Potential of combined CFOSAT, SWIM, altimeter and SCAT Measurements: a Tropical Cyclone Case Study

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Motivation

- Combined TC wind-wave observations (satellites, buoy, aircraft) are critical for forecasting purposes and to help advance air-sea interaction fundamental studies.
- Full sophisticated models (e.g. WAM, WAWEWATCH III) are certainly capable to provide detailed wave information, but precise well-resolved surface winds are necessary, and/or needs to consider large ensembles of solutions invite developments of more simplified and rapid solutions.
- The simplified 1D parametric model (Kudryavtsev et al., 2015) has recently been extended for 2D (Kudryavtsev et al., 2021), to model wave field evolution forced by space-time varying wind field.
- **Equations are solved by the method of characteristics, Lagrangian ray-paths**, to provide efficient visualization on how the different wave systems develop under a moving TC, and to finally outrun it as long wave swell systems.
- **Importantly, solutions can be analytically reduced using self-similar functions**, for rapid first guess evaluation for azimuthal-radial distributions of the primary wave system parameters (SWH, wavelength, direction) given the TC characteristics, maximum wind speed, radius, translation velocity.
- **CFOSAT combined-observations (altimeter, SWIM, scatterometer) offer unique opportunities, and together with Sentinel-1 and Radarsat-2 SAR acquisitions, help to assess capabilities of the new wave-model framework.**
- The powerful TC Goni case (Oct. 29th, 2020) is considered

Model Governing Equations

Energy and momentum conservation (Hasselmann et al., 1976; Phillips, 1977):

$$\partial E / \partial t + c_{gj} \partial E / \partial x_j = S^E$$

$$\partial M_i / \partial t + c_{gj} \partial M_i / \partial x_j = S_i^M$$

$E(\omega,\varphi) = A(\varphi - \varphi_p) F(\omega)$ - energy spectral density

$M_i = k_i E/\omega = \kappa_i \omega E/g$ - momentum spectral density

$\kappa_i = [\cos\varphi, \sin\varphi]$

$S^E = S_W - S_D + S_N$ - energy source

$S_i^M = \kappa_i \omega S^E / g$ - momentum source

c_{gj} - group velocity

$$\int\int d\varphi d\omega$$

and some algebra...

- Wind input:

$S_W = \beta\omega A(\varphi - \varphi_p) F(\omega)$, (Miles, 1957)

$\beta = c_\beta (u_*/c)^2 \cos^2(\varphi - \varphi_W)$ - growth rate (Plant, 1982; Meirlink et al. 2003)

- Dissipation:

Wave breaking (Longuet-Higgins, 1969)

$D = \omega_p e (k_p{}^2 e / \varepsilon_T{}^2)^n$

$D = \int S_D d\varphi d\omega$

$e = \int E d\varphi d\omega$

- Non-linear interactions:

Four-wave interactions (Hasselmann, 1962)

Energy transfer towards low frequencies:

$\langle S_N \rangle \sim E^3$

(Zakharov, 2010; Badulin et al., 2007)

Complete System of Equations

$$\begin{cases} \dfrac{d}{dt} x_j = \kappa_j^p \overline{c}_g & \text{- wave train position} \\ \dfrac{d}{dt} \ln(\overline{c}_g e) = -\overline{c}_g G_n + \omega_p \left(\tilde{I}_w - \tilde{D} \right) & \text{- modified energy} \\ \dfrac{d}{dt} c_{gp} = -\dfrac{r_g C_\alpha}{2} \Delta_p g \left(k_p^2 e \right)^2 & \text{- spectral peak group velocity (from eq. for frequency)} \\ \dfrac{d}{dt} \varphi_p = C_\varphi \alpha^2 \omega_p H_p \sin\left[2(\varphi_p - \varphi_W) \right] & \text{- spectral peak direction} \\ dG_n / dt + G_n / T + \overline{c}_g G_n^2 = G_W^n / T & \text{- peak direction gradient (focusing term), } G_n = \Delta\varphi_p / \Delta n \end{cases}$$

(or two eq. instead: for $\Delta\varphi_p$ and Δn)

The system describes the development of surface waves under a varying wind field in both space and time, and the evolution of swell propagation in the absence of wind forcing (swell phase speed >> wind speed)

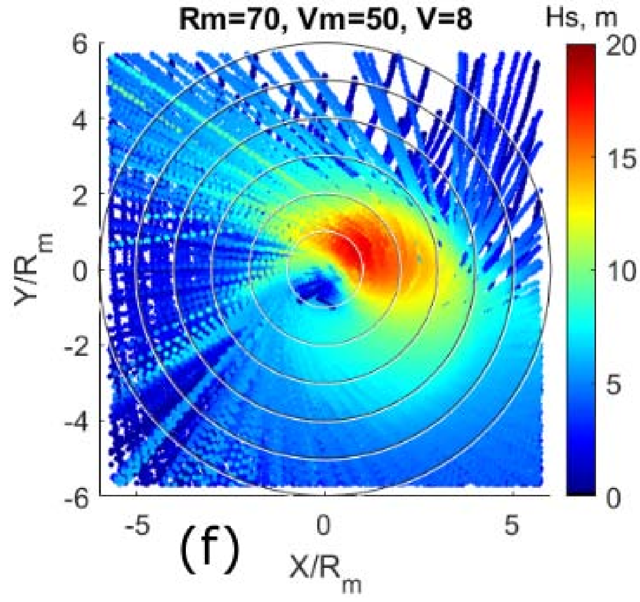
Method of Characteristics (ray-path trajectories)

- The model is solved in the storm frame of reference using the wind field input (e.g. Holland 1980 model, or satellite data estimates)

- Each wave train location and wave parameters at each moment of time are obtained with the use of 4th order Runge-Kutta scheme

- Wave-rays visualize how wave trains develop and travel through the TC varying wind field, and how they leave the storm area as swell systems.

- The wave train with maximal wave length/energy in a given grid cell can be treated as the primary wave system. Each grid cell can be considered to analyze multiple wave systems and their time evolution.

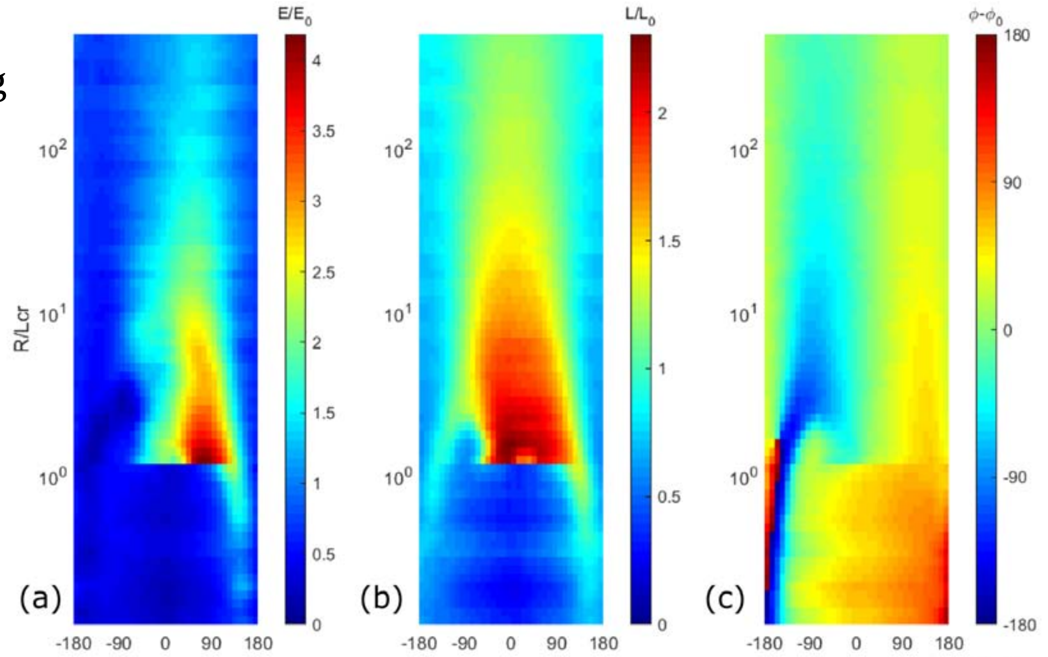


An array of wave train <u>coordinates</u>, peak <u>frequency</u>, <u>energy</u> and <u>direction</u> at any time moment (0-72 hours)

Model Reduction: TC-Wave GMF

The model was run for 63 combinations of [*Rm*,*Um*,*V*] with Holland (1980) wind profile, and results were analytically reduced using self-similar functions (Kudryavtsev et al. 2021):

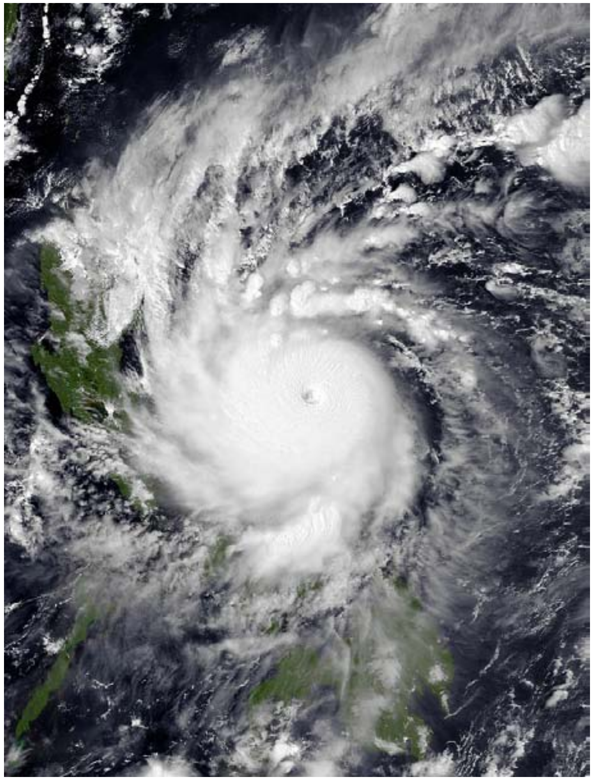
- The energy and wavelength of primary wave trains are normalized by their corresponding stationary values and represented as function of azimuth and r/Lcr,
  r is the distance from TC center and *Lcr* is a critical fetch depending on *V* and *u* [Kudryavtsev et al. 2015].
- These fields were further averaged over the ensemble of 63 considered TCs in a Look-up table.
- Transects of these functions over the TC azimuth at fixed x=Lcr provide azimuth distributions of the primary wave system parameters relative to a stationary TC condition.



Self-similar solutions (TC-wave GMF) generalize the 1D fetch laws for 2D TC-generated waves.

TC-wave GMF is rapid to quantitatively assess the significant wave height, wavelength and direction fields under a moving TC prescribed by Rm, Um and V

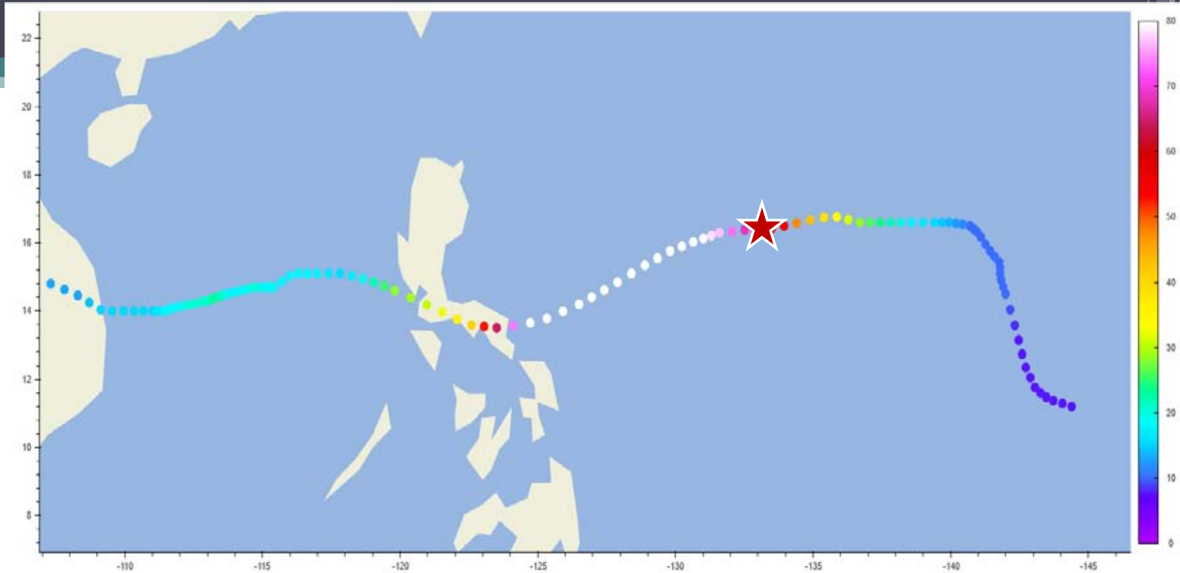
TC Goni



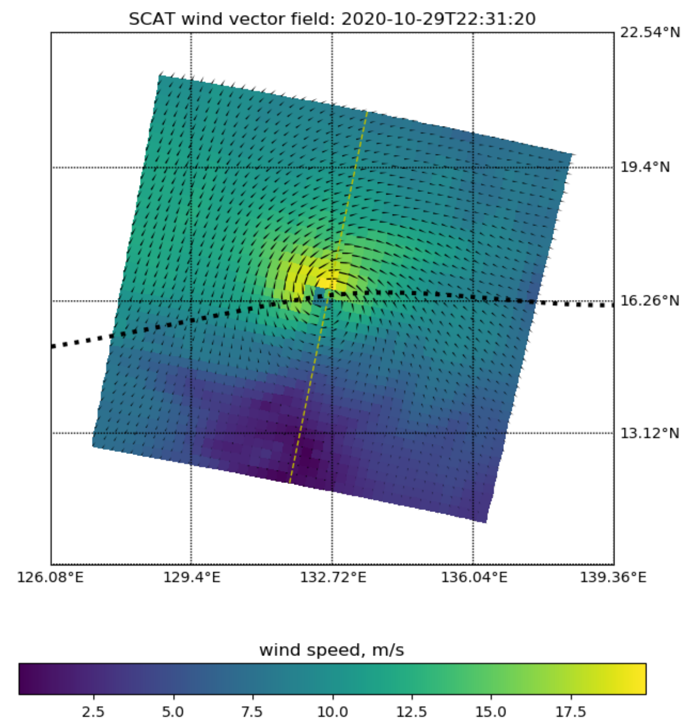
- October 26 - November 6, 2020
- Intensified over the Philippine Sea on Oct. 29th, 2020
- Damage: $415 million
- Lowest pressure: 905 hPa
- Highest winds:

60 m/s (10 min sustained)

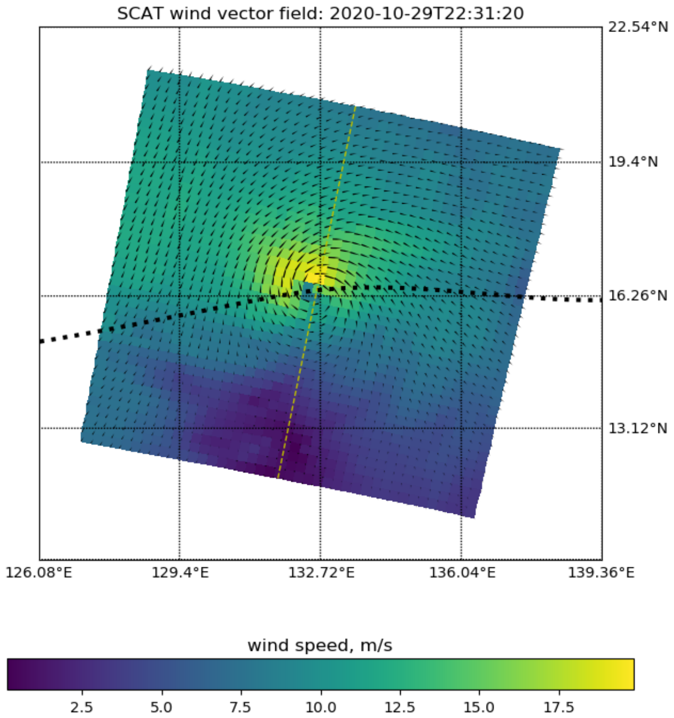
85 m/s (1 min sustained)

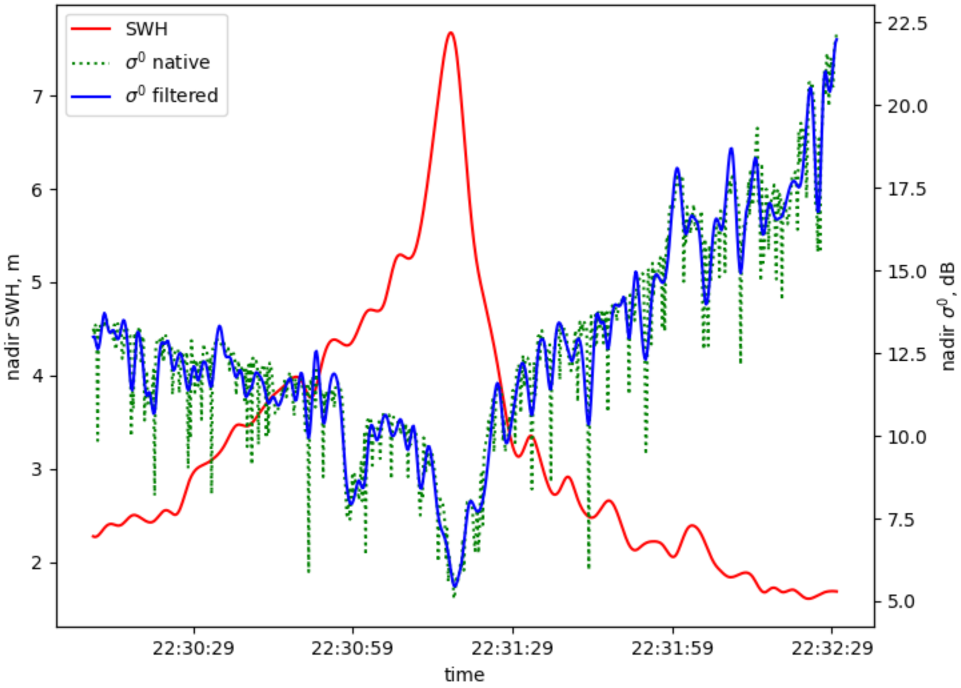


Star is the location of TC in the present case study: 2020-10-29, 20:57 (SAR) and 22:30(CFOSAT).

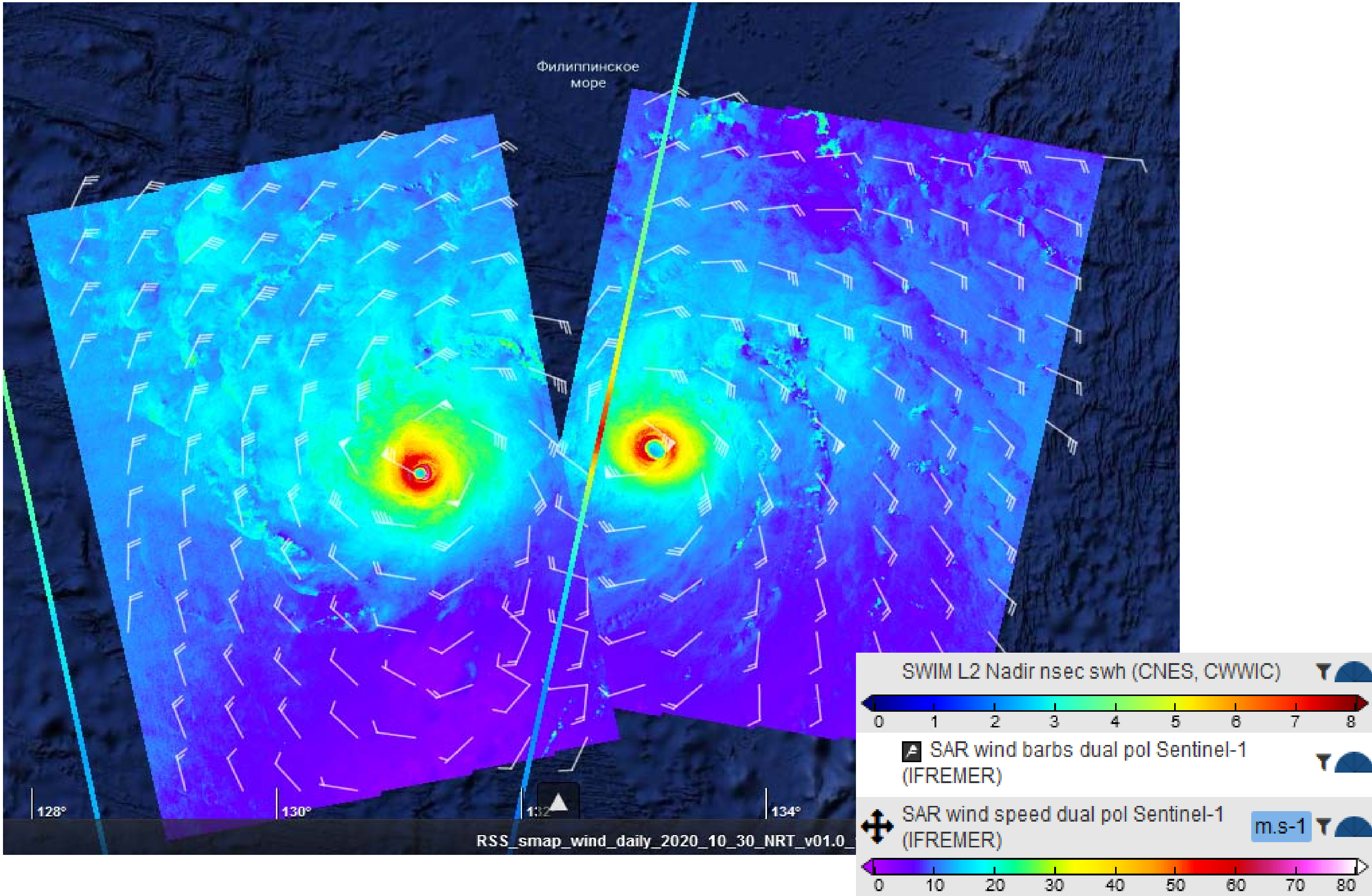


CFOSAT Ku-band scatterometer+altimeter measurements

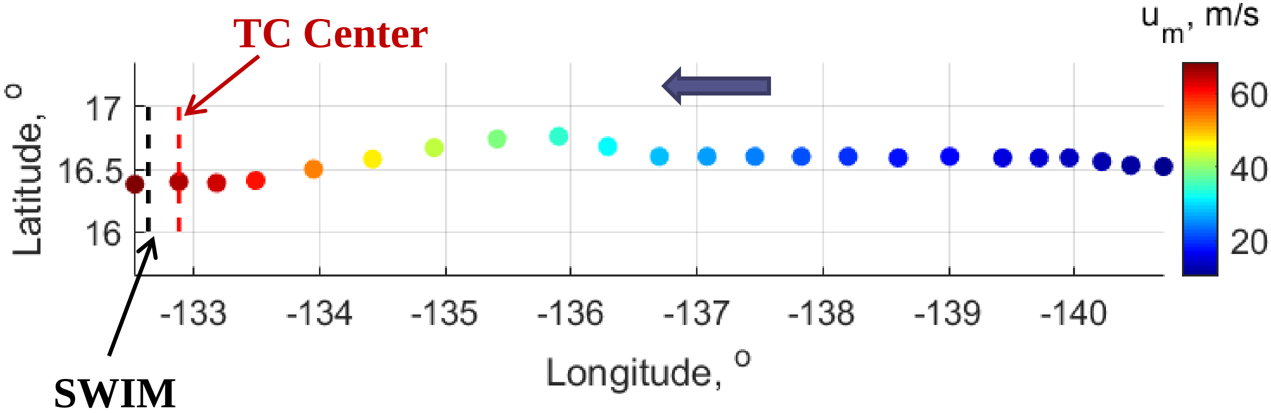


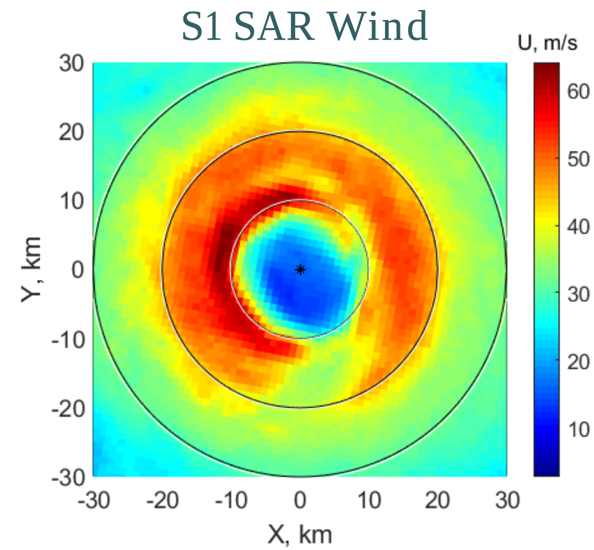


SAR Wind and SWIM Hs Track

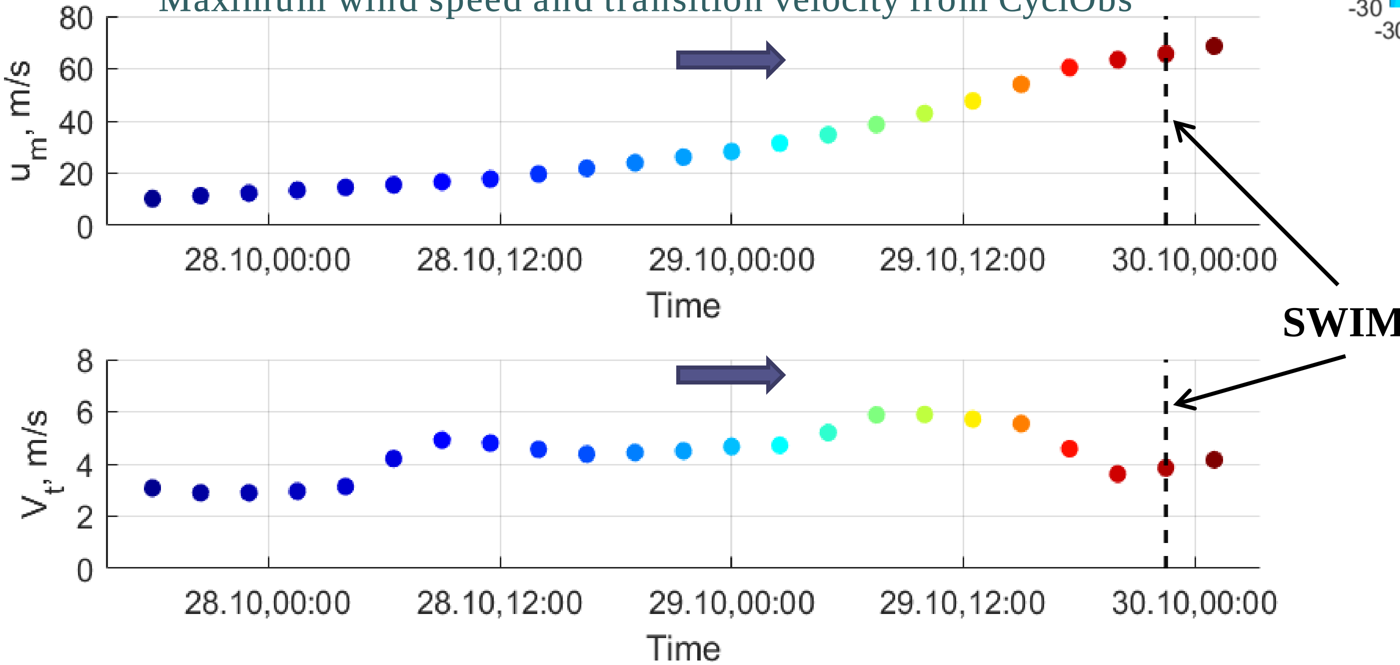


TC GONI Characteristics





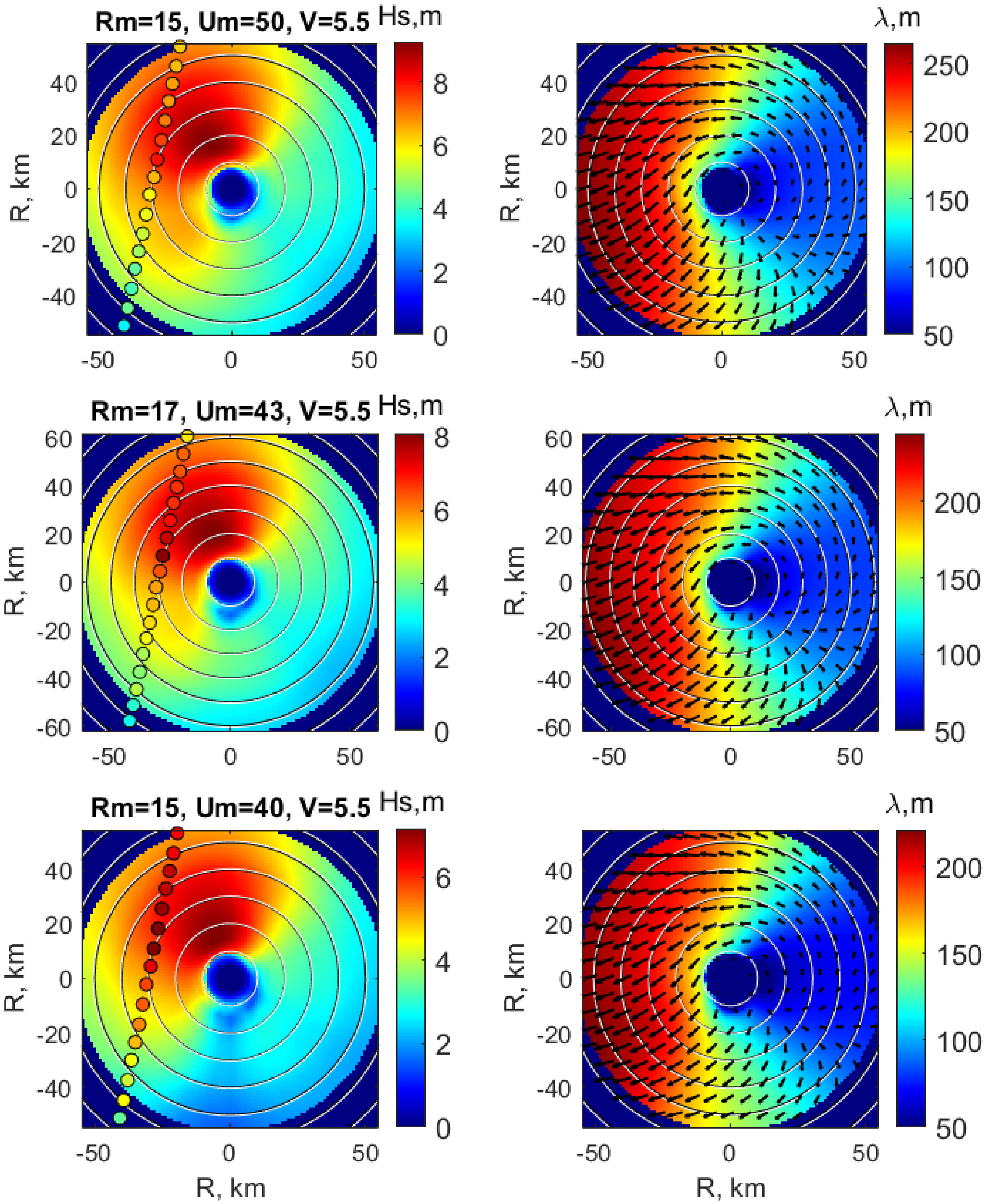
Maximum wind speed and transition velocity from CyclObs



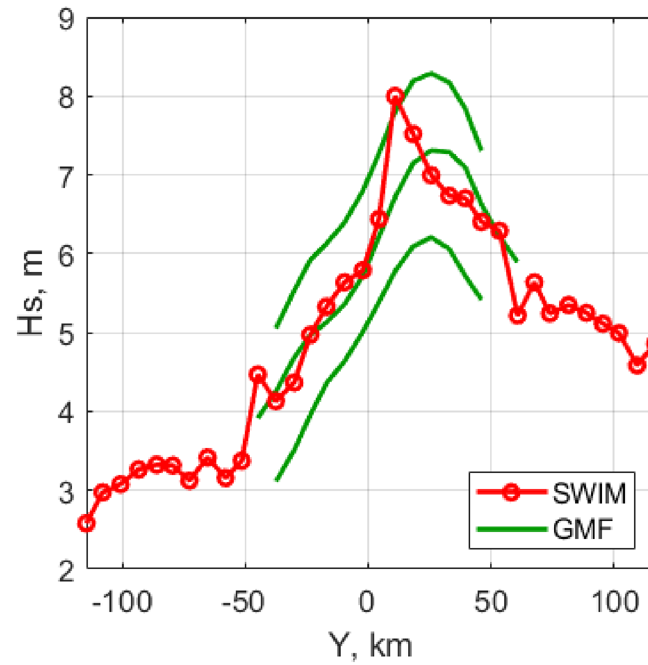
<u>For TC-wave GMF</u>:

Rm: 13-15 km
Um: 45-60 m/s
V: 4.5-5.5 m/s, 90-110 deg

First Guess: TC-wave GMF

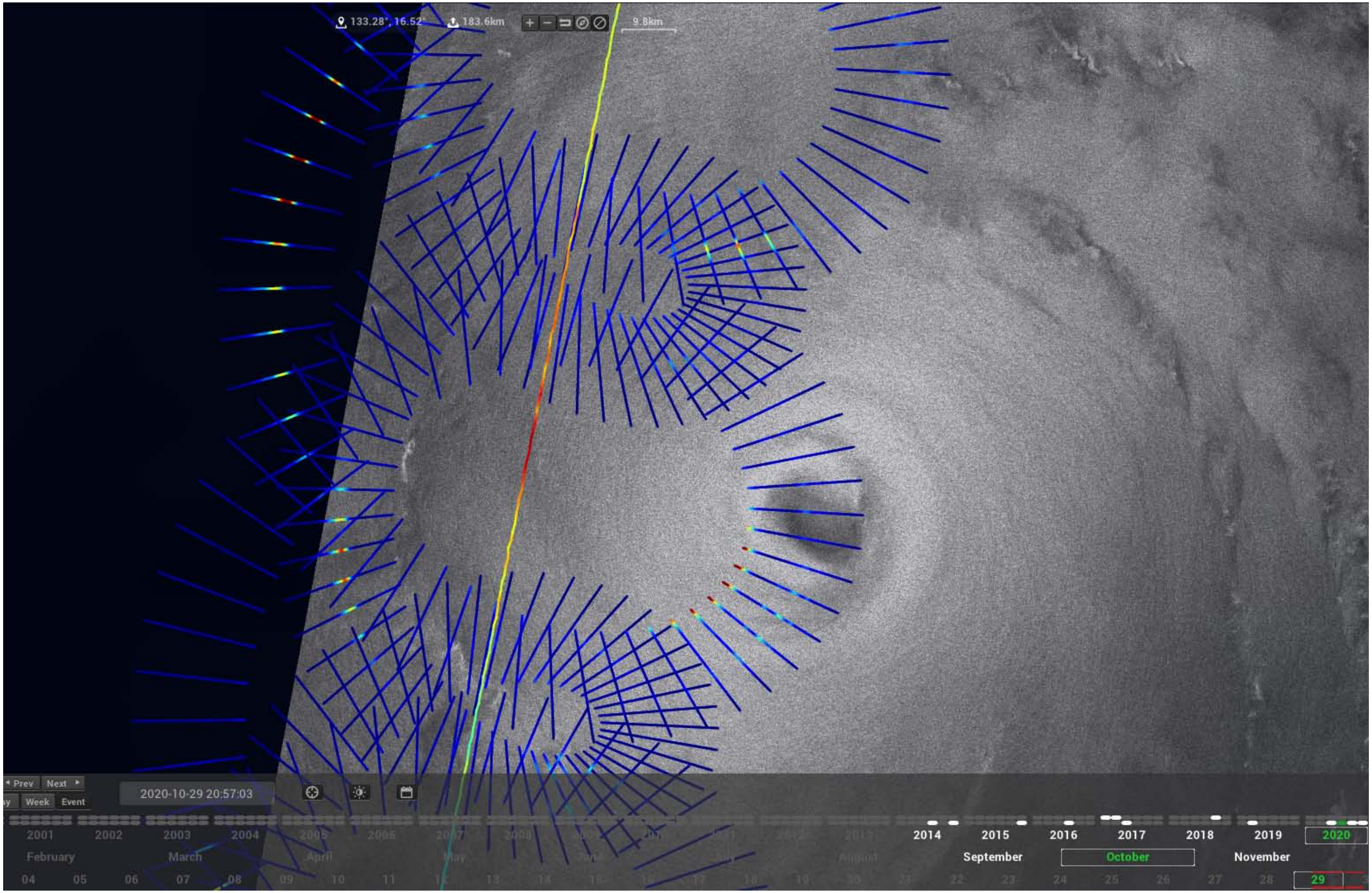


- For a range of inputs: relative close quantitative behavior, but scattered along-track profiles



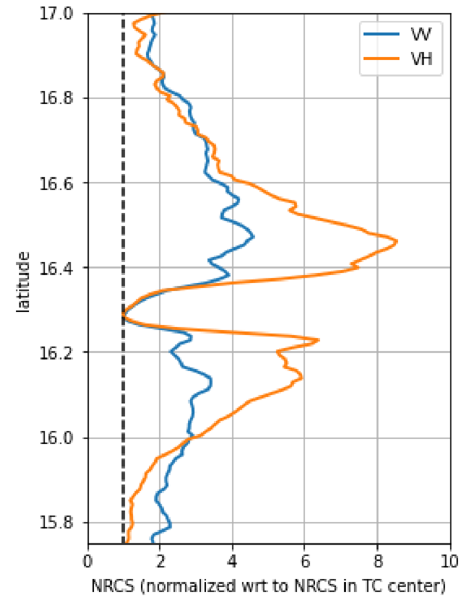
Wind field characteristics

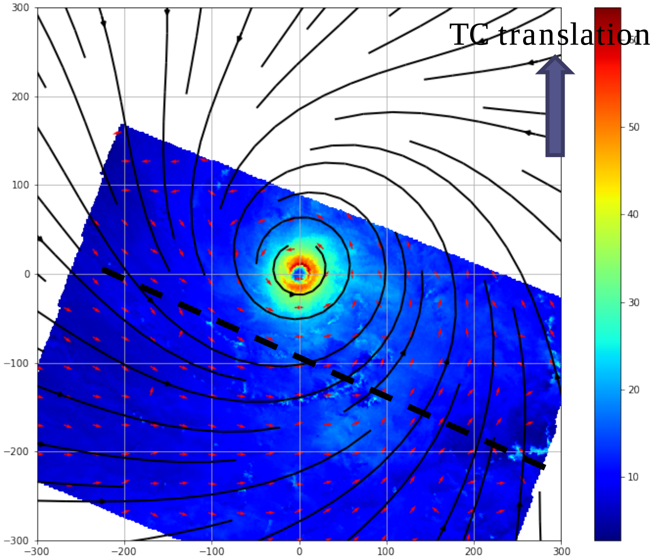
Combined SWIM (4,6), altimeter (SWH), SAR (roughness)



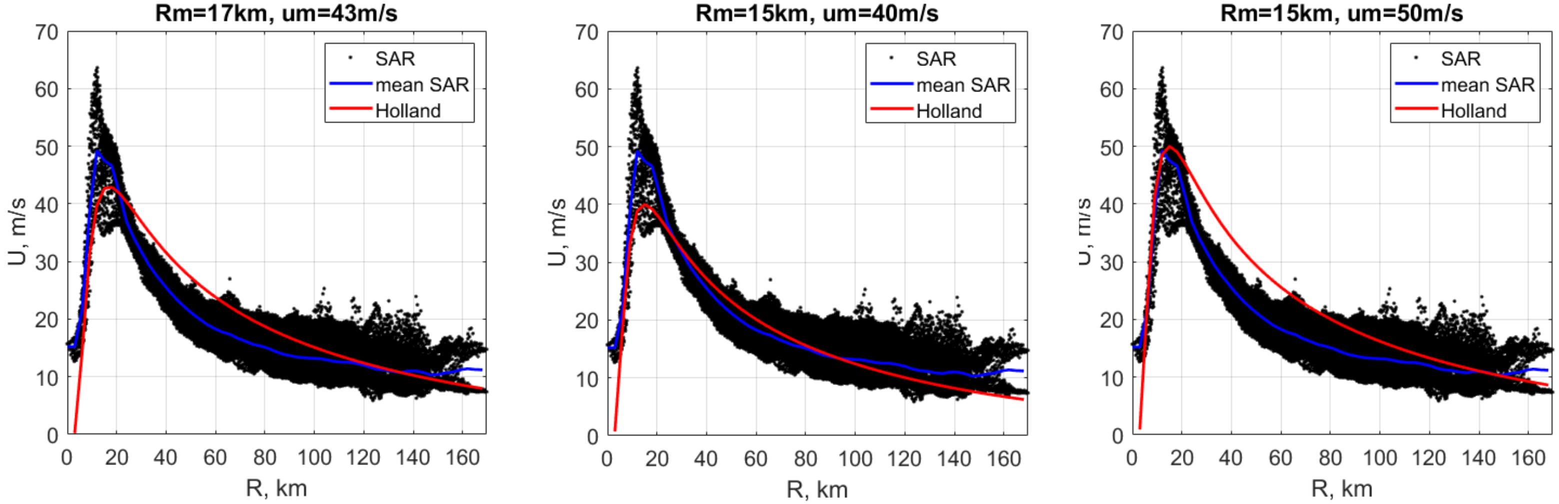
High Resolution SAR wind field

- SAR C-band co- and cross-polarization measurements are used to provide a first guess of a more realistic high resolution 3-km wind field (speed and direction):
  - The higher sensitivity of C-band VH measurements dominates the wind speed inversion scheme for extreme events (Mouche et al., 2017, 2019).
  - The signature of secondary atmospheric circulation (rolls, rain bands) observed at high resolution in TC observations in both VV and VH polarizations is analyzed with Local Gradient (Koch 2004).
  - After TC center detection, it is used to constrain a parametric inflow model (Zhang & Uhlhorn, 2013) in the storm frame for a full estimate of the wind direction at the same resolution than the wind speed.





Wind Profile



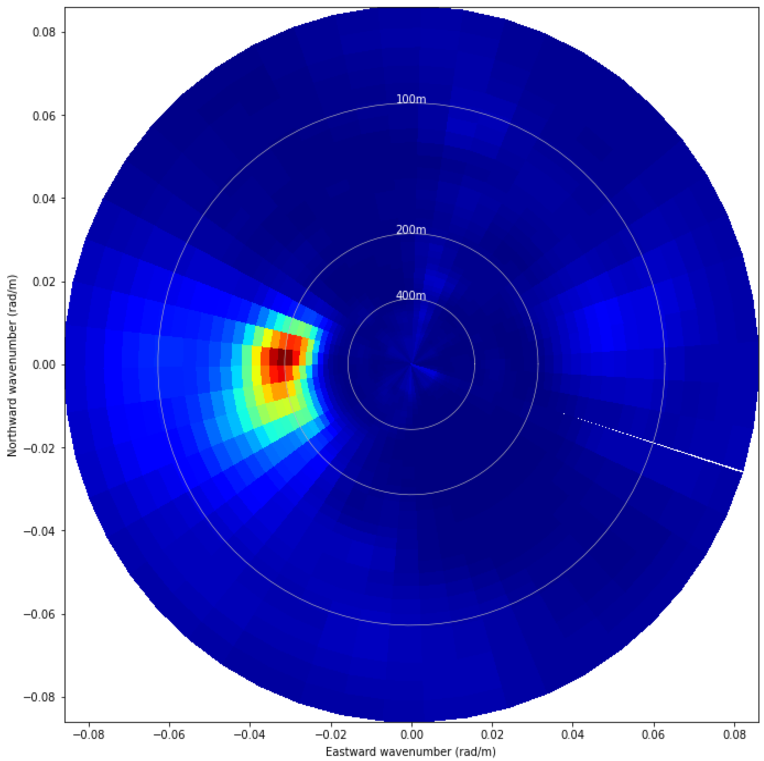
$$u(r)=\left[\left(u_m^2+u_m rf\right)\left(\frac{R_m}{r}\right)^B \exp\left(-\left(\frac{R_m}{r}\right)^B+1\right)+\left(\frac{rf}{2}\right)^2\right]^{1/2}-\frac{rf}{2}$$

(Holland, 1980)

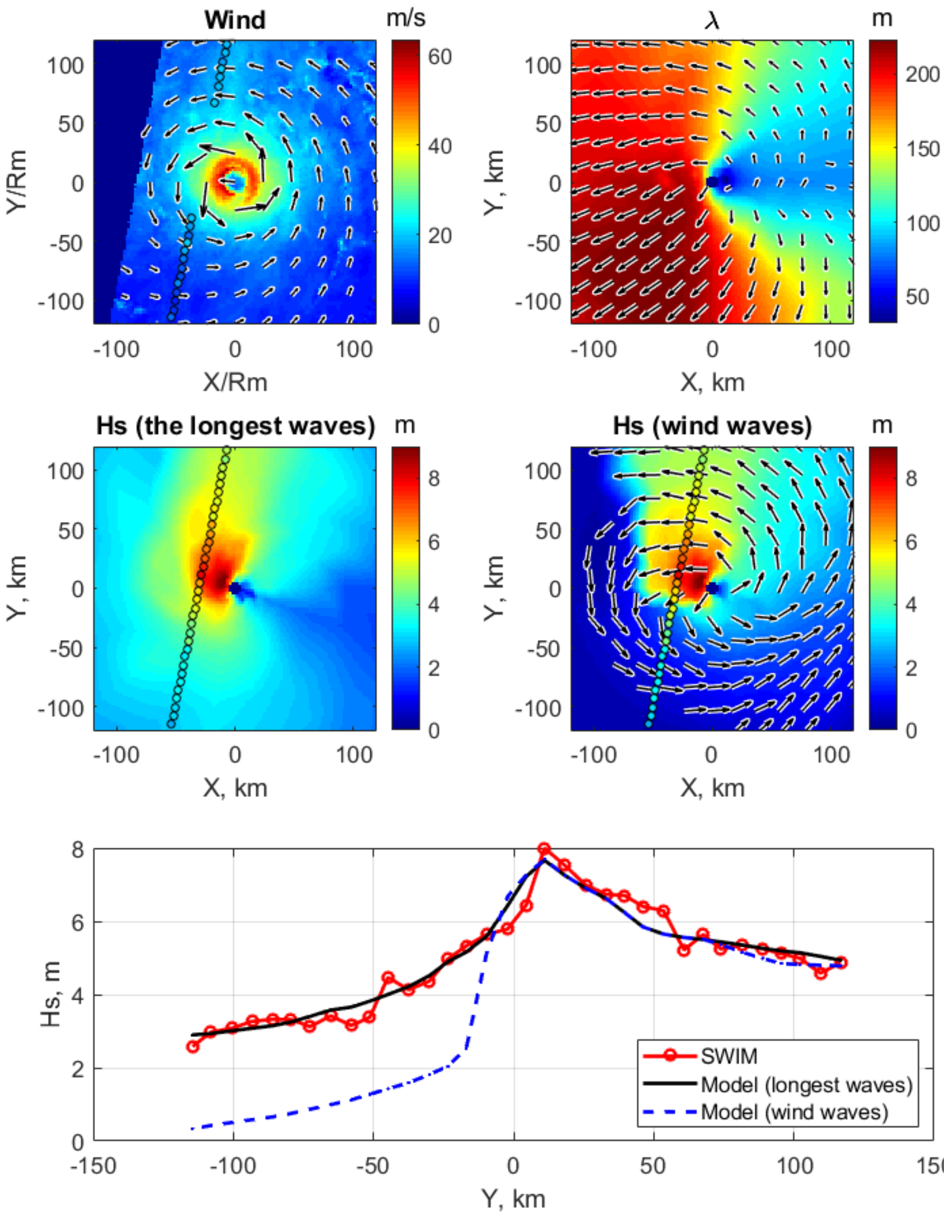
- TC-wave GMF constructed for Holland wind profiles with B=1.5 do not match Goni SAR-derived wind profiles

Full model simulation with the more realistic wind is needed to provide more accurate wave information

Simulation using SAR High-res wind field characteristics



2D wave spectrum from CFOSAT



Conclusions

- A fully consistent 2D parametric model of wave development under spatially and/or time varying winds can be exploited to jointly analyze CFOSAT SWIM, SCAT and altimeter data together with Sentinel-1 and Radarsat-2 SAR acquisitions.

- The powerful TC Goni, explosively intensifying over the Philippine Sea on Oct. 29th, 2020, can be used as a test-bed case.

- The 2D wave model is solved in the storm frame of reference can use wind fields from CFOSAT SCAT, SAR estimates and/or models.

- First results are very encouraging and confirm a strong azimuth asymmetry for the out-running wave systems, resulting from group velocity resonance between growing traveling waves and the moving TC.

- **Combined CFOSAT SWIM, SCAT and altimeter data open new perspectives** to refine the proposed practical 2D parametric wave-model, especially to derive new improved **self-similar solutions**.

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Thank you for your attention!