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LATMOS

Directional ocean wave spectrum properties from the SWIM instrument under tropical cyclone conditions

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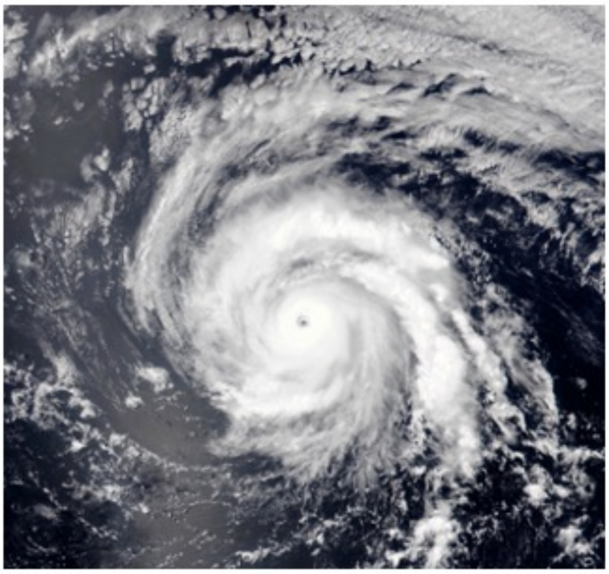
Outline

- Introduction
- Methods
- Case study
- Statistical study
- Conclusions



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Introduction

- Tropical cyclones (TC) are extreme meteorological events associated with extreme winds, waves and precipitations.
- TC impact the maritime navigation, the risk in coastal areas
- TC modify the ocean–atmosphere interactions
- TC are moving systems with winds in rotation around the TC centre and complex features (asymmetry, radial gradients)
- Importance of improving our knowledge on the wave field generated by tropical cyclones to better understand and model their evolution and their impact on air–sea interactions in these conditions

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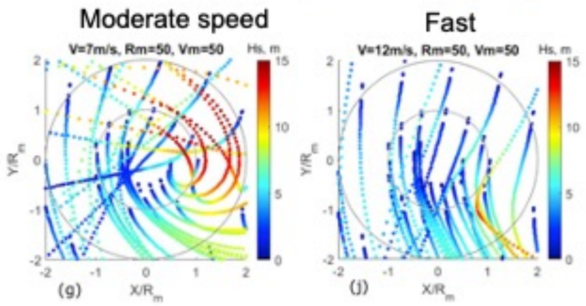
Here, we first we recall the characteristics of tropical cylones, and the importance of better knowing wind and wave fields associated with these meteorological events

Introduction

- Hs field is asymmetric in TCs, even when the wind field is symmetric (Young 2006, Kudryavtsev 2015; Shi 2021)
- Explained by "extended fetch" or "trapped waves", in the forward right quadrant of Northern Hemisphere systems (Young 1998 , Boywer and McAffe,2005),
- Translation speed of TCs impact the wave development (Lagrangian model of Kudryavstev et al, 2021)



Kudryavtsev et al., 2021

Here and in the next slide, we summarize was is known from recent studies on waves in tropical cyclones, based on either observations (mainly Hs from altimetry , or buoy measurements in coastal zones) or from model (fully discretized wave models like WAM or parametric Lagrangian model as developed by Kudryavstev et al, JGR2021)

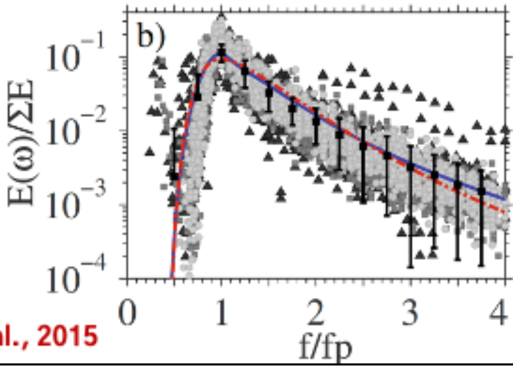
The figures at the bottom are from Kudryavtsev et al., JGR 2021 who show from a numerical study in a Lagrangian frame that depending on the displacement sped of the cyclone V (and for a given maximum wind velocity Vm), the ray of wave energy propagation is completely different, and that there are conditions (related to V, Vm and the radius of maximum wind) where the waves are trapped in the cyclone(their group velocity is close to the displacement speed of the cyclone), generating a clear maximum of significant wave height in the right front quadrant.

Introduction

- Shape of 1D/2D spectra analyzed by e.g.Young (2006), Hwang and Walsh (2018) , Tamizi and Young (2020) , Esquivel-Trava et al., (2015) (buoy measurements, airborne measurements)

- 1D frequency spectra have similarities with fetch-limited spectra. This is explained by several authors (e.g; Young, 2006, Tamizi and Young, 2021) as being due to continuous non-linear wave-wave interactions transferring energy from wind sea to swell whose propagation direction are very different.

- 2D spectra tend to become multi-modal on the left side of the TCs



- Spectral shape in fetch-limited conditions

Esquivel-Trava et al., 2015

The figure is from Equivel-Trava et al (Ocean Dynamics 2015) who analyzed wave spectra measured by wave buoys in 14 tropical cyclones in the Gulf of Mexico. It represents the omni-directional spectra (normalized by the total energy and plotted as a function of the normalized frequency f/f_p where f_p is the peak frequency). It refers to observations in the front-right sector of the TCs (sectors defined relative to the cyclone displacement- Light dots are spectra recorded at distances less than $3R_m$ (R_m is the radius of maximum wind of the TC), dark squares are from 3Rm to 6Rm and black triangles are from $6R_m$ to $10R_m$. The blue line represents the Jonswap spectrum adjusted by Young (2006) and the red-dashed line indicates the Pierson-Moskowitz spectrum. Black squares with a one standard deviation bar represent mean values in 0.2 f/f_p bins.

Introduction

- **Objective this study: exploit the new CFOSAT observations (wave spectra at the global scale) to:**
  - further investigate the properties of ocean wave spectra and of their main parameters under TC conditions.
  - Based on a global and open ocean data set over a 2-year period (May 2019 and August 2021)
  - Taking into account recent publications: analysis of the ocean wave spectra according to different classes **of relative displacement speed** of the cyclones and at **different distances** within the TC

Here we present the objective of our study

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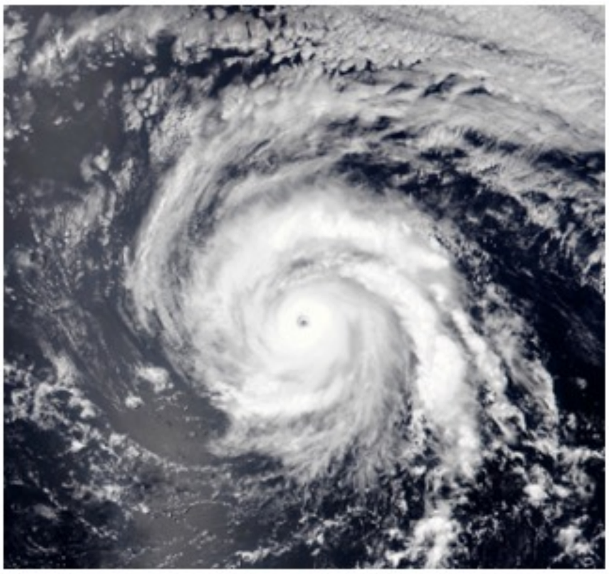

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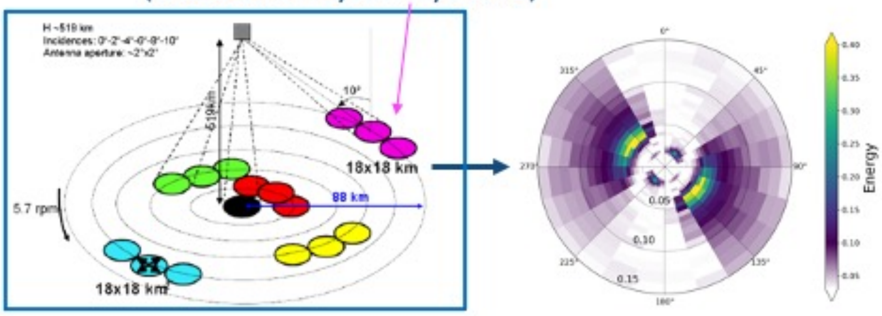
Methods

Observations

CFOSAT satellite

- SWIM= nadir beam => Significant wave Height –SWH)– as any other altimeter
- Off–nadir beam rotating beam (10° incidence) => directional wave spectra (Hauser et al, 2017, 2021)



- At global scale, every 70 km along–track.
- Information on waves between ~ 30 and 500 m.
  - Wave spectra
  - Wave parameters (in particular dominant wavelength and direction)

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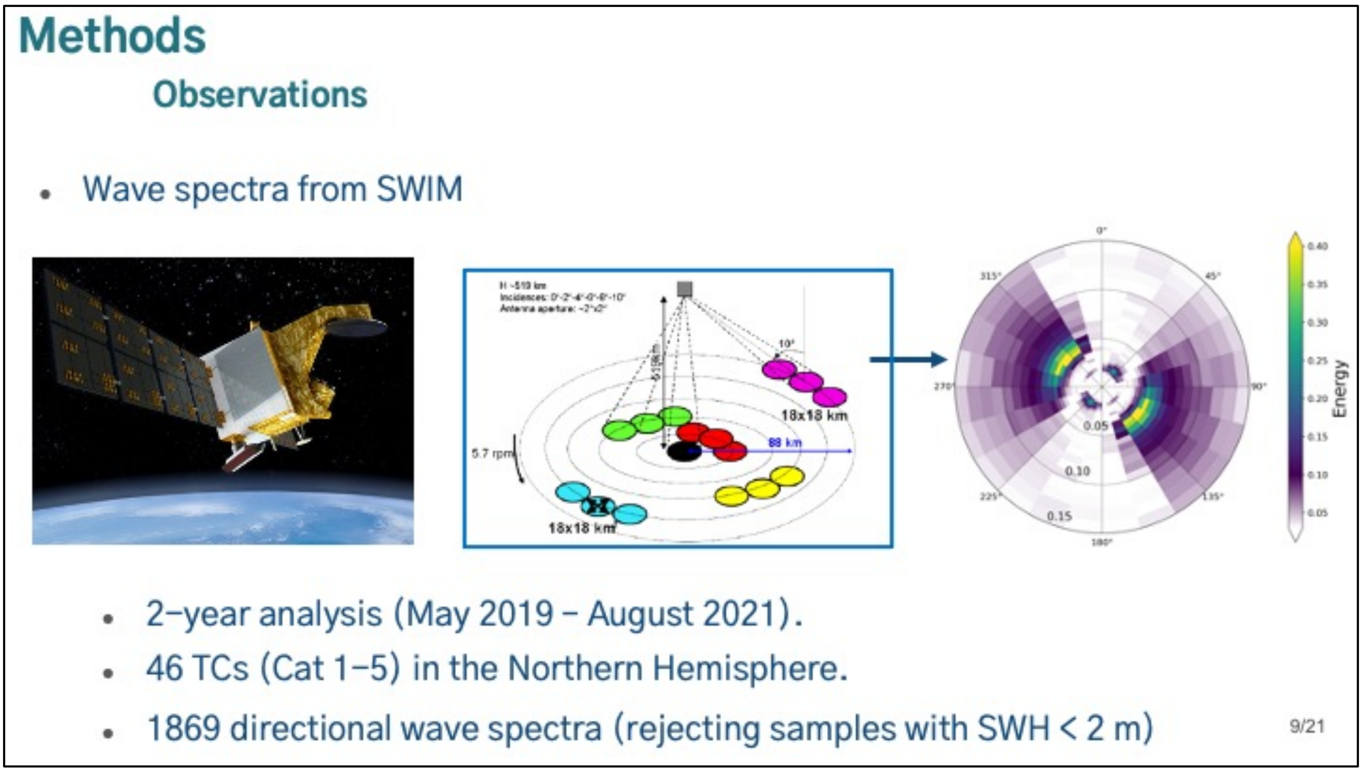
The left figure shows the geometry of the SWIM instrument on board the CFOSAT satellite. It has 6 illuminating beams (in Ku-Band), one pointing towards nadir (like any altimeter) and 5 off-nadir (around 2°, 4°, 6°, 8°, and 10°). All beams are conically scanning around the vertical at a rate of 5.6 rpm. The radar range resolution is 0.47 m before on-board processing. Beams at 6°, 8°, and 10° are used to estimate the wave spectra (based on the principle that the tilt of the long waves induces a radar cross-section modulation when the radar points into the wave propagation direction- see e.g.Hauser et al, TGRS 2017). Results from previous studies during the CAL VAL have shown that the best performances in terms of wave spectra and wave parameters are those provided by the 10° beam. Here we use the wave spectra estimated from the observations at 10° incidence.

The figure on the right is an example of a directional wave spectrum deduced from the SWIM observations. The energy density is in color. The angle (0-360°) indicates the wave propagation direction (with an ambiguity of 180°). The distance from the center of the figure is the wave frequency (in Hz). This example illustrates a case with a long swell of low frequency, propagating at 45°from North ±180°) superposed with wind sea (propagating at 120°±180°]. The wave spectra are provided in wave cells of about 70 km along-track by 90 km across-track, on each side of the nadir track.



We have used two years of SWIM observations in the Northern hemisphere. During this period, SWIM crosses 46 TC of category 1 to 5 . We have selected SWIM data when the nadir track position is at a distance of less than 4 times Rm (Rm radius of maximum wind) with a time difference of less than 1h30. Along these tracks, observations within 9 R_{max} were selected to perform the analysis.

Because we know from the CAL/VAL and previous publications that the uncertainty on the wave spectra and wave parameters is less at SWH less than 2m, we have filtered out the data which correspond to SWH < 2m.

Methods

Tropical cyclone (TC) classification

Analyze the wave field by taking into account the TC parameters:

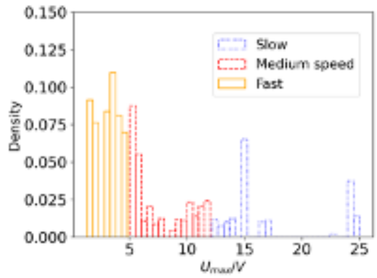
- radius of maximum wind (R_{max}),
- maximum sustained wind (U_{max}),
- translation speed (V_t).

- All these TC parameters (V_t, U_{max} , R_{max}) are taken from the NOAA IBTrACS data base (https://ibtracs.unca.edu/)

Methods

Tropical cyclone classification

- Based on the numerical studies of Kudryavstev et al (2021) => we chose 3 TC categories, according to their relative speed of displacement V_t / U_{max}
  - Slow $12 < U_{max}/V_t$
  - Moderate speed $5 \leq U_{max}/V_t \leq 12$
  - Fast $U_{max}/V_t < 5$



=> half of the SWIM observations correspond to fast moving TCs

- 3 distance ranges relative to R_{max} :
  - $0 \leq d/R_{max} < 3$
  - $3 \leq d/R_{max} < 6$
  - $6 \leq d/R_{max} < 9$

Note: R_{max} varies between 10 and 210 km (and R_{max} > 100 km for 70% of fast TC, 15% of moderate speed TC, 51% of slow TC)

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In order to study the impact of the TC characteristics on the wave field, the TCs have been separated into 3 classes based on the ratio between the maximum sustained wind speed U_{max} and the translation speed V_t. Here we show the histogram of the SWIM observations as a function of the ratio U_{max}/V_t). We can see that half of the observations correspond to fast moving TCs.

Even if the categories are here established with the ratio U_{max}/V_t, we have checked that it is the translation speed V_t that is governing the classification.

Note that by choosing classes in d/R_{max}, the maximum distance considered in the cyclone varies significantly between the different TC classes as R_{max} is the largest for the fast TC.

Methods

Number of observations per class

	$12 < U_{max}/V_t$	$5 \leq U_{max}/V_t \leq 12$	$U_{max}/V_t < 5$
	Slow	Moderate speed	Fast
$0 \leq d/R_{max} < 3$	63 (10)	86 (20)	134 (10)
$3 \leq d/R_{max} < 6$	118 (14)	181 (26)	353 (15)
$6 \leq d/R_{max} < 9$	103 (13)	185 (26)	290 (15)

- 3 distance ranges relative to R_{max} :
  - $0 \leq d/R_{max} < 3$
  - $3 \leq d/R_{max} < 6$
  - $6 \leq d/R_{max} < 9$

Note: Rmax varies between 10 and 210 km

This table gives the number of wave spectra (and the number of cyclones in parenthesis) per class of cyclone displacement speed and per class of range with respect to R_{max}.

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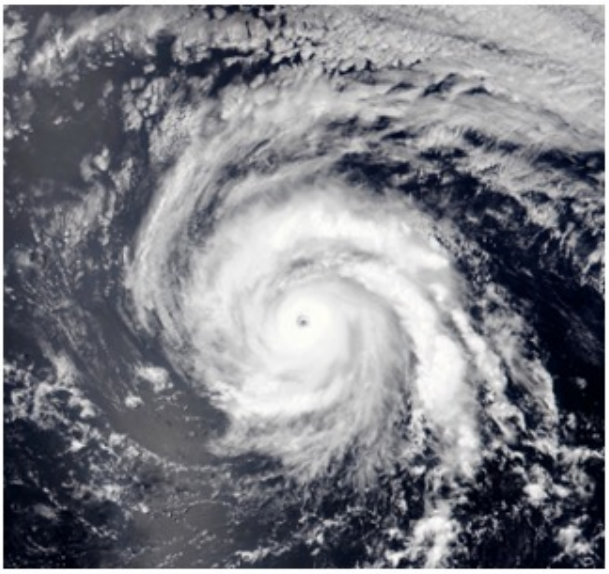

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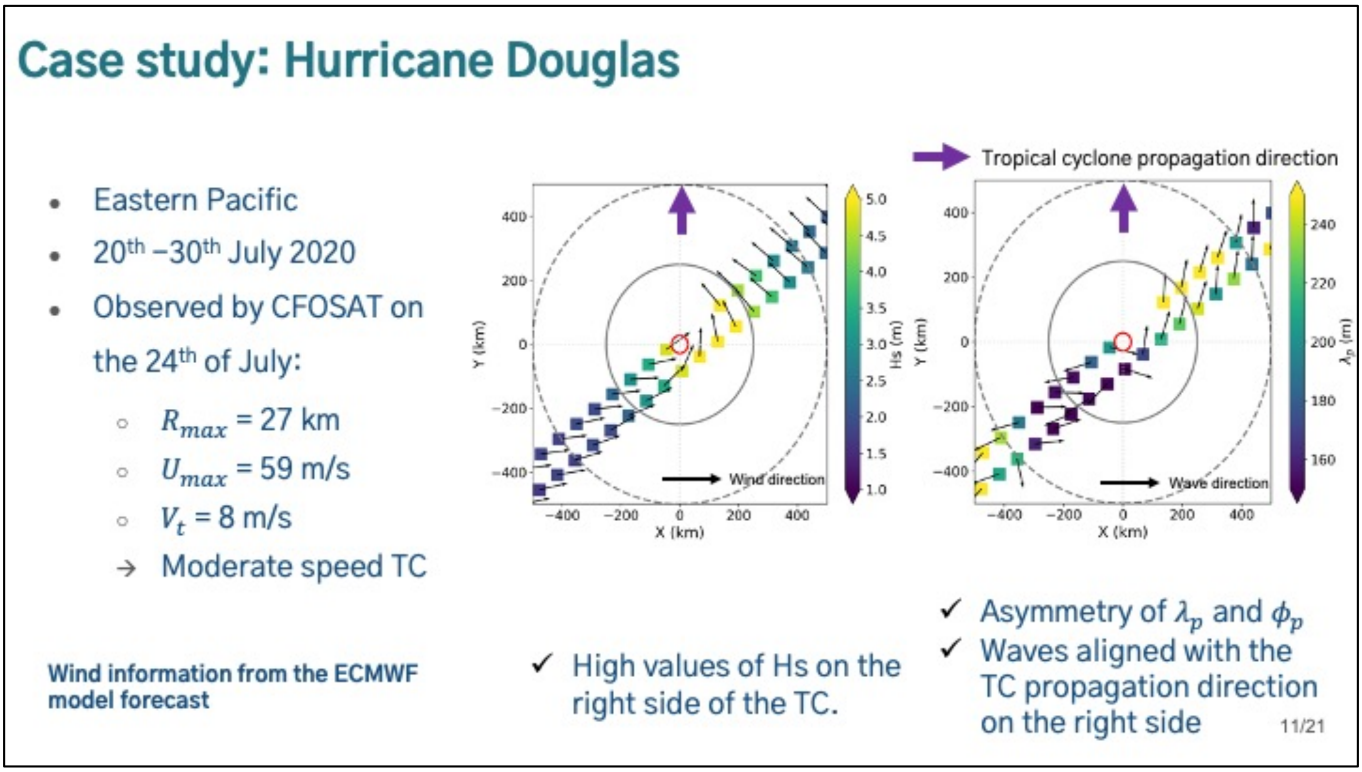
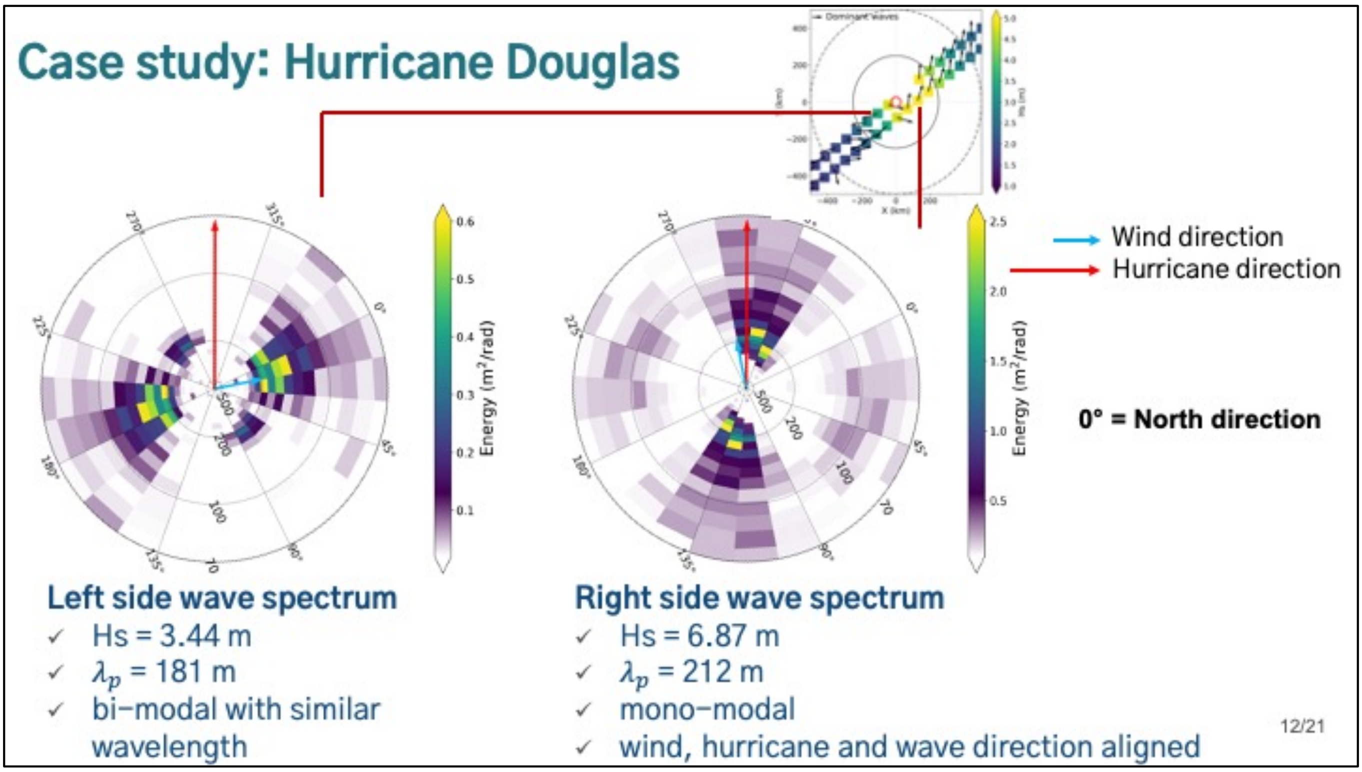


The TC center is at the center of the figures, and its direction propagation is towards the top of the figure indicated by the violet arrow. The red circle indicate the radius of maximum wind and the grey circle represents 9 times this radius of maximum wind.

On the left panel, the color of the observation point is the significant wave height and the arrow indicates the wind direction. Information of the wind is taken from the ECMWF model. We can see that the highest values of Hs are observed on the right side of the TC as mentioned in the literature.

On right panel, the color stands for the dominant wavelength and the arrow indicates the dominant wave direction. We can see that we have also an asymmetry of the wavelength and the direction: the lower wavelengths are observed on the left side of the TC and the directions are aligned with the propagation direction of the TC on the right side, whereas on the left side they are perpendicular.



The propagation direction of the TC is towards the top of the figure, and the 0° indicates the North direction. We can see that the spectrum obtained on the rear left side of the TC is bi-modal whereas the spectrum obtained on the front right side of the TC is mono-modal with the wind, wave and TC propagation direction are all aligned.

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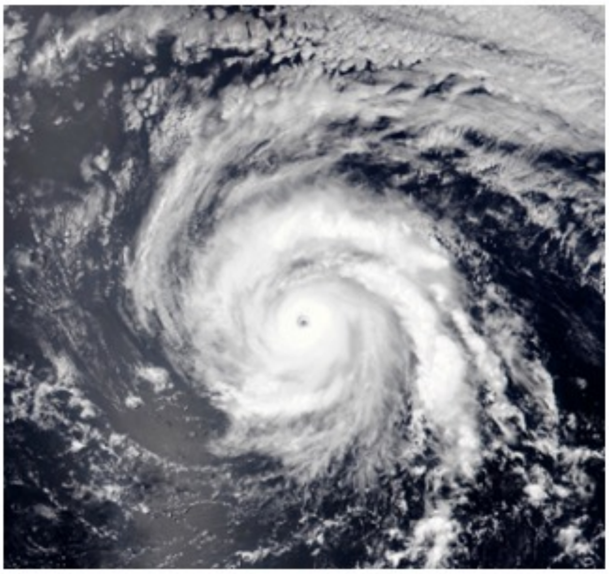

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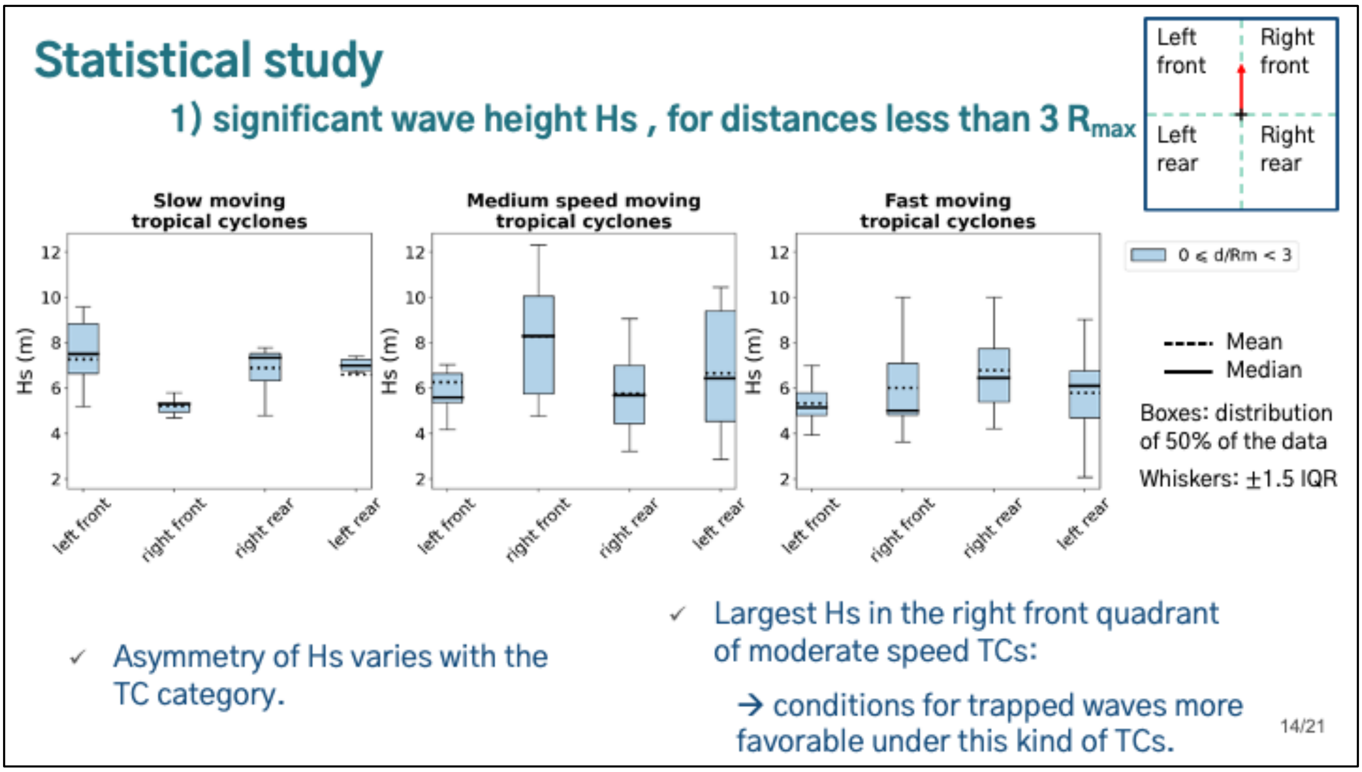
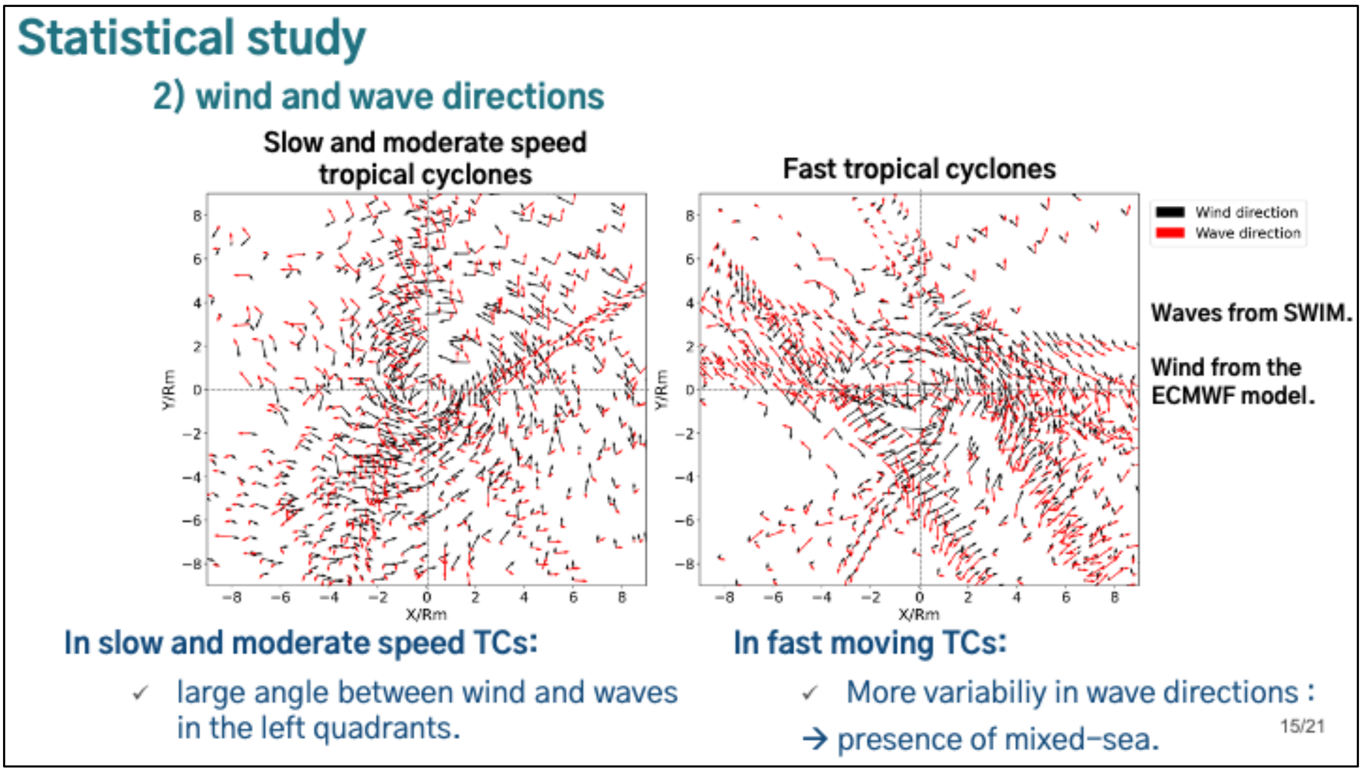
Now let’s move to the statistical study.



Results are presented here for the significant wave height, and only for distances less than 3 R_{max}.
Each boxplot represents the distribution in a TC quadrant as indicated on the horizontal axis.

We can see that the distributions are different depending on the TC category. In slow moving TC, the highest Hs are obtained in the left front quadrant whereas in moderate speed, the highest Hs are obtained in the right front quadrant. In fast moving TCs, even if there is less differences between the distributions, the highest Hs are obtained in the right rear quadrant.

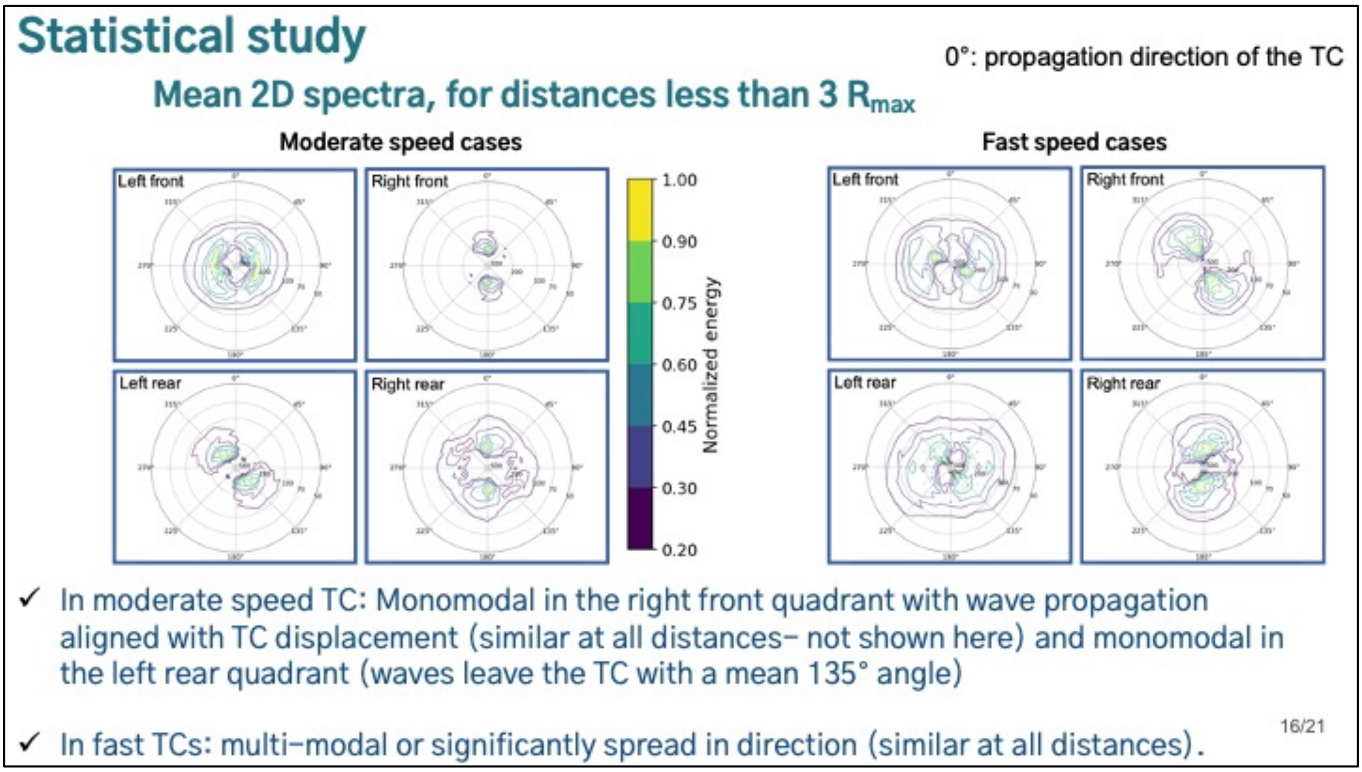
From all the distributions, the highest Hs are obtained in the right front quadrant in moderate speed TCs which means that it is under these kind of TCs, that the conditions are the most favorable for trapped-waves phenomena.



Here we show the wind and dominant wave mean directions for slow and moderate speed TC (on the left) and for fast moving TC (on the right). Each arrow results from averaging data overall the considered TC situations and within a grid of 0.25 R_{max} resolution. The ambiguity on the wave direction has been removed by assuming that the waves always propagate to the right of the wind direction. The length of the black arrows corresponds to the 10m height wind speed and the length of the red arrows is proportional to the dominant wavelength. We recall that the wind information is from the ECMWF model forecast provided.

It is clear that for TC with slow and moderate speeds (left panel), the wave propagation is almost aligned with the TC propagation in the right front quadrant, but at an angle of 40 to 50° to the right of the wind. In the left front quadrant the dominant waves propagate almost perpendicular to the wind whereas in the rear left quadrant the angle between wind and waves is larger than 90° and the waves exit the TC by the rear. In the rear right quadrant the angle between wind and waves remains generally less than 90°

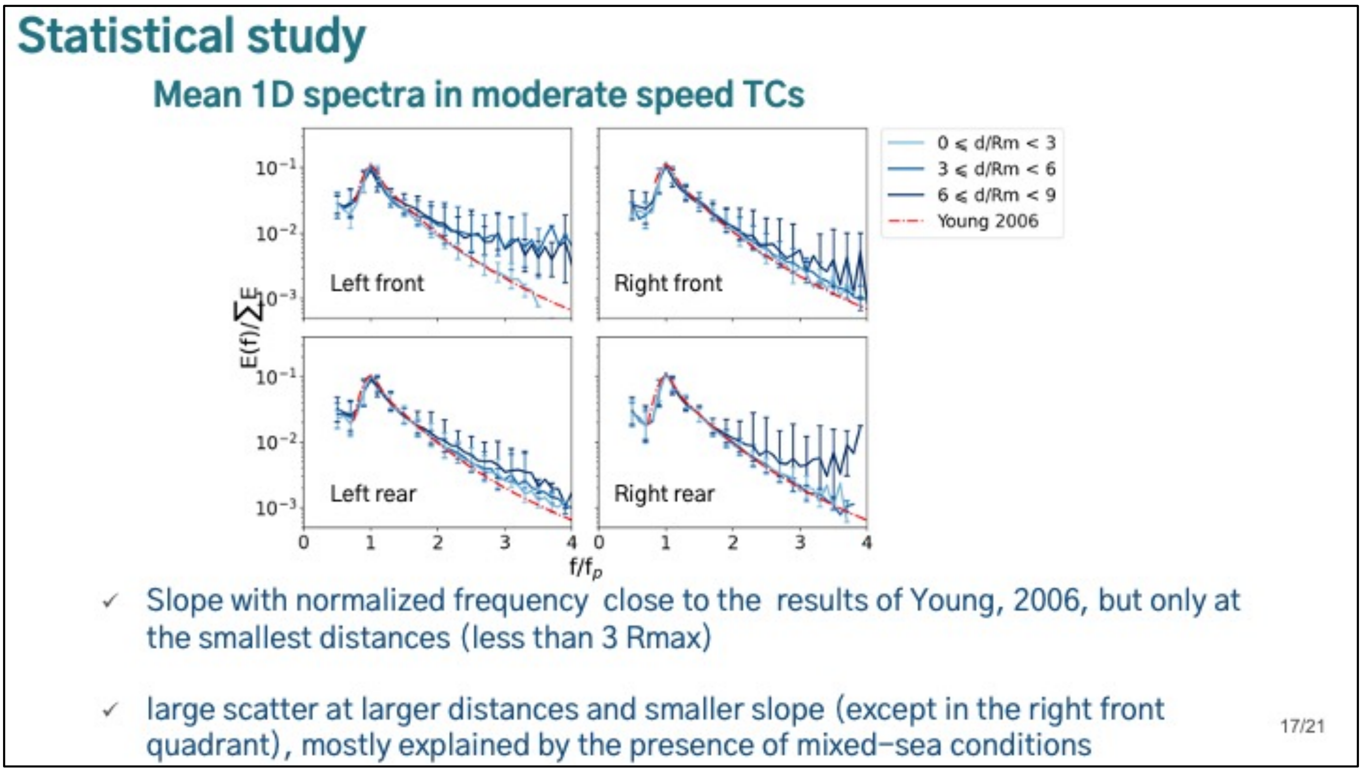
For the fast TC (right plot), the main features are observed at X/R_{max} larger than about 3 R_{max} and the results are more confused elsewhere. We think this is because the dominant wave direction is not well-defined in these cases (fluctuating between different energy peaks in the 2D spectrum, see below).



Here we show mean directional spectra obtained for each quadrant in fast and moderate speed TCs and for $d/R_m < 3$.

For the moderate speed TCs (left panel), wave spectra are clearly unimodal in direction in the front right and in the rear left quadrants. In the front right quadrant, the dominant wave propagation, is clearly aligned with the TC propagation direction (towards the top of the figure). In opposite , in the other quadrants, the spectra are multi-modal with similar wavelengths or widely spread in direction .

For the fast speed cases (right panel) , in all quadrants, the directional spectra are widely spread in directions and/or multimodal with energy splinted between swell and wind sea.



Here we show the mean omni-directional wave spectra obtained for each quadrant in the cases of moderate speed TCs The mean spectra are estimated as energy normalized spectra expressed as a function of the normalized frequency f/f_p (where f_p is the peak frequency of the spectrum). The color correspond to the distance of the observation with respect to the radius of maximum wind Rm (see legend). The red dashed line corresponds to the spectral parametric form estimated by Young 2006, which is an adaptation of the JONSWAP spectral model (wind waves).

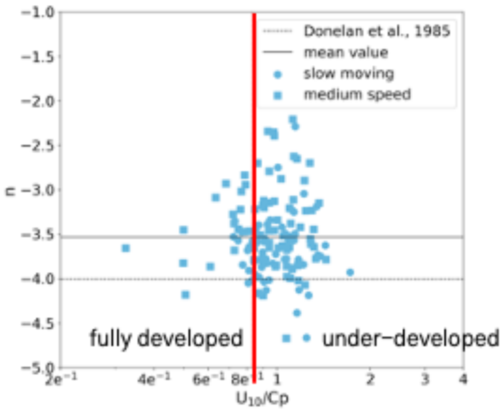
In all quadrants, spectra in light blue (distances at less than 3 Rm) are in good agreement with the Young spectrum. In opposite, for the spectra in dark blue (at large distances), the agreement is less satisfying especially in the left front and right rear quadrant. Moreover, in these cases the dispersion increases at high frequency. This is probably explained by averaging spectra with double components (wind sea and swell). This analysis shows that the decay of wave energy with frequency varies with the quadrant and the distance from the TC center. This decay is further analyzed in the next slide.

Statistical study

Frequency decay exponent

- Exponent n such as: $E(f) \sim Af^{-n}$
- Calculated between 1.5 and 3.5 f_p

Here results illustrated for slow and medium speed TC only, and d < 3 R_{max},



- No obvious relationship between the frequency exponent and the inverse wave age (same as in Tamizi and Young (2020)
- Absolute mean value of n from SWIM data (3.58) is smaller than the value from Donelan et al (4) and smaller than that from Tamizi and Young (4.68)

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We have fitted the wave energy spectra with an exponential law (as a function of f/f_p) and estimated the n exponent. For this fit, we have restricted the wave frequency domain to [1.5-3.5] fp. To avoid cases with multi-peaks (swell and wind waves) we restrict here our analysis to cases of slow and medium speed and d < 3 R_{max}.

This figure shows the variation of n as a function of the inverse wave age. The the symbol corresponds to the TC category (see legend). The red line is for the value of U10/cp=0.83 which separates under-developed (short fetch) from fully developed waves (long fetch).

The mean absolute value of value of n is 3.38 indicating a smaller decay of energy with f/fp compared to the fetch-limited observations analyzed by Donelan et al (1985), or compared to the analysis in tropical cyclones by Tamizi and Young (2020). As for the results in fetch-limited cases (Donelan et al) , we do not find here any obvious trends with wave age.

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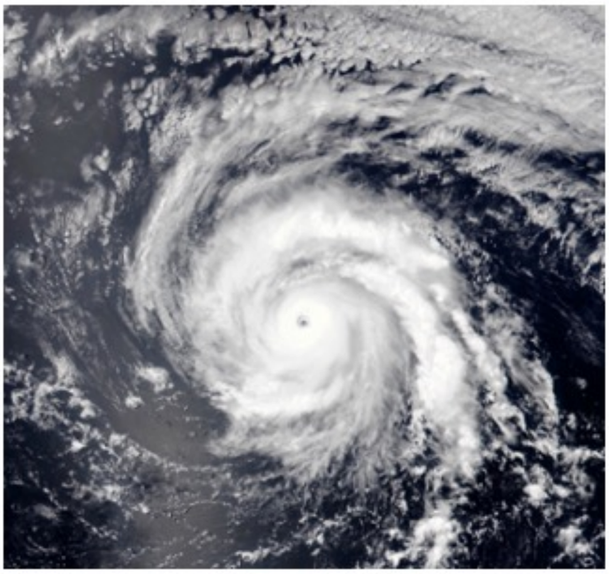

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Conclusions (1/2)

- **The nea-nadir wave spectrometer SWIM carried by the CFOSAT mission provides unprecedent detailed and repeated observations to study wave characteristics in tropical cyclones:**

- **SWIM brings new insights:**
  - Asymmetry of wave parameters (SWH and wavelength) confirmed, but only in TC of slow and moderate speed:
    -

    → conditions for trapped waves are more favorable in these conditions → confirmation of the model of Kudryavstev et al, JGR 2021, generalization of the results of Yurovskaya et al , Remote Sensing 2022

Conclusions (2/2)

- multi-modal spectra are observed on the left side of slow and moderate speed TCs and in all quadrants in fast TCs

- New results with respect to Young (2006), Esquivel-Trava (2015) or Tamizi and Young (2020, 2021): the self-similarity of wave spectra is observed only in certain conditions (slow, moderate speed, close to the center) and the decay of wave energy with the normalized frequency seems to be smaller in average than that observed in fetch-limited condition (Jonswap experiment, Donelan et al, 1985).

- *Results presented in the manuscript by Le Merle et al (2022), currently under review at JGR*

See also additional material presneted in appendix

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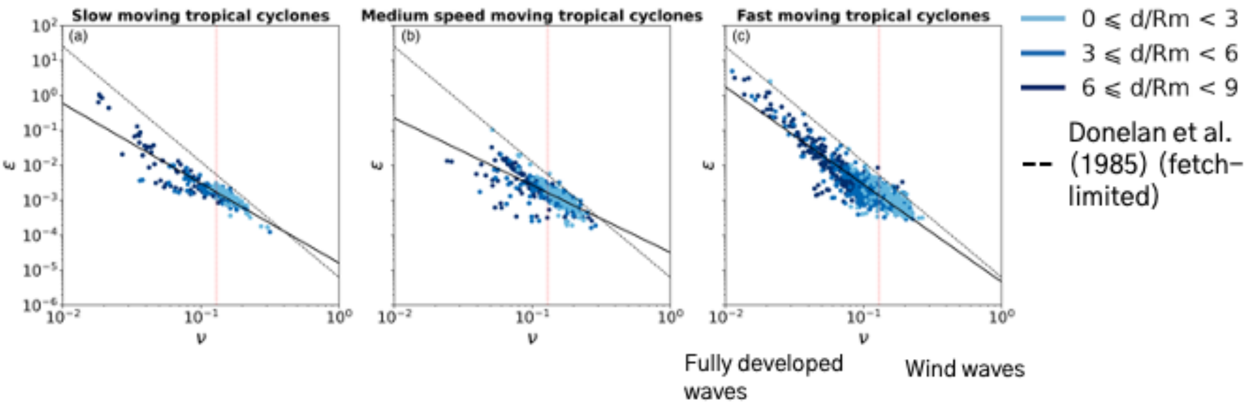
Thank you for your attention.

See also supplementary material in the following slides

Statistical study

Nondimensional frequency and energy

- $\varepsilon = g^2 \frac{E_{tot}}{U_{10}^4}$ nondimensional energy
- $\nu = f_p \frac{U_{10}}{g}$ nondimensional frequency



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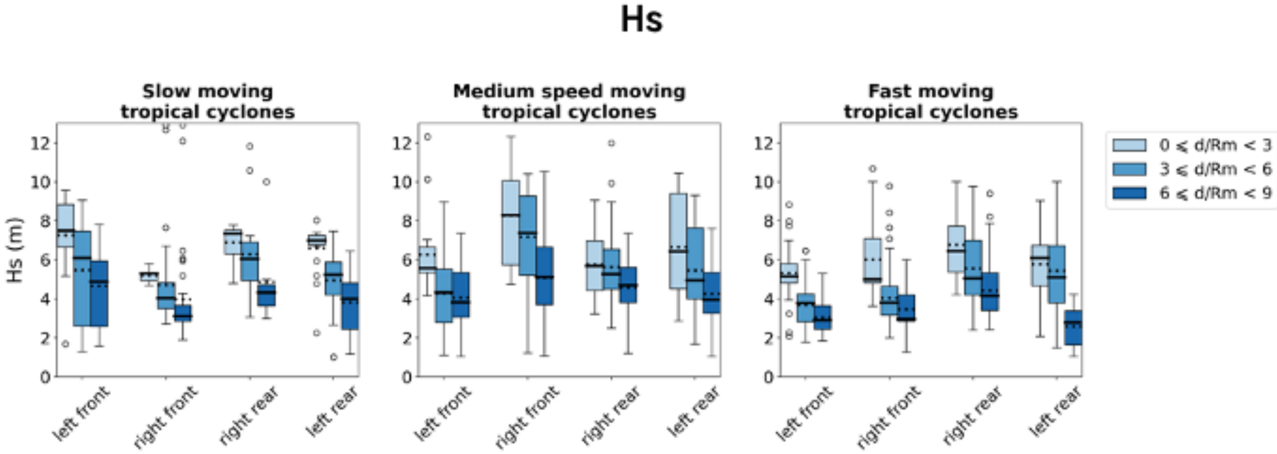

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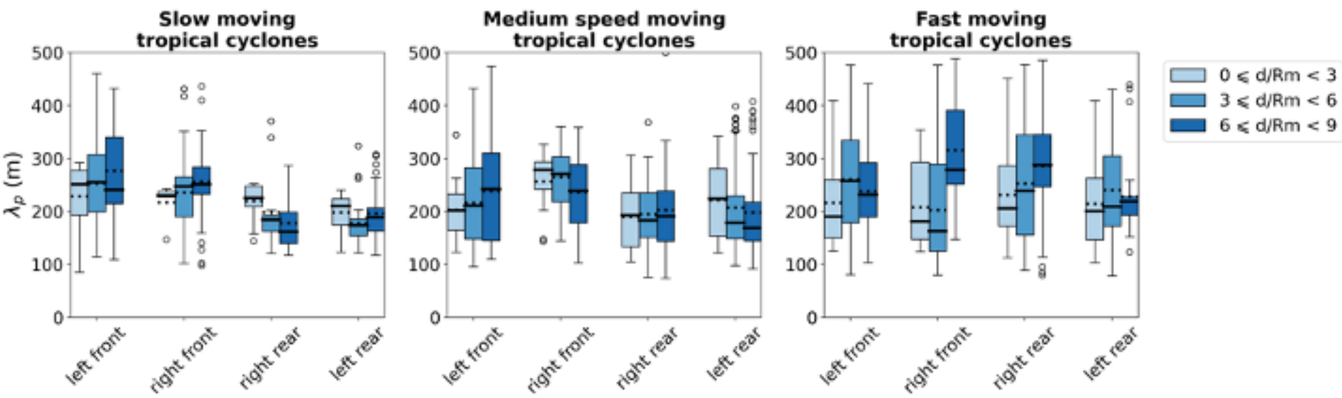
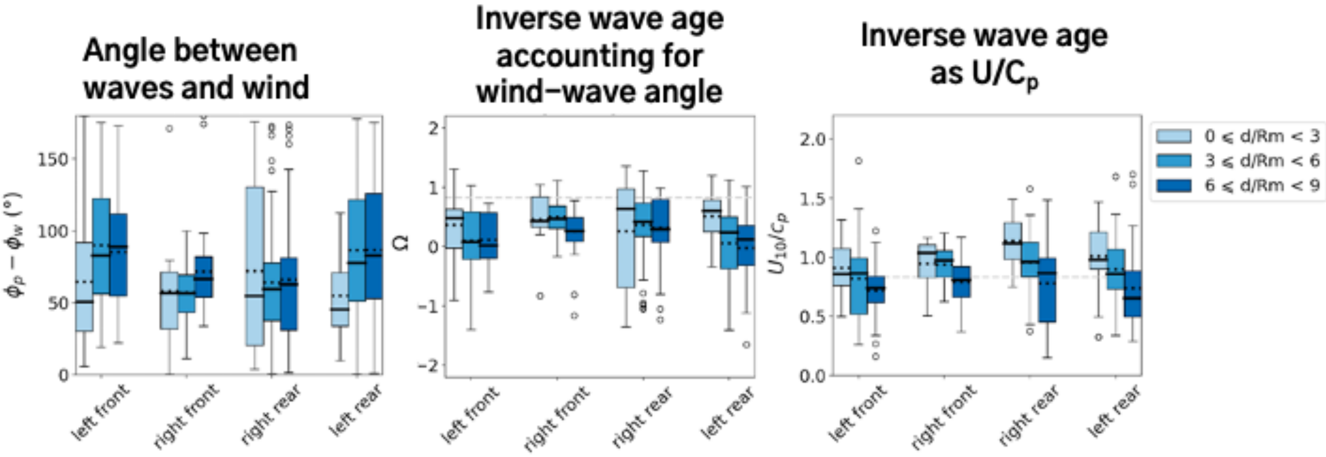
Dominant wavelength



- ✓ Asymmetry of λ_p different according to the TC category
- ✓ Higher dispersion of the λ_p distributions in fast moving TCs:

  → Presence of mixed−sea conditions

Cases of moderate translation speed



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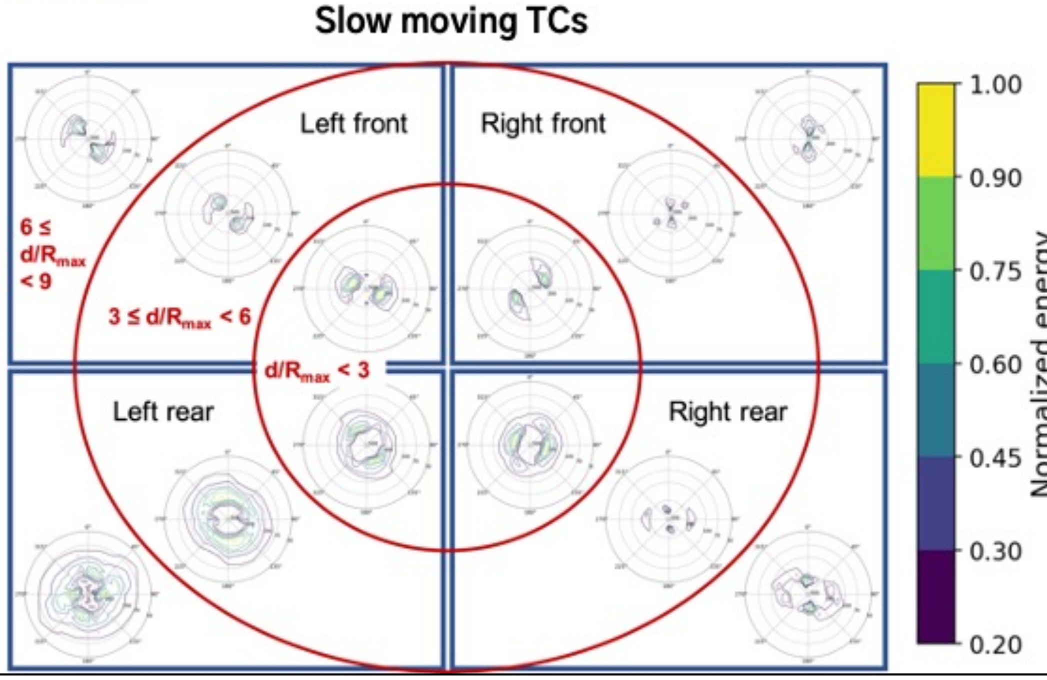

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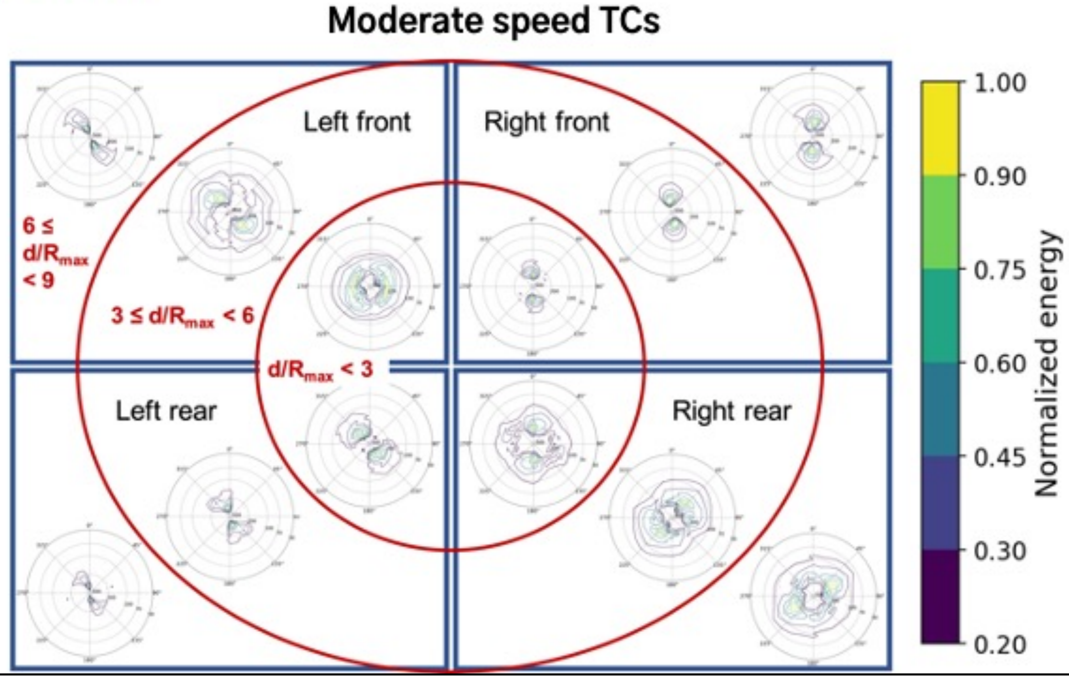

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