves are key drivers of the coupled ocean/atmosphere system, have direct impacts on the marine environment, are essential variables for marine safety and for operational ocean « users », and also essential markers of the climate change impacts. Therefore, the objectives of CFOSAT are to monitor, at the global scale, ocean surface winds and waves so as to improve knowledge and modeling of the coupled processes at the interface between atmosphere and ocean, to improve wind and wave forecast for marine meteorology (in particular in cases of severe events), to improve the results of the coupled ocean/wave models, to contribute to the acquisition of long time-series on ocean surface essential variables. In complement, as CFOSAT acquires also data over the continent, it offers an opportunity to complement other satellite missions for the estimation of land surface parameters (in particular soil moisture and soil roughness) and polar ice sheet characteristics.

Since the launch of CFOSAT in 2018, scientific activity based on CFOSAT observations is carried out by different groups in France, China and other countries. The Science Team gathers most of the teams which are developing activity with CFOSAT observations. In response to the call on research applications issued by CNES in 2018 and directed towards the non-Chinese research groups, 29 teams, have manifested their interest in using CFOSAT data (7 in France, 9 in Europe outside France, 5 in USA/Canada, 8 in Russia/Korea/Australia/New Zeeland). In China, 34 different scientific groups (gathering ~90 persons) are also involved in this scientific activity (separate call from the Chinese organization). All the co-investigators of these projects are members of the Science Team. Since 2018, an annual meeting of the Science Team has been organized by the PIs (except in 2020 because of the Covid crisis), during which progress made in the different groups were presented and discussed.

In this document, we summarize the main advances obtained by these different groups, thanks to CFOSAT observations since the launch in 2018. First the results on the validation and improvement of inversion methods are described (section 2). Section 3 then proposes an overview on geophysical studies based and SWIM and/or SCAT observations. The use of observations in numerical wave prediction models and in ocean/wave coupled models is described in section 4. Section 5 describes the current status and perspectives on data products and data processing. Section 6 explains how CFOSAT data are used by operational centers. Section 7 and 8 provide a summary over the period 2018-2022 on respectively, publications/communications, and international cooperations. Section 9 announces the scientific and application perspectives for the future. Finally, section 10 provides the list of publications and communications closely related to CFOSAT.

Apart from validation studies, the scientific studies effectively started after the ground segment data processing become stabilized (~ July 2020). So, most of the results presented in sections 3 to 7 correspond to about two years of effective scientific exploitation.

2. VALIDATION AND IMPROVEMENT OF INVERSION METHODS AND PRODUCTS

Here below we summarize the main scientific activities with contribution from the scientific teams on the validation of the products defined before the CFOSAT launch, and on improvements of the pre-defined algorithms. Other results on alternative algorithms or products are described in section 5.

2.1. SWIM

The originality of the SWIM radar consists in the fact that for the first time, a real aperture radar is used from space to provide at the global scale the directional spectrum of the waves and the associated wave parameters (in addition to the significant wave height - SWH, wave direction, wavelength of the full spectrum and of wave partitions). So far, only synthetic aperture radars (SAR) have been used for this objective (example Sentinel-1). The advantage of the new concept used with SWIM is to overcome the SAR limitations, that are due to the impact of the motion scatters at the surface on the SAR image formation, and that results in a filtering of the shortest waves (only wavelengths greater than about 200 m can be imaged by the SAR when wave propagation is close to the along-track directions). The choice of a real aperture radar for SWIM was designed to overcome this problem. On the other hand, this choice is accompanied by a measurement geometry never used before from space: near nadir incidence (0 to 10°) and azimuthal scanning over 360°, which made it necessary to analyze the radar signals in depth in parallel to the development and assessment of new inversion algorithms. Another originality of SWIM is to combine the "off-nadir" beams designed for the measurement of wave spectra, with a nadir beam, the measurement of which is analyzed in terms of surface wind and wave height in the same way as for conventional altimetry missions, but with a different sampling rate and a different analysis of the radar returned waveform (retracking method).

In this context, a number of studies during these last four years have focused on data validation, on the assessment of the geophysical product quality, and on the continuous improvement of inversion algorithms. In addition to the technical reports on the CAL/VAL phase, the main landmark publications in this field are those of Hauser et al, 2021 (first validations of level 1 and 2 SWIM data, comparisons of geophysical products with numerical wave model data), Tourain et al, 2021 (detailed presentation of the nadir waveform analysis algorithm and validation of associated products), Liang et al, 2021 (validation of wave parameters from SWIM against data in situ), Jiang et al, 2021 (validation of spectral partition parameters).

Concerning the inversion of the nadir return echo, the choice made by CNES before the CFOSAT launch was to implement a recently-developed new retracking method (called the adaptive method) not yet implemented in other conventional altimeter NRT processing chains. During the first year after the launch, the French scientific groups contributed to validate the parameters inverted from this algorithm (significant wave height and wind speed) and to publish a paper on the method and on the result assessment (Tourain et al, 2021). Figure 1 below illustrates the performance of SWIM nadir parameters compared to those provided by the Jason3 and AltiKa missions.

It shows that these sets of observations are in very good agreement at least for ranges of wind speed and wave height range where there were enough cross-over points for the analysis. Using this new retracking algorithm, it was shown that the statistical uncertainty on significant wave height (rms error) was of the same order of magnitude as that of more standard algorithms (MLE4) applied in other missions, although the number of independent samples used from SWIM is less, due to alternate sampling of nadir and non-nadir beams.

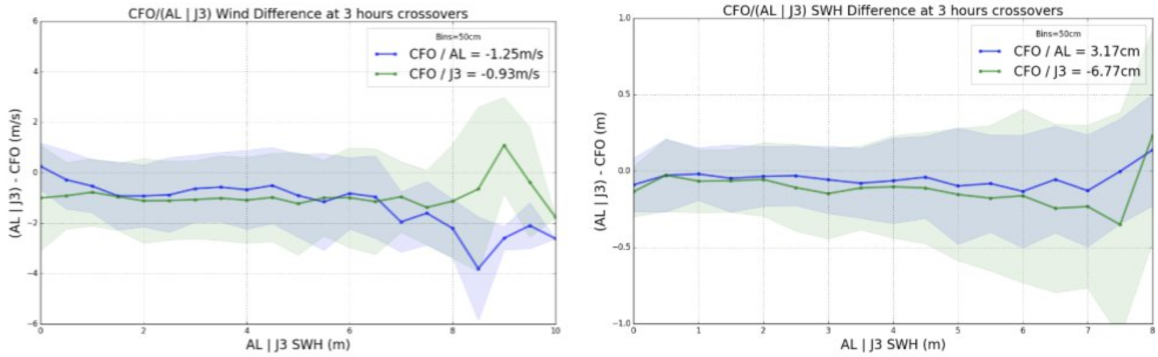


Figure 1 - From Tourain et al, 2021 : Bias (and std of the bias) between SWIM and two altimeter missions (SARAL/AltiKa in blue, Jason-3 in green) for SWH (left) and wind speed (right) . The data set is from cycle 21 to 28 of CFOSAT.

With regard to performance on the wave spectra and the main parameters associated with them (significant height, direction and dominant wavelength), it was shown that the SWIM beam pointed at 10° incidence was that which provided the best data. It was also shown from studies based on the recent processing versions (above 5.2.1) that the performances on the estimation of the significant height of the waves are excellent (rms difference with respect to model or altimeter of the order of 0.25 to 0.30 m), those on the wavelengths and dominant directions quite suitable for most of the open ocean scientific exploitation with rms difference with respect to model data of the order of 30m and 15-20°, respectively (see Figure 2 below for some illustrations). However, limits have been highlighted in cases of SWH lower than about 2m (Hauser et al, 2021, Xu et al, 2022), which lead to either noisy wave spectra or presence of parasitic peaks in these low sea-state conditions.

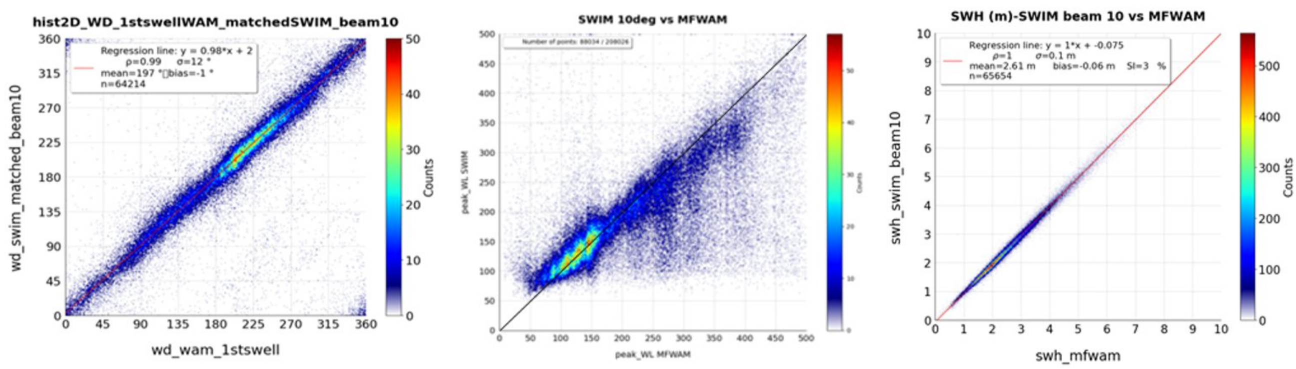


Figure 2 : Validation of SWIM parameters by comparison to wave model results (MFWAM model). Left: wavelength of the swell, middle: dominant wavelength, right: significant wave height. This analysis was done over the global ocean using 13 days of observations.

Using an original approach Xu et al (2022), analyzed the consistency between SWIM and in situ buoy data not only in terms of mean wave parameters but also regarding the spectral shape of the omni-directional wave height spectrum and the directional function. For that, they proposed a new approach for the comparison, based on the analysis per classes of sea-state (38 classes defined according to swell or wind-sea conditions, to values of SWH, dominant wavelength, wind speed,..), and analyzed without co-location requirements, 2 months of SWIM spectra and one year of buoy spectra (NDBC network). The results show that under medium and high sea conditions, wave directional spectra provided by the SWIM beams at 8 ° and 10 ° incidence have a high consistency with those from buoy data (see illustration for some cases in Figure 3 below). Under low sea conditions, limitations have been identified mainly due to three phenomena which are, by order of importance, the presence of a parasitic peak at low wavenumber due to amplification of the speckle noise floor, a slight non-linear behavior in the wave imaging mechanism with SWIM, and a slight underestimate of speckle noise for the shortest detected wavelengths. This study, recently published, is very useful to better characterize the conditions where the confidence in the SWIM observations is the best.

The continuous improvement of the SWIM data processing algorithms at the level 1 (radar cross-section and signal fluctuation spectra), and 2 (wave spectra and parameters characterizing the waves) has been made possible thanks to close collaboration between the expert scientific groups (LATMOS - with support from ACRI-ST, LOPS - with support from OceandataLab and Odyn - and Météo-France) and CNES teams (with support from CLS and CS). It is in particular the work of the scientific teams that has made it possible to propose an empirical modeling of speckle noise and its inclusion in the inversion algorithm, as well as a method for normalizing wave spectra in terms of spectra height (see section 5.3.1). These two elements have been taken into account in the most recent versions of SWIM processing and reprocessing. Frequent and fruitful interactions between these groups and CNES teams also made it possible to improve the correction of the antenna gain pattern at the Level-1 level and to better characterize by flags, the scenes disturbed by the presence of rain or spatial inhomogeneities.

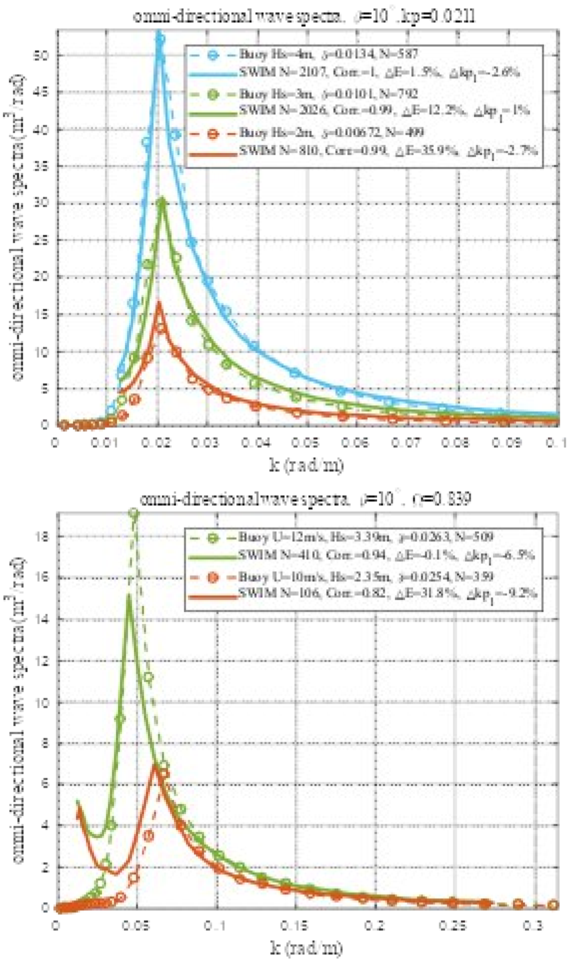


Figure 3 - From Xu Ying et al (2022): Mean omni-directional wave height spectra as a function of the wavenumber of the waves from SWIM (solid lines) and buoy observations (dashed lines with open symbols). The analysis was done over a 2 months data set of SWIM and a 1-year data set of buoy data (NDBC buoys) by splitting the observations in 38 different classes of sea-state conditions. Here are shown the results for 5 of these classes: the swell cases with dominant wavelength of 300 m ±10% and 3 different SWH (left), and fully developed wind-sea for two wind conditions (10 and 12 m/s) on the right.

2.2. SCAT

The originality of the wind scatterometer radar is also its measurement geometry, which combines the specificities of two types of existing or past scatterometers: both a wide swath (like the ASCAT wind scatterometer on METOP for example) and an azimuthal scanning (like the Quickscat concept for example). Therefore, the wind estimation performance was also assessed in detail. The most significant publications in this field are those of Liu et al, 2020, Zhen et al, 2021, Ye et al, 2021. For example, Ye et al, 2021 find a good agreement between the CFOSAT winds and the buoy measurements (cross-over points over 217 buoys): the root mean square errors (RMSEs) of wind speed and direction were estimated to be 1.39 m s^{-1} and 34.3°, respectively, whereas negligible biases were found. These performances are similar to those of other scatterometers (e.g. ASCAT on METOP). Zhen et al, 2021, indicate however that the bias on wind estimate varies slightly with the position within the scatterometer swath; the best wind estimation is found in the sweet swath (between outer and nadir swath), thanks the diversity in geometric conditions in this part of the swath.

The contribution of the French groups concerning the analysis of the SCAT data and the wind inversion algorithm is logically less than the Chinese contribution given the Chinese responsibility on the SCAT. However, it has made it possible to propose an improved method of data inversion (see section 5.5.5 below). In addition, the French contribution made it possible to highlight certain instabilities of the SCAT signals during a transitional period in 2020. Also, the monitoring of the quality of the surface wind from Météo France is still ongoing. First assimilation experiments in ARPEGE operational atmospheric model indicate slight improvement, but also demonstrate the need to avoid using unstable/corrupted data in the assimilation system.

3. GEOPHYSICAL STUDIES

SWIM or SCAT data or a combination of SWIM/SCAT data have started to be used for geophysical analyses, dealing with the properties of wave fields under various conditions (global, waves in cyclones, wave/current interactions, wave/sea ice interactions, waves around coral reefs), global statistical properties of sea states, the impact of waves on exchanges at the air/sea interface.

3.1. WAVE SPECTRAL CHARACTERISTICS AT THE GLOBAL SCALE

For the first time from space, Le Merle et al (2021) could provide global maps of parameters that characterize the spectral shape, in particular the spectral width of the omni-directional spectrum, and the directional spread of the 2D spectrum and compared these results with the same parameters from the MFWAM model. They showed some systematic and significant differences in the shape of the omni-directional spectra with SWIM omni-directional spectra more narrow and peaked than the model spectra with differences amplified in high sea-state conditions as those encountered in the Southern Ocean. One possible reason invoked by Le Merle et al (2021) to explain these differences is the numerical approximations done in the MFWAM model (as in almost all operational models in the world) in the representation of the non-linear interactions between waves. The directional spread was also compared to that corresponding to the MFWAM model spectra, with some differences evidenced (Figure 4 below).

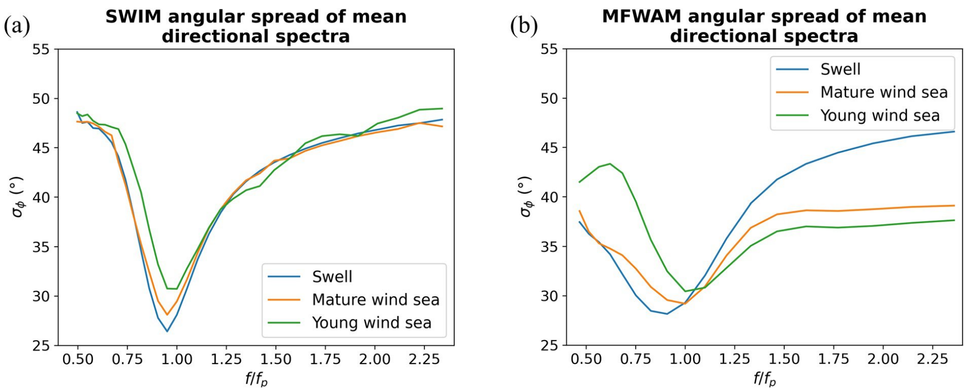


Figure 4 - From Le Merle et al, 2021: Directional spread of the dominant waves as a function of the a-dimensional wave frequency for mean directional spectra in the Southern Ocean corresponding to SWIM (left) and MFWAM (right) . The color code refers to mean spectra estimated for different sea-state category: cyan for swell, orange for mature wind sea and green for young wind sea.

These spectral parameters (frequency width directional spectral), combined with estimates of SWH and dominant wavelength were also used by Le Merle et al (2021) to calculate the so-called Benjamin-Feir index

(BFI). This index is one of those proposed in the literature to characterize the probability of extreme waves. Hence, for the first time, maps of BFI index could be provided (see Figure 5).

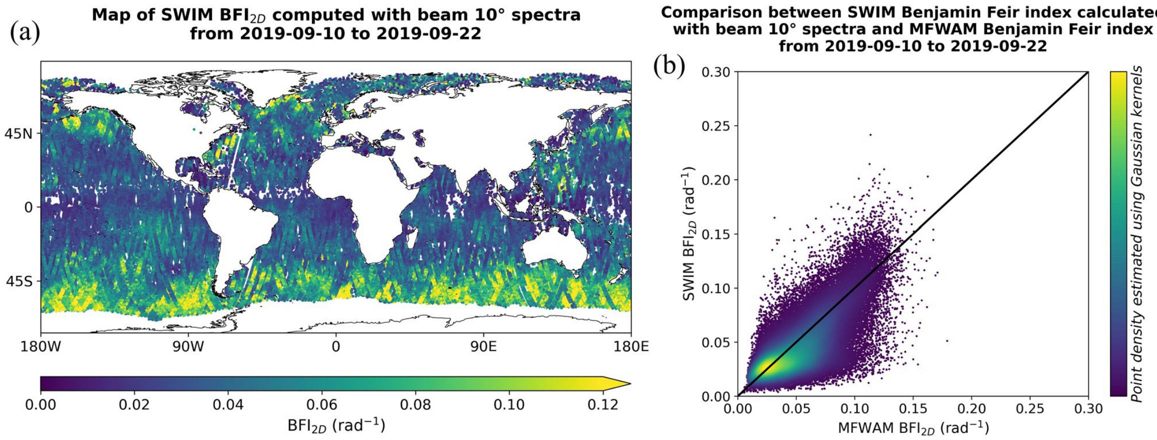


Figure 5 - From Le Merle et al, 2021: (a) Map of the BFI index from SWIM. (b) scatter plot of the BFI index from SWIM (vertical) compared to MFWAM (horizontal).

CFOSAT provides observations that can also be used at the global scale to better characterize the different wave regimes over the ocean. In this domain, Li Huimin et al. (2022) have used estimates of wind speed, significant wave height, inverse wave age and mean surface velocity estimated from the CFOSAT observations to create global statistics of a wind-wave ensemble. Then, a clustering method (k-means) has been applied to classify the sea state into 6 classes, each characterized by a unique centroid and mutually independent. They showed that the use of multiple quantities extracted from CFOSAT observations allows to better describe the complex sea state and to estimate the occurrence of each class at the global scale, showing that different sea states are region specific. This new grouping scheme complements the wind-sea and/or swell classification by resolving the diversity within each wave regime.

3.2. WAVES IN TROPICAL CYCLONES

The very high waves generated by tropical cyclones impact the maritime navigation, the risk in coastal areas and modify the ocean-atmosphere interactions. Wave fields in tropical cyclones have very complex features, due both to the wind field features and to the displacement of the cyclone. Observations are still needed to improve the characterization of the waves in tropical cyclones, better understand the wave growth or dissipation in these extreme conditions and evaluate their impact on the air-sea interaction processes.

Four different studies on tropical cyclones (TC) have already been published with CFOSAT data (Xiang et al, 2021, Shi et al, 2021, Yurovskaya et al, 2022, Le Merle et al, 2022). First, concerning the surface wind in tropical cyclones estimated from SCAT, Xiang et al 2021 showed by a triple colocalization method that CFOSAT provided the least noisy winds compared to those of ERA5 and to the Windsat microwave radiometer. In a complementary work, Zhao et al (2022) show that although rain is a major factor in degrading the wind quality, similarly to Ku-band pencil-beam scatterometers, the CFOSAT-SCAT high wind speed retrievals are generally unbiased for low and moderate rain conditions (up to 6 mm/h), due to the compensated rain effects between low and high incidence angle measurements which are combined in the wind cells.

Regarding the wave fields in tropical cyclones, Shi et al, 2021 found with the SWIM data, some asymmetry in the wave height field, that they relate to the intensity of the cyclones and the geographical area. But the work of Yurovskaya et al (2022) and Le Merle et al (2022) show that this asymmetry depends rather on the displacement speed of the cyclone, in agreement with theoretical studies of Kudryavstev et al (2021).

Le Merle at al (2022) show, on the basis of an analysis of 46 cyclones sampled by SWIM for 1 year, that tropical cyclones with a moderate displacement speed are those whose significant height is maximum and which present the strongest wave height values in the front right quadrant. They also show that fast-moving cyclones do not show asymmetry and are characterized by lower wave heights. These results are consistent with the semi-empirical Lagrangian wave devolution model applied by Yurosvkaya on cyclone Goni (Fig. 6) and confirm that the trapped wave process (group wave velocity of the order of the displacement velocity of the cyclone) is at work mainly in slow or moderately moving cyclones. An additional contribution of the work of Le Merle et al (2022) with respect to previous publications is to discuss the spatial distributions within the cyclones of not only waveheights but also of wavelengths and directions, as well as the shape directional and omni-directional spectra (Fig 7-8). This work also shows the benefit of having observations of wave spectra over a wide range of wavelengths (from approximately 50 to 500 m), covering both the swell domain and that of the wind sea, which the SAR observation does not allow.

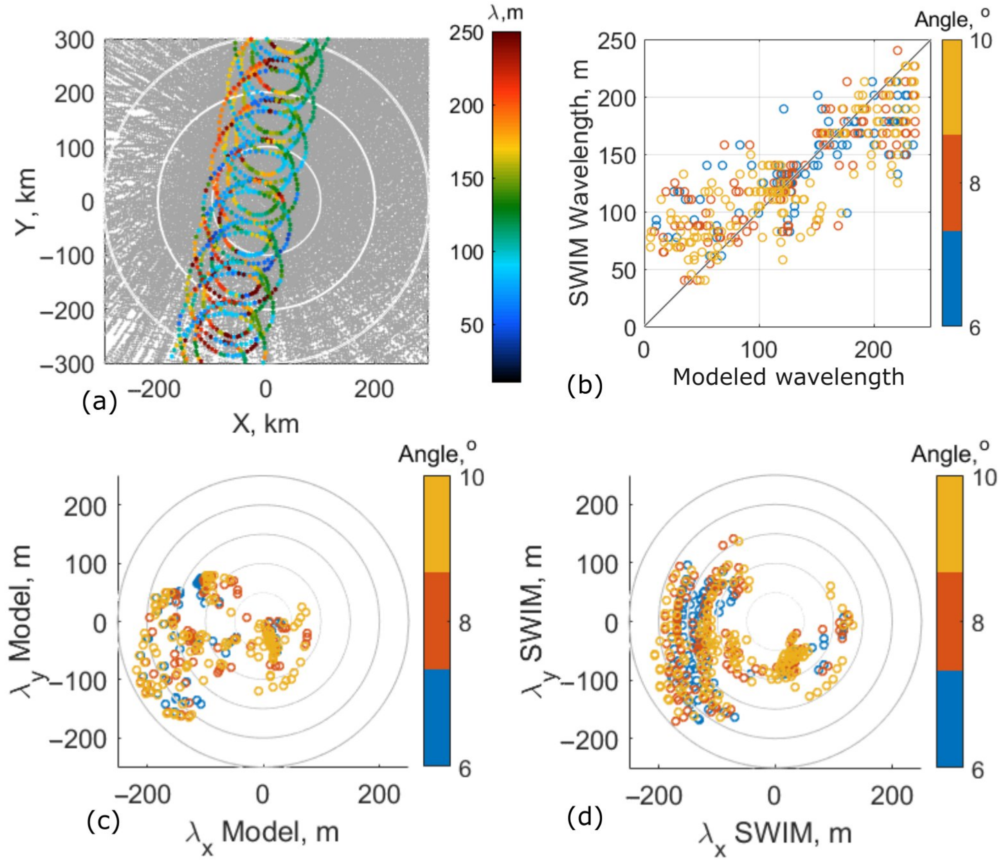


Figure 6 - From Yurovskaya et al, 2022 : (a) The modeled wave-rays (gray) and SWIM off-nadir measurements (6°, 8° and 10° incidence angles). Color indicates the peak wavelength of 1D spectrum transect. (b) SWIM- and KYCM-model derived wavelength comparison. (c) Wavelengths of modeled waves traveling in SWIM viewing direction in the vicinity of acquisition (9 km x 9 km). (d) Peak wavelengths of SWIM-derived spectrum transects.

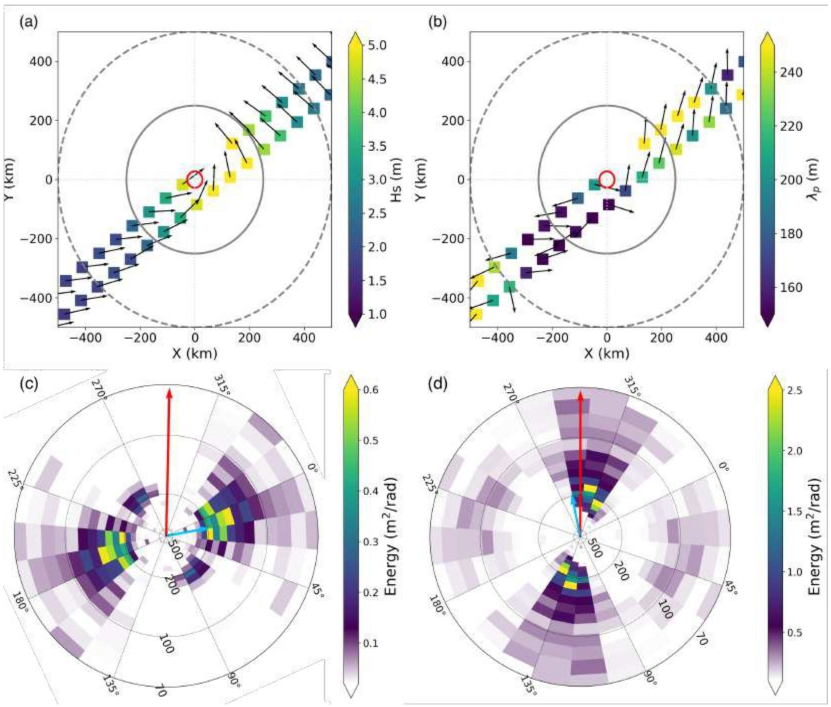


Figure 7 -From Le Merle et al, 2022: SWIM significant wave height and wind direction (a) and dominant wavelength and wave direction (b) along the SWIM track over the hurricane Douglas. The track is presented in the tropical cyclone reference frame (displacement towards the top of the figures). The red circle stands for the radius of maximum sustained wind speed, the dashed grey circle represents 9 times the radius of maximum sustained wind speed and the solid line grey circle represents a radius of 500 km around the storm position during the SWIM flyover. Bottom panels (c and d) show wave slope directional spectra obtained on the left side (c) and on the right side ((d)) of the TC. The blue arrow shows the wind dominant direction and the red arrow shows the propagation direction of Douglas. 0°stands for North direction.

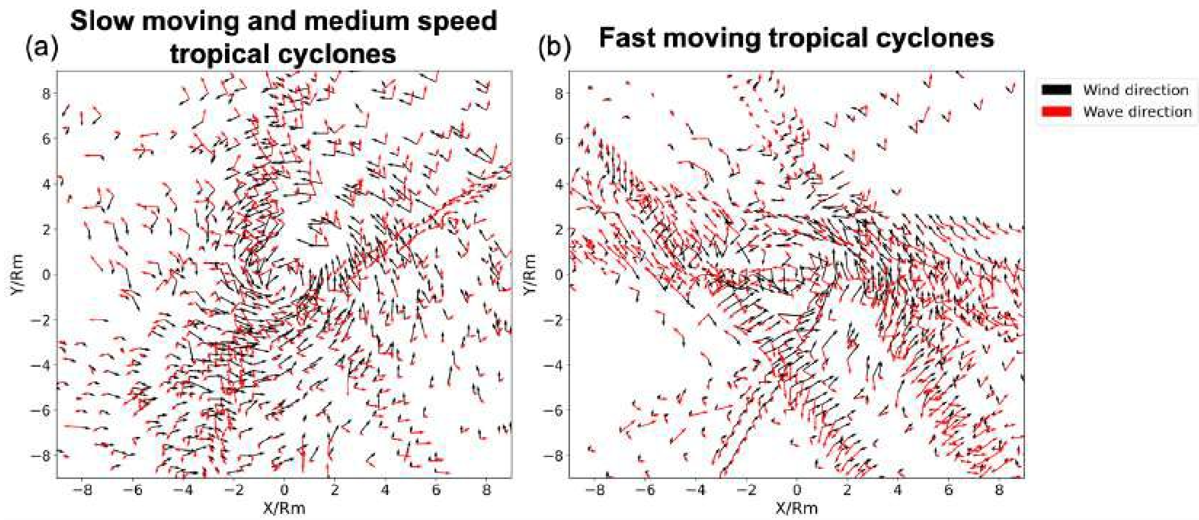


Figure 8- From Le Merle et al, 2022: *Maps of wind (black) and dominant wave (red) directions in slow-moving and moderate speed (a) and in fast-moving (b) TC conditions. All data are plotted in the reference frame of the cyclones (displacement towards the top of the figures). The length of the arrow corresponds to the wind speed at 10 m according to the ECMWF model and to the dominant wavelength, respectively.*

3.3. IMPACT OF WAVES ON THE MOMENTUM FLUX

Another important subject is that of the impact of waves on momentum exchanges between the atmosphere and the ocean. Indeed, it is known that the momentum flux (or wind stress) is at the first order dependent on the wind velocity at the surface but that due to surface roughness modifications, it is also modulated by the presence of the long waves. Moreover, this modulation depends on the type of sea state (locally created wind sea or swell propagated from remote distances). In their study, Chen et al (2021) estimated from SWIM and SCAT observations and an empirical wave-induced stress model, that the ratio of the wave-induced stress to the total stress can reach 30% in zonal mean (Figure 9). To obtain this result, they used a combination of SWIM and

SCAT measurements which allowed them to take into account in a differentiated way the impact of the wind sea (generated locally) and the swell (propagated from the source regions of the storms).

Another way to characterize the wave-induced stress is through the estimation of the mean square slope at the surface (mss). Indeed, the wave-induced stress is directly related to the total mean square slope. From the radar normalized cross-section observations at near nadir incidence like those provided by SWIM, it is possible to estimate this mss quantity assuming that the backscatter follows a geometrical optic law. However, one must also account on the fact that under such an approximation, the mss estimate is a filtered mss which does not take into account the stress supported by the very short waves (shorter than about 2 times the radar wavelength i.e. a few centimeters) which contribute to electromagnetic wave diffraction. Recent developments on the analysis of the SWIM radar cross-section indicate that by adding correcting terms in the backscattering model, it should be possible to estimate the total mean square slope from the SWIM observations (personal communication from Gombert and Poustis). Work is under progress to assess these estimates of the total mean square slope.

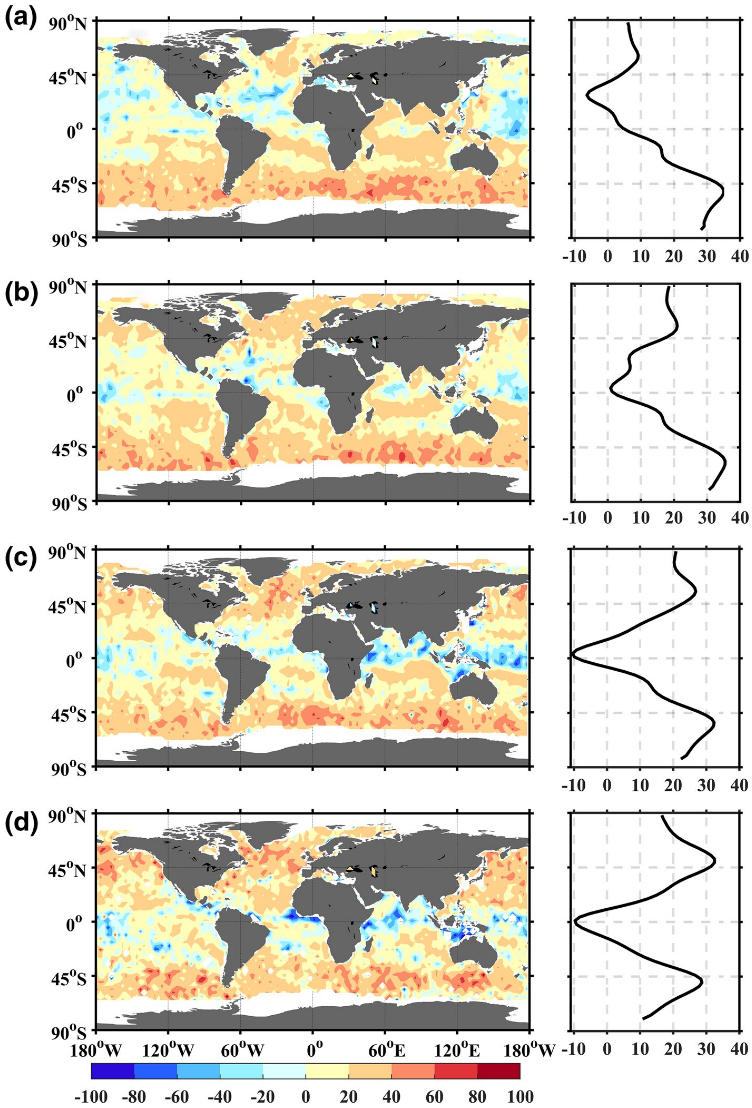


Figure 9 - From Shi et al (2021): The global distributions (left) and zonal variations (right) of the percentage of increase or decrease in wind stress relative to the absence of wave effects for (a) August, (b) September, (c) October, and (d) November in 2019.

3.4. WAVE/CURRENT AND WAVE/ICE INTERACTIONS

The analysis of interactions between waves and current is an important topic, in order to better characterize the regions where the waves are modified by the currents (in amplitude, direction and wavelength). This impacts the focusing effect on waves (which may induce risks for the navigation), and also affects the properties of the waves arriving in coastal areas. It is known that the spatial variability of the significant wave height is amplified in regions of current gradients. As shown by Ardhuin et al (2018), at scales smaller than about 100 km, currents account for more than 75% of the spatial variability of wave heights. The PhD thesis work of Gwendal Marechal, contributed to this topic in a combined analysis of wave spectra evolution in the Aghulas current region using models and CFOSAT observations. It indeed shows the impact of the Aghulas current on the spatial evolution of the SWH as measured by SWIM and on the directional distribution of the waves.

The characteristics of ocean waves in eddies has been investigated by Xie et al (oral presentation, Science team 2021) from simultaneous CFOSAT observation and altimetry data. They showed in particular that the significant wave heights are generally higher inside the eddy than that outside the eddy, and that the wave propagation directions change significantly at the eddy edge.

In a different study, using the surface winds provided by the scatterometer, Wu et al (2022) showed that the non-geostrophic currents estimated from the SCAT wind information (Ekman currents) allow to better predict the drifter trajectories in the Indian Ocean South Equatorial Current than when the winds analysis from ERA5 are used (Fig.10 below). They also concluded from this study that a-geostrophic component could contribute up to 45% of the southward movement of the SEC meander.

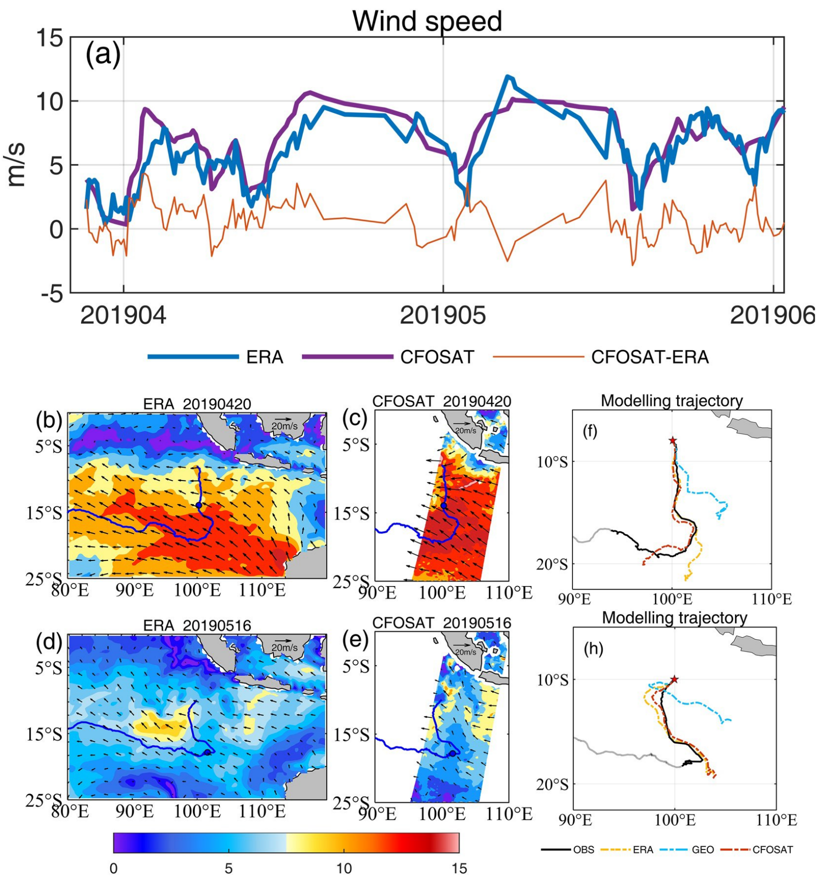


Figure 10-: From Wu et al (2022): (a) Wind speed (line, units: m s −1) along the trajectory of one of the drifters (No. 1342879) derived from ERA5 (blue line) and CFOSAT (purple line) data sets, respectively. The orange line denotes the difference between the two data sets. Wind velocity (vector, units: m s −1) and speed (shading, units: m s −1) of ERA5 (left panel) and CFOSAT (right panel) in (b–c) 20 April; (d–e) 16 May 2019. The blue line and point indicate and the trajectory and location of drifter No.1342879 (b–c); No. 1343747(d–e), respectively. Drifter trajectories (black line) of (f) No. 1342879 and (h) No. 1343747 and trajectories simulated by geostrophic current only (blue line) and reconstructed current field in which includes Ekman component calculated by ERA5 (yellow line) and CFOSAT (red line) from 28 March 2019 to 15 June 2019.

Wave observations from SWIM are also of interest to estimate the Stokes drift due to the presence of the waves, which contributes, together with the Eckman current to the surface kinematics (see preliminary results in section 5.4.2 with Fig. 21 and 22). Even if the Stokes drift estimation form SWIM is still preliminary, these developments offer very interesting perspectives for the modeling of the coupled ocean/wave modeling. As the Stokes drift also impacts the kinematic under the surface (depending on the wavelengths of the waves) estimation of the Stokes drift from SWIM will help to constrain or validate the modeling of the ocean mixing in the upper layers.

It is known that in the Marginal Ice Zone, long waves propagate under the sea-ice. A better knowledge of wave evolution under the ice is necessary to better take into account the wave-ice interactions in the sea-ice spatio-temporal evolution. Remote sensing observations in the polar regions (either radar, or optical sensors) can be helpful for that. Collard et al (2022) have shown that CFOSAT observations may be a useful tool to provide wave spectra under the sea-ice, provided that the sea-ice cover is spatially homogeneous (Fig. 11). This opens new possibilities for the exploitation of SWIM data, taking into account that the probability of sea-ice presence can also be derived directly from the SWIM data (see section 5.4.4).

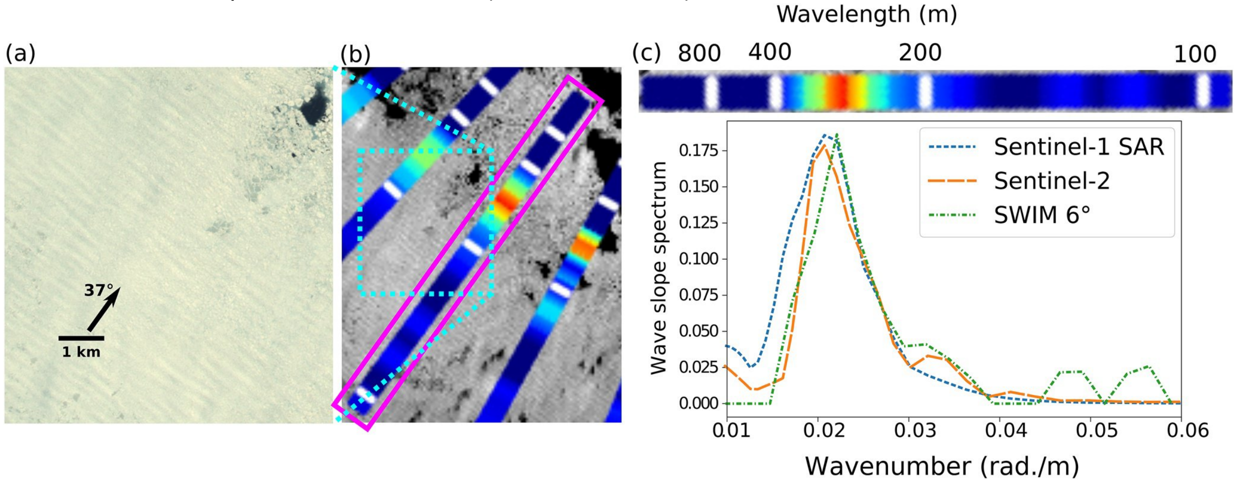


Figure 11 - From Collard et al, 2022: (a) Wave patterns around 76.7°N, 30°E on 12 March 2021 from Sentinel-2, (b) Extended view of (a) with overlaid, the CFOSAT-SWIM spectrum from de 6° beam of SWIM along azimuth 37° (color strips along axis representing the wavenumber scale with white marks corresponding to wavelengths 800, 400, 200, and 100 m) (c) comparison of the directional spectra of the waves under the ice from the SAR image of Sentinel-1 SAR; from the optical image of Sentinel-2 and from SWIM (mean spectrum in the 37° azimuthal direction) in the same region. See Collard et al (2022) for details.

3.5. COMPLEMENTARITY OF SWIM AND SAR OBSERVATIONS

Today there are only two types of missions which can provide the directional spectra of ocean waves and the related parameters: SAR missions (like Sentinel-1; Radarsat-2, Goafeng-3), and CFOSAT with the SWIM instrument. As SWIM is based on a completely different concept compared to SAR, comparisons of observations between the two types of missions is necessary to better identify their complementarity for wave studies at the global scale. In a study focused on observations in the vicinity of coral reef islands (French Polynesia, Pacific Ocean), and after validating the SWIM data against in situ measurements, Oruba et al (2021) have shown that even in this region dominated by long swells originating from the Southern Ocean, SAR-S1 observations are not fully appropriate to characterize the waves on a long-term basis. Indeed, as illustrated in Figure 12 below, the cutoff in azimuth present in the SAR data leads to important distortion in the spectrum compared to the MFWAM model spectrum, whereas the SWIM spectrum is quite consistent with this latter. Statistically over a two year-period, the consistency between SAR and SWIM significant wave height is consistent only if the significant wave height is estimated for waves longer than 160 m (Figure 13 below). On the other hand, Oruba et al (2022) also illustrate from different case study that the S1-SAR provides better estimates of wave parameters in case of low sea-state conditions (below 1.5 m in significant wave height).

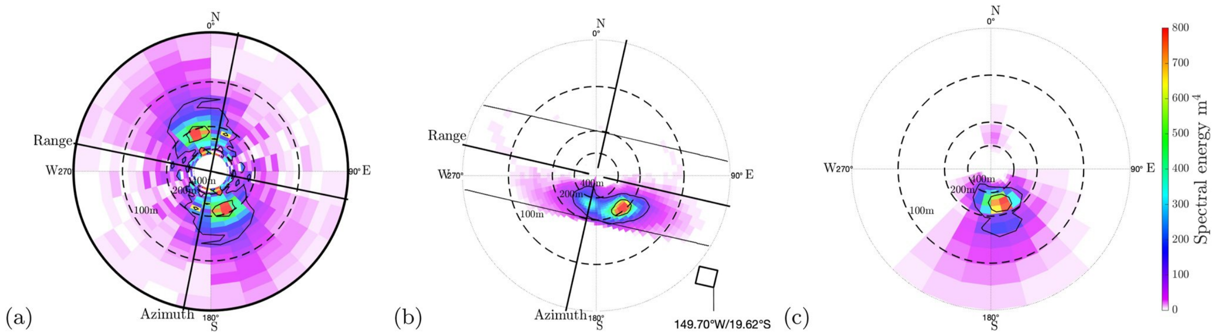


Figure 12 : From Oruba et al, 2022: Example of a two-dimensional wave height spectra in the vicinity of the Moorea Island from (a) SWIM (the 180° ambiguity direction is not removed in this figure), (b) the SAR imagette of S-1 and (c) the colocalized Météo France WAM model. In (a and b) the directions of azimuth and range are indicated as solid lines. In (b), the shortest detectable wavelengths are indicated by the thin solid lines.

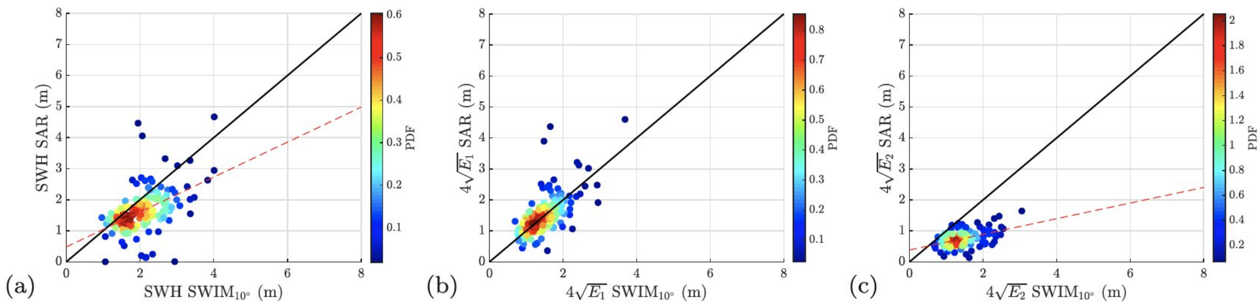


Figure 13 - From Oruba et al, 2022 : (a) 2D histograms of significant wave height (represented as probability density function in colors) from 159 collocated wave measurements of the S-1 SAR (in ordinate) and SWIM-beam 10° (in abscissa). (a) Total significant wave height; (b) partial significant wave height estimated for waves longer than 160 m ; (c) partial significant wave heights for waves shorter than 160 m.

Another study undertaken by Ollivier et al (communication at LPS 2022) illustrates the complementarity between SWIM and Sentinel-1 at the global scale. This is exemplified in Figure 14 below, which shows comparisons for all sea-state situations with dominant wavelengths between 200 and 500 m of the dominant direction, dominant wavelength and significant waveheight from SWIM, Sentinel-1 and the MFWAM model. This shows that SWIM is in better consistency with the reference (model MFWAM) than are the results from Sentinel-1. When we analyze the same maps for conditions when dominant wavelengths are between 0 and 200m, this is also the same conclusion (not shown), except for the direction in the intertropical regions of low significant waveheight, where dominant directions and significant wave heights from Sentinel-1 are in better agreement with MFWAM than are the same parameters from SWIM. For sea-state conditions with wavelengths longer than 500 m (long swell), SWIM reaches its detectability limit (the maximum wavelength provided is 500m), whereas the SAR from S-1 provides consistent data. Hence, it appears that SWIM is very complementary to SAR observations, not only in terms of spatial coverage but also for its better capacity to monitor wave properties in the range [0-500m] than the SAR.

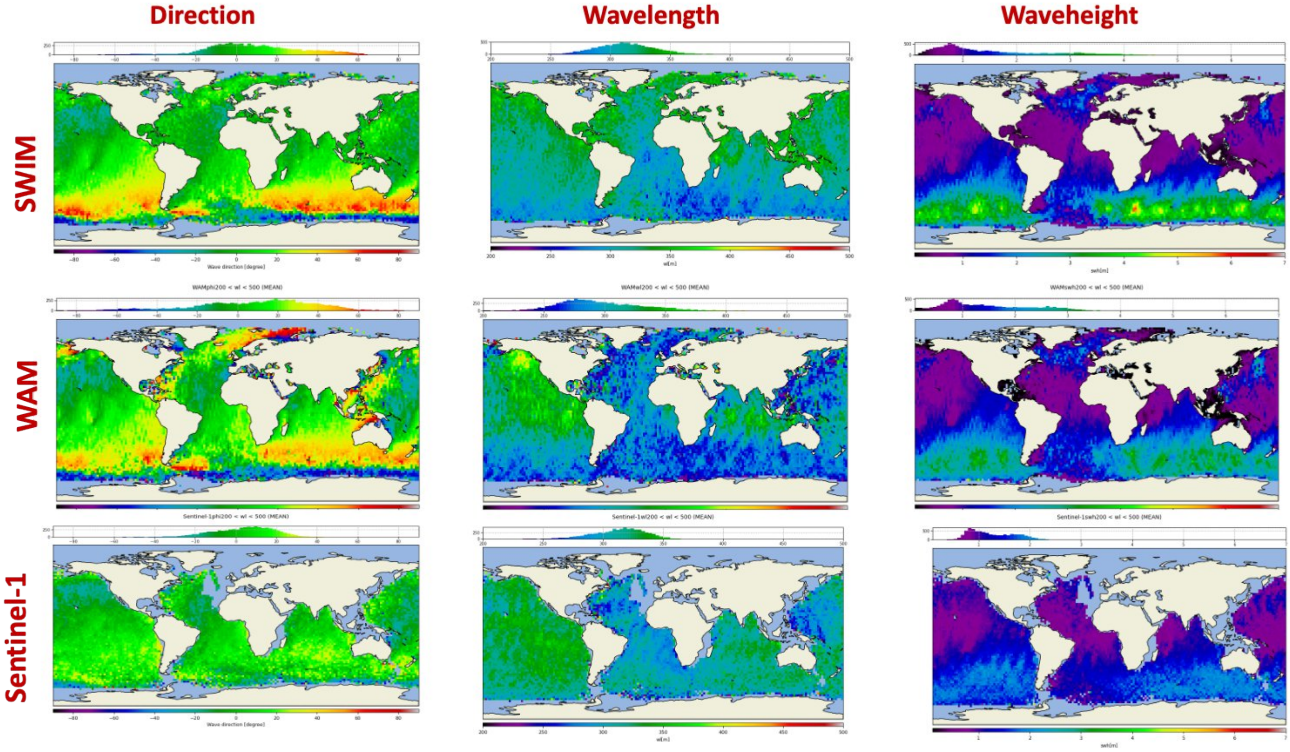


Figure 14- From Ollivier et al (communication at LPS 2022) : Maps of dominant direction (left), dominant wavelength (middle) and significant wave height (right) from SWIM (top), MFWAM (middle) and the SAR of Sentinel-1 (bottom). The parameters are analyzed as mean values estimated over a 2° x 2° grids and a period of 3 months (April to June 2021).

In an analysis combining Sentinel-1 SAR in wave mode, CFOSAT, and the numerical model WW3, Wang et al (2022) estimated statistical errors on the significant wave height of swell for each of these sources of information. By considering only those of the swell wave trains detected by the Sentinel-1 SAR that origin from a unique remote storm center, Wang et al (2022) show from their analysis via a triple collocated method, that SWIM has the least uncertainty in terms of significant waveheight of the swell (0.2 m rmsd, scatter index 11%), followed by Sentinel-1 SAR in WV1 mode and WW3 modeling (0.4 m rmsd , scatter index 17%–20%).

4. USE OF OBSERVATIONS IN NUMERICAL PREDICTION (WAVES) AND MODELLING

Nowadays, most of operational ocean wave forecast systems include the assimilation of satellite data. However, until recently, only the significant waveheight from altimeter observations was considered. It was shown to be efficient but due to the spectral nature of wave energy, the efficiency remains limited (only the total significant wave height is used to rescale the wave spectrum during the assimilation process). Assimilation schemes for assimilating directional spectra have been developed since the years 2000, in particular in the context of the development of the SAR wave mode observations from ERS and ENVISAT, but it is only recently that such an approach has been used operationally, first with ENVISAT data (Aouf et al. 2012, Hasselmann et al. 2013), and now with both Sentinel-1 and CFOSAT data (Aouf et al. 2022).

It was shown with tests performed with the MFWAM model that the directional wave observations provided by SWIM induce a significant correction of the model first-guess during the wind-wave growth phase, particularly for ocean areas dominated by severe storms with unlimited fetch conditions as the Southern Ocean. Figure 15 illustrates the significant reduction of the bias in SWH in the Southern Ocean after the assimilation of directional spectra in comparison with control run without assimilation. This achievement increases the reliability of operational wave forecasting systems to track dangerous seas. Further studies on SWIM directional spectra assimilation also showed that only the assimilation of directional spectra was able to improve the dominant wave period by about 20% especially for swells with wavelengths longer than 200 m. SWIM wave spectra are complementary to SAR of S1 by better detecting shorter waves up to 50 m of wavelength.

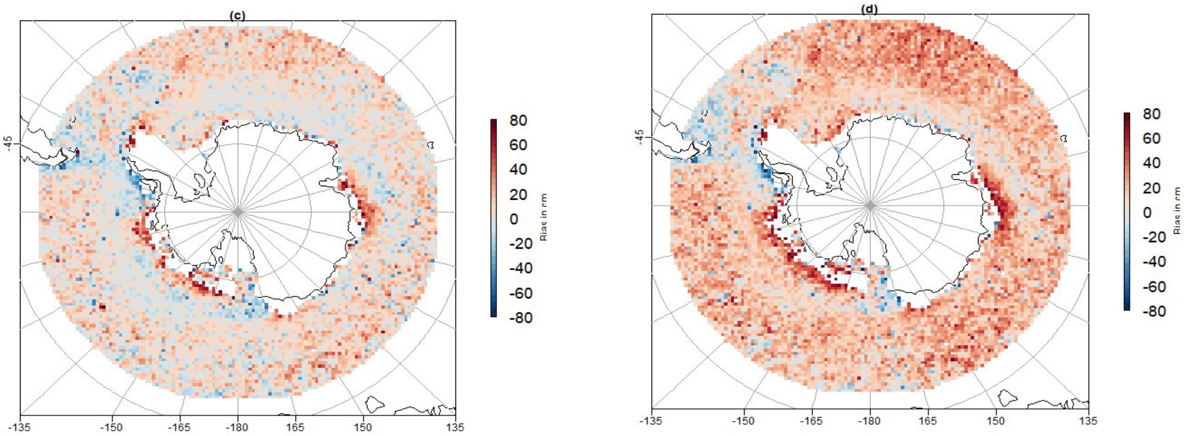


Figure 15 : Bias in significant wave height between model results and altimeter observations (Jason-3, Saral, S3) during the period of January to March 2020. (left) run with assimilation of SWIM wavenumber components, (right) control run without assimilation. Red color means overestimation of the model, while blue stand for underestimation of the model. The maximum bias is of 80 cm.

The assimilation of both directional wave spectra from CFOSAT and S1 has indicated the enhancement of the persistency of the impact up to 4 days in the forecast period (Aouf et al 2022 IGARSS conference). Figure 16 shows the increase of the reduction of scatter index of SWH in the forecast period when using jointly CFOSAT and S1 wave spectra.

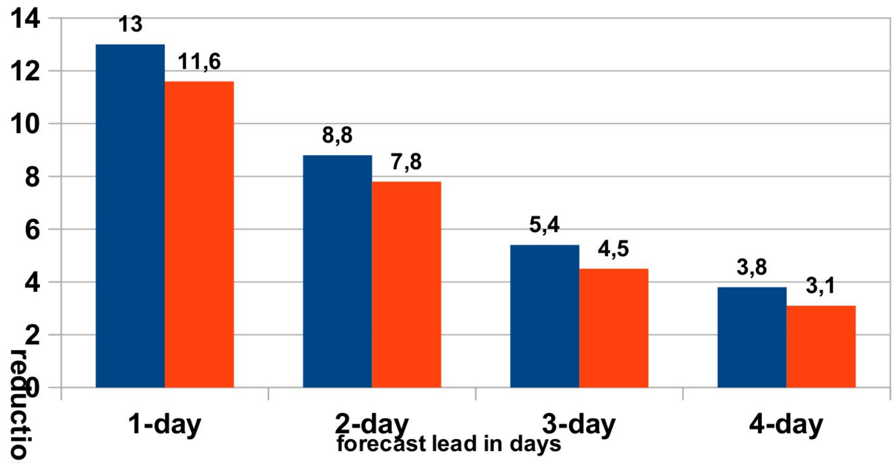


Figure 16: Reduction of the scatter index of SWH in the forecast period. Blue bars stand for assimilation run using jointly CFOSAT wave data (SWH and wave spectra), Sentinel-1 wave spectra and HY2B SWH. While red bars indicate assimilation run without including S1 wave spectra.

Better modelling of sea state at the ocean surface plays a key role in improving the representation in the models of the physical processes that drive ocean circulation. It has been clearly shown that when using SWIM directional wave spectra, surface stress and Stokes drift are significantly improved. This better wave forcing to ocean model leads to a significant improvement of the surface currents in tropical areas and in high latitudes such as the Antarctic Circumpolar Current (ACC) circulation region. Figure 17a indicates the mean difference of zonal surface currents with and without wave forcing improved by the assimilation of SWIM wave spectra, where we can see the significant impact up to 15 % in average, particularly in the tropics and Southern Ocean. Furthermore, as illustrated in Figure 17b, the zonal mean of zonal surface currents reveals good consistency with the climatology mean from drifter observations, and more remarkably better estimate of zonal currents in comparison with CMEMS level 4 altimetry surface currents in mid southern latitudes and southern ocean. The coupled wave/ocean simulations also revealed an improvement of the surface temperature in the tropical regions (not shown) mainly due to a better surface stress and an improvement of the oceanic mixing in the upper ocean layers.

(a) *(b)*

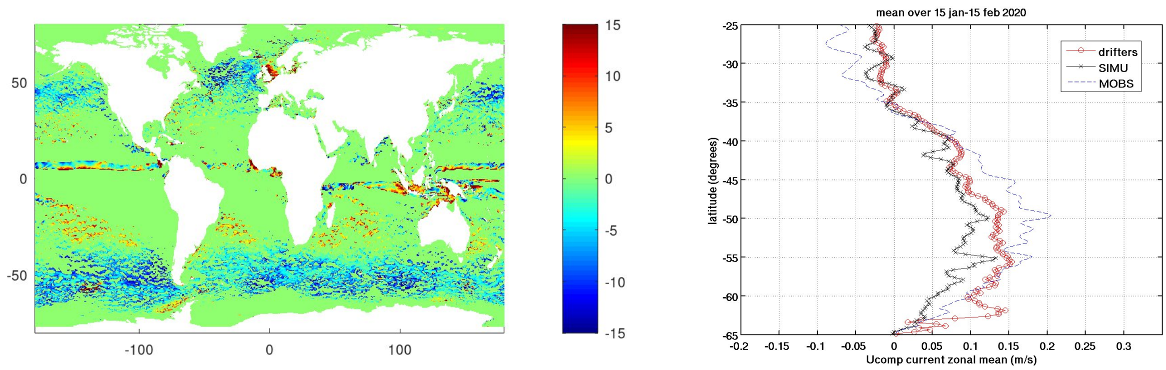


Figure 17 : (a) Mean difference of zonal surface current U with and without wave forcing in the coupled NEMO model experiment during January and February 2020. The wave forcing concerns improved (by the assimilation of CFOSAT wave data) surface stress, Stokes drift and wave breaking inducing turbulence in the ocean mixed layer processes. (b) Zonal mean of zonal surface currents U during austral summer (from 15 January to 15 February 2020). Red circles, black crosses and dashed line stand respectively for drifter climatology, coupled experiment with wave forcing and CMEMS altimetry surface current products (MOBS).

In other respects, directional wave spectra from SWIM have indicated the capacity of better describing the wave variability in the Marginal Ice Zone, with a possibility of estimating the wave attenuation under ice floes. Figure 18 indicates the energy damping as a function of the wave frequency when waves go through ice floes, as obtained from the MFWAM which assimilates in this test, SWIM wave spectra on sea ice free locations. Such developments will open the perspective of implementing a wave-ice interaction source term in the wave model, which will lead to a better understanding of ocean mixing in the MIZ.

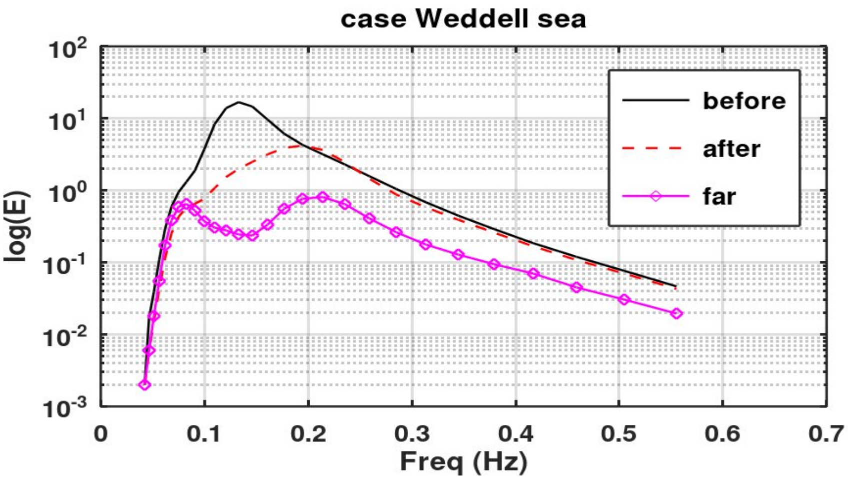


Figure 18 : Variation of 1-D spectral wave energy with frequency in the Weddell Sea on 18 January 2020. The black solid line, the red dashed line and the pink line with circles stand respectively for positions ahead, after and at far distance from the ice floe, respectively. Wave spectra on these locations are provided by model run with assimilation of SWIM wave spectra on sea ice free ocean area.

5. DATA PRODUCTS AND PROCESSING

5.1. ORGANIZATION

It must first be recalled how the data processing and data distribution is organized within the French ground segment.

There are two mission centers in France:

CWWIC operated by CNES in Toulouse (France) for Near-Real Time processing, up to the Level2 products. CWWIC is also in charge of upgrading the level 2 processing chain when this is necessary, and of producing reprocessed SWIM data sets when major release is implemented (about once a year). The products generated by CWWIC are freely distributed (after registration) by the data portal AVISO+ (https://www.aviso.altimetry.fr/en/missions/current-missions/cfosat/access-to-data.html). The products are also referenced on the ODATIS/Data-terra portal (https://www.odatis-ocean.fr/index.php?id=12#/metadata/aef5f7d7-6eed-4201-95fa-8e5b2bd0aa39). CWWIC also transfers within 3 hours after acquisition the SWIM products to EUMETSAT who makes these data available through the meteorological network system (EUMETCast) to agreed meteorological centers (EUMETSAT member states and ECMWF).

IWWOC operated by Ifremer in Brest (France) for differed-time data processing, distribution and archiving (alternative L2 products-called L2S, L3 and L4). The products are detailed and distributed on CERSAT portal (https://wwz.ifremer.fr/cersat/Projects/Recent-and-ongoing-projects/IWWOC) or accessible from the ODATIS French oceanic data center (https://www.odatis-ocean.fr/donnees-et-services/acces-aux-donnees/catalogue-complet/#/search?from=1&to=30&sortBy=resourceTitleObject.default.keyword&languageStrategy=searchInDetectedLanguage&any=IWWOC). The data are available in a free and open manner through FTP or HTTPS. They are fully reprocessed upon each new major release.

In addition, SWIM products (called "L2P") are generated by CLS under the supervision of CNES to feed the European Copernicus Marine Service and made available through the data portal AVISO+ (https://www.aviso.altimetry.fr/en/missions/current-missions/cfosat/access-to-data.html).

The following products are currently available from the French data centres:

from the AVISO+ portal:

- SWIM products from the latest version (presently version 6) of the operational CWWIC chain named "CFO_OPxx", and products periodically reprocessed (about once a year). L1a products include the normalized radar cross-section NRCS at the original SWIM radar sampling, L2 products include the nadir parameters (NRCS, SWH, wind speed), as well as the directional wave spectra and associated wave parameters obtained from the off-nadir beams (6°-8°-10°) and the mean values of radar cross-sections from 0 to 10° incidence. L1 b products are intermediate between L1a and L2 (signal modulation spectra).

- SWIM products called "L2P" products: sub-sample of the CFO_OPxx products with additional data quality control and selection of the main and best variables (when redundancy exists). These products are those which feed the Copernicus Marine Service for their multi-satellite products. See details in https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/SWH_CFOSAT_L2P_Nadir_handbook_SALP.pdf and https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/CFOSAT_L2PBOX_handbook_SALP.pdf;

- SCAT products called from the Chinese NSOAS processing chain implemented at CWWIC: in the global attribute “product version” of CFO_OPER_SCA* products.

from the IFREMER/CERSAT portal

- An alternative SWIM L2 processing, called L2S, providing along-track directional wave spectra in a ribbon geometry, as well as the integrated parameters of the associated wave systems (wave length, significant wave height, direction), over the global ocean;
- sea ice backscatter maps generated daily from SCAT scatterometer over Arctic and Antarctic poles allowing discrimination between sea ice and water but also first-year and multi-year ice;
- a combined product between SWIM and SCAT collocating the measurements of both instruments over the SCAT geometry, with multiple auxiliary fields. This product is especially intended to explore new topics by combining observations from both instruments;
- systematic colocations between CWWIC SWIM L2 and IWWOC SWIM L2S wave measurements and wave spectra estimated from WaveWatch3 model.

In addition, the following products are available since mid 2022 from both the Chinese data centers:

- SCAT products with 12.5 km resolution generated in NSOAS, which optimize coastal wind inversion and named “CFO_EXPR_SCA_C*_coa*_”.

A large part of the expert groups since the CFOSAT launch has been devoted to improve inversion algorithms and products of the CWWIC or IWWOC processing centers. But in addition, new analyses have been carried out (some still under progress) on SWIM or/and SCAT data with the aim to go beyond the variables and products already operationally provided in order to maximize the scientific exploitation. Here below we describe results from the dual activity (improvement or assessment of processing chains and products already implemented, developments of new algorithmic ideas and prototypes)

5.2. SWIM NADIR

As explained in section 2.1, the processing of the SWIM nadir signal is different from that implemented in processing chains of the conventional altimeters. It was verified that this choice provides data of high accuracy in spite of the relatively lowest sampling rate with SWIM compared to conventional altimeters (due to the time spent to sample the signals at off-nadir beams). This offers the possibility of using, for certain applications, the parameters estimated at the highest rate of sampling (5 Hz for SWIM nadir) without further averaging. Therefore, a demonstration product containing the significant wave heigh and wind speed at 5 Hz is now delivered by AVISO (instead of 1 Hz) and made available to the Copernicus Marine Service CMEMS. The interest of such a high sampling rate for the significant wave height was shown in particular by Dalphinet (personal communication) in coastal or island environments (Figure 19 below) for better characterizing waves in this type of environment and to validate or improve high resolution wave models. Figure 15 below shows for example how this 5 Hz sampling enables to characterize the significant wave height evolution in a rapidly changing bathymetry (going from deep water offshore to 30m depth in the coral reef lagoon).

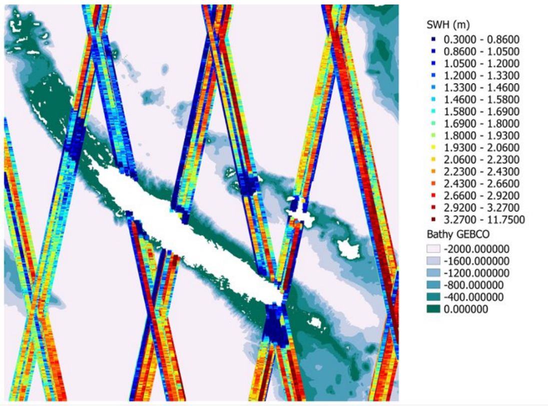


Figure 19 - From Alice Daliphinet (personal communication): six months observations of significant wave height sampled at 5 Hz along the SWIM nadir track close the Nouvelle Calédonie Island (January to June 2021).

5.3. SWIM OFF-NADIR WAVE PRODUCTS

5.3.1. L1 AND L2 PRODUCTS (CWWIC)

Concerning the CWWIC algorithms developed for inverting the wave spectra from the off-nadir beams of SWIM, although they were operational at the date of the launch, they required further successive refinements. In 2020, the first outcome of the scientific expert groups was the evidence of an issue in the on-board processing which prevented to detect the waves in certain directions. Data analysis and simulations were both helpful to find the reason of this problem (error in the on-board processing of the range migration compensation) and convince CNES to correct the on-board software (this was effectively done by CNES in April 2019).

Then, in 2019, 2020 and beginning of 2021, a lot of developments have been done in the scientific expert groups and at CNES/CLS. First, it was necessary to improve the empirical representation of the speckle noise. Indeed, in order to convert the observed radar signal modulation into wave modulations, it is necessary to correct from speckle effects. It was first shown that the simple analytical correction implemented before the launch did not succeed to correct all the speckle perturbations (in particular important perturbations remaining in the along-track directions). Then an analytical model was established, using the SWIM data themselves. It was shown that this speckle perturbation not only depends on the observation direction (which was expected), but also on latitude and surface conditions (wind and waves). A new empirical model was developed (see Hauser et al, 2021), implemented in the CNES operational processing chains and activated in these chains in July 2020 (version 5). Another point which needed evolutions after the launch was the Modulation Transfer Function, i.e. the function which relates the signal modulations (in absence of speckle) and the slope of the waves (and hence provide wave slope or wave height spectra). With the initial version implemented in the operational processing chain, important biases on the wave energy spectra and associated significant wave height were observed. Therefore, after several trials, it was finally decided to use the significant wave height provided by the nadir beam to normalize the off-nadir wave height directional spectra. This modification was implemented in the version 5.1.2 of the operational near-real time processing (December 2020). In parallel, work is still under progress to establish a MTF empirical model. This is carried out by developing IA methods based on collocated SWIM and model (or situ) data.

5.3.2. L2S PRODUCT (IWWOC CENTRE)

In complement to the operational CNES processing chain (called CWWIC) which delivers SWIM near-real time products (in less than 3 hours after acquisition), an alternative processing chain, more specifically oriented towards research users, has been developed and implemented by IFREMER/LOPS (called IWWOC). It provides in particular alternative SWIM L2 products (called L2S) in deferred time. The main specificity of this chain is that it does not estimate the wave spectra in wave cells organized along the nadir track as in the operational CNES product (see Fig. 20 left), but keeps the original geometry along a cycloid geometry (called also ribbon)- see Fig. 20 (right). Another specificity is that it keeps the observations from the 2° and 4° to tentatively estimate wave properties from these beams (although not specified for this objective and therefore perturbed by the absence of correction for range migration). This chain is also used by the LOPS to test alternative versions of the speckle and Modulation Transfer Function correction (still under progress). An example of products in the L2S geometry is illustrated in Fig. 20 (right).

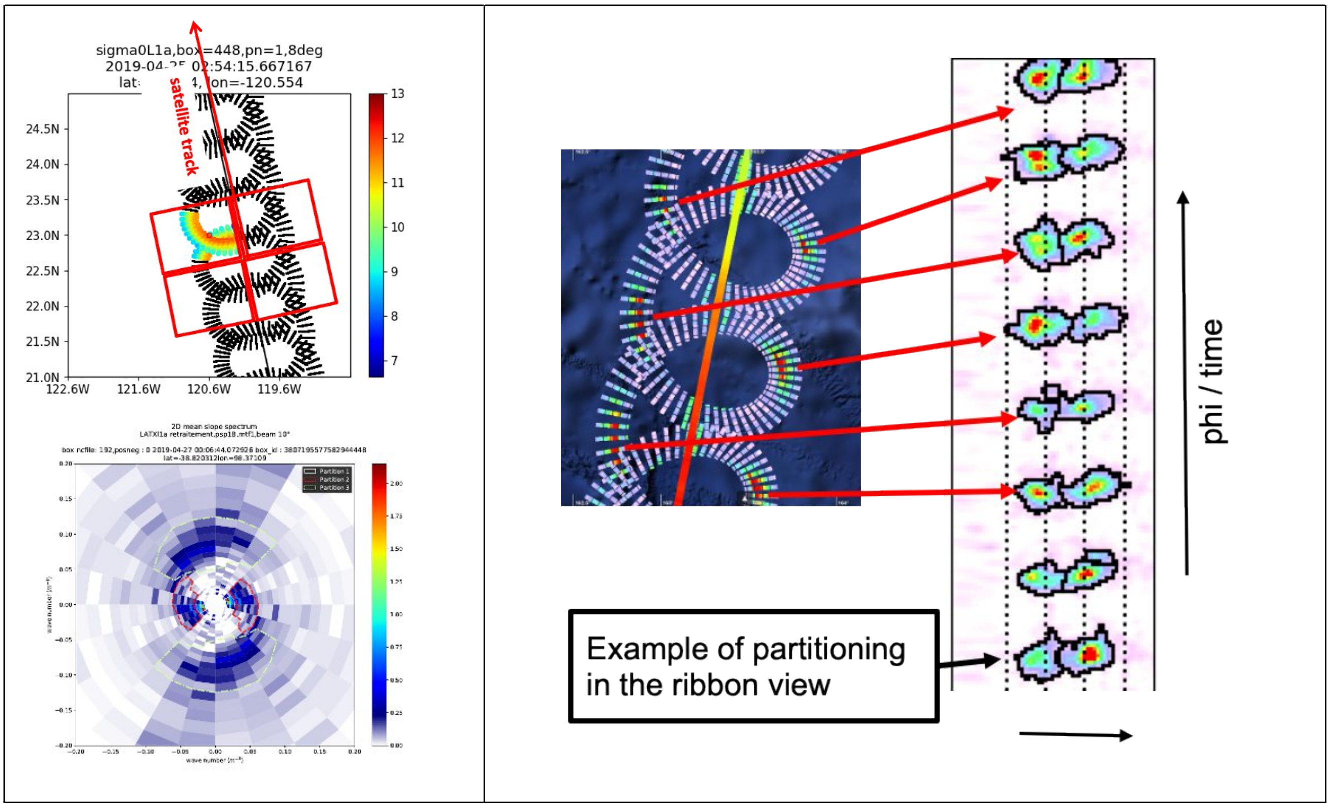


Figure 20- Left top: Geometry of SWIM wave cells (red boxes) as defined in the CWWIC product: the overlap of successive azimuthal scans – (illustrated here for the beam 10°) is used so as to build directional spectra (defined over 180°) in the wave cells on each side of the nadir track (red boxes)- Left bottom= example of a 2D wave slope spectrum built from directions samples in a wave cell. Right: products as analyzed by the IWWOC processing chain: the colored segments organized in cycloid, represent the energy density of the wave spectrum along the radial directions sampled by the SWIM beam (here with the 6° beam incidence). The scale along each segment is the wave number (small wave numbers at the interieur of the cycloid). The color along the nadir track refers to the significant wave height. Right: wave partitions estimated from the results presented along the cycloid. The horizontal axis is the wave number, the vertical axis is time.

The interest of this type of product compared to the standard CWWIC product is mainly for case studies in non-homogeneous conditions (fronts, storms, regions close to coasts, islands or ice margin), as the spectral information can be exploited without requiring to gather all the 180° directions in a given wave cell. But work is still under in progress to provide wave information with all the necessary corrections. In particular, a method based on IA is currently under development for estimating the MTF applicable in all conditions. Another advantage of the L2S product is that it does not filter the spectral energy at wavelengths longer than 500m, which enables a better characterization of long wave situations provided that the wave significant wave height is large (so as to avoid the parasitic peaks).

5.4. DEVELOPMENT OF ALTERNATIVE AND/OR COMPLEMENTARY PRODUCTS AND THEIR PERSPECTIVE OF USE

5.4.1. WAVE HEIGHT ON AN EXTENDED SWATH

Based on the synchronous and partly co-located observations from the wind scatterometer (SCAT) and from the wave scatterometer (SWIM), Wang et al (2021) have developed a method based on a deep neural network approach, for retrieving the significant wave height over an extended swath compared to the swath of SWIM. It was shown that the method enables to estimate the significant wave height over SCAT grid points over a swath of up to 200 km with a good accuracy (rms difference of about 0.26 m against independent match-ups with Jason-3 and SARAL/AltiKa), thanks to a combined use of information from the SCAT (wind speed), and SWIM (sigma0 from nadir, peak period and significant wave height). It was also shown by Wang et al (2021) that assimilating this extended-swath SWH enhances the positive impact of assimilation compared to the case when only SWH from nadir observations are used. Further, the assimilation of such swath SWH allows tracking swell generated by severe storms from open ocean to coastal areas. It is now envisaged to assimilate routinely this extended-swath SWH in operational wave model to improve the wave submersion warnings. Currently NSOAS is implementing the processing of swath SWH as level 3 products to be disseminated to operational users.

5.4.2. STOKES DRIFT FROM SWIM OBSERVATIONS

As mentioned in section 3.4 another byproduct of SWIM observations is the estimation of the Stokes drift current. Peureux (personal communication presented during French Workshops) estimated the Stokes drift (omni-directional estimate) by using the wave spectra information and showed its consistency at the global scale (Fig. 21).

He also estimated the empirical relationship between the Stokes drift, wind speed and significant wave heights (Fig. 22) and showed that this relation is consistent in a statistical sense with the results from the numerical prediction model WAM. The results also show that for a given wind speed, the Stokes drift is dependent of the sea-state conditions (young or developed wind sea or swell). Even if this Stokes drift estimation only accounts for waves longer than 30m (thus underestimating its intensity without further correction), it is a variable which will interest applications related to drift of pollutants. Work is under progress to compensate the underestimation due to the detection limit of SWIM (around 30 m) and to propose a vectorial estimate of this parameter.

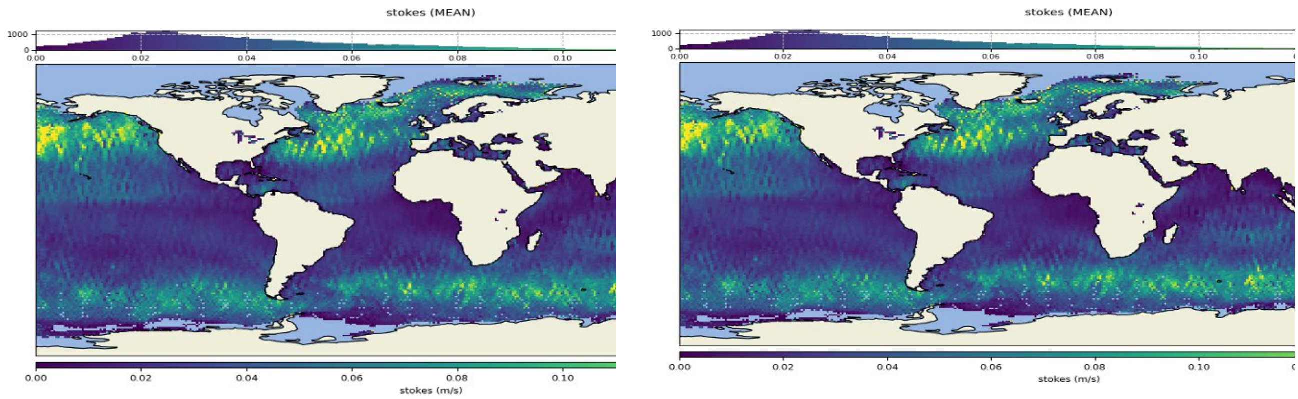


Figure 21 - From Peureux (personal communication): Stokes drift intensity (left) and Stokes drift transport (right) estimated from the SWIM omni-directional wave spectra for the month of January 2021

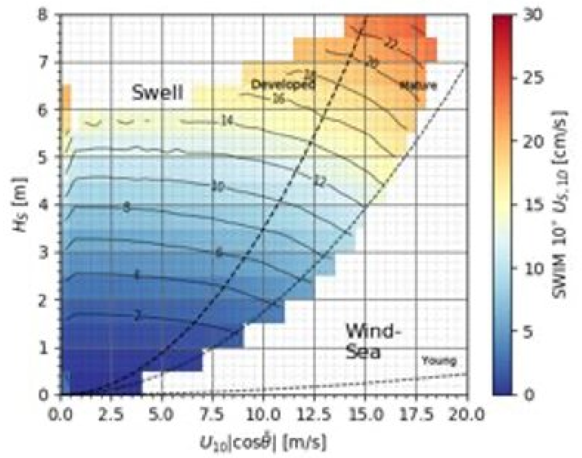


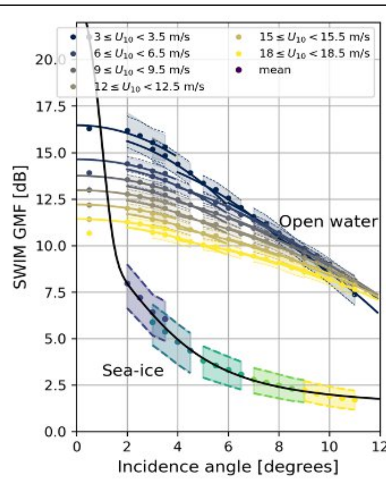
Figure 22 - From Peureux (personal communication): Histogram of the Stokes drift intensity estimated from SWIM observations plotted as a function of wind speed and significant wave height.

5.4.3. REVOMING THE 180° AMBIGUITY ON THE WAVE PROPAGATION DIRECTION

In a collaboration between French and Chinese groups, a study has been carried out to analyze the possibility to remove the 180° ambiguity in the propagation direction. This work was carried out by analyzing, from the L1 products, the upwave/downwave asymmetry of the spectral modulation spectra. It showed promising results (Li Huimin et al, 2021). However, it is not yet envisaged to transfer it to the operational CWWIC processing chain.

5.4.4. SEA ICE FROM SWIM AND FROM SCAT

Although the SWIM observations are mainly dedicated to monitor surface ocean waves, they can also be used to monitor other surface parameters and in particular the sea-ice properties. A Bayesian method has been developed by Peureux et al (2021) to estimate the sea-ice coverage probability based on the analysis of the normalized radar cross-section and its dependence with incidence angle (see Figure 23 below). First maps of sea-ice flag at a resolution of about 20 x 20 km were provided in Peureux et al (2021) but intrinsically the method can be used at a higher resolution. The method is under implementation in a prototype processing chain by CNES, so as to offer a demonstration product.



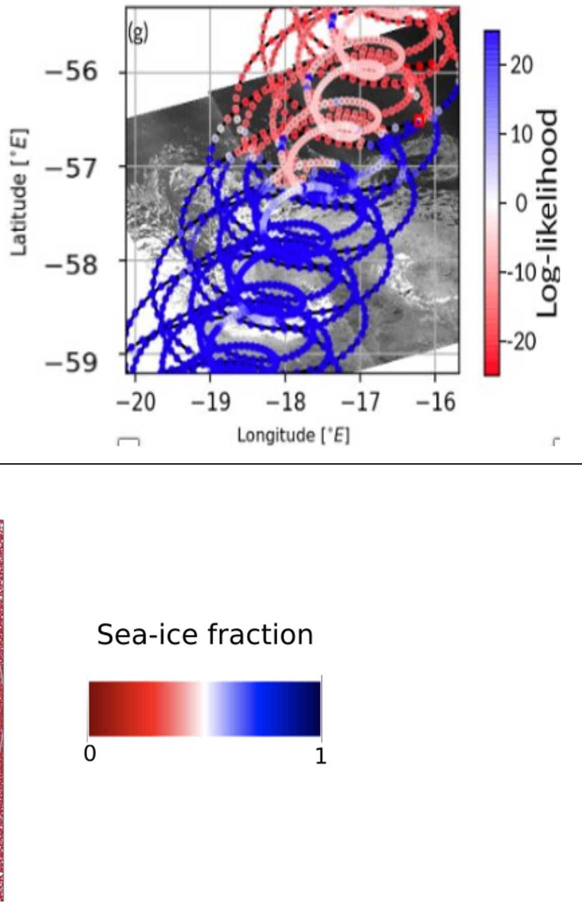


Figure 23 -From Peureux et al, 2021 and Peureux personal communication, 2022 : Top left : Mean and standard deviation of the Normalized Radar Cross-section as a function of incidence angle between 0 and 11°, over open water and sea-ice. For the open water case, the curves depend on wind speed (see inset). Top right: Log likelihood of the presence of sea ice for one example of SWIM track. Bottom: sea ice fraction around Antarctica estimated from the Bayesian algorithm applied to the 10° beam observations

Benefiting for more than 30 years of expertise on the ice detection and characterization from scatterometer measurements, IWWOC extended these methods to the analysis of the CFOSAT normalized backscatter coefficient to provide a CFOSAT-SCAT ice product in both Arctic and Antarctica regions, which contains at the 12.5 km resolution the ice/water mask, and parameters on ice edge, ice extension, nature of ice (annual or multi-year).

5.4.5. IMPROVED SCAT INVERSION

The complementarity between SWIM and SCAT has been exploited to improve the wind retrieval from the scatterometers observations. This method uses an additional constraint in the inversion of SCAT data, by integration the SWIM nadir beam parameters in the cost function used for inversion. This method has not yet been implemented operationally but should be soon (within the IWWOC non-real time processing center of IFREMER).

6. TRANSFER TO OPERATIONAL APPLICATIONS

The assimilation of SWIM directional wave spectra into operational wave models has been significantly improved with the updated level 2 processing OP05. Results have shown the ability of SWIM wave spectra to better scale wind-wave growth and to better describe the propagation of long swell generated over stormy areas such as in the Southern Ocean. Since February 2021, the Météo-France global wave models assimilate SWIM wave spectra from beam 10° in operational mode. One of these operational chains provides global wave products for the Copernicus Marine Service (CMEMS). The regional CMEMS systems over the IBI (Iberian Biscay Ireland) area managed by NOLOGIN (Spain) will implement into operational production the assimilation of SWIM wave spectra at the end of 2022. Directional wave observations from SWIM provided by CMEMS-Thematic Assembly Center (TAC) contribute to the quality verification of the integrated sea state parameters developed by the regional forecasting centers of the MED (Mediterranean Sea), BAL (Baltic sea), BS (Black sea) and Arctic ocean domains. Other meteorological agencies (ECMWF, UK Met Office, Environment Canada, JMA,...etc) are currently carrying out work on assimilation of SWIM spectra and also on validation of the wave physics of their wave models. These agencies have strongly requested the availability of SWIM data in the GTS network managed by WMO.

In other respects, CFOSAT is the only mission providing a better sampling of SWH at 5 Hz from nadir. The 5 Hz SWH from SWIM-nadir have shown an excellent ability to describe near-shore wave variability and to monitor wave/current interactions. Furthermore, the quality of SWH with 5 Hz sampling opens perspectives for exploitation in the assimilation for fine-scale and coastal wave models. Impact studies of 5Hz wave height assimilation have shown strong improvement in the scatter index for SWH below 2 m.

7. PUBLICATIONS & COMMUNICATIONS

The number of publications in international journals with peer-review since 2014 is given in Figure 24 below. Since 2018, the total number is 56 publications in peer-review journals.

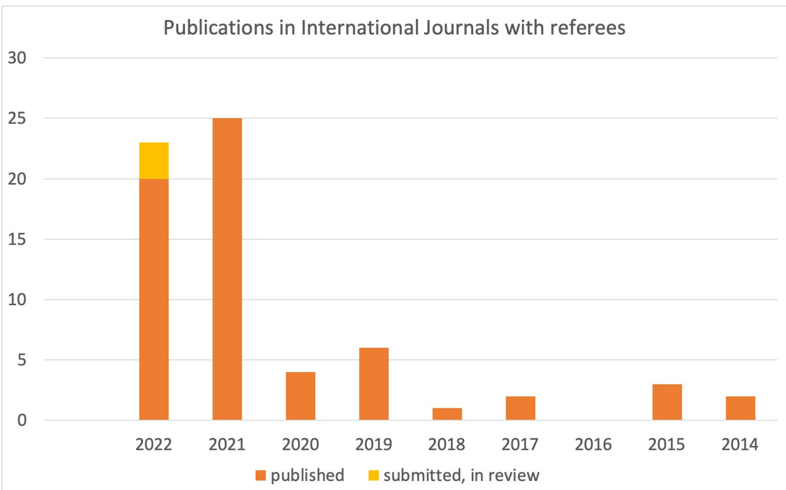


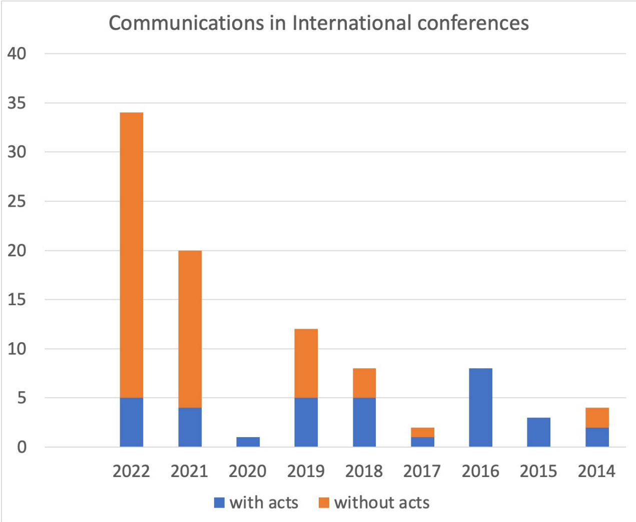
Figure 24 : number of publications in international journals with peer-review since 2014 dealing with CFOSAT observations

The detailed list of publications associated with CFOSAT **since 2018** is in given section 11.

It should be noted that thanks to an active solicitation from the CFOSAT PIs to Journal editors, a special collection on CFOSAT has been issued by AGU in 2021: it gathers 15 of the publications submitted and accepted in 2020 and 2021 to AGU journals (Geophysical Res. Letters, Journal of Geophysical research Oceans, and Earth and Space Sciences). This approach was proposed in order to give visibility to the results obtained from this new mission.

According to Web of Science (query on July 2021) the number of publications with CFOSAT cited is 528 and the citation index with "CFOSAT" as keyword is 11. This is not yet a large number but with a clear increase in 2021 and 2022.

As concerns the communications only an approximative number is shown in the figure below.



The main workshops, conferences or symposia during which results from CFOSAT have been presented to the international community are:

- On an annual basis, at the OSTST meeting (splinter session dedicated to CFOSAT, 6 to 10 presentations on CFOSAT)
- Annual IEEE Symposium on Geoscience and Remote Sensing -IGARSS- (between 2 and 7 presentations since 2016)
- European Geophysical Union Symposium (2 to 3 presentations each year)
- Living Planet Symposium (2 to 8 presentations in 2016, 2019 and 2022)
- Waves in Sea Water Environment -WISE meeting (2 to 4 presentations in 2019, 2020, 2022)

In addition, about 30 presentations are given and discussed during the annual CFOSAT Science team meeting, jointly organized by the PIs and CNES (2018, 2019, 2021, 2022)

Finally, It is worthwhile to cite two invited communications on CFOSAT (Hauser, 2021) in the context of :

- ISSS (international Institute for Space Studies)- Bern (March 2021)
- the CCI sea-state user meeting (March 2021)

8. INTERNATIONAL COOPÉRATION

The main collaborations between French research groups and other groups are identified here below. Several of them are developed in the context of projects proposed in response to the research call issued by CNES, while others follow either historical contacts or contacts initiated during CFOSAT science team meetings and/or presentations on CFOSAT in various conferences or working groups (WISE, CMEMS, …).

[France/China or France/China/other] :

- LATMOS/Huazhong University: SWIM data assessment, theoretical studies on speckle effects (using also airborne data from KurOS), analysis of non-linear MTF effects on SWIM wave spectra retrieval

- Météo-France/NMEFC (National Marine Environment Forecasting Center) : new products from SWIM using deep learning methods, data assimilation (also supported by the ESA Dragon 5 program)

- LATMOS-LOPS/NUIST: SWIM data analysis (attempts to remove the directional ambiguity), analysis of wave regimes at the global scale

- LOG/Xiamen University/NSOAS: scales of variability of wind and waves (also supported by the ESA Dragon 5 program)

- ODL/China University of Geosciences/University of Melbourne: assessment of wave products

- LOPS/KNMI/NUIST/NSOAS/NOTC: assessment of wave products, rain impact on SWIM data

[France/Spain] :

Météo-France/NOLOGIN: Assimilation of wave spectra in the frame of CMEMS-MFC-IBI, impact of SWIM on ocean/wave coupling (sub-meso scale criculation), assessment of SWIM products on IBI ocean domain

[France/Italy]:

LATMOS/CNR-ISMAR: waves at the global scale, waves in tropical cyclones

[France/Portugal] :

LATMOS-Meteo-France/University of Lisbon: wave/current interactions

[France/Germany] :

Météo-France/HEREON: Assimilation of wave spectra in coastal regions, assessment of SWH (5Hz).

[France/United Kingdom] :

LATMOS/Keele University: use of radar observations (KuROS, SWIM) in support of new theoretical or numerical methods to represent the non-linear interactions between waves

[France/Russia] :

LOPS/MHI-Sevastopol/Russian State Hydrometeorological University, Saint Petersburg: waves in tropical cyclones, wave/current interactions

[France/Canada] :

Météo-France/Environment Canada: Assimilation of wave spectra and SWH in wave model, Rogue waves indicators

Meteo-France/Shirshov Institue of Oceanograpghy,: modéeisation/observation of the wave evolution

[France/Japan] :

Météo-France/University of Kyoto (Amin Chabchoub, Nobuhito Mori) : extreme wave indicators from CFOSAT

Météo-France/University of Tokyo (Takuji Waseda) : Wave/ice interactions in the Marginal Ice Zone

[France/Malaysia] :

Météo-France/University of Malaya/Institute of Ocean and Earth Sciences (Wee Cheah) : Validation of CFOSAT wind and wave data in Malaysian seas

[France/Australia] :

Météo-France/CSIRO/University of Melbourne: Wave climatology, ocean/wave coupling, wave-ice interactions, synergy between Sentinel-1 and CFOSAT

9. PERSPECTIVES

9.1. PROGRAMMATIC CONTEXT

The CFOSAT mission leads to better understanding of the physical processes at the ocean surface and their important role in a coupled earth system (ocean/wave/atmosphere/ice). The cooperation with the Chinese teams is of excellent quality and has resulted in several major scientific publications. We want to continue and strengthen this cooperation to make the best use of CFOSAT observations (SWIM and SCAT) and also the synergy with other missions like HY-2 and Sentinel-1. With the loss of Sentinel-1B, the CFOSAT mission will be more solicited to fill the missing data in the framework of the Copernicus Marine Service (CMEMS). Several CMEMS forecasting centers are implementing assimilation algorithms to exploit the directional wave observations of SWIM in Near Real Time applications. CFOSAT will also play an important role in the qualification of CMEMS wave systems and the impact on the coupling with global and regional ocean models.

The cooperation with ESA in the DRAGON-5 and CCI programs will be strengthened to integrate the CFOSAT wave data into the framework of essential variables for wave climate analysis and the ocean-atmosphere interactions.

The CFOSAT mission is the first satellite to observe waves and wind in the same ocean region, allowing closer analysis of wind wave growth. This experience puts CFOSAT in a key role for the future Earth Explorer missions such Harmony and Seastar. The interaction with the project teams in the CFOSAT science team will allow to better prepare these missions to reach their objectives. In addition, the CFOSAT mission will also play an important role in the CAL/VAL phase of SWOT. This concerns the aspects of improving the retrieval of wave products, dependency of swell properties and understanding the wave-ocean coupling for the mesoscale circulation.

The success of CFOSAT also opens a perspective of continuity in a new follow-on mission. Improved concepts in the SKIM project have already been carried out and show a great interest to continue the development of these directional wave observations accompanied by surface current observations (Doppler capacity). Further, the need of such wave and currents data is crucial for the reliability of future Earth system models.

9.2. SCIENTIFIC OBJECTIVES

The objectives of the extension of the CFOSAT mission are of course to continue increasing the number and quality of wave and wind observations from SWIM and SCAT, and to strengthen the scientific applications identified from the latest achievements in the framework of the science team and the needs expressed by the scientific community. The objectives are in line with the following thematic axes:

- Exploit the novelty of SWIM directional wave observations in the physics of wind waves and their impact on ocean-atmosphere interactions. This includes to:

- Better characterize and forecast wind and waves in extreme events (tropical and extra-tropical cyclones) and their impact on the ocean
- Better characterize wave/current interactions at the global scale

- Better understand and represent in models the impact of waves on the oceanic mixing layer (in particular in marginal ice zone, tropical regions and regions affected by big storms)
- Exploit the SWIM capacity of proving the sea ice fraction (and sea ice properties) and use this information in relation with the study of SWIM wave spectra in the marginal ice zone and the processes of wave/ice/ocean interactions.

- Intensify the use of SWIM directional observations for coastal ocean areas including coral reef regions (characterize the incident waves on the coasts), study their direct or indirect impact

- Further analyze the synergy between SWIM and SCAT, in particular in coastal areas (wind)

- Use SWIM wave spectra to validate the retrieval of directional observations from imaging sensors (Sentinel-1 and Sentinel-2)

- Contribute to the survey of essential climate variable monitoring (CFOSAT proving new information on wavelengths and directions of wave systems)

- Exploit the synergy between SWIM and CSCAT observations and other ocean surface wind, wave and current observations from space (ASCAT, S-1, S-2, S-3, S-6, Saral, Cryosat-2, Cygnss, GPM, ..)

- Contribute to validate or prepare new satellite missions (SWOT, Seastar, Harmony, WACM) or new products from altimetry such as FFSAR (Fully Focused SAR) for directional spectrum retrieval in the framework of Sentinel-3 and S6MF missions. This latter is a great challenge for next generation altimetry missions.

- Enhance the cooperation with Chinese teams and synergy between CFOSAT and HY2 missions.

9.3. APPLICATIONS

The release of the data on the GTS will accelerate the use of CFOSAT wave data for meteorological centers such as EC, JMA, UKMO, ECMWF and NOAA, and also other WMO affiliated centers. The wave data will be used at least for model validation and preparation of marine safety bulletins by forecasters.

One also can mention that research work is ongoing in some centers to assimilate both SWH and wave spectra CFOSAT NRT data into operational wave models. For SCAT wind data, the priority is to have stable wind data over a long period in order to foresee an operational use in NWP models.

The upgrade of the processing chains for both SWIM and SCAT will play an important role in improving the quality of the data and to include new parameters. This will allow the use of the data in model reanalyses such as the ones implemented in frame of CMEMS and also for users linked to ESA CCI project. Reprocessing will also encourage the development of wave and wind climate analysis in some critical ocean regions.

Additional specific objectives and challenges at the operational level are also identified as to:

- Develop the use of SWIM directional observations for operational sea state forecast in coastal areas.

- Propose and/or test indicators of extreme waves from SWIM wave data and develop the perspective of exploitation by the actors of maritime transport, navigation safety and wave submersion warnings from operational forecasting centers.

9.4. PLANNED ACTIVITIES

The scientific activities will be different by different groups around the word Most of them have formally submitted a proposal in response to the research opportunity announcement issued by CNES in April 2022 (20 received from 12 different countries). But we know that other groups will also develop scientific activities based on SWIM data even if then did not respond to this call.

Overall, the objectives and expected studies are the following ones:

- Improvement of wave models or coupled ocean/wave/atmospheric models based on SWIM and/or SCAT observations. This objective is dual: i) operational wave forecast, ii) development of research coupled models to better understand the interactions between all components of the Earth system (7 proposals within the 20 received)

- Improvement of understanding and representation of wave generation and evolution in extreme conditions (tropical and extra-tropical cyclones), evaluating conditions of occurrence of extreme waves (7 proposals within the 20 received + another study on wave groups in big storms)

- Better characterization of the wave and/or wind field in specific areas = 8 proposals with identified areas of interest such as Southern Ocean, shallow coastal sea East around Korea, inland waters - lakes, Baltic sea, Caribbean sea, coasts of Chili, waves in coral reef environment, marginal ice zone)

- Better understanding and characterization of the impact of waves on the coupled ocean/wave system (3 proposals), or on wave/ice interactions (2 proposals)

- Use of CFOSAT observations for applications (1 proposal on marine energy ressources)

- Further assessment of wave or wave and wind products, better account of perturbing effects (rain): 10 proposals with in situ measurements (specific buoy deployments, oceanic campaigns …)

- Develop new approaches for a synergetic use of CFOSAT with other space missions to assess other mission observations and/o develop use of combined products (S-1, Cryosat-2, S-6, Cygnss, GPM, SWOT)

- Complementary analysis of SWIM signals for improving the product content: removing the 180° ambiguity, links between sigma0, wave spectra and other sea-surface parameters (turbulent fluxes)

- Developing sea ice classification using SCAT, SWIM or both

- Develop and validate different methods for estimating the Stokes drift

- Developing indicators of extreme waves (BFI, maximum wave height, crossed-sea)

To ensure a good communication between the groups involved in the analysis of CFOSAT observations, we will maintain the annual meeting of the science team.

We also plan to reinforce the contacts and collaborations with various international groups or services involved in wind and wave observations and modeling such as OSTST, IOWVST, CCI sea-state, Copernicus Marine Service)

Closed contacts will also be developed with the PI of upcoming or proposed satellite missions which will benefit from the CFOSAT results and observations (SWOT, Harmony, Seastar, WacM,…)

10. LIST OF PUBLICATIONS

10.1. INTERNATIONAL JOURNALS WITH PEER REVIEW SINCE 2018

Amarouche, K., Bingölbali, B. & Akpinar, A. New wind-wave climate records in the Western Mediterranean Sea. Clim Dyn, 2021, https://doi.org/10.1007/s00382-021-05997-1

Aouf L., D. Hauser, B. Chapron, A. Toffoli, C. Tourrain, C. Peureux, New directional wave satellite observations: Towards improved wave forecasts and climate description in Southern Ocean, Geophys. Res. Letter, special collection, doi : 10.1029/2020GL091187, 2021

Chen Ping, Gang Zheng, D. Hauser, Fei Xu, Quasi-Gaussian probability density function of sea wave slopes from near nadir Ku-band radar observations, Remote Sensing of Environment, 217, 86–100, doi 10.1016/j.rse.2018.07.027, 2018

Chen Ping and D. Hauser, Shihao Zou, Jianyang Si, Eva Le Merle, Speckle noise spectrum at near-nadir incidence angles for a time-varying sea surface IEEE Transactions on Geoscience and Remote Sensing, 2021, 10.1109/TGRS.2020.3037910, vol. 60, pp. 1-20, 2022, 2021

Chen Sheng, Anna Rutgersson, Xunqiang Yin, Ying Xu, and Fangli Qiao, On the First Observed Wave-Induced Stress Over the Global Ocean, Journal of Geophysical Research Oceans 125(12), DOI: 10.1029/2020JC016623 , 2020

Collard F., L. Marié , F. Nouguier , M. Kleinherenbrink, F. Ehlers, and F. Ardhuin, Wind-Wave Attenuation in Arctic Sea Ice: A Discussion of Remote Sensing Capabilities, Journal of Geophysical Research: Oceans,127, e2022JC018654. https://doi.127, e2022JC018654, 2022

Delaunay Xavier, A. Courtois, and F. Gouillon, Evaluation of lossless and lossy algorithms for the compression of scientific datasets in netCDF-4 or HDF5 files, Geosci. Model Dev., 12, 4099–4113, doi :10.5194/gmd-12-4099-2019, 2019

Frappart Frédéric, Jean-Pierre Wigneron, Xiaojun Li, Xiangzhuo Liu,Amen Al-Yaari, Lei Fan, Mengjia Wang, Christophe Moisy, Erwan Le Masson,Zacharie Aoulad Lafkih, Clément Vallé, Bertrand Ygorra, and Nicolas Baghdadi, Global Monitoring of the Vegetation Dynamics from the Vegetation Optical Depth (VOD): A Review Remote Sensing 2020,12, 2915; doi:10.3390/rs12182915, 2020

Gao Y., F.G. Schmitt, J. Hu, Y. Huang, Scaling analysis of the China France Oceanography SATellite along track wind and wave data Journal of Geophysical Research, 126(8), special collection, first published July 2021, 10.1029/2020JC017119, 2021

Grigorieva V.G. , S. I. Badulin, and S.K. Gulev, Global Validation of SWIM/CFOSAT Wind Waves against Voluntary Observing Ship data,Earth and Space Sciences, 10.1029/2021EA002008, 2022

Hauser D. C. Tourain and JM Lachiver, CFOSAT : A new mission in orbit to observe simultaneously wind and waves at the ocean surface Space Research Today, Volume 206, December 2019, Pages 15-21, 2019

Hauser D., Cedric Tourain, Laura Hermozo, Dunya Alraddawi, Lotfi Aouf, et al., New observations from the SWIM radar on board CFOSAT: instrument validation and ocean wave measurement assessment, IEEE Transactions on Geoscience and Remote Sensing, 2021, 59 (1), pp.5-26. ⟨10.1109/TGRS.2020.2994372, 2021

Jiang Haoyu, A. Mironov, Lin Ren, A. V. Babanin , Lin Mu, Validation of Wave Spectral Partitions from SWIM instrument on-board CFOSAT against In-situ Data, IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3110952, 2022

Jiang Haoyu, A. Mironov, Lin Ren, A. V. Babanin , Lin Mu, Validation of Wave Spectral Partitions from SWIM instrument on-board CFOSAT against In-situ Data, IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3110952. 2022

Ke Zhao, Chaofang Zhao and Ge Chen, Evaluation of Chinese Scatterometer Ocean Surface Wind Data: Preliminary Analysis, Earth an Space Sciences, 8, e2020EA001482, https://doi.org/10.1029/2020EA001482, 2021

Le Merle E., D. Hauser, C. Peureux, L. Aouf, P. Schippers , C.Dufour and A. Dalphinet Directional and frequency spread of surface ocean waves from SWIM measurements, Journal of Geophysical Research, special collection, doi: 10.1029/2021JC017220, 2021

Le Merle E., D. Hauser, C. Tison, Directional wave spectra at the regional scale with the KuROS airborne radar: comparisons with models, Ocean Dynamics,1-21, doi 10.1007/s10236-019-01271-5, 2019

Le Merle D., D. Hauser, C.Yang, Wave field properties in tropical cyclones from the spectral observation of the CFOSAT/SWIM spaceborne instrument, J. Geophys. Res. 2022, submitted

Li Bo, Junmin Li , Junliang Liu , Shilin Tang, Wuyang Chen, Ping Shi, and Yupeng Liu, Calibration Experiments of CFOSAT Wavelength in the Southern South China Sea by Artificial Neural Networks, Remote Sens. 2022, 14, 773, doi 10.3390/rs14030773, 2022

Li Huimin, D. Hauser, B. Chapron, F. Nouguier, P. Schippers, Biao Zhang, Jingsong Yang, and Yijun He, Up-to-downwave asymmetry of the CFOSAT, SWIM fluctuation spectrum for wave direction, ambiguity removal, IEEE Trans. on Geoscience and remote Sensing, vol. 60, pp. 1-12, 2022, Art no. 5103012, doi: 10.1109/TGRS.2021.3086483, 2021

Li Huimin, B. Chapron; D. Vandemark, Chen Wang, D. Hauser, Biao Zhang, Yijun He, Statistical comparison of ocean wave directional spectra derived from SWIM/CFOSAT satellite observations and from buoy observations, Remote Sensing of Environment, submitted, 2022

Li Xiuzhong, Vladimir Karaev, Mariya Panfilova, Baochang Liu, Zhixiong Wang, Ying Xu, Jianqiang Liu, Yijun He Measurements of total sea surface mean square slope field based on SWIM data, IEEE Transactions on Geosciences and Remotre Sensing, vol. 60, pp. 1-9, 2022, Art no. 5114109, doi: 10.1109/TGRS.2022.3174392, 2022

Li Zhen, Ad Stoffelen, Anton Verhoef, Jeroen Verspeek, NWP Ocean Calibration for the CFOSAT wind scatterometer and wind retrieval evaluation, Earth and Space Science, 8, e2020EA001606, 2021

Liang Guozhou, Yang Jungang, Wang Jichao, Accuracy Evaluation of CFOSAT SWIM L2 Products Based on NDBC Buoy and Jason-3 Altimeter Data, Remote Sens. 2021, 13, 887, 2021

Lin Wenming, Xiaolong Dong, Marcos Portabella, Shuyan Lang, Yijun He, Risheng Yun, Zhixiong Wang, A Perspective on the Performance of the CFOSAT Rotating Fan-Beam Scatterometers, IEEE Transactions on Geoscience and Remote Sensing, vol. 57, no. 2, pp. 627-639, 2019, doi: 10.1109/TGRS.2018.2858852, 2019

Liu Jianqiang, Wenming Lin, Xiaolong Dong et al., First results from the rotating fanbeam scatterometer onboard CFOSAT, IEEE Transactions on Geoscience and Remote Sensing, DOI: 10.1109/TGRS.2020.2990708, 2020

Liu Meijie, Ran Yan, Jie Zhang, Ying Xu, Ping Chen, Lijian Shi, Jin Wang, Shilei Zhong and Xi Zhang, Arctic Sea Ice Classification Based on CFOSAT SWIM Data at Multiple Small Incidence Angles, Remote Sens. 2022, 14 (1), 91, 2022

Marié L., F. Collard, F. Nouguier, L. Pineau-Guillou, D. Hauser, F. Boy, S. Méric, C. Peureux, G. Monnier, B. Chapron, A. Martin, P. Dubois, C. Donlon, T. Casal, and F. Ardhuin, Measuring ocean surface velocities with the KuROS and KaRADOC airborne near-nadir Doppler radars: a multi-scale analysis in preparation of the SKIM mission, Ocean Sci., 16, 1399–1429, 2020

Oruba Ludivine, D. Hauser, S. Planes, E. Dormy, Ocean waves in the South Pacific: complementarity of SWIM and SAR observations, Earth and Space Sciences, 2021EA002187-TR, https://doi.org/10.1029/2021EA002187 2022

Peureux C., N. Longépé, A. Mouche, C. Tison, C. Tourain, J-M. Lachiver, D. Hauser, Sea-ice detection from near-nadir Ku-band echoes of CFOSAT/SWIM scatterometer, Earth and Space Sciences, 10.1029/2021EA002046, 2022

Ren, L., Yang, J., Xu, Y., Zhang, Y., Zheng, G., Wang, J., et al., Ocean surface wind speed dependence and retrieval from off-nadir CFOSAT SWIM data, Earth and Space Sciences, 2021

Shao Weizeng, Tao Jiang, Yu Zhang , Jian Shi and Weili Wang, Cyclonic Wave Simulations Based on WAVEWATCH-III Using a Sea Surface Drag Coefficient Derived from CFOSAT SWIM Data, Atmosphere 2021, 12, 1610, 2021

Shi, Y., Du, Y., Chu, X., Tang, S., Shi, P., & Jiang, X., Asymmetric wave distributions of tropical cyclones based on CFOSAT observations, Journal of Geophysical Research: Oceans, 126 , e2020JC016829, 2021

Sun, Meng, Du, J., Yang, Y., Yin, X., Evaluation of Assimilation in the MASNUM Wave Model Based on Jason-3 and CFOSAT, Remote Sensing, 13, 3833, 2021

Tang Shilin, Chu Xiaoqing , Jia Yongjun, Li Junmin, Liu Yiting, Chen Qiong , Li Bo, Liu Junliang , and Chen Wuyang, An Appraisal of CFOSAT Wave Spectrometer Products in the South China Sea, Earth and Space, Science, 9, e2021EA002055. https://doi.org/10.1029/2021EA002055, 2022

Tourain C., F. Piras, A. Ollivier, D. Hauser, F. Poisson, F. Boy, P. Thibault, L. Hermozo, , C. Tison, Benefits of the Adaptive algorithm for retracking altimeter nadir echoes: results from simulations and CFOSAT/SWIM observations, IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3064236, 2021

Verron J., B. Ryan, P. Bonnefond and J. Benveniste, et al., Altimetry for the Future: Interdisciplinary Recommendations Following the "25 Years of Progress in Radar Altimetry", Advances in Space Research, doi 10.1016/j.asr.2021.01.02, 2021

Wang He, A. Mouche , R. Husson, B. Chapron, Jingsong Yang , Jianqiang Liu , and Lin Ren, Quantifying Uncertainties in the Partitioned Swell Heights Observed From CFOSAT SWIM and Sentinel-1 SAR via Triple Collocation; IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 60, 2022

Wang Jin, Brandon J. Bethel, Changming Dong, Chunhui Li and Yuhan Cao, Numerical Simulation and Observational Data Analysis of Mesoscale Eddy Effects on Surface Waves in the South China Sea, Remote Sens. 2022, 14, 1463, 2022

Wang Jiuke, L. Aouf, A. Dalphinet, Xu Ying, and Liu Jiangquang, Acquisition of Significant Wave Height from the CFOSAT SWIM Spectra through Deep Neural Network: Impact on Assimilation in Wave Model, Journal of Geophysical Research: Oceans, 126, e2020JC016885. https://doi.org/10.1029/2020JC016885

Wang Jiuke, L. Aouf, A. Dalphinet, Y. G. Zhang, Y. Xu, J. Q. Liu, D. Hauser, The Wide Swath Significant Wave Height: An innovative retrieval from CFOSAT SWIM and Scatterometer Based on Deep Learning Approach, Geophys. Res. Letter, 48(6), e2020GL091276. , doi 10.1029/2020GL091276, 2021

Wang Lili, Zhenyu D , Lei Z , et al., CFOSAT-1 Realizes First Joint Observation of Sea Wind and Waves, [J]. Aerospace China, 20(01):22-29. DOI: 10. 3969/ j. issn. 1671-0940. 2019. 01. 004, 2019

Wu Ke, Li Xiao. Ming, & Huang Bingqing, Retrieval of ocean wave heights from spaceborne SAR in the Arctic Ocean with a neural network, Journal of Geophysical Research: Oceans, 126, e2020JC016946, 2021

Wu Wei, Du Yan, Qian Yu-Kun, Chen Ju, and Jiang Xingwei, Large South Equatorial Current Meander in the Southeastern Tropical Indian Ocean Captured by Surface Drifters Deployed in 2019, Geophysical Research Letters, 49, e2021GL095124, doi: 10.1029/2021GL095124, 2022

Xiang Kunsheng, Xiaobin Yin, Shuguo Xing, Fanping Kong, Yan Li, Shuyan Lang, Preliminary Estimate of CFOSAT Satellite Products in Tropical Cyclones, IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3103277, 2021

Xiuzhong Li, Ying Xu, Baochang Liu, Wenming Lin, Yijun He, Jianqiang Liu, Validation and Calibration of Nadir SWH Products from CFOSAT and HY-2B with Satellites and in-situ Observations, Journal of Geophysical Research Oceans, 2021

Xu Rui, Chaofang Zhao, Xiaochun Zhain and Ge Chen, Arctic Sea Ice Type Classification by Combining CFOSCAT and AMSR-2 Data, Earth and Space Sciences, doi: 10.1029/2021EA002052, 2022

Xu, Ying, Liu, J., Xie, L. et al., China-France Oceanography Satellite (CFOSAT) simultaneously observes the typhoon-induced wind and wave fields, Acta Oceanol. Sin. 38, 158–161, 2019

Xu Ying, D. Hauser, Jianqiang Liu, Jianyang Si, Chen Yan, Shufen Chen, Junmin Meng, Chenqing Fan, Meijie Liu, Ping Chen, Statistical comparison of ocean wave directional spectra derived from SWIM/CFOSAT satellite observations and from buoy observations, IEEE Trans. On Geoscience and Remote Sensing, doi: 10.1109/TGRS.2022.3199393, 2022

Ye Haijun, Li Junlin, Li Bo, Liu, Juanliang,Tang Danling, Chen Wuyang, Yang Hongjiangn Zhou Fenghua, Zhang Rongwang, Wang Sufen , and Tang Shilin, Evaluation of CFOSAT Scatterometers Wind Data in Global Oceans, Remote Sens., 13, 1926, https://doi.org/10.3390/rs13101926, 2021

Ye Jing, Wan Yong & Dai Yongshou, Quality evaluation and calibration of the SWIM significant wave height product with buoy data, Acta Oceanol. Sin. 40, 187–196, 2021

Yun Risheng, Dong Xiaolong, Liu Jianqiang, Lin Weiming , Zhu Di , Ma Jianying, Shuyan Lang, and Zhisen Wang, CFOSAT Rotating Fan-Beam Scatterometer Backscatter Measurement Processing, Earth and Space Science, 8, e2021EA001969, 2021

Yurovskaya, M.; Kudryavtsev, V.; Mironov, A.; Mouche, A.; Collard, F.; Chapron, B., Surface Wave Developments under Tropical Cyclone Goni (2020): Multi-Satellite Observations and Parametric Model Comparisons, Remote Sens. 2022, 14, 2032, https://doi.org/10.3390/rs14092032, 2022

Zhang K., X.Dong,D.Zhu,R.Yun, Estimation and Correction of Geolocation Errors of the CFOSAT Scatterometer Using Coastline Backscatter Coefficients, IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, 2021

Zhang K., X.Dong,D.Zhu,R.Yun,B.Wang,L.Yu , An Improved Method of Noise Subtraction for the CFOSAT Scatterometer, IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, 2021

Zhao Xiaokang, Wenming Lin, Marcos Portabella, Zhixiong Wang, Yijun He, Effects of rain on CFOSAT scatterometer measurements , Remote Sensing of Environment 274 (2022) 113015, 2022

Zhu Benlu, Jinrui Chen, Ying Xu,, Quanan Zheng, Xueding Li, Validation of the CFOSAT scatterometer data with buoy observations and tests of operational application to extreme weather forecasts in Taiwan Strait Earth and Space Science, doi: 10.1029/2021EA001865, 2022

10.2. PROCEEDINGS OF INTERNATIONAL CONFERENCES

Aouf L., A. Dalphinet, D. Hauser, L. Delaye, C. Tison, et al., On the Assimilation of CFOSAT Wave Data in the Wave Model MFWAM : Verification Phase. IGARSS Yokohama (Japan), 2019

Aouf L., D. Hauser, F. Collard, B. Chapron, C. Tourain Waves attenuation in the Marginal Ice Zone: thanks to directional wave satellite Ocean from Space (Venezia, Italy), 2022

Aouf L., Danièle Hauser, Céline Tison, Alexis Mouche, PERSPECTIVES FOR DIRECTIONAL SPECTRA ASSIMILATION: RESULTS FROM A STUDY BASED ON JOINT ASSIMILATION OF CFOSAT SYNTHETIC WAVE SPECTRA AND OBSERVED SAR SPECTRA FROM SENTINEL-1A, IGARSS, Valencia (Spain), 2018

Aouf L., J. Wang, D. Hauser, B. Chapron, C. Tourain, On the assimilation of wide swath SWH and directional wave observations in wave model: Perspective to operational use, Proceedings of IGARSS 2022, Kuala-Lumpur, Malaysia.

Aouf L., Wang J., Hauser D., Chapron B., Tourain C., On the assimilation of wide-swath significant wave height and direction wave observations in wave model: perspective to operational use, IGARSS Kuala-Lumpur, 2022

Dong X , Zhu D , Zhang L , et al., Preliminary Results of the CFOSAT Scatterometers, IGARSS 2019 , Yokohama, Japan, DOI: 10.1109/IGARSS.2019.8899837, 2019

Gressani V. , F. Nouguier , A. Mouche, Wave spectrometer tilt modulation transfer function unsing near-nadir Ku- and Ka-band GPM measurements, IGARSS, Valencia (Spain), 2018

Hermozo L. et al, CFOSAT latest improvements in the SWIm products and contribution to oceanography, IGARSS Kuala-Lumpur, 2022

Le Merle E., D. Hauser, C. Peureux , L. Aouf, P. Schippers and C. Dufour, Directional and frequency spread of surface ocean waves from CFOSAT/SWIM measurements, IGARSS online, 2021

Le Merle E., D. Hauser, R. Santoleri, C. Yang, Directional ocean wave spectrum properties from the SWIM instrument under tropical cyclone conditions, Ocean from Space (Venezia, Italy), 2022

Le Merle Eva, Hauser D., Tison C., Aouf L., Spectral properties of surface ocean waves from real−aperture radar observations IGARSS, Valencia (Spain), 2018

Mironov., A., Y. Quilfen, B. Chapron, V. Kudryavtsev Ku-band Polarization Difference Model for Scatterometric Wind Inversion, IGARSS online, 2021

Rodriguez Suquet R., A. Mouche, B. Chapron, F. Collard, C. Dufour, et al., CAL/VAL phase for the SWIM instrument onboard CFOSAT, IGARSS Yokohama (Japan), 2019

Rodriguez Suquet R., C. Tourain, C. Tison, L. Delaye, D. Hauser, P. Schippers, F. Gouillon, T. Amiot, E. Riviere, P. Castillan, The SWIM instrument towards the launch; IGARSS, Valencia (Spain), 2018

Tourain C., D. Hauser, L. Hermozo, R. Rodriguez Suquet, P. Schippers, L. Aouf, A. Dalphinet, A. Mouche, B. Chapron, F. Collard, C. Dufour, F. Gouillon, A. Ollivier, F. Piras, M. Dalila, G. Guitton, J-M.Lachiver, C. Tison, CAL/VAL phase for the SWIM instrument onboard CFOSAT, IGARSS, online 2021

Tourain C., D. Hauser, L. Hermozo., R. Rodriguez Suquet, P. Schippers L. Aouf, et al., Evolutions and improvements in CFOSAT SWIM Products, IGARSS online 2021

Xingou Xu, Xiaolong Dong, Wenming Lin, Risheng Yun, Wind Field Retrieving for SCAT Onboard CFOSAT Based on PCA Method, IGARSS, Valencia (Spain), DOI:10.1109/IGARSS.2018.8519234, 2018

Xu, X., Stoffelen, A., Portabella, M., Lin, W., and Dong, X., A Comparison of Quality Indicators for Ku-Band Wind Scatterometry & for Typhoons Lekima and Krosa IGARSS online, 10.1109/igarss47720.2021.9553678, 2021

Yun R , Dong X , Zhang L , et al., CFOSAT Scatterometer Data Level-1 Processing and Preliminary Results IGARSS 2019 , Yokohama, Japan, DOI: 10.1109/IGARSS.2019.8897758, 2019

Zhu Di, Lei Zhang, Xiaolong Dong, Risheng Yun, Wenming Lin, Shuyan Lang, Preliminary Calibrations of the CFOSAT Scatterometers, IGARSS, Yokohama, Japan, DOI: 10.1109/IGARSS.2019.8898712, 2019