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Wave field properties in tropical cyclones from the spectral observation of the CFOSAT/SWIM spaceborne instrument

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Key Points:

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8	•	Ocean wave spectra measured with the CFOSAT/SWIM spaceborne instrument
9		are investigated under tropical cyclones over a three-year period.
10	•	The asymmetry of the wave parameters depends on the ratio of the maximum sus-
11		tained wind speed and the TCs speed.
12	•	The shape of the omni- and directional spectra varies according to the TC class
13		and to the distance from the center of the TC.

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14 Abstract

Tropical cyclones (TCs) are extreme events that generate, because of their movement, 15 complex wave fields. The SWIM instrument is a real aperture radar that provides un-16 precedented detailed information about the waves with dominant wavelength between 17 70 and 500 m in all directions at the global scale. In this study we collocated 3 years of 18 SWIM data with 67 TCs in the Northern Hemisphere to analyze the impact of the TC 19 characteristics on the wave field. TCs have been classified into three different classes (slow, 20 moderate speed and fast) estimated based on the ratio between the maximum sustained 21 wind and the displacement velocity. In order to analyze the characteristics of the wave 22 field in the space domain, the observations have been separated according to the distance 23 with the TC center and the quadrant. The results show that the characteristics of the 24 TCs impact the wave field: the more favorable conditions for trapped wave phenomenon 25 appears to be under moderate speed TC conditions. In slow and moderate speed TCs, 26 close to the center the directional spectra are mono-modal and tend to become bi- or multi-27 modal when the distance to the center increases whereas in fast-moving TCs, the direc-28 tional spectra are always bi- or multi-modal. Omni-directional spectra show similarities 29 with fetch-limited spectra in slow and moderate speed TCs whereas in fast-moving TCs, 30 because of the presence of mixed-sea, the decrease of energy with frequency is less steep 31 than in fetch-limited conditions. 32

³³ Plain Language Summary

Tropical cyclones (TCs) are extreme meteorological events, causing in-land dam-34 ages such as inundations, but also storm surges due to the intense sea states. Even if fore-35 cast models provide satisfying estimation of the sea state under TC conditions, we still 36 need observations to improve their representation and evolution during these events. The 37 France Oceanography Satellite (CFOSAT), carries a real aperture radar that provides 38 detailed wave energy distribution with direction and wavelength at the global scale. In 39 this study we choose to use this information to study the impact of the TC character-40 istics on the wave field. To do so, we classified TCs into three classes according to their 41 displacement velocity (slow, moderate speed and fast). CFOSAT observations confirm 42 some of the conclusions obtained in previous studies such as the asymmetry of the wave 43 height previously observed with airborne and buoy measurements. Moreover, in slow-44 moving and moderate speed TCs, close to the TC center, the wave field show some sim-45 ilarities with wave field obtained in conditions of wave growth by stable wind. However, 46 in fast-moving TCs the wave field is more variable with the presence of several wave sys-47 tems interacting between each other. 48

49 **1** Introduction

Tropical cyclones (TCs) are extreme meteorological events which generate extreme winds, waves and precipitations. The very high waves generated by the cyclones impact the maritime navigation, the risk in coastal areas and modify the ocean-atmosphere interactions (Prakash et al., 2019; Zhang et al., 2021; Lin et al., 2021; Fan et al., 2020). Therefore, a detailed description and a better understanding of the wave field properties under TC conditions is a topic of great relevance to oceanographic research and engineering applications.

Tropical cyclones are moving systems characterized by rotational winds with complex features such as radial gradients and asymmetry, with usually stronger winds on the right (left) side of the TC displacement direction in the Northern (Southern) Hemisphere. These complex wind fields generate wave fields with even more complex structures. The wave field characteristic most often cited in the literature is the significant wave height (Hs) asymmetry characterized by the presence of the highest waves on the right side of the TCs (Young, 2006; Kudryavtsev et al., 2015; Shi et al., 2021). This feature is explained

by the concept of "extended fetch" for waves which travel in the same direction as the 64 cyclone (Young, 1998) or by the "trapped waves" concept related to a resonance phe-65 nomenon (Bowyer & MacAfee, 2005) that occurs when the wind-generated waves can-66 not escape from the cyclone area because their group velocity remains of the order of the 67 displacement velocity of the system. Moon et al. (2003), who analyze the wave field of 68 TC Bonnie at two different stages, suggest that the hurricane-generated wave field is in-69 fluenced not only by the radius of maximum wind but also by the TC displacement ve-70 locity. This conclusion was also proposed by Young (1998, 2017), although Shi et al. (2021) 71 found that the asymmetric behavior of the significant wave height mainly depends on 72 the TC intensity. In order to better characterize the wave field behavior under TC con-73 ditions, Kudryavtsev et al. (2015) proposed a simplified model, parameterized in terms 74 of maximum wind and displacement speed, which explains this significant wave height 75 asymmetry even in absence of wind field asymmetry. Hell et al. (2021) and Kudryavtsev 76 et al. (2021a) proposed numerical model of wave parameter evolution in a Lagrangian 77 frame within moving TCs. Despite numerical efforts to further document and represent 78 the wave field behavior and to further validate these theoretical concepts, additional spec-79 tral wave observations are required and need to be analyzed under different classes of 80 TCs. This paper fits into this context. 81

In addition to the significant wave height, other wave parameters and the distri-82 bution of the wave energy also need to be investigated. In the early 2000s, thanks to ob-83 servations from the airborne Scanning Radar Altimeter (SAR), Wright et al. (2001) showed 84 that additionally to the Hs field, the frequency and the direction field of the dominant 85 waves was also asymmetric. Moreover, they analyzed the energy distribution of the wave 86 spectra and concluded that in the right front quadrant the wave field tended to be uni-87 directional, more or less aligned with the wind direction, whereas in the other quadrants, 88 bi- or tri-modal wave systems with similar wavelength were observed. This was later con-89 firmed by Hu and Chen (2011) who analyzed directional buoy data during the passage 90 of 7 TCs, and Hwang and Walsh (2018) who extended this analysis of SRA spectral ob-91 servations within 11 cyclones. Esquivel-Trava et al. (2015) also provided additional de-92 tails on the wave energy distribution by classifying directional spectra from buoy data 93 within 14 TCs according to their distance from the TC center. 94

Several studies such as Esquivel-Trava et al. (2015) and Tamizi and Young (2020) 95 have shown that, despite the presence of mixed-sea situations and an important disper-96 sion, the shape of the omni-directional frequency spectra and the self-similar non-dimensional 97 law relating wave energy to the wave frequency were close to those in conditions of wind-98 wave growing under fetch-limited conditions. For example, under TC conditions, the omniqq directional spectra are characterized by a mono-modal spectrum shape in frequency and 100 a constant spectral slope on the right of the peak, even if the spectra are sharper than 101 those under fetch-limited conditions. The results of Hwang et al. (2017) indicate that 102 this spectral slope may vary according to the sectors of the TCs. Young (2006) (among 103 others) justified this mono-modal spectrum shape in frequency despite the presence of 104 several energetic wave components separated in directions by the non-linear interactions 105 between the waves. The modeling work of Hu and Chen (2011) indicates however that 106 even if the non-linear interactions are important in particular in the right quadrant, the 107 other mechanisms, such as wind input and dissipation, cannot be neglected. In addition, 108 although the parametric model proposed by Kudrvavtsev et al. (2021a) which estimates 109 wave spectra parameters in a Lagrangian approach does not take into account explic-110 itly the non-linear interactions, the consistency of their results with observation is rather 111 convincing. On the other hand, the numerical simulations of Tamizi et al. (2021)show that at distances close to the center of the TC, except in the right front quadrant, the 113 non-linear interactions are crucial to explain the mono-modal shape of the spectrum. 114

¹¹⁵ In order to further characterize, understand and model the wave field associated ¹¹⁶ with tropical cyclone, there is a need to continue the analysis of wave spectral proper-

ties within tropical cyclones. Advances in space instrumentation provide systematic ob-117 servations of the wave field on large spatial and temporal scales. In particular, the Sur-118 face Wave Investigation and Monitoring (SWIM) instrument on-board the China-France 119 Oceanography Satellite (CFOSAT) mission, launched in space in October 2018, now pro-120 vides globally, and on a systematic basis, directional ocean wave spectra every 90 km with 121 detailed wave information with dominant wavelength between 70 and 500 m (Hauser et 122 al., 2021). Some studies already showed that the SWIM observations are useful in sev-123 eral ways, such as improving wave forecasting models (Aouf et al., 2021), analyzing the 124 directional properties of the wave or the probability of extreme waves at the global scale 125 (Le Merle et al., 2021) or estimating the wave induced stress at the global scale (Chen 126 et al., 2020). Oruba et al. (2022) also shows that, as SWIM observations are not affected 127 by the cutoff effect as the SAR observations, SWIM provides complementary informa-128 tion in comparison to SAR instruments to document wave spectra in moderate and high 129 sea state conditions. 130

In this paper, by using the SWIM observations, we further investigate the distri-131 bution of ocean wave spectra and of their main parameters, obtained under TC condi-132 tions. The analyzed data set spans over more than three years of observations between 133 May 2019 and September 2022 during which 67 TCs with maximum sustained wind speed 134 stronger than 30 m/s occurring in the Northern Hemisphere are observed. The original-135 ity of our study is to analyze the ocean wave spectra properties according to the TC char-136 acteristics such as the relative displacement velocity. This was chosen to better charac-137 terize the impact of the displacement velocity and the maximum wind speed on the wave 138 parameter asymmetry. We defined three different classes of TCs according to the ratio 139 of the maximum sustained wind speed to the displacement velocity of the TC: slow, mod-140 erate speed and fast-moving TCs (see section 2.3). For each class, the spectral shape of 141 the directional and omni-directional ocean wave spectra is investigated as well as the wave 142 parameters. 143

The paper is organized as follows. In section 2, the data sets and the methods are introduced. Section 3 presents an example of TC observed by the SWIM instrument. Section 4 presents a statistical analysis of the wave parameters characterizing the wave spectra. The results on the spectral shape of the directional and omni-directional spectra are presented in section 5. In section 6, a discussion is proposed to relate the different results presented in the previous sections. Finally, the conclusion is in section 7.

¹⁵⁰ 2 Data set and methods

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2.1 Tropical cyclones data

TC parameters used in this study are taken from the International Best Track Archive 152 for Climate Stewardship (IBTrACS) which combines TC best track data from 11 TC fore-153 cast centers all around the globe (Knapp et al., 2010, 2018). This database is recognized 154 as the best source of information concerning TCs. The data set contains information about 155 the storm time, position and category on one hand, and information about TC charac-156 teristics such as the maximum sustained wind, the minimum central pressure and the 157 different wind radii on the other hand. TC characteristics used in this study are the max-158 imum sustained wind speed (U_{max}) , the radius of maximum sustained wind speed (R_{max}) . 159 and the displacement speed (V_t) . These characteristics are available every 3 hours. Over 160 the period of SWIM observations retained in this study (from May 2019 to September 161 2022), 134 TCs of category 1 to 5 occurred in the Northern Hemisphere. The CFOSAT 162 mission provided observations in 67 of these TCs. 163

¹⁶⁴ 2.2 Wave data

The SWIM instrument is a wave scatterometer with six radar-beams rotating around the nadir axis at small incidences (close to 0° , 2° , 4° , 6° , 8° , 10° , respectively). Details on the measurement principle can be found in Jackson et al. (1985a), and the space-borne configuration with SWIM is detailed in Hauser et al. (2017).

Using the concept of real-aperture scanning radar, SWIM measures in all azimuth 169 directions the signal modulations related to the slope of the long waves. The wave spec-170 trum is estimated in each look direction from a Fourier analysis of the signal modula-171 tions (assumed to be linearly related to the slope of the long waves). The full directional 172 spectrum is calculated (with an ambiguity of 180°) by combining observations covering 173 180° in azimuth. Wave parameters (such as dominant wavelength and direction) can then 174 be estimated from the spectra. From the nadir beam observations, SWIM also provides 175 176 the significant wave height /Hs), similarly to altimeter missions. In the version used here, this Hs measurement is used to normalize the directional spectral energy (as explained 177 in Le Merle et al. (2021) their Equation 1, and as used in the operational near-real time 178 processing since December 2020). 179

The data set corresponds to the L2P products provided by the AVISO+ French 180 Data Center. They consist in directional spectra defined in 32 wavenumber bins from 181 0.013 rad/m and 0.28 rad/m and 12 direction intervals of 15° between 0° and 180° . The 182 directional spectra are provided with an ambiguity in direction of 180°. Each spectrum 183 is representative of an area of 90 km across-track and 70 km along-track called wave cell. 184 The sampling is continuous along the satellite track and provides two spectra on each 185 side of the nadir track. In the following, we only consider spectra obtained over the open 186 ocean (without land or sea ice in the wave cell) and with valid data in each azimuth sec-187 tor. 188

The validation of SWIM data has been the subject of several previous papers. In 189 particular, comparisons on a point-by-point basis at the global scale using buoy and wave 190 model data have been discussed by Hauser et al. (2021) and Le Merle et al. (2021). They 191 proved the general good consistency of the mean wave parameters in cases of significant 192 wave height larger than about 1.8 m, with smaller uncertainties on wave parameters when 193 they are estimated from the 10° SWIM beam compared to the 6° and 8° beams. There-194 fore, in the present study we only use the spectra estimated from the 10° beam obser-195 vations. Also, based on a statistical analysis per category of sea-state using buoy mea-196 surements, Xu et al. (2022) illustrate that for the conditions of SWIM acquisition cho-197 sen here (beam 10°), even in high sea-state conditions characterized by fully developed 198 wind-sea or long swell as those encountered in the TCs, the distributions of wave energy 199 with frequency and direction are very consistent with those observed with buoy data (see 200 e.g. their Figures (2-f-i-l) and (5c-f-I)) and the spectral correlation coefficient between 201 buoy and SWIM spectra is close to 1 (see e.g. their Figure 6(a)). In fact, the study by 202 Xu et al. (2022), shows that the conditions where some non-linearity in the relation be-203 tween wave slope and the measured signal modulations may alter the shape of the spec-204 tra and induce bias in the dominant wavelength are those of young wind seas, and large 205 significant slope. As discussed later in Section 4, these are not the conditions that dom-206 inate the wave field in TCs. Finally, in the analysis presented in this paper, the spec-207 tral energy is normalized by the significant wave height Hs provided by the SWIM nadir 208 beam (see Le Merle et al. (2021) their Equation 1). As several previous validations have 209 assessed the very high consistency of Hs from the SWIM nadir observations compared 210 to either altimeter missions or buoy measurements (e.g. Hauser et al., 2021; Tourain et 211 al., 2021; Ye et al., 2021; Li et al., 2021), we are very confident in the spectral energy 212 analyzed here. 213

We recall here that Hs is related to the directional ocean wave height spectrum $(F(k,\phi))$ by :

$$Hs = 4 \times \sqrt{\int \int_0^{\pi} F(k,\phi) \ k \ dk \ d\phi}$$
(1)

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with k the wavenumber and ϕ the azimuth direction.

The wave products extracted from AVISO+ include additional wave parameters 218 such as the wavelength and the direction of the dominant waves (λ_p and ϕ_p , respectively) 219 estimated from the directional wave slope spectra expressed in wavenumber. Here, in or-220 der to analyze wave parameters similar to those already discussed in the literature on 221 waves in TCs (e.g. Young, 2006; Tamizi & Young, 2020; Esquivel-Trava et al., 2015), we 222 recalculated the dominant direction and the dominant wavelength from the directional 223 wave height using the same approach as mention in the Product User Guide. The frequency directional wave height spectra were therefore converted from the wavenumber 225 directional wave slope spectra provided in the SWIM products. Moreover, as indicated 226 in Le Merle et al. (2021) and in Tourain et al. (2021), some of the directional wave height 227 spectra have non-geophysical energy peaks at low wavenumbers/frequencies that can af-228 fect the calculation of the dominant frequency and direction. In order to attenuate this 229 spurious energy, a 2D Gaussian filter is applied to smooth the directional spectrum be-230 fore the calculation of the wave parameters. The estimated λ_p is obtained from the dom-231 inant frequency, f_p , using the dispersion relationship in deep water: 232

$$\lambda_p = \frac{g}{2\pi f_p^2} \tag{2}$$

)

with g the gravitational acceleration which is equal to 9.81 m/s².

As mentioned at the beginning of this section, the SWIM spectra are provided with 235 a 180° ambiguity in the wave propagation direction. Therefore, the direction of the dom-236 inant waves can only be provided with an ambiguity of 180°. However, even if the wind 237 and wave fields are complex in TCs, it is possible to remove this 180° ambiguity. Pre-238 vious results in the literature showed that, under TCs conditions, the angle between the 239 direction of the wind and the direction of wave propagation is always lower than 180°. 240 This has been confirmed with buoy observations, and simulated wave spectra (e.g. Hu 241 & Chen, 2011; Esquivel-Trava et al., 2015; Kudryavtsev et al., 2021b; Young, 2006). There-242 fore, to raise this 180° ambiguity on the SWIM wave spectra, we calculate the difference 243 between the wind and the wave direction propagation and if this difference is higher than 244 180° , we add 180° (modulo 360°) to the direction of the dominant waves. Please note 245 that this correction is only applied to estimate the direction of propagation of the dom-246 inant wave for each of the wave spectra obtained by SWIM. 247

Here, in order to analyze the development stage of the wave field around TCs, we calculated the inverse wave age (Ω) , defined as classically as:

$$\Omega = \frac{U_{10}\cos\left(\phi_w - \phi_p\right)}{C_n} \tag{3}$$

with U_{10} the wind speed at 10 m height and ϕ_w the wind direction relative to the North. C_p is the wave phase velocity. The wind information is taken from the ancillary data available in the SWIM products. It is provided by the ECMWF atmospheric model 6-hours forecast collocated with the SWIM observations.

255 **2.3 Methods**

In this study we choose to focus our analysis on category 1 to 5 TCs according to the Saffir-Simpson scale. It means that the maximum sustained wind speed is at least 30 m/s, exceeding tropical storm and tropical depression intensity.

The purpose of this study is to investigate the impact of the TC characteristics on 259 the distribution of the wave field. However, the wave field asymmetry varies according 260 to the hemisphere with the highest waves on the right (left) side of the TC in the North-261 ern (Southern) Hemisphere. In order to exclusively consider the TC impacts on the wave 262 field, we decided to analyze the SWIM data crossing over TCs occurring only in the North-263 ern Hemisphere. Every CFOSAT track passing within a distance of 4 R_{max} from the TC 264 center and with a time difference of less than 1h30 is selected. Along these selected tracks, 265 observations within 9 R_{max} are selected to perform the analysis. 266

This analysis has been carried out over more than a three-year period, between May 268 2019 and September 2022. During this period SWIM flew over 67 different TCs and pro-269 vided 2360 ocean wave spectra in the Northern Hemisphere. However, we filtered out 270 cases with Hs lower than 1 m and λ_p lower than 70 m (which represents less than 2.5% 271 of the data (56 spectra)) because it was demonstrated that SWIM has some limitations 272 in these situations (Le Merle et al., 2021). As TCs last for several days, it is not rare to 273 have two or three flybys of a same event.

As mentioned in the introduction, several studies have shown that the displacement 274 velocity of the TC has an impact on the wave field. Due to the displacement of the TC, 275 the wind field can move forward with the waves it has generated and in certain condi-276 tions the waves remain under the action of strong winds for extended periods. In order 277 to consider this process of extended fetch we choose to establish three classes of TCs based 278 on the ratio of the maximum sustained wind speed to the displacement speed: U_{max}/V_t . 279 The boundary of these classes are inspired by the numerical study of Kudryavtsev et al. 280 (2021b). We choose the following classes: slow-moving TCs have $12 < U_{max}/V_t$; mod-281 282 erate speed moving TCs have $5 \leq U_{max}/V_t \leq 12$ and fast-moving TCs have $U_{max}/V_t < 12$ 5.283

Figure 1(a) shows the normalized histogram of SWIM observations according to 284 U_{max}/V_t . The majority of SWIM observations are obtained in fast-moving TCs (48%) 285 of the SWIM spectra) whereas only 14% of the SWIM spectra have been obtained in slow 286 moving TCs and 38% have been obtained in moderate speed TCs. It is interesting to 287 note that all slow-moving TCs have displacement speed slower than 5 m/s whereas mod-288 erate speed TCs have $2 < V_t < 9$ m/s and fast-moving TCs have $V_t \ge 6.7$ m/s. Slow 289 and moderate speed moving TCs have maximum wind speed between 30 m/s and 67 m/s 290 whereas 94% of the observations in fast-moving TCs have been acquired under condi-291 tions with wind speed between 30 and 45 m/s. Therefore, even if the classes are estab-292 lished with the ratio U_{max}/V_t , the displacement velocity mainly controls the TC clas-293 sification. 294

Figure 1(b) shows the normalized histograms of the SWIM observations according to the R_{max} for each classes. Despite the fact that most of the moderate speed TCs have R_{max} lower than 100 km, the distributions of R_{max} for each of the TC class overlap each other meaning that this characteristic is not impacted by the classification.

Recently, Kudryavtsev et al. (2021b) designed a 2D parametric model that can be used to forecast the main wave paramter under TC conditions. In this context they define a "true" criterion dividing TCs into two classes: fast or slow. This criterion has been established thanks to fetch and wave growth laws and is expressed as the ratio between the radius of maximum wind and the critical fetch: R_{max}/L_{cr} with the critical fetch expressed as:

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$$L_{cr} = C_{cr} \times \frac{U_{max}^{-2}}{g\left(2V_t\right)^{-4}}$$
(4)

With C_{cr} a constant established thanks to the fetch laws. According to Kudryavtsev et al. (2021b), fast TCs correspond to $R_{max}/L_{cr} < 1$ and slow TCs correspond to $R_{max}/L_{cr} >$ 1. Figure 1(c) shows the normalized distributions of the ratio between the maximum sustained wind speed and the displacement velocity of the TCs $\left(\frac{U_{max}}{V_t}\right)$ for cases with the

criterion R_{max}/L_{cr} greater and lower than 1 (in blue dotted line and in orange, respec-310 tively). In our data, cases with the criterion $R_{max}/L_{cr} < 1$ correspond to situations 311 with U_{max}/V_t lower or equal to 5 and the distribution of the cases with the criterion R_{max}/L_{cr} > 312 1 correspond to situations with U_{max}/V_t higher or equal to 3.5. So, although the two dis-313 tributions are overlapping between $3.5 \leq U_{max}/V_t \leq 5$, the two criteria are mutually 314 consistent to classify TCs. This is because U_{max} and V_t also appear in R_{max}/L_{cr} , although 315 with a different weight of V_t compared to that in our criterion. Furthermore, values of 316 R_{max} are not really clearly related to any TC class according to U_{max}/V_t (see Figure 1(b)). 317

In order to compare the wave field observed by SWIM under TC conditions, the 318 observations obtained in each TC of each class need to be combined in a same reference 319 system. To do so, the SWIM observations are projected into a reference frame centered 320 on the TC center with the frame upward direction aligned with the TC displacement di-321 rection. This reference frame is separated into four quadrants according to the center 322 and to the displacement direction of the TC: the left front, right front, right rear and 323 left rear quadrants. Moreover, the spatial scale is divided into three classes of radial dis-324 tances normalized in terms of R_{max} : $0 \leq d/R_{max} < 3, 3 \leq d/R_{max} < 6$ and $6 \leq d/R_{max} < 10$ 325 $d/R_{max} < 9$, with d the distance between the TC center and the SWIM observation. 326

Table 1 reports the number of ocean wave spectra obtained by SWIM for every TC 327 class and for every class of radial distance. The numbers in brackets indicates the num-328 ber of different TCs observed. Please note that, as the classification of the TCs is based 329 on their characteristics which vary over time, it is possible that a TC observed twice ap-330 pears in two different classes if its characteristics have changed between the two obser-331 vations. Overall, the majority of observations was obtained for radial distances between 332 3 and 6 R_{max} , whereas the less sampled radial distances are those close to the TC cen-333 ter (up to $3 R_{max}$). 334

In the following sections, the evolution of the wave parameters, the shape of the mean directional and omni-directional spectra are analyzed in the four quadrants and in the three classes of radial distances for the three TC classes.

338 3 Case study - Hurricane Douglas

The hurricane Douglas occurred in the Western Pacific between the 20^{th} and the 339 30^{th} of July 2020 and has been observed by the CFOSAT mission the 24^{th} of July at 4:15 340 a.m. At this time, according to the IBTrACS data, the radius of maximum sustained wind 341 speed was 27 km, the maximum sustained wind speed was 59 m/s and the displacement 342 velocity was about 8 m/s. When SWIM flew over the hurricane Douglas, it was a mod-343 erate speed moving tropical cyclone according to our classification $(U_{max}/V \sim 7)$. Fig-344 ures 2(a,b) show the evolution of Hs and λ_p along the SWIM track projected in the TC 345 reference frame. The arrows represent the wind and the dominant wave propagation di-346 rection, respectively. The direction of the dominant waves has been corrected accord-347 ing to the method explained in section 2.2. The SWIM track is presented in the trop-348 ical cyclone reference frame with the hurricane Douglas in the middle of the map and 349 the propagation direction of the hurricane aligned with the upward direction. 350

According the the ECMWF model, in the right front quadrant, the wind direction 351 is oriented towards the North-East direction relative to the TC propagation direction. 352 Within the area between the TC center and 9 R_{max} , the wind direction varies rapidly 353 in space, rotating around the TC center (Figure 2(a)). The highest values of Hs are on 354 the right side of the hurricane, whereas the smallest values of the dominant wavelengths 355 are on the left side of the hurricane Douglas track indicating an asymmetry of both wave 356 parameters (Figure 2(a-b)). Moreover, in the right quadrant, up to 500 km from the TC 357 center (dashed line circle), the dominant wave direction is almost aligned with the TC 358 direction propagation whereas in the left quadrant the dominant direction is perpendic-359

ular to the propagation direction of the hurricane. One can also notice a variation of about 180° of the wave direction from one spectrum to the other in the left quadrant which is

due to the limitation of the ambiguity correction.

Figures 2(c-d) show two examples of wave slope directional spectra obtained at a distance of approximately 4 R_{max} on the left and on the right side of the TC, respectively. The spectrum obtained on the left side of the TC shows two energy peaks corresponding to two wave systems with similar dominant wavelength (Figure 2(c)). The most energetic system is aligned with the wind direction. The spectrum obtained on the right side of the TC shows different features from the other one, with only one wave system which is aligned with both the wind and the TC propagation direction (Figure 2(d)).

³⁷⁰ 4 Statistical analysis of wave parameters

In this section we present a statistical analysis of the wave field parameters estimated from the SWIM data. Wave parameters are analyzed for the three TC classes, in each of the four quadrants and for the three classes of radial distances $(0 \le d/R_{max} < 3, 3 \le d/R_{max} < 6$ and $6 \le d/R_{max} < 9)$.

Figure 3 shows the statistics of the significant wave height. The three different pan-375 els correspond to the TC classes: slow (left panel), moderate speed (middle panel) and 376 fast (right panel). In each panel, the distributions are shown as boxplots with, from left 377 to right, the distributions of the left front, right front, right rear and left rear quadrant 378 respectively. The light, medium and dark blue colors stand for the distance ranges ($0 \leq$ 379 $d/R_{max} < 3, 3 \le d/R_{max} < 6$ and $6 \le d/R_{max} < 9$, respectively). The solid box rep-380 resents the interquartile range (IQR), i.e. the distance between the first and third quar-381 tile. The whiskers delimit the ± 1.5 IQR interval, and the circle symbols show the val-382 ues outside this range. The horizontal solid (respectively dotted) line represents the me-383 dian (respectively mean) value. 384

One common feature for all the TC classes and all quadrants is that Hs decreases 385 from the near range (light blue) to the far range (dark blue). A significant asymmetry 386 is observed in all TCs at distances up to 6 R_{max} , but the maxima are not in the same 387 quadrant according to the TC class: at distances less than $3 R_{max}$, the highest mean Hs 388 $(\approx 7.5 \text{ m})$ are observed in the right front quadrant for moderate speed moving TCs, whereas 389 for slow and fast moving TCs, they are found in the left front and right rear quadrant, 390 respectively. Overall, there is a marked difference in the Hs asymmetry between fast, 391 slow and moderate speed TCs meaning that the relative displacement speed of the TC 392 has a significant impact on the asymmetry of Hs. This is consistent with the simulations 393 carried out by Kudryavtsev et al. (2021b) - see their Figure 7. Furthermore, the high-394 est values of Hs are observed in fast moving TCs, which is consistent with the results 395 of Collins et al. (2021) who found the maximum values of Hs increase with the TC dis-396 placement speed. 397

Figure 4 shows the distributions of the dominant wavelengths (λ_p) estimated from 398 the wave height SWIM spectra in frequency as explained in section 2.2. The distribu-399 tions of the dominant wavelengths are more homogeneous within the TCs than the sig-400 nificant wave height in the sense that the average values stay between 200 m and 280 401 m. There is almost no case with peak wavelength shorter than 100 m and the maximum 402 value of all IQR is lower than 350 m. However, a slight asymmetry is visible: longer wave-403 lengths are observed in the left front quadrant for slow-moving TCs and in the right front quadrant for the moderate speed TCs (at least at distances up to 6 R_{max}). In opposite, 405 there is no clear trend of asymmetry of λ_p in fast moving TCs. 406

Figures 5(a-b) show fields of wind and dominant wave direction. Slow and moderate speed TCs have been superposed on the same panel in Figure 5(a) whereas results for the fast-moving TC conditions are illustrated in Figure 5(b). The black arrows in-

dicate the direction towards which the wind is blowing and the red arrows represent the 410 propagation direction of the dominant waves. All arrows are plotted in the TC reference 411 frame (the TC propagation direction is oriented towards the top of the page). The length 412 of the black arrows corresponds to the wind speed at 10-m height and the length of the 413 red arrows is proportional to the dominant wavelength. We recall that the wind infor-414 mation is from the ECMWF model forecast provided in the SWIM product files. In these 415 figures, the dominant wave direction have been corrected from the 180° ambiguity as ex-416 plained in section 2.2. To make the maps of Figure 5 more readable, all the directions 417 of wind and waves have been average in space on a regular grid with a resolution of 0.25418 R_{max} . 419

The wind direction from ECMWF is found consistent with the typical wind direc-420 tion field analyzed with buoy observations by (e.g. Hu & Chen, 2011; Esquivel-Trava et 421 al., 2015). It is notable that the waves are never aligned with the wind direction, except 422 very close to the TC center. In the main part of the right front quadrant, the dominant 423 waves propagate along the TC trajectory, whereas the wind travels to the left of the di-424 rection of the TC displacement. For slow and moderate speed TCs (Figure 5(a)) the com-425 posite map is in qualitative agreement with the one established by Esquivel-Trava et al. 426 (2015) for distances up to 10 R_{max} from buoy observations in 14 hurricanes: the small-427 est angles between wind and waves is found in the forward quadrants (especially the right 428 front quadrant) and the largest values are at the rear where wind direction is often opposite to the waves (angles large than 90°). 430

In fast-moving TCs (Figure 5b), the wind and wave fields are more confused. This 431 may be due either to the fact that under fast-moving TCs the wind field is less homo-432 433 geneous than in slow or moderate speed moving TCs or that the forecast model have difficulties to correctly represent the wind field in these cases. Additionally, the more con-434 fused wave directions may be due to the presence of several wave systems as it will be 435 discussed in the next section. This wind and wave direction fields indicate that in fast-436 moving TCs both the wind and the wave fields are more complex than in slow and mod-437 erate speed TCs. 438

Figures 6(a-c) show the distributions of the angles between the direction of the dom-439 inant waves and the direction of the wind in slow, moderate speed and fast-moving TCs, 440 respectively. These distributions have been obtained by first removing the 180° ambi-441 guity on the wave direction, assuming that the waves always propagate to the right side 442 of the wind direction (see Section 2.2). This explains why the scale of Figures 6(a-c) is 443 between 0° and 180° . The shaded area in these plots highlight values greater than 90° , ллл corresponding to cases where the wind blows with a component opposite to the wave di-445 rection. From these figures, it is clear that there are numerous conditions where the wind 446 does not blow in the wave direction: for example it occurs under fast TCs, at all distances, 447 and for the other classes of TCs, at distances greater than 6 R_{max} . In contrast, in TC 448 of slow and moderate speed, the wind has a component aligned with the waves for a ma-449 jority of samples in the right quadrants, where the angle between wind and waves is also 450 the smallest. We can expect that the wind efficiently forces the wave growth only when 451 it has a component aligned with the waves, provided that the ratio of wind speed to phase 452 velocity (also called inverse wave age Ω) is greater than 0.83 (see e.g. Donelan et al. (1985)). 453 454 Figures 6(d-f) show this inverse wave age estimated by accounting for the angle between wind and waves (parameter Ω Eq.3), whereas Figures 6(g-i) show the inverse wave age 455 estimated without accounting for the angle between wind and waves (noted U_{10}/C_p). 456

It is clear from Figures 6(d-f) that there is only a small number of samples where Ω is larger than 0.83 (that is, condition of non-fully developed waves) whatever is the TC class; the fast moving TCs are however more favorable for this condition. In contrast, from Figures 6(g-i), we can see that if U_{10}/C_p is chosen as the inverse wave-age parameter, then the number of samples with non-fully developed waves is quite large, in particular at small distances (less than 3 R_{max}). Thus, it appears that it is the angle between wind and waves that governs the effective wave age, and that this latter is not in favor of an efficient wave growth by wind energy input.

Figures 6(d-f) also show a large number of samples with negative values of Ω (cor-465 responding to cases with an angle between wind and waves larger than 90°). In these 466 cases at least, it is evident that wind is not an efficient mechanism for the wave growth 467 and that other mechanisms must be invoked to explain the maintenance of large signif-468 icant wave heights. Tamizi et al. (2021) have shown with numerical simulations that in-469 deed the non-linear interactions between waves dominate the wave energy source terms 470 when the directional spectra are spread in direction, thus confirming the intuition of Young 471 (2006). But this simulation concerns only two cases of TC with slow to moderate dis-472 placement speed. We will come back to this discussion in the next sections. 473

In Figures 6(g-i), it is also notable that for almost cases, U_{10}/C_p decreases with distance. We checked that this variation is mainly due to the decrease of wind speed with distance rather to increase in C_p . This variation with distance is however not anymore visible when Ω is considered as the inverse wave age parameter.

By combining the results presented above on the main wave parameters in the three classes of TCs, the main conclusions are the following. First, the highest significant wave heights are observed at distances less than 3 R_{max} and in the right front quadrant of moderate speed TCs, in the left front quadrant of slow TCs and in the right rear quadrant of the fast TCs. This occurs whilst the inverse wave age Ω (which takes into account the angle between wind and waves), corresponds to a large majority of cases of fully developed waves ($\Omega < 0.83$), even if the along-wind inverse wave age U_{10}/C_p indicates nonfully developed waves.

In the cases of moderate speed TCs, the highest significant wave height occurring 486 in the right front quadrant at distances less than 3 R_{max} (IQR \approx [6-9] m) are associated 487 with the smallest angles between wind and waves $(IQR=[40-80]^{\circ})$, and with the longest 488 dominant wavelengths (IQR \approx [220-300] m), indicating that wind input may still be ef-489 ficient for wave growth is spite of low Ω values. The wave growth by the wind is prob-490 ably facilitated by the fact that the waves remain for a long time under the wind forc-491 ing in these conditions of TC with moderate displacement speed, as shown by the sim-492 ulations of Kudryavtsev et al. (2021b). 493

For the slow-moving TCs, the highest values of Hs occurring in the left front quadrant at distances less than 3 R_{max} (IQR \approx [7-9] m) are associated with long wavelengths (IQR \approx [200-280] m), large angles between wind and waves (sometimes even with the wind blowing against the waves), and wave age values corresponding to fully developed waves. In these conditions, it is rather unlikely that growth by the wind explains the maximum values of Hs.

For the fast-moving TCs, the highest values of Hs occurring in the right rear quadrant at distances less than 3 R_{max} (IQR \approx [6-10] m) are associated with a broad distribution of the angle between wind and dominant waves (IQR [25-150]°), and with wavelengths about IQR \approx [200-350] m. We suspect that this is because wave spectra have multiple peaks of similar energy so that the dominant waves are found at directions and wavelengths which are not very stable in space. This point is further discussed in section 5.2.

⁵⁰⁶ Overall, the asymmetry of Hs and of λ_p between the four quadrant decreases with ⁵⁰⁷ the distance from the center of the TC. This is the most visible in fast-moving TCs and ⁵⁰⁸ this is consistent with the numerical results of Kudryavtsev et al. (2021b).

509 5 Spectral shape analysis

510

5.1 Directional spectrum

In this subsection mean wave height directional spectra are analyzed in all quadrants and distance ranges for slow, moderate and fast-moving TCs (Figures 7, 8, 9, respectively). Before calculating the mean spectra, they were rotated so that the 0° direction of every spectrum corresponds to the displacement direction of the TC.

It is worthwhile to note that generally, the spectra show complex and variables features with either mono-modal, multi-modal features or important spread in the energy depending on the position within the TC and on the TC class. In order to differentiate in our discussion mono-modal to multi-modal features in direction, we consider a that a secondary peak is significant when its maximum energy reaches at least 45% of the maximum energy of the entire spectrum.

In slow-moving TCs (Figure 7), in the entire left front quadrant the wave field is 521 essentially mono-modal and the waves propagates at $\sim 45^{\circ}$ to the left of the displacement 522 direction of the TC. In the left rear quadrant the spectrum close to the center of the TC 523 is mono-modal with a significant directional spreading of the energy. While the distance 524 from the TC center increases the energy spreads in direction leading to a bi-modal spec-525 trum at distances larger than 6 R_{max} with two peaks of similar maximum energy and 526 similar dominant wavelengths of approximately 170 m and 200 m. In the right front quad-527 rant and at distances larger than 3 R_{max} , the dominant direction is aligned with the dis-528 placement direction of the TC. In the right rear quadrant, the spectra are bi-modal with 529 similar dominant wavelengths at distances less than 3 R_{max} . The difference between the 530 dominant wavelengths increases with the distance from the TC center. 531

For the moderate speed class (Figure 8), mono-modal spectra with limited spread 532 of energy in direction are observed in the right front quadrant, with the wave propaga-533 tion clearly aligned with the displacement direction of the TC. There are also mono-modal 534 spectra in the left front quadrant and the waves propagate with an angle of $\sim 45^{\circ}$ on the 535 left of the displacement direction of the TC as in slow moving TCs. In the left rear quad-536 rant the mean spectrum at distances less than 3 R_{max} is also mono-modal but its en-537 ergy spreads in direction. While the distance from the TC center increases; the mean 538 spectra become bi-modal with the secondary peak less energetic than the dominant one. 530 In the right rear quadrant, the energy spreads in direction while the distance from the 540 TC center increases leading to a bi-modal spectrum at distances larger than 6 R_{max} . 541

In fast-moving TCs (Figure 9), the mean spectra in both left quadrants are either multi-modal or significantly spread in direction. In opposite, in both right quadrants, the mean spectra are mono-modal, except the one at distances larger than 6 R_{max} in the right front quadrant which is bi-modal with a peak of energy close to 500 m in wavelength. In the entire right front quadrant the dominant waves are aligned with the displacement direction of the TCs whereas in the right rear quadrant, it is only the case for the mean spectrum at distances less than 3 R_{max} .

549

5.2 Omni-directional spectrum

Figure 10 presents the omni-directional spectra obtained in situations of moder-550 ate speed TCs as a function of the normalized frequency (f/f_p) where f_p is the dom-551 inant frequency of the waves. The energy density is also normalized by the total energy 552 of the omni-directional spectrum. The name of the quadrants are indicated in the top 553 right corner of each panel. In all quadrants, the trend of the mean spectra (black squares) 554 show a continuous decrease of energy at frequencies higher than f_p . At f/fp > 2, one 555 can notice that the dispersion of the spectral energy becomes more important especially 556 for observations obtained at more than 3 R_{max} . The mean and standard deviation of 557

the spectral energy (black squares and yellow error bars in Figure 10, calculated over all spectra present in each quadrant, are clearly impacted by this dispersion.

In the following we show and discuss the mean normalized spectra calculated for 560 each distance range in each quadrant for the moderate speed TCs (Figure 11). The spec-561 tral parametric form estimated by Young (2006) is also plotted in each quadrant. This 562 model is an adaptation of the JONSWAP (Donelan et al., 1985) spectral model estimated 563 from buoy observations in 9 hurricanes along the Australian coasts. We calculated this 564 parametric model by using the average wind speed (U_{10}) (from the ECMWF model co-565 localized with the SWIM spectra) and the mean dominant frequency of all the SWIM spectra obtained in each quadrant. We also checked that these mean "Young2006" spec-567 tra are close to the mean spectra obtained by averaging all the "Young2006" spectra cor-568 responding to all observations. 569

Figure 11 indicates that on the right-side of the dominant frequency $(f/f_p > 1)$ 570 the mean spectra are mono-modal in all quadrants, at all distance ranges. In all quad-571 rants, we can also see a secondary energy peak at lower frequencies (at about $f/f_p \sim$ 572 0.5). This peak indicates the presence of at least a secondary wave component at a lower 573 frequency than the dominant frequency as it is illustrated by the turquoise curve in Fig-574 ure 12 which show an example of a wave height spectrum obtained under moderate speed 575 TC condition, at a distance larger than 6 R_{max} . This spectrum exhibits two energy peaks: 576 the dominant one at $f/f_p = 1$ and another one at $f/f_p \approx 0.7$ which can be assimilated 577 to a swell component. 578

Coming back to Figure 11, observations obtained close to the TC center $(d/R_{max} <$ 579 3), the decreasing trend of the normalized energy with the normalized frequency does 580 not change significantly from one quadrant to another and it is very close to the para-581 metric model proposed by Young (2006). On the contrary, at largest distance from the 582 TC center, this trend differs significantly from the Young's model (Young, 2006) with 583 a more gentle decrease of the normalized energy with f/f_p , especially in the left front 584 and right rear quadrants. In the individual normalized spectra used to obtain Figure 11, 585 f_p generally corresponds to a low frequency peak which does not change significantly with 586 position within the TCs whereas depending on the quadrant and the distance, the fre-587 quency of the secondary peak (wind sea) may be more variable. In consequence, after 588 applying the averaging process to obtain the mean spectra of Figure 11, this leads for 589 certain quadrants and distances, to an increase of energy at $f/f_p > 1.5$ to 2. This phe-590 nomenon is illustrated in Figure 12 by the orange wave spectrum where a secondary peak 591 of energy appears at $f/f_p \approx 2.3$. In these conditions, the omni-directional spectra are 592 normalized with respect to the dominant frequency of the swell whereas the wind-sea part 593 may have a variable dominant frequency and therefore increases the energy at high fre-594 quencies $(f/f_p > 1)$. 595

In case of slow-moving TCs, the conclusions are similar to the ones discussed just above for the moderate speed cases. However, in fast-moving TCs, the trend of the mean spectra is less steep than the trend of the parametric model proposed by Young (2006) in each quadrant and in each distance ranges. This is explained by the presence of several wave systems since, as we mentioned in section 5.1, in fast-moving TCs, for almost all quadrants and distances, directional spectra exhibit mixed-sea conditions, or a significant spreading of the energy.

This analysis of the shape of the spectra shows that it is important to sort the data according to both the distance to the center and the relative speed of the TC. Indeed, the slope of the mean spectrum is different depending on whether the spectra are averaged over the entire quadrant (black squares in Figure 10) or over a particular distance range such as in Figure 11.

Similarly to the study of Tamizi and Young (2020) we also estimated the n factor 608 with the omni-directional SWIM spectra. However, because of the possible impact of mixed-609 sea on its estimation, we decided to calculate the n factor only for slow and moderate 610 speed TCs, for observations obtained close to the TC center ($d < 3R_{max}$). This fac-611 tor is estimated between $1.5f_p$ and $3.5f_p$ as shown in Figure 12 and in order to account 612 for the limitations of the SWIM detection, we filtered out the energy at frequency higher 613 than 0.2 Hz which corresponds to 40 m of wavelength. Furthermore, we kept the obtained 614 n value only if its estimation is based on more than 5 points. However, as discussed pre-615 viously, at distances larger than 3 R_{max} , there are some cases of mixed-seas that can bias 616 the estimation of n. Therefore, to avoid this limitation, the n factor has been calculated 617 for observations acquired at distances less than 3 R_{max} in slow or moderate speed TCs. 618

Figure 13 shows the *n* factor as a function of U_{10}/C_p . As in Tamizi and Young (2020), 619 we obtained an important scatter and there is no an obvious relationship between this 620 factor and the U_{10}/C_p . So, conclusions obtained by Tamizi and Young (2020) are con-621 firmed by the SWIM data but only for TC of slow and moderate speed. However, the 622 mean value obtained with the SWIM data is lower than the one obtained by Tamizi and 623 Young (2020) $(3.53\pm0.45$ and 4.68, respectively) and lower than the value obtained by 624 Donelan et al. (1985). 625

Finally, the non-dimensional relationships between wave energy and dominant fre-626 quency are analyzed. Figures 14(a-c) represent the variation of the non-dimensional en-627 ergy ϵ with the non-dimensional frequency ν for slow, moderate and fast-moving TCs, 628 respectively. Non-dimensional energy and frequency were determined as: 629

$$\nu = \frac{f_p U_{10}}{g} \tag{5}$$

(6)

630

 $\epsilon = \frac{g^2 E_{tot}}{U_{10}^4}$ with E_{tot} the total energy of the wave spectrum. The black solid line represents the lin-632 ear fit for the data obtained in each class, whereas the black dashed line represents the 633 fetch-limited relationship estimated by Donelan et al. (1985). It is interesting to note that 634 for each class, a clear non-dimensional relationship is found when we combined all ob-635 servations obtained at all distances. Observations obtained at less than 3 R_{max} from the 636 TC center (light blue circles) behave similarly between all classes and are close to the 637 values provided by Donelan et al. (1985) relationship. 638

6 Discussion 639

The analysis of the SWIM data performed by separating the TCs in different classes 640 according to their relative speed allows us to highlight that the wave field is different from 641 one class to another. According to our results, we find as in Young (2006) or Shi et al. 642 (2021) that Hs is higher on the right front quadrant of the TCs, but this is true only 643 in situation of moderate speed TCs. In case of slow-moving TCs, the highest Hs are ob-644 served in the left front quadrant, whereas in fast-moving TCs the highest Hs are observed 645 in the right rear quadrant.

The impact of the TC relative displacement speed on Hs field is in agreement with 647 the model results of Kudryavtsev et al. (2015, 2021a, 2021b), both with the physically-648 based model which treats the wave parameters evolution along wave rays in a Lagrangian 649 reference frame, and with the fully parametric model based on the TC parameters. It 650 is also interesting to compare our statistical results with the analysis recently proposed 651 by Yurovskaya et al. (2022) of the cyclone Goni (2020). In this study the authors com-652 pared SWIM observations to model results obtained from the two approaches developed 653 by Kudryavtsev et al. (2021a, 2021b), when Goni had a relative displacement velocity 654

corresponding, according to our classification, to the moderate speed class $(U_{max}/V_t \sim$ 9). Model results shown by Yurovskaya et al. (2022) -their Figure 4- are qualitatively consistent with our statistical results for the moderate class: largest significant wave height close to the TC center and in the right front quadrant, longest (resp. shortest) dominant wavelengths in the right front (resp. right rear quadrant).

It is also interesting to compare our results on the directional spectra with those 660 obtained in the cyclone Bonnie (1998), which is probably the most extensively documented 661 TC in the literature concerning the waves thanks to the analysis of airborne measure-662 ments with the Scanning Radar Altimeter Wright et al. (2001); Hwang and Walsh (2018) 663 and associated wave modeling Moon et al. (2003). According to our classification, at the 664 time of the airborne measurements when Bonnie was over the open ocean, it was a mod-665 erate speed TC ($U_{max}/V_t \sim 10$). Qualitatively, in similar conditions, the correspondence 666 between our statistical results (Figure 8) at $d/R_{max} < 3$) and those from the above-667 mentioned authors (e.g. Figure 3 of Hwang and Walsh (2018) for d < 200 km, i.e d/R_{max} 668 up to 2.7 with $R_{max} = 74$ km) is very good in terms of dominant wave directions, dom-669 inant wavelengths and shape of the spectra (mono- or multi-modal). This allows to gen-670 eralize some of the conclusions previously proposed in the literature. 671

In particular, one clear feature is that in the right front quadrant, directional spectra are mono-modal in moderate speed TCs with waves propagating along the displacement direction of the TC. In contrast, in the right front quadrant of slow and fast TCs, the energy is more spread in direction and wavelength and the dominant waves are not always aligned with the cyclone track. In the left front quadrant, for all TC classes, the dominant waves propagate towards the NW of the TC track and at significant angle from the wind direction.

In the left rear quadrant, spectra for moderate speed TCs have a clear dominant wave direction along SE direction relative to the TC and a secondary maximum along the W-E axis whereas in slow and fast-moving TCs, the shape of the mean spectra is more complex with multi-modal spectra and varying dominant wave direction with the distance from the TC center. In the right rear quadrant, the mean spectra are multi-modal in moderate and slow TC classes as well as in fast TCs (at least close to the center), with varying dominant wave direction propagation according to the TC class.

In their study, Esquivel-Trava et al. (2015) calculated composite directional spec-686 tra per quadrants by averaging individual spectra from 0 to 10 R_{max} from 14 cyclones. Because no distinction was made in their case with respect to the cyclone displacement 688 speed nor with the distance from the center, the comparison is not straightforward. How-689 ever, in the two right quadrants and in the left front quadrant their spectra are similar 690 to our mean spectra obtained under moderate speed TC conditions with the direction 691 of the dominant waves aligned with the displacement direction of the TC in the right 692 front quadrant. The tendency to have more spread in the energy distribution in both 693 left and right rear quadrants is also consistent with our findings. 694

As mentioned in section 4, the effective inverse wave age Ω (which takes into ac-695 count the phase speed of the dominant waves and the angle between wind and these dom-696 inant waves) does not seem an appropriate parameter to characterize the continuous growth 697 of waves. Indeed, Ω corresponds almost everywhere to fully developed waves (Ω smaller 698 than 0.83), mainly due to the important angle between wind and waves. So, we have to 699 speculate that either the wind input remains efficient even in cases when dominant waves 700 are not aligned with the wind or, as suggested by Young (2006), that another mecha-701 nism such as the 4-waves non-linear interactions plays an important role to maintain the 702 waves under an efficient growing stage. According to Young (2006), and Tamizi and Young 703 (2020), for wave spectra at distances of about 3 R_{max} , a smooth transition in energy oc-704 curs between the swell (remotely generated) and locally generated wind-sea. They sug-705 gest that this could be the signature of efficient non-linear wave-wave interactions that 706

could explain the absence of bimodality in the omni-directional spectra. This intuition 707 was later verified by Tamizi et al. (2021) by evaluating, for two cases of TC (slow and 708 moderate speed according to our classes) the different source and sink terms of the wave 709 growth equation in a numerical wave model. They found that except in the right front 710 quadrant where the wind input remains efficient for wave growth over all wave frequen-711 cies, the non-linear interactions play a major role in redistributing energy for spectra in 712 the other quadrants, i.e. when the angle between wind and dominant wave is large. In 713 absence of numerical modeling (which is out of the scope of this paper), it is not pos-714 sible to firmly assess these conclusions with our observations. However, our results in the 715 same conditions as those studied by Tamizi et al. (2021), i.e. slow and moderate cases 716 and distances less than 6 R_{max} seem to support these conclusions. 717

The behavior of the omni-directional spectra also shows similarities but also some 718 differences with respect to previous results. In fact, clear similarities with Young (2006) 719 and Tamizi and Young (2020) are found when the individual spectra are mono-modal 720 in frequency. This occurs close from the TC center in slow and moderate speed TCs but 721 not in fast-moving TCs. The systematic presence of multi-modal spectra either far from 722 the TC center or in fast-moving cases induce an estimation of the trend with the nor-723 malized frequency much less steep than in the above-mentioned reference. It has to be 724 noted that spectra illustrated in Young (2006), and Tamizi and Young (2020) only re-725 fer to observations close to the TC center and probably to TC with slow to moderate 726 speed. Our results, which cover a large range of distances and TC classes, indicate that 727 the similarity with the laws of wind-waves under fetch-limited conditions holds only at 728 less than 3 R_{max} in slow and moderate speed TCs. 729

730 Surprisingly, concerning the non-dimensional relationship between ν and ϵ , we find a relationship which is consistent with the fetch-limited relationship, whatever is the TC 731 class even if samples far from the TC center are considered. This result is surprising be-732 cause far from the center the wave field is characterized by multi-modal spectra with con-733 tributions of both swell and wind-sea with generally swell energy dominating. But the 734 slope of the relationship ν and ϵ seems to remain the same for all ranges of ν either above 735 0.13 (wind waves dominating) or less than 0.13 (swell dominating). This confirms the 736 results of Tamizi and Young (2020) and extends them to the cases of fast moving TCs. 737 Thus, in TCs this self-similarity law between non-dimensional frequency and non-dimensional 738 energy seems to hold even in mixed sea conditions. 739

740 7 Conclusions and perspectives

SWIM data have been analyzed in TC conditions over more than 3 years (May 2019-September 2022) in the Northern Hemisphere. The objective of this study was to characterize the impact of the TC features on the wave field. Several studies of the SWIM data at the global scale allow us to target the strengths and the limitations of the instrument (Hauser et al., 2021; Le Merle et al., 2021) and confirmed that the limitations of SWIM were limited in TC situations.

Thanks to the IBTrACS data we have established three TC classes based on the maximum sustained wind speed and on the displacement velocity. After collocating the SWIM data with the TC and referencing them in a coordinate frame centered on the TCs, we analyzed the distributions of the wave parameters and the spectral shape as a function of the quadrant and the distance between the observations and the center of the TC.

The analyses of the wave parameters indicate that there is an asymmetry of Hsand of the dominant wavelength (λ_p) . This asymmetry varies with the TC class, and the maximum values observed are obtained in the right front quadrant in moderate speed TCs and in the right rear quadrant in fast moving TCs. We also calculated mean directional spectra for each TC class, each quadrant and each distance. It appears that the spectral shape varies according to these different classes of observations. In moderate and slow-moving TCs, close to the TC center, the wave spectra tend to be mono-modal whereas far from the TC center and in fast moving TCs (especially in the left side), the spectra tend to become bi- or even multi-modal.

We have compared mean omni-directional spectra to a parametric model proposed by Young (2006) which generalizes the JONSWAP form in case of TCs. In slow and moderate moving TCs, close to the center, omni-directional spectra present consistencies with the "Young2006" spectrum whereas far from the TC center and in fast-moving TCs, the agreement is less satisfying. This can be partly explained by the presence of mixed-sea in which the swell is dominant.

Because of these situations of mixed-sea impact significantly the shape of the normalized omni-directional spectra, the n factor was discussed only for spectra in slow and moderate speed TCs, close to the TC center. It appears that the mean value of n obtained in these situations is close to the one obtained by Donelan et al. (1985) in fetch limited conditions. As previously shown by Tamizi and Young (2020), there is no obvious relationship between this n factor and the inverse wave age.

We also analyzed the relationship between the non-dimensional frequency and the non-dimensional energy from the SWIM spectra. These non-dimensional laws are verified but with a slope smaller than the one obtained by Donelan et al. (1985) in fetchlimited conditions. This smaller slope is also find in the numerical simulations of Tamizi et al. (2021).

Overall, from an analysis over 67 TCs, we confirm features already been mentioned in the literature such as the asymmetry of the wave field with higher waves in the right front quadrant and a spectral shape that have similarities with the fetch-limited parametric models. But, we also show that the TC characteristics, in particular its relative displacement speed, have an impact on the wave field. In particular, under fast-moving TCs none of these features could be evidenced.

784 8 Open Research

The SWIM data set used here corresponds to the files reprocessed in version 5 and made available by CLS on the ftp server of AVISO+ (ftp-access.aviso.altimetry.fr/, directory /cfosat/swim_l2p_box_nrt) accessible to anyone after registration.

The IBTrACS data used in this study correspond to the last 3 years file with reprocessed data in version 4 (IBTrACS.last3years.v04r00.nc). Data are available here:https:// doi.org/10.25921/82ty-9e16. The data have been downloaded on the 9th of August 2021.

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 work on the reprocessing of the L2 products.

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964 Tables

Table 1. Number of ocean wave spectra measured by SWIM for each TC class in the Northern Hemisphere between May 2019 and August 2021. The number in brackets corresponds to the number of different TC observed. R_{max} is the radius of maximum sustained wind and d is the haversine distance of the observation.

	Slow	Moderate speed	Fast
$ \frac{0 \le d/R_{max} < 3}{3 \le d/R_{max} < 6} \\ 6 \le d/R_{max} < 9 $	$\begin{array}{c} 63 \ (10) \\ 118 \ (14) \\ 103 \ (13) \end{array}$	$\begin{array}{c} 86 \ (20) \\ 181 \ (26) \\ 185 \ (26) \end{array}$	$\begin{array}{c} 134 \ (10) \\ 353 \ (15) \\ 290 \ (15) \end{array}$

965 Figures



Figure 1. (a): normalized histogram of SWIM observations according to the relative speed U_{max}/V_t . (b): superposition of the normalized histograms of SWIM observations according to the radius of maximum sustained wind speed (R_{max}) for each of the TC class. The colors represent the TC classes as reported in the legend in (a). (c): superposition of the normalized histograms of SWIM observations with the ratio $R_{max}/L_{cr} > 1$ in blue and with the ratio $R_{max}/L_{cr} < 1$ in orange according to the ratio between U_{max}/V_t .



Figure 2. 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 with the red arrow showing the direction displacement of the hurricane Douglas. The magenta circle stands for the radius of maximum sustained wind speed, the dashed grey circle represents 9 time 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 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 3. Boxplots showing the distribution of the significant wave height (Hs) for slow (*left panel*), moderate speed (*middle panel*) and fast (*right panel*) moving tropical cyclones in every quadrants as reported on the horizontal axis. The color of the box represents the distance ranges. The boxes represent the distribution of the first to third interquartile range, the error bar stand for and the black circles are the outliers. The solid lines and the dotted lines represent the median and the mean of the distribution, respectively.



Figure 4. Boxplots showing the distribution of the dominant wavelength (λ_p) of the whole spectrum for slow (*left panel*), moderate speed (*middle panel*) and fast (*right panel*) moving tropical cyclones in every quadrants as reported on the horizontal axis. The figure characteristics are the same as in figure 3.



Figure 5. Maps of wind (black) and dominant wave (red) directions in slow-moving and moderate speed (a) and in fast-moving (b) TC conditions. The length of the arrow corresponds to the wind speed at 10 m according to the ECMWF model and to the dominant wavelength, respectively.



Figure 6. Boxplots showing the distribution of the differences between the dominant wave direction and the wind direction $(top \ row)$, the inverse wave age $(\Omega) \ (middle \ row)$ and U_{10}/C_p $(bottom \ row)$ for slow $(left \ column)$ moderate speed $(middle \ column)$ and fast $(right \ column)$ moving tropical cyclones in every quadrants as reported on the horizontal axis. The figure characteristics are the same as in figure 3. The grey area represents the values higher than 90°, the dashed grey line indicates $\Omega = 0$ and the dotted red line represents the limit between fully and non-fully developed sea $(\Omega \ or \ U_{10}/C_p = 0.83)$.



Figure 7. Average normalized wave height directional spectra in case of slow-moving tropical avelance. Each blue accurate a quadrant and the red simples stand for the distance



Figure 8. Average normalized wave height directional spectra in case of moderate speed trop-



Figure 9. Average normalized wave height directional spectra in case of fast-moving tropical scales of the sector of the secto



Figure 10. Omni-directional wave height spectra as a function of the normalized frequency (f/f_p) for each quadrant under moderate speed tropical cyclone conditions. The energy of the spectra is normalized with the total energy. The color of the circles correspond to the distance ranges as reported in the legend. The black squares and the orange error bars represent the mean and the standard deviation of the spectra for every bin of 0.25 f/f_p .



Figure 11. Average omni-directional spectra as a function of the normalized frequency (f/f_p) for each quadrant under moderate speed tropical cyclone conditions. The energy of the spectra is normalized with the total energy. The color of the lines, squares and error bars correspond to the distance ranges as reported in the legend. The red dashed-dotted line corresponds to the JONSWAP spectrum adjusted by Young (2006).



Figure 12. Examples of SWIM omni-directional frequency wave height spectrum as a function of f/f_p obtained in moderate speed moving TC at distances larger than 6 R_{max} . The grey area indicates the portion of the spectrum over which is calculated the *n* factor. The spectra are normalized according to their respective maximum of energy.



Figure 13. Variation of the frequency decay exponent n with U_{10}/C_p for observations at less than 3 R_{max} in slow (circle symbol) and moderate speed (square symbol) moving TCs. The black line shows the mean values of the SWIM data, the black dashed line shows the mean value obtained by Donelan et al. (1985), in fetch-limited conditions (n = -4) and the red dotted line indicates the limit value of $U_{10}/C_p = 0.83$ separating young wind sea and swell.



Figure 14. Variation of the non-dimensional frequency ν with the non-dimensional energy ϵ for (a) slow, (b) moderate and (c) fast-moving TCs. The color of the symbol corresponds to the distance ranges following the same convention as in the previous figures. The black dashed line shows the relationship estimated by Donelan et al. (1985) and the red dashed line indicates the limit value of $\nu = 0.13$ separating young wind sea and swell.