Measuring Tropical Cyclone Internal Properties from SAR Imagery

Current Capabilities and Perspectives for the Improvement of Intensity Forecasts.

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Context

- TC intensity is determined by the strength of the eyewall convection, which relies on an interplay between the symmetric secondary circulation and a range of asymmetric processes that act to dissipate or aggregate the vorticity from local to vortex scale
- SAR is able to measure extreme winds at kilometric resolution
  → captures the strength and spatial distribution of winds in the eyewall vicinity
- Eyewall mesovortices, convective bursts and asymmetry organization are directly observable
- SAR measures winds at the surface : grants access to valuable information on boundary layer dynamics
- SAR acquisition rate is still limited :

➢ How can we derive dynamically-relevant information from SAR given their limited temporal resolution ?

➢ Is this information able to characterize intensity changes and traduce the physical processes that govern these changes ?

I. SAR measurement of inner-core asymmetry

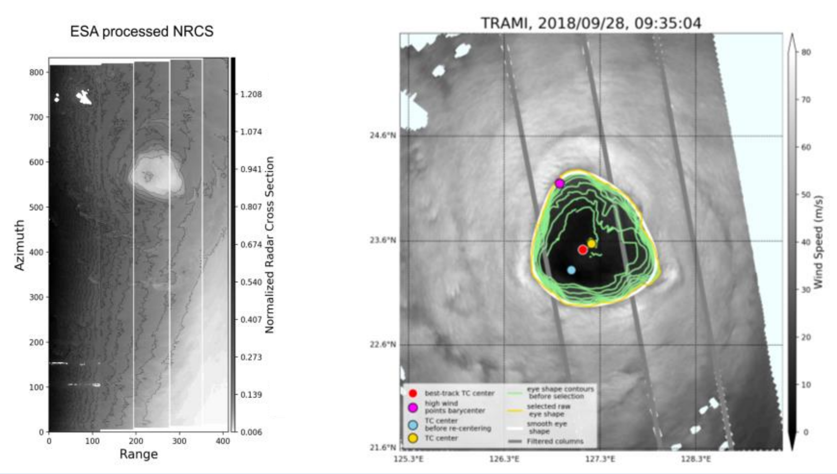
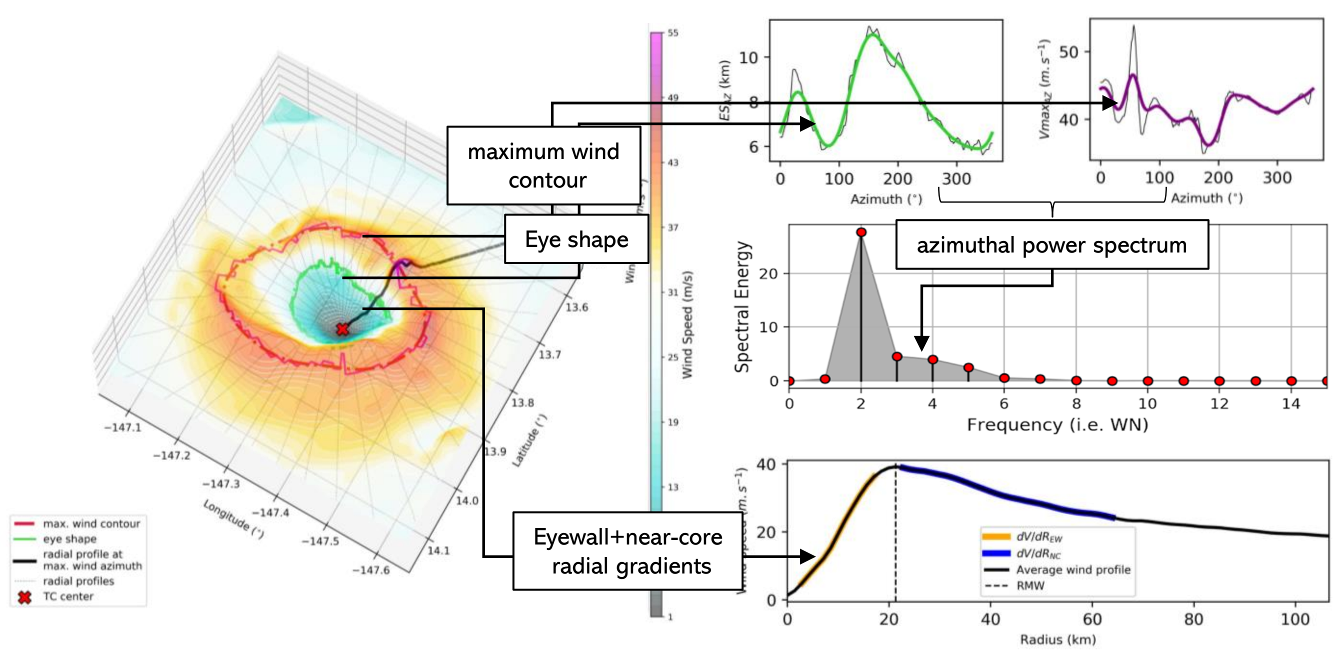


Image processing : NRCS conversion to wind speed + TC center retrieval

A processing method was designed to retrieve :

- centers
- mean profile eyewall & near-core slope
- azimuthal distributions of max. wind, eyewall radial wind gradient, radius of maximum wind and eyewall radius



Extraction of characteristic signals : azimuthal power density spectra (asymmetric) and mean profile radial gradients (symmetric)

- A dataset of 188 SAR images was used to derive metrics measuring eyewall and maximum wind asymmetry
- SAR image processing relies on the dual-polarization inversion algorithm developed by Mouche et al., 2017
- Maximum wind V_{max} and radius of maximum wind R_{max} were validated by Combot et al. 2021 against best-track and SFMR

I. SAR measurement of inner-core asymmetry

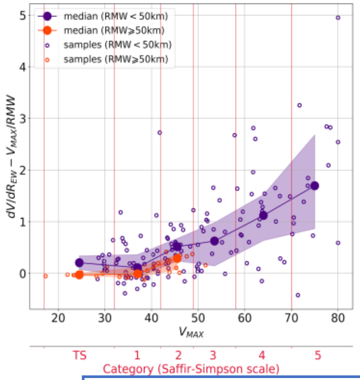
Observations of Tropical Cyclone Inner-Core Fine-Scale Structure, and Its Link to Intensity Variations

Léo Vinour,[a] Swen Jullien,[a] Alexis Mouche,[a] Clément Combot,[a] and Morgan Mangeas[b]

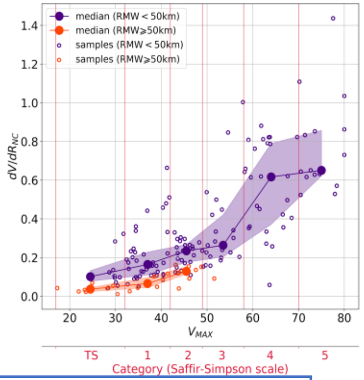
- Statistics on the SAR database

- Intensity and internal structure :
  - Near-core and eyewall radial gradients increase with intensity
  - Asymmetry decreases with intensity

eyewall

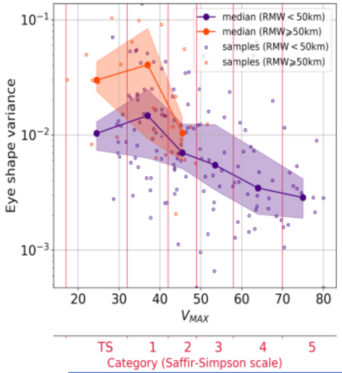


near-core

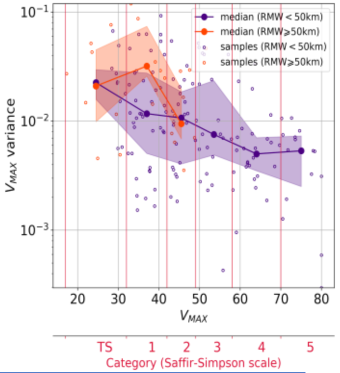


Radial gradient // intensity
purple/orange=small/large R_{max}

eyewall radius



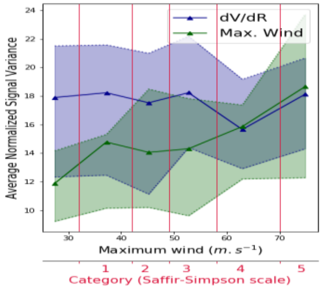
max. wind contour



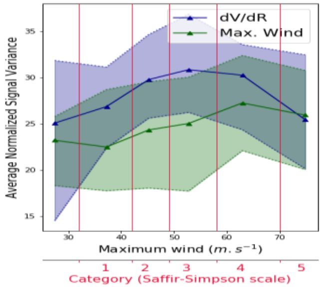
Azimuthal variance // intensity
purple/orange=small/large R_{max}

- Power spectral density in the maximum wind ring shifts from large to local scale with increasing intensity

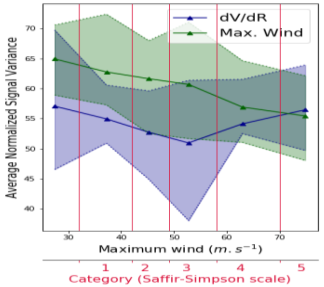
WNs 1-2



WNs 3-5



WNs 6-180



Grouped wave number variances // intensity
blue/green=eyewall radial gradient/max. wind distribution

I. SAR measurement of inner-core asymmetry

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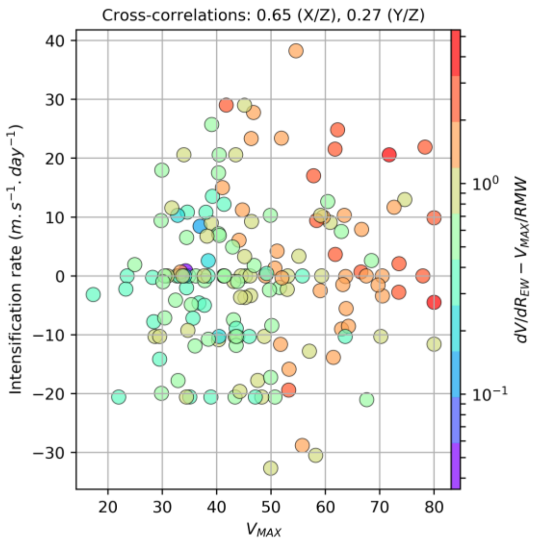
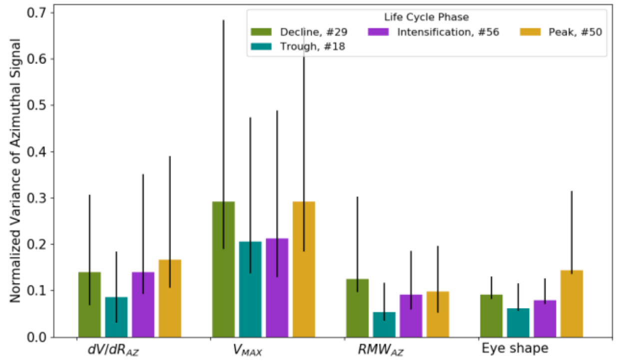
- Dynamical content of SAR snapshots ?
- Requires colocation with IBTrACs intensification rate (IR) estimates, causing a loss of coherence
- Direct comparison of IRs with internal descriptors :
    - Eyewall radial gradient shows a slight connection to short-term intensity changes
    - Asymmetry shows no significant trend on scatter plots
- Binning by life cycle phase (decline, trough, intensification, intensity peak) :
    - Slightly lower variance for troughs & intensifications
- No visible correlation with the WN distribution, except using ML classification



Eyewall profile curvature vs. V_{max} & intensification rate (from IBTrACs)



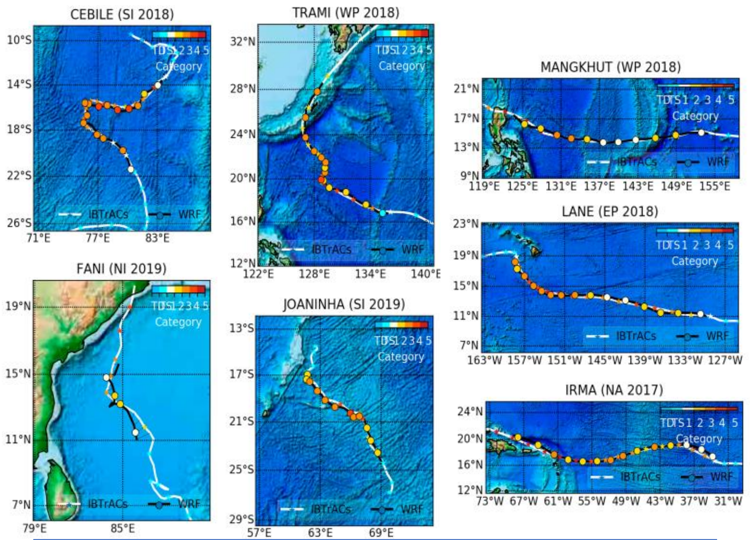
Mean variance of 4 azimuthal signals separated by life cycle phase :
decline (green), trough (blue),
intensification (purple), peak (yellow)

II. Diagnosing short-term dynamics from SAR : numerical simulation of regular SAR acquisitions

Diagnosing Tropical Cyclone Intensity Variations from the Surface Wind Field Evolution

Léo Vinour,[a] Swen Jullien,[a] and Alexis Mouche[a]

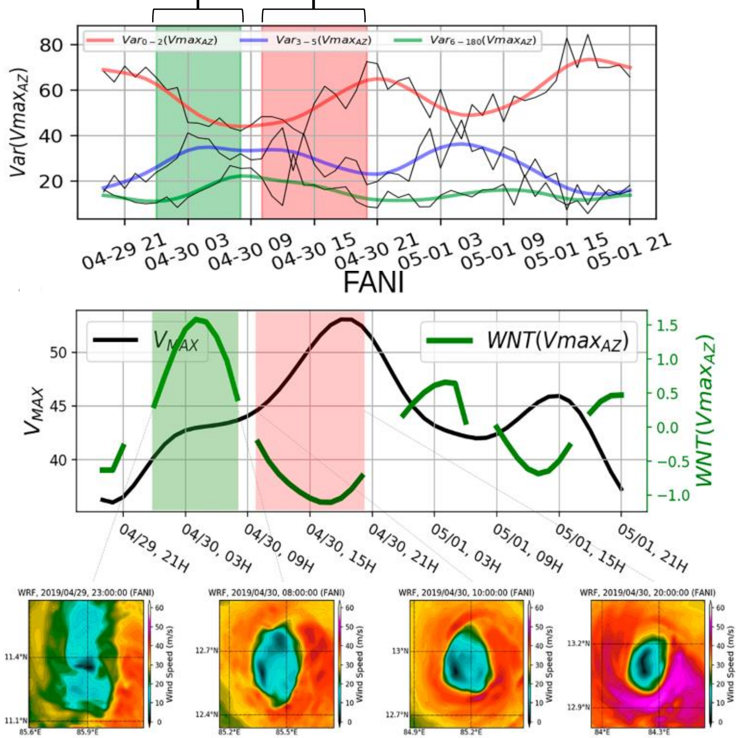
- Extended analysis of internal dynamics was performed using realistic simulations
  - Analyses performed on SAR were reproduced
  - A Wave Number Transition (WNT) parameter is developed to measure the evolution of power spectrum between low and high WNs in the maximum wind ring and eyewall



Simulation setups : seven events with realistic settings but permissive nudging to ensure small domain autonomy

Distribution phase : ⬇ of low-WN + ⬆ of high-WN variance

Polarization phase : ⬇ of high-WN + ⬆ of low-WN variance



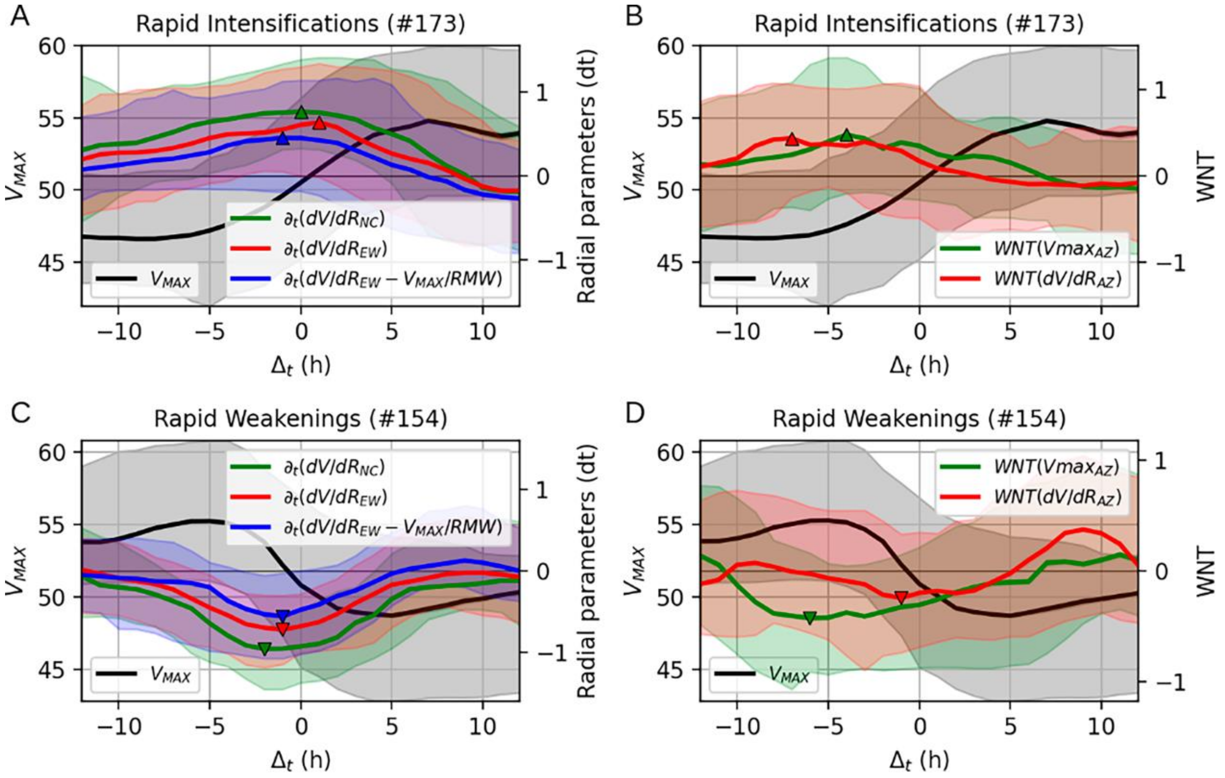
FANI simulation : extraction of 2 events of strong max. wind contour spectrum density change and corresponding snapshots

II. Diagnosing short-term dynamics from SAR

Diagnosing Tropical Cyclone Intensity Variations from the Surface Wind Field Evolution

LÉO VINOUR,[a] SWEN JULLIEN,[a] AND ALEXIS MOUCHE[a]

- Case study + statistics on seven simulations :
  - The temporal change in the power spectrum distribution goes with short-scale intensity fluctuations (~6h)
  - Intensity restoration events are preceded by vortex to local-scale transpositions of the spectrum power density in the maximum wind ring
  - ➢ Local-scale wind variance (>WN5) increase traduces the generation of convective bursts as indicators of intensity restoration
  - ➢ Increase of vortex-scale asymmetry (i.e. growth of WN1-2 asymmetry) on the contrary tends to indicate deterioration/weakening events



Statistics over all WRF outputs : radial gradients changes (left) and azimuthal dissipation/polarization (right) averaged over all RI (top) and RW (bottom) events.

Summary and conclusions

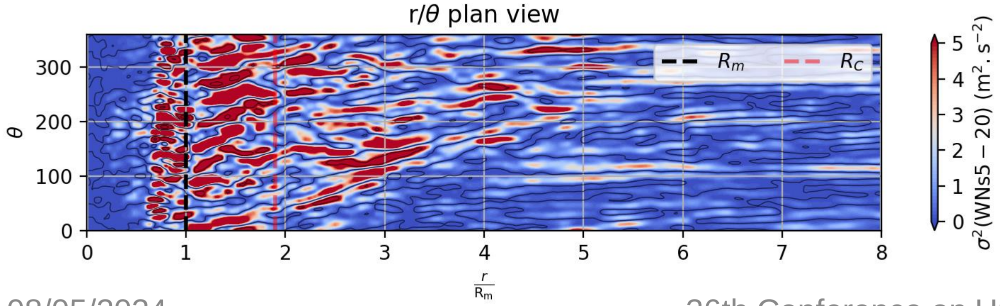
A large dataset of SAR-extracted wind fields is used to analyze the internal structure of Tropical Cyclones

- Wind fields were processed to retrieve center, mean profile (eyewall+near-core graidents), and azimuthal distributions (power density spectrum of max. wind contour & eyewall signals)
  - Dependence on intensity : more intense TCs = U-shaped eyewall, contracted profile, more symmetric with less polarized asymmetry (max. wind contour variance →→ high WNs)
  - Dependence on dynamics : consistent trends are hard to establish : slight trend for more U-shaped profiles w/ intensifications; lower asymmetry during troughs/intensifications than peaks/declines
- Extension of SAR analysis to the temporal domain are carried out with high-resolution simulations to characterize more consistently the evolution of asymmetry in direct conjunction with intensity
  - A metric is set up to measure the temporal evolution of the azimuthal power spectral density between local and vortex-scale
  - Max. wind speed contour tends to evolve towards more distributed asymmetry during RI events, and more polarized asymmetry during RW, with an anticipation of ~6h on intensity changes

Perspectives :

- SAR diagnoses of asymmetry (notably max. wind contour) can have a direct value for forecast improvement provided more regular acquisitions : RCM in processing will soon expand the wind dataset
- Exploit the 3D wind field. We limited analyses to 1D distributions : convenient for statistics (low number of variables) but lots of aspects remain to be dealt with. Recent work aims at studying BL inflow and inner/outer-core separation through the 2D distribution of WNs 5-20 : more to come !

Variance of WNs 5-20 for one SAR image



Thank you for your attention !

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III. Symmetric BL structure : a new perspective issued from high resolution

- Observable spiral signatures in the SAR wind field can be extracted through WN decomposition and sum of WNs 5-20
- Average spiral band inflow is constant in the outer-core (mean value~33°)
- Spiral signatures are hard to detect under 2.5-3 Rmax
- Constant inflow regime traduces a property of the boundary layer : amplitude of the inflow can be identified as a drag coefficient over a characteristic BL height

Link between inflow angle and drag : starting from the momentum NS equation in stationnary case, with $m \sim rv$ the relative angular momentum, $\tan\alpha = \frac{u}{v} = \frac{\lambda}{\frac{v}{r}+f}$

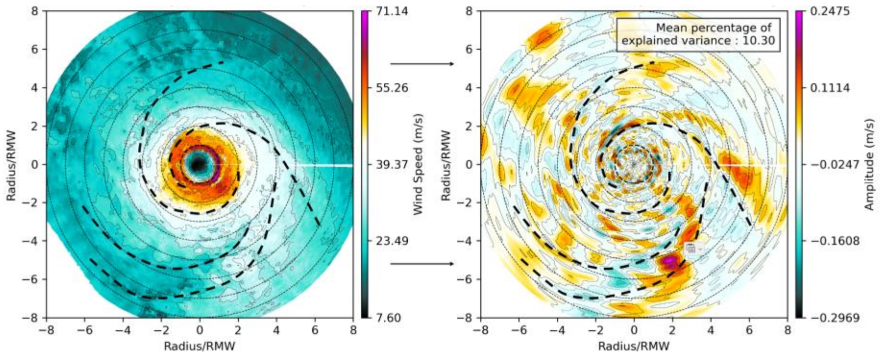
with λ an effective frictional term.

Identificating with the stress component integrated over the BL, we get :

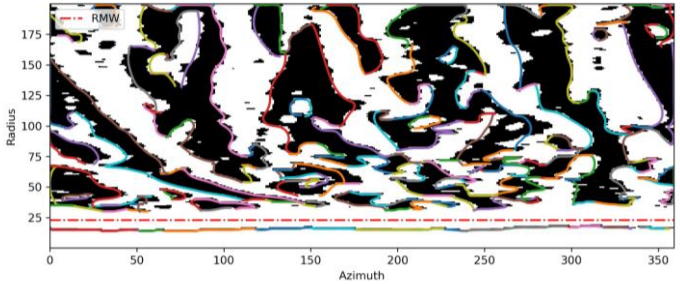
$\lambda = \left(\frac{v}{r}+f\right)\tan(\alpha) = \frac{rC_d v^2}{h}\cdot\frac{1}{rv}$, hence the inflow angle can be approximated as

$\alpha \approx \tan^{-1}\left(\frac{C_d v}{h}\cdot\frac{1}{\left(\frac{v}{r}+f\right)}\right)$

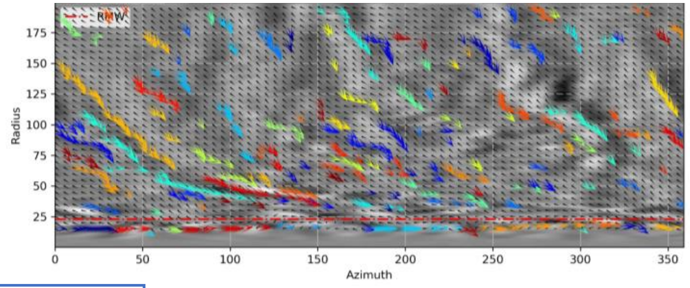
SAR wind field + visible spiral signatures → Polar Fourier decomposition → Sum of WNs 5-20



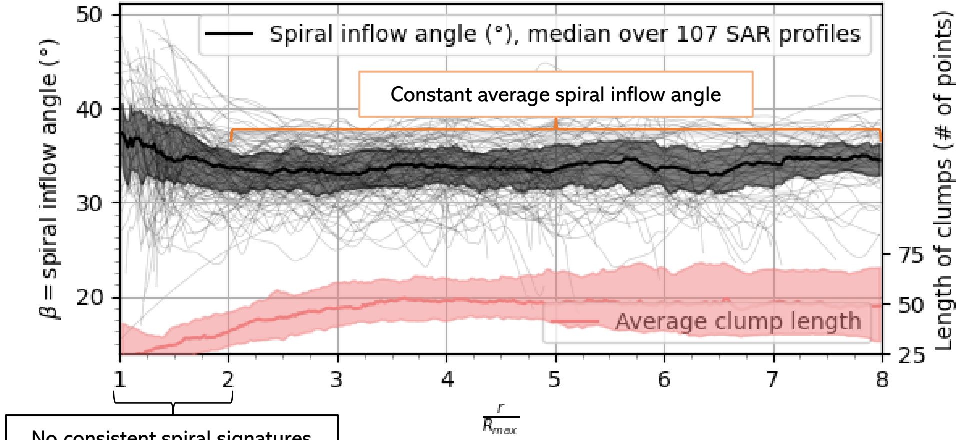
Binary contours (Θ/r plan) + clumps extracted from the contours (colored lines)



Directional spiral inflow field : clumps isolated vectors (colored) + interpolated vectors (black vectors)



Θ-averaging



No consistent spiral signatures

III. Symmetric BL structure : a new perspective issued from high resolution

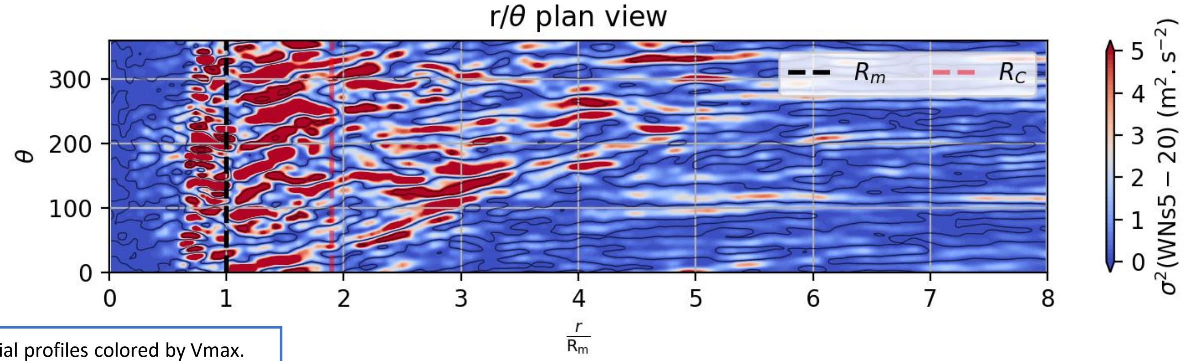
- In the inner-core, heterogeneity denoted by WNs 5-20 becomes difficult to measure : variance is much larger, but associated to small-scale patches instead of spirals
- The transition between inner and outer core can be identified by a critical radius on individual profiles of variance
- This radius compares well with the radius of onset of potential vorticity (and vertical velocity)

➢ WN decomposition allows to measure properties of the inflow layer and of the size and amplitude of the convective eyewall column

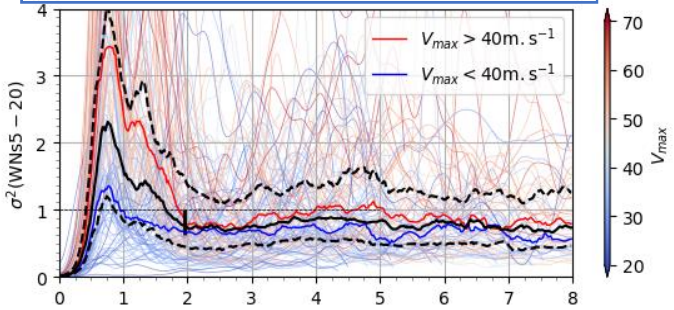
Ekman pumping : $w_E(r) = \frac{1}{r}\frac{d}{dr}\left(\frac{C_d r v^2}{\omega_z + f}\right)$

Assuming $C_d r v^2 \approx cst, w_E$ becomes large for $\omega_z \gg f$
→ we estimate the characteristic radius R_+ directly from the profile of $\omega_z = \frac{1}{r}\frac{\partial}{\partial r}(rv)$

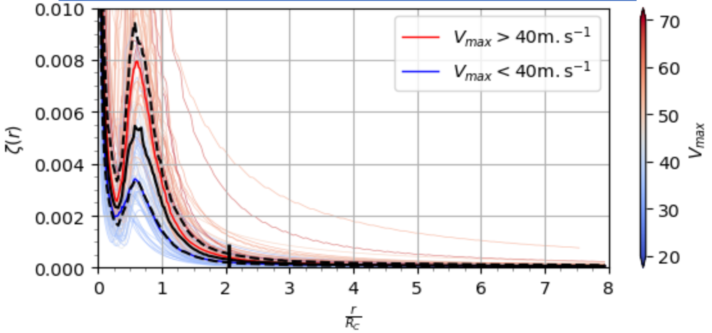
Variance of WNs 5-20 for one SAR image (r/Θ plan)

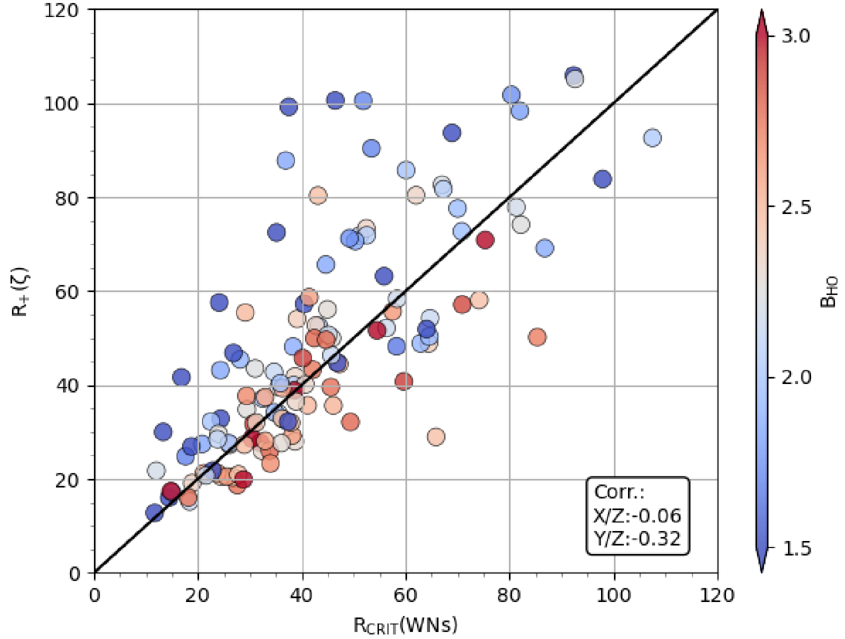


Variance of WNs 5-20 : all radial profiles colored by Vmax. Black = median+quartiles (marker = median R_{CRIT})



Potential vorticity : all radial profiles colored by Vmax. Black = median+quartiles (marker = median R_+)





Individual comparison between the two characteristic radii, colored by Holland B parameter