国防科技大学
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Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Waterstaat

Improved Tropical Cyclone Observations by Scatterometers, using SAR learning

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Contents

Background

Difference between SAR and Scatterometer

	SAR
1	Resolve winds to scales of 1 km
2	Narrow swath and sporadic
3	Complex scheduling issues

VS.

	Scatterometer
1	20-km true spatial resolution
2	Large coverage, short revisit time
3	**Abundant data**

The number of TC acquisitions by ASCAT-A and ASCAT-B in the 2016 and 2017 TC seasons (from May 1 to October 31) is **1,179**, while only **99** TC images are provided by Sentinel and RadarSat-2.

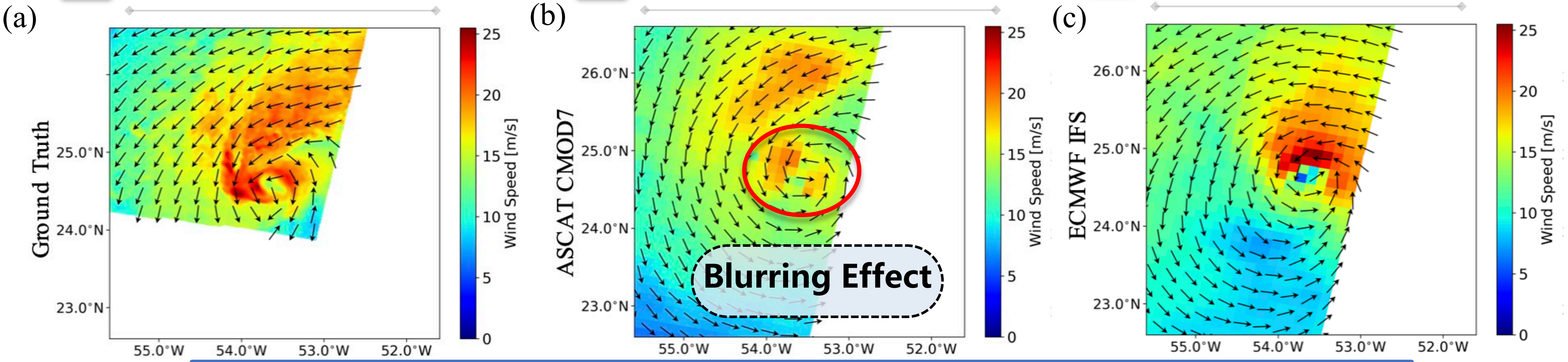
SAR **99**

ASCAT **1,179**

Background

- SAR : Retrieve winds on 1-km scale, yet having **sporadic availability**.
- ASCAT: Global coverage but with relatively **low spatial resolution**.
- ECMWF forecasts: Clear TC inner-structure, but can be **artificial**.

SAR **ASCAT** **ECMWF IFS**



TC Name: Florence Acquisition Time: 08-09-2018

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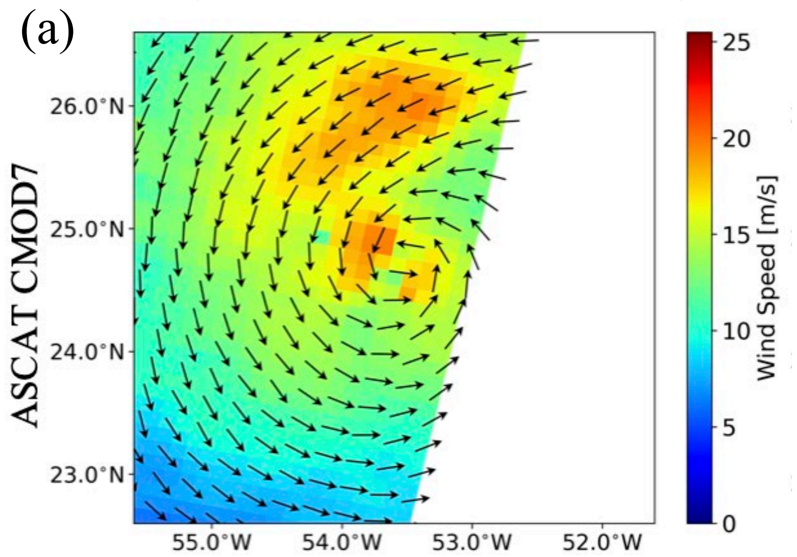
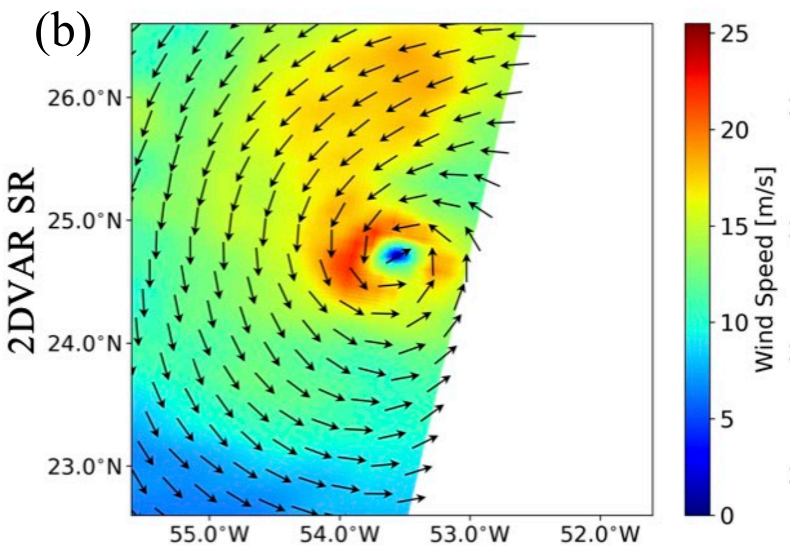
Aim of Research

A method for generating super-resolution (SR) winds from low-resolution wind scatterometers using **2DVAR analysis method**, wherein SR structure functions are empirically trained on SAR data.

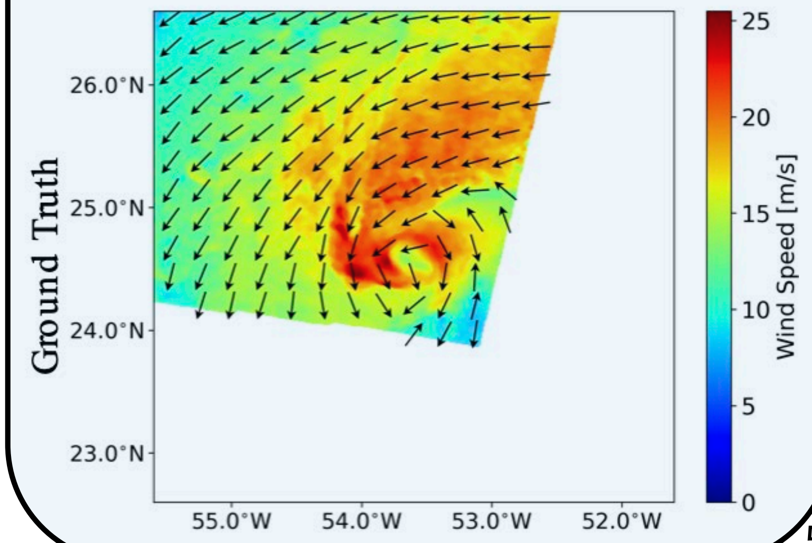
ASCAT



SR Winds



SAR Winds



Aim of Research

2DVAR Cost Function

Background Term

$$J_b = \delta x^T B_{t,l}^{-1} \delta x \xrightarrow[\text{Fourier Transformation}]{\text{Helmholtz Transformation}} J_b = \delta\hat{\xi}^T B_{\hat{\psi},\hat{\chi}}^{-1/2} B_{\hat{\psi},\hat{\chi}}^{-1/2} \delta\hat{\xi}$$

where: $B_{\hat{\psi},\hat{\chi}} \approx \begin{pmatrix} B_{\hat{\chi},\hat{\chi}} & 0 \\ 0 & B_{\hat{\psi},\hat{\psi}} \end{pmatrix}$

Gaussian Assumption:

$$\begin{cases} B_{\hat{\psi},\hat{\psi}}^{-1/2}(p,q) = \sqrt{\frac{\pi}{2}(1-\boldsymbol{\upsilon^2})}\boldsymbol{\varepsilon_l R_\varphi^2} e^{-\frac{1}{2}\pi^2 R_\varphi^2 (p^2+q^2)} \\ B_{\hat{\chi},\hat{\chi}}^{-1/2}(p,q) = \sqrt{\frac{\pi}{2}}\boldsymbol{\upsilon\varepsilon_t R_\chi^2} e^{-\frac{1}{2}\pi^2 R_\chi^2 (p^2+q^2)} \end{cases}$$

Observation Term

$$J_o = \sum_{m=1}^{N_{obs}} \left[\sum_{k=1}^{K} \left(\frac{\left(\delta\bar{u}_m - \delta l_{m,k}^{(o)}\right)^2}{\boldsymbol{\sigma_l^2}} + \frac{\left(\delta\bar{v}_m - \delta t_{m,k}^{(o)}\right)^2}{\boldsymbol{\sigma_t^2}} - 2lnP_k \right)^{-4} \right]^{-1/4}$$

Parameters of interest:
$(\boldsymbol{R_\psi}, \boldsymbol{R_\chi}, \boldsymbol{\upsilon^2}, \boldsymbol{\varepsilon_l}, \boldsymbol{\varepsilon_t}, \boldsymbol{\sigma_l}, \boldsymbol{\sigma_t})$

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SAR and ASCAT Wind Speed Reconciliation

Parameters of interest: $(R_\psi, R_\chi, \upsilon^2, \boldsymbol{\varepsilon_l, \varepsilon_t, \varepsilon_u, \varepsilon_v})$

How to determine background and observation errors?

Idea: Determine $\boldsymbol{\varepsilon_o, \varepsilon_b}$ using Triple Collocation analysis method.

Wind Triplet: System 1 SAR | System 2 ASCAT | System 3 ECMWF IFS → Triple Collocation Analysis →

$$\sigma_1^2 = C_{11} - \frac{C_{13}(C_{12} - a_2 r^2)}{C_{23}},$$
$$\sigma_2^2 = C_{22} - \frac{C_{23}(C_{12} - a_2 r^2)}{C_{13}},$$
$$\sigma_3^2 = C_{33} - \frac{C_{23}C_{13}}{C_{12} - a_2 r^2}$$

Original

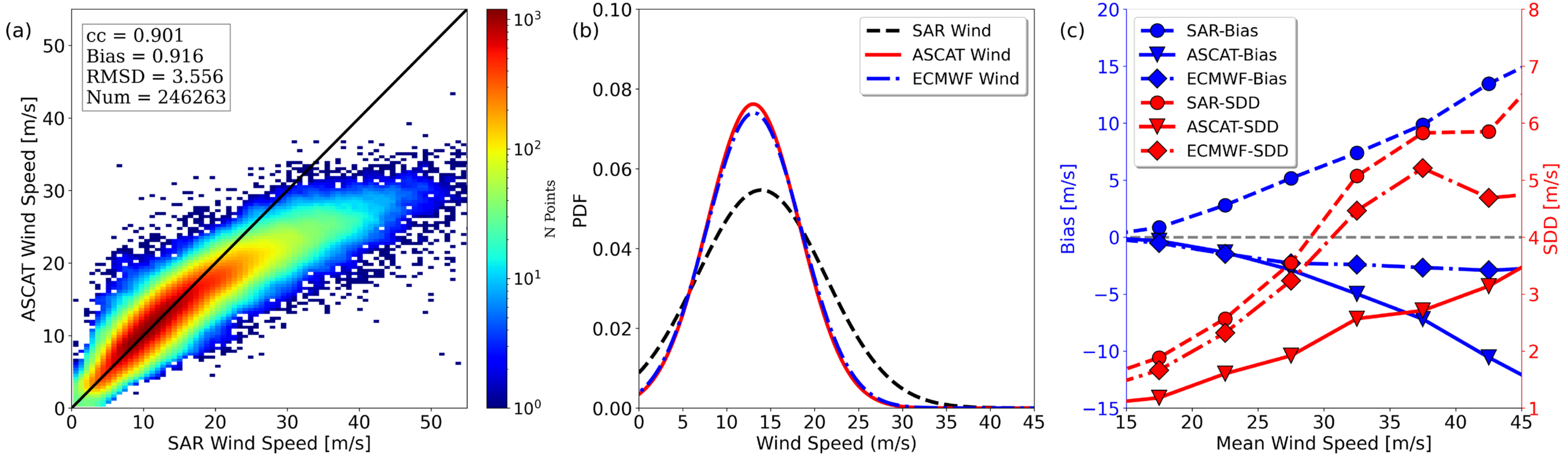

Figure 3. (a) ASCAT CMOD7 winds versus SAR MS1AHW winds. (b) Wind speed PDFs as a function of wind speeds. (c) Bias (blue curves) and SDD values (red curves) of three wind sources as a function of mean wind speeds.

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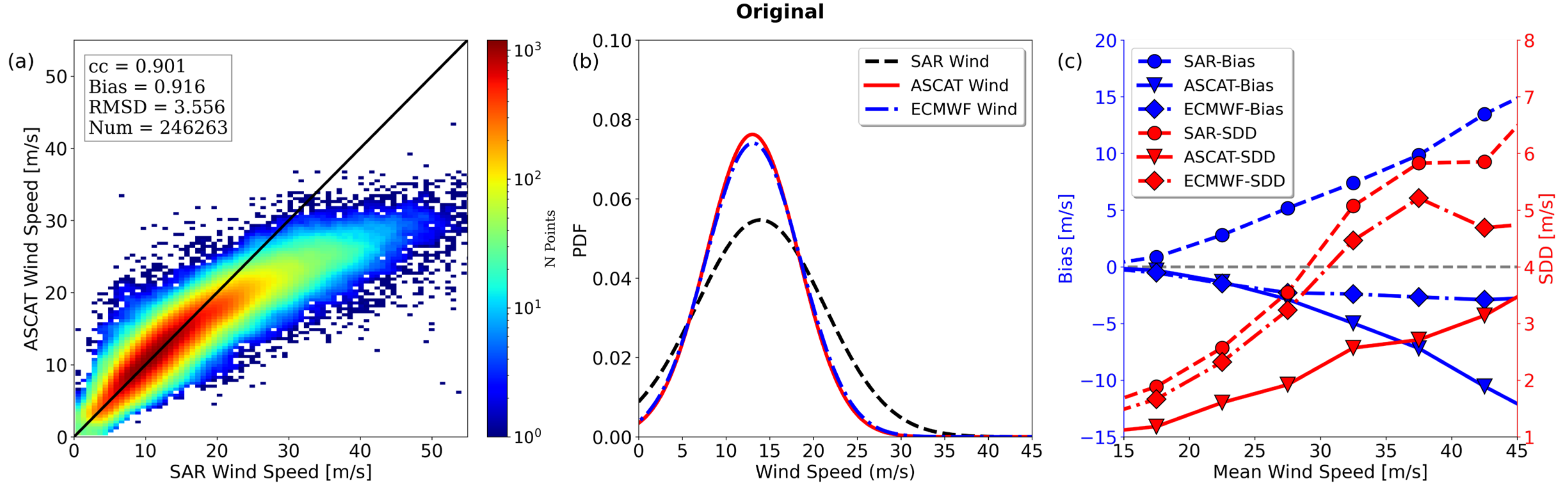
SAR and ASCAT Wind Speed Reconciliation



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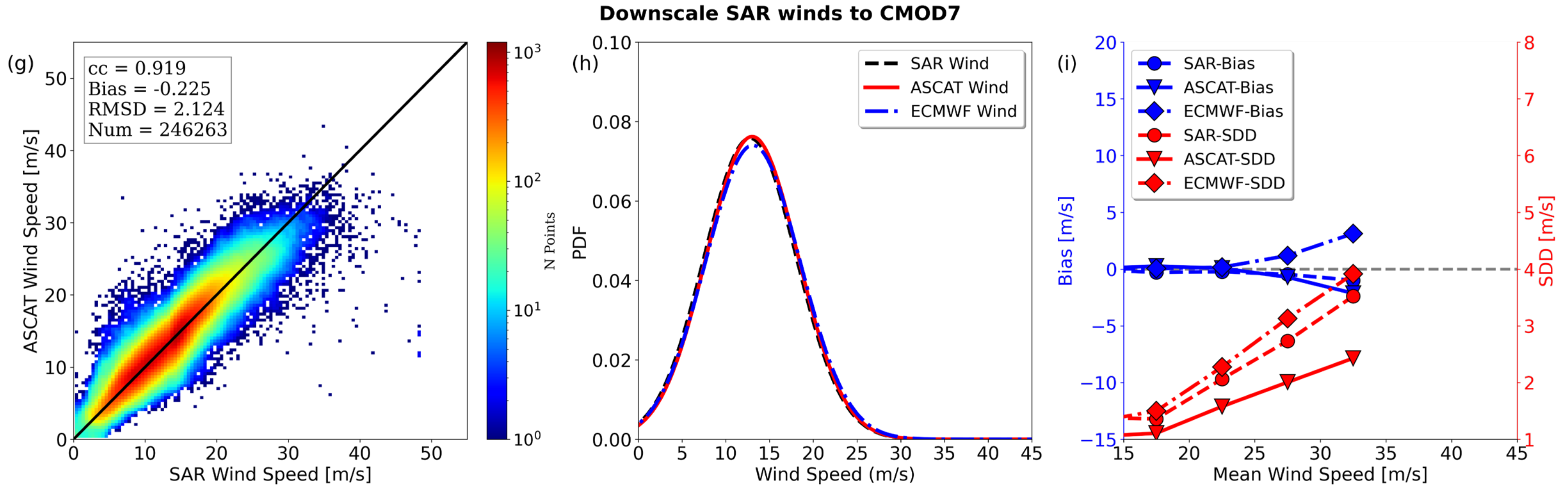

Figure 4. Same as Figure 3 but for adjusted ASCAT CMOD7 winds.

ASCAT CMOD7 Winds
Versus
SAR MS1AHW Winds

A clear wind speed **underestimation** can be found for ASCAT data when wind speeds are higher than 14 m/s.

CMOD7D-v2
Adjustment

$$V_{CMOD7} = \left[\frac{V_{CMOD7D} + 5.81}{0.88}\right]^{\frac{1}{1.18}}$$

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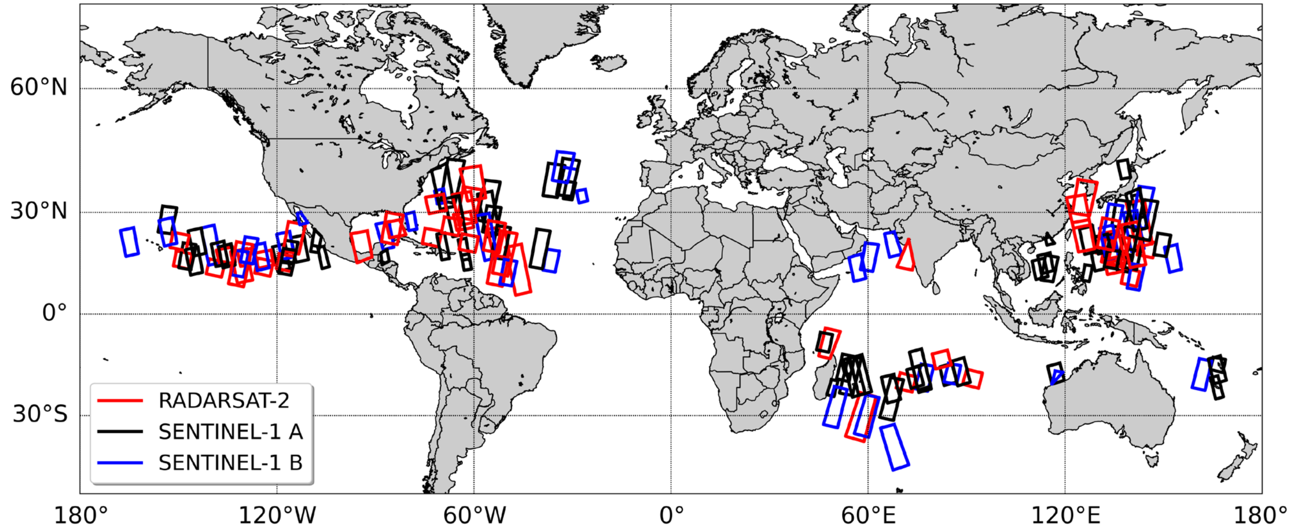
Ni W, Stoffelen A,Ren K, et al.SAR and ASCAT Tropical Cyclone Wind Speed Reconciliation [J]. Remote Sensing. 2022.

Tropical Cyclone Resolution Enhancement

■ TC Distribution.

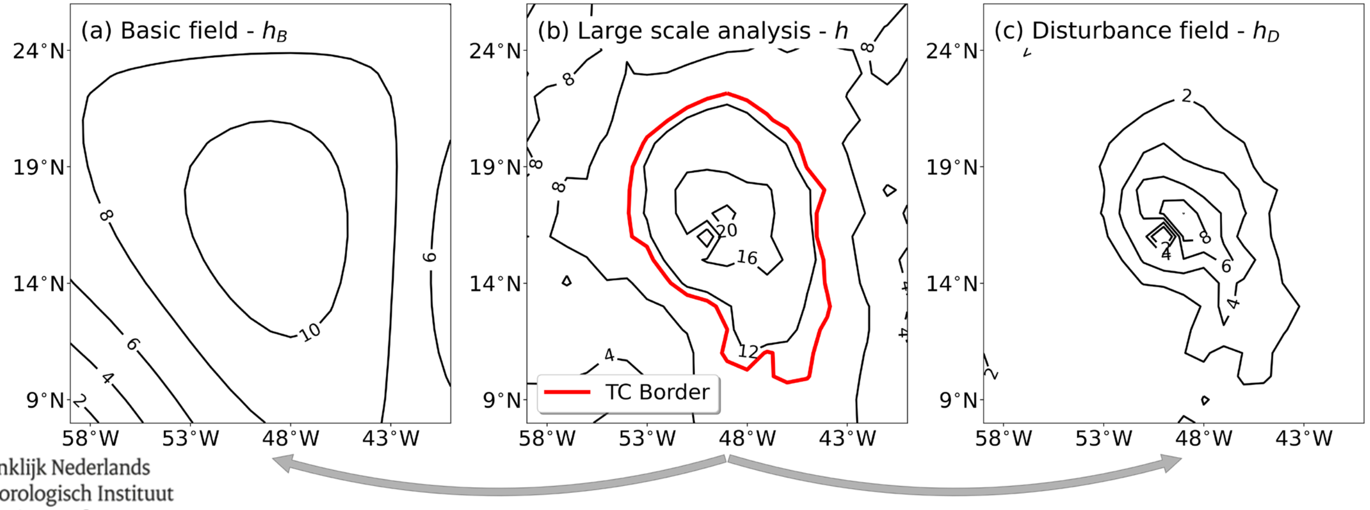


Dataset

RADARSET-2: 47
Sentinel-1A: 68
Sentinel-1B: 33

Figure 5. The geographic locations of SAR TC images used in this study. Note that simultaneous ASCAT acquisitions with a time departure less than 3.5h can be found.

■ TC Impact Region.



Local three-point smoothing operator

■ TC impact region is determined using local three-point smoothing operator.

$$\bar{h}_{\lambda,\varphi} = h_{\lambda,\varphi} + K\left(h_{\lambda-1,\varphi} + h_{\lambda+1,\varphi} - 2h_{\lambda,\varphi}\right) \quad (1)$$

$$K = \frac{1}{2}\left(1 - cos\frac{2\pi}{m}\right)^{-1} \quad (2)$$

where m in sequentially varies as 2, 3, 4, 2, 5, 6, 7, 2, 8, 9, 2.

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Tropical Cyclone Resolution Enhancement

Observation and Backgroud Errors

Weak Category

- Tropical Storm
- Category 1 Hurricane

Moderate Category

- Category 2 Hurricane
- Category 3 Hurricane

Strong Category

- Category 4 Hurricane
- Category 5 Hurricane

Table 1. Error SDs (m/s) for (l, t) SAE Wind Triplets under different TC categories

TC Category	SAR		ASCAT		ECMWF		$r_l^2(m^2/s^2)$	$r_t^2(m^2/s^2)$	Number of Point
	$\varepsilon_l(m/s)$	$\varepsilon_t(m/s)$	$\varepsilon_l(m/s)$	$\varepsilon_t(m/s)$	$\varepsilon_l(m/s)$	$\varepsilon_t(m/s)$			
Weak	2.78	2.59	1.71	1.59	2.78	2.59	2.31	2.04	111,820
Moderate	2.53	2.20	1.90	1.66	2.54	2.21	2.27	1.17	59,994
Strong	2.10	2.02	1.96	1.70	2.10	2.02	1.51	1.51	30,443

Observation Errors

Background Errors

Tropical Cyclone Resolution Enhancement

Length Scale (R_φ, R_χ)

Length scale of Stream Function (R_φ)

R_φ versus RMW?

Length scale of Velocity Potential (R_χ)

R_χ versus Asymmetry Scale?

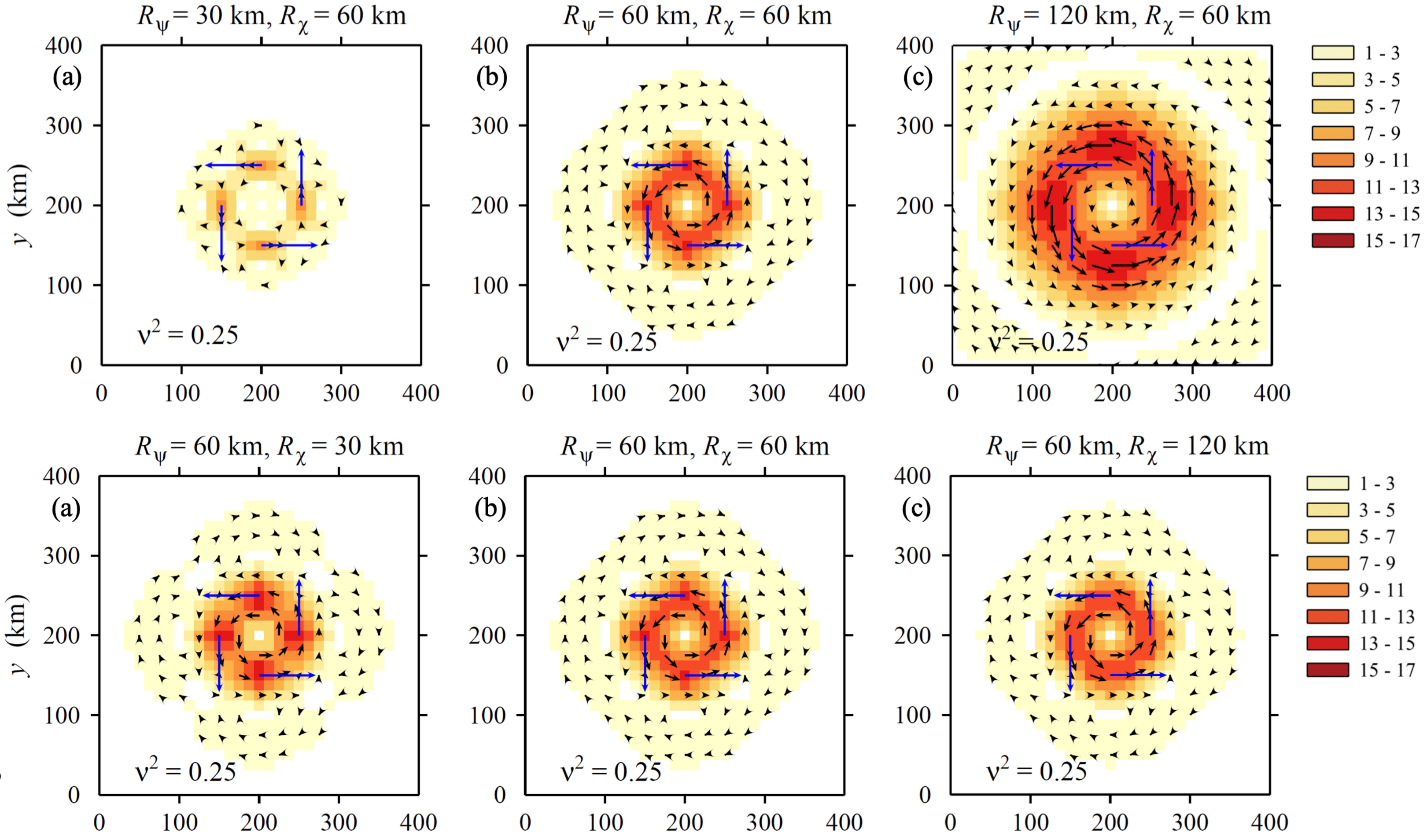

Figure 7. Impacts of (R_φ, R_χ) in 2DVAR analyses.

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Tropical Cyclone Resolution Enhancement

Quality of Analysis with respect to (R_ψ, R_χ)

$$V_{RMS} = \left\{\frac{1}{N}\left[\sum_i^N \left(v_{SAR}^{(i)} - v_{2DVAR}^{(i)}\right)^2\right]\right\}^{\frac{1}{2}}$$

Eq. (3)

- The changes in ν^2 (from 0.25 to 0.5) have **slight** impacts on qualities of 2DVAR analyses.

-- υ^2 = 0.25

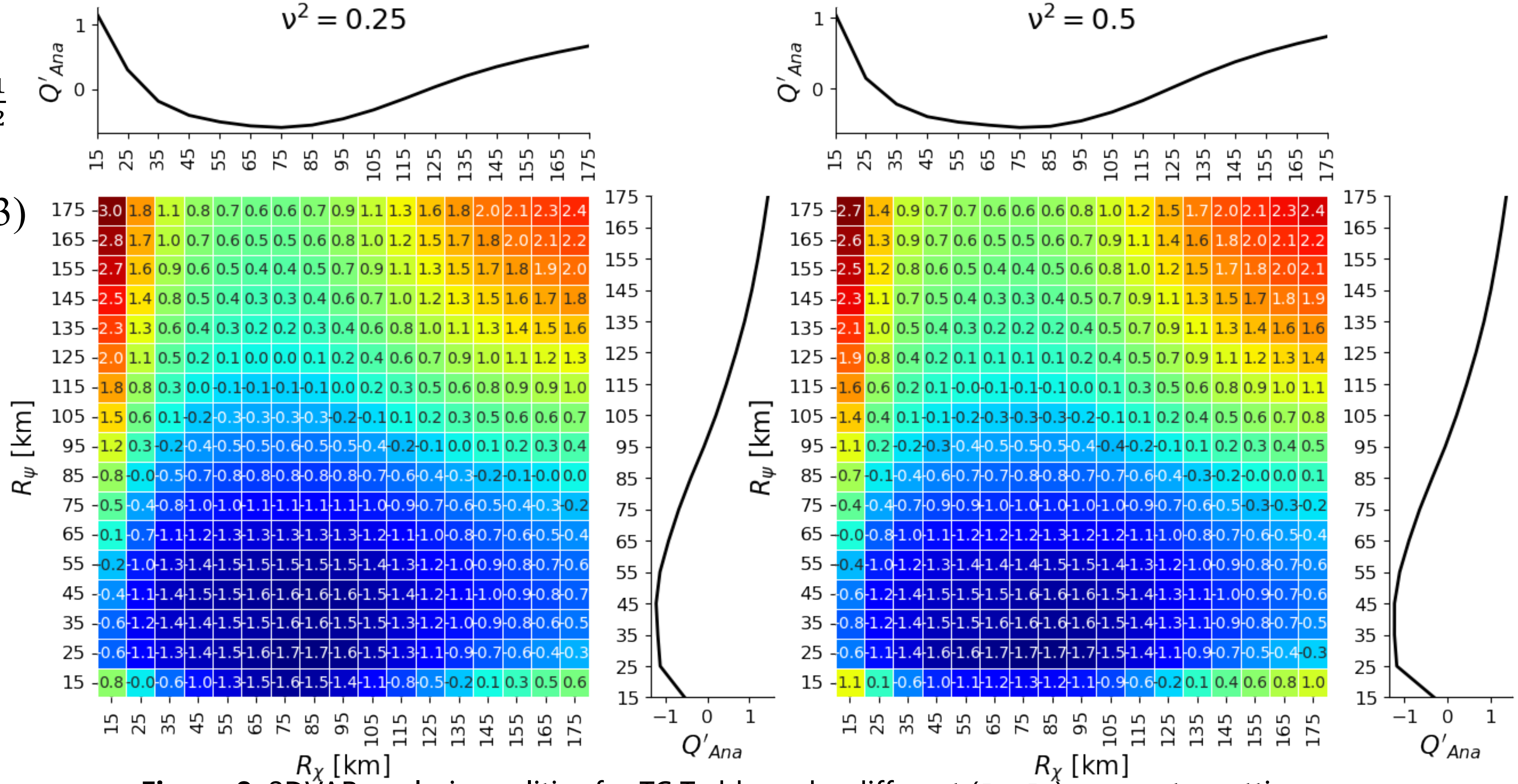


Figure 8. 2DVAR analysis qualities for TC Teddy under different (R_ψ, R_χ) parameter settings: (a-c) ν^2 = 0.25; (d-f) ν^2 = 0.5.

Tropical Cyclone Resolution Enhancement

Statistical Results

- TC features are retrieved from **SAR observations**.
- R_φ values increase **linearly** along with TC RMW
- The fitting curve between R_χ and TC asymmetry scales resembles **a family of rectangular hyperbolas**.

R_φ-RMW

R_χ-Asymmetry Scale

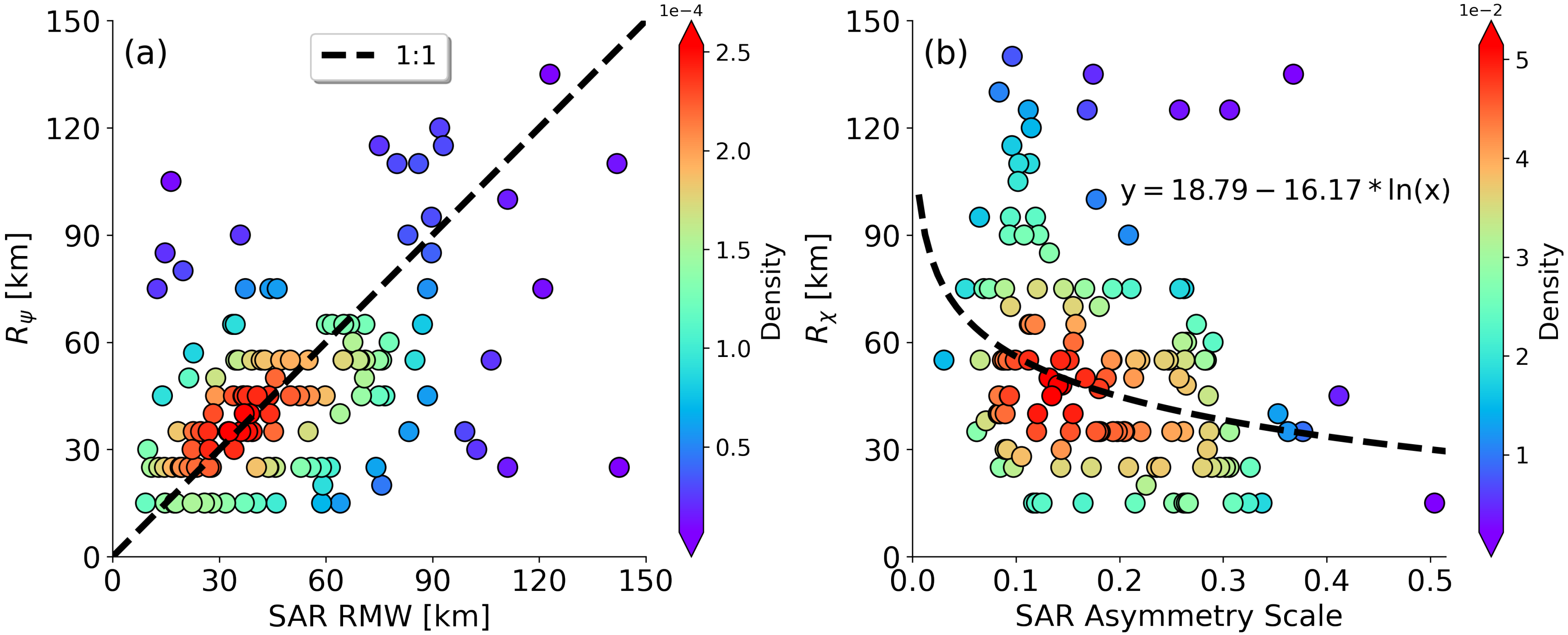


Figure 9. The relationships between the optimal (R_ψ, R_χ) values and TC characteristics.

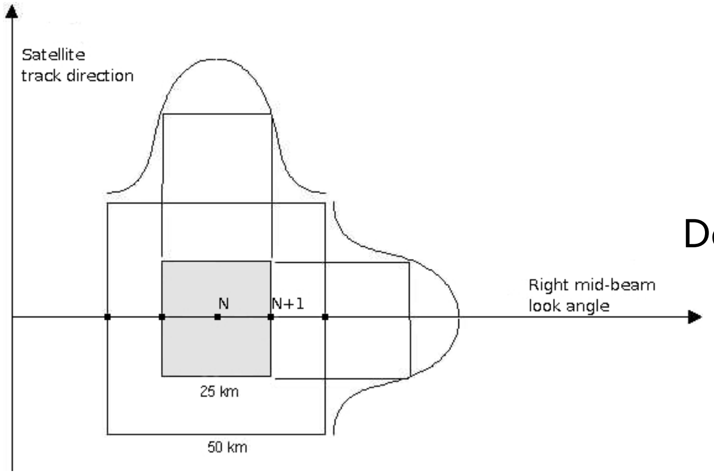
2DVAR Batch Grid and Innovation Estimation

- (1) 2DVAR batch grid

  Interpolate ECMWF forecasts into 1.8 km grids.

- (2) Innovation (δx) Estimation

  Estimate innovations taking advantage of footprint operator: $\delta x = x_o - \bar{x}_b$, with $\bar{x}_b$ the **mean values** of background over the footprints of ASCAT products.



Determine the footprint according to the **ground geometry**

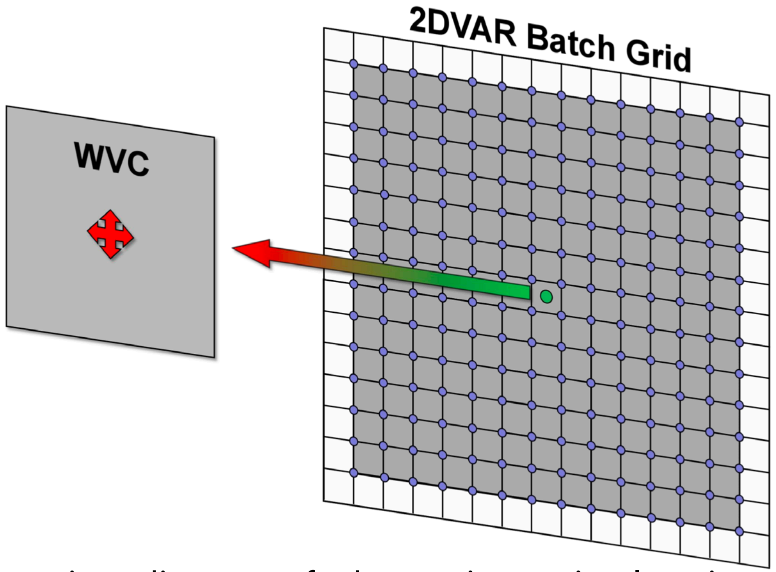


Figure 10. Ground geometry of the spatial smoothing for NRCS values for the 12.5 km ASCAT products (Verhoef et al., 2011).

Figure 11. Overview diagram of observation point locations and observation operator in a 2DVAR batch grid.

Results

2DVAR SR Products

- When TC structures are significantly **smoothed** in ECMWF forecasts.
- The obtained 2DVAR SR results depict more apparent vortex structures than ASCAT observations.

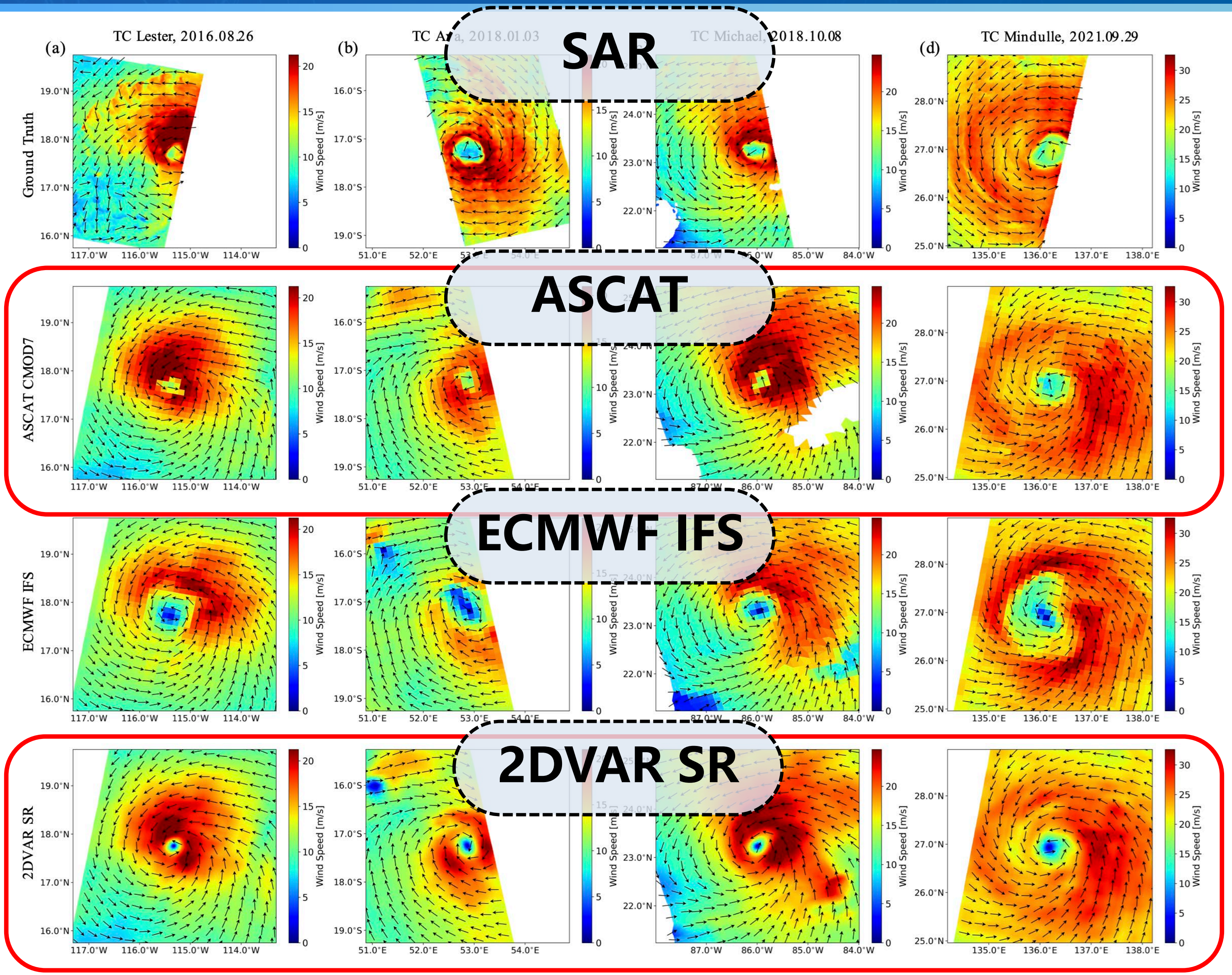


Figure 12. 2DVAR SR products when ECMWF IFS forecasts are smoothed.

Results

2DVAR SR Products

- ASCAT sensors may **fail** to describe TC vortex structures.
- With an appropriate structure function, the 2DVAR scheme can **effectively enhance vortex structures**, even when vortex in ECMWF forecasts are different from real observations.

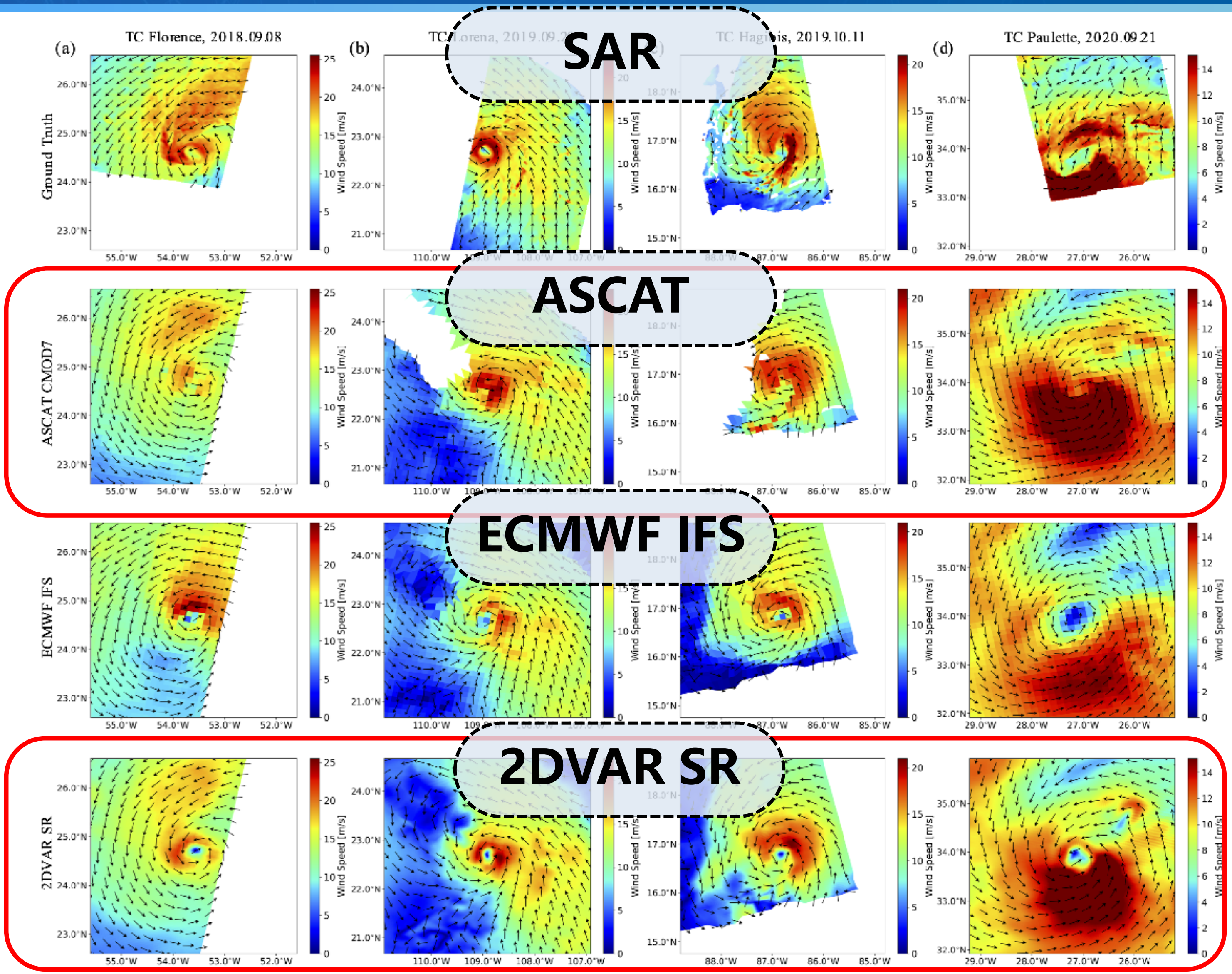


Figure 13. 2DVAR SR products when ASCAT cannot depict TC vortex structures.

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Validation

1. The proposed SR method is capable of preserving consistency at large scales with original ASCAT winds while compensating for the ASCAT footprint blurring effect of the small-scale information and **enhancing TC vortex structures in a physically meaningful manner**, regardless of TC strength category.
2. The obtained SR products possess the correct small-scale properties of TC inner-core structures, such as **Radius of Maximum Wind, TC asymmetry and wind variability**.

Morphological Analysis

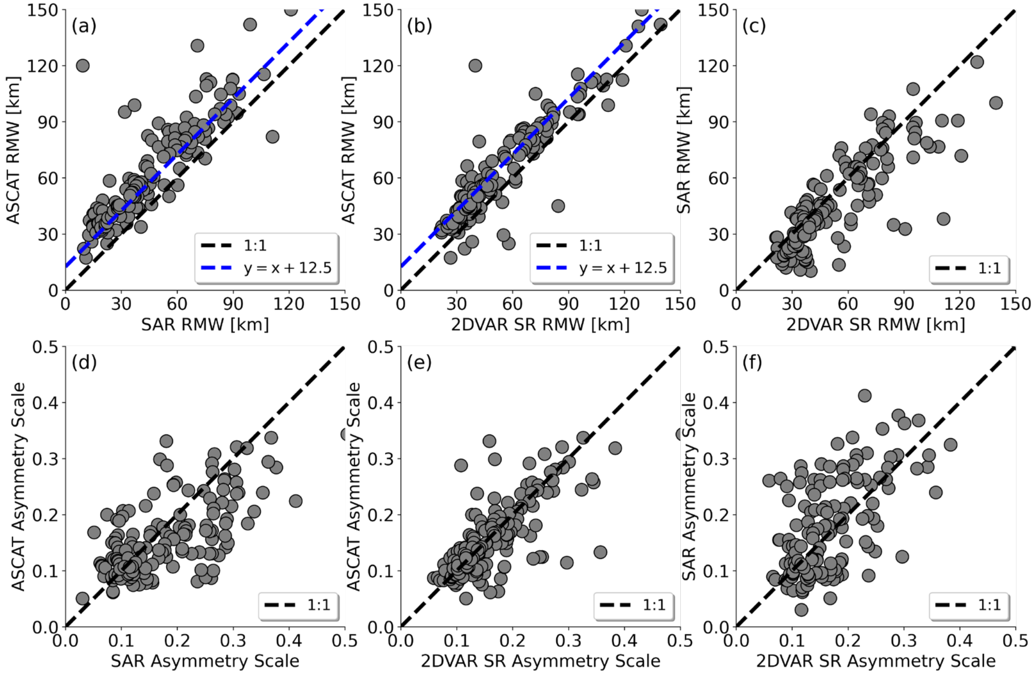

Figure 14. Morphological analysis regarding 2DVAR SR products

Spatial Variance Estimates

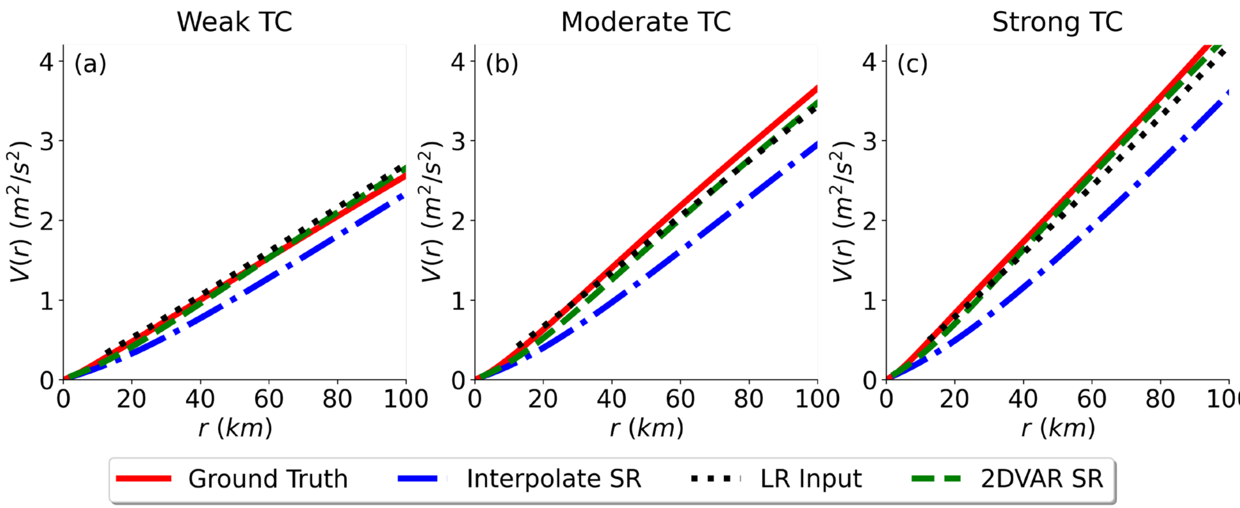

Figure 15. Spatial variance estimates from different wind products under different TC category.

Conclusion

- **Backgroud**: The blurring effects in scatterometers remain a huge issue, which impedes the research of dynamical behaviou for TC inner-core regions and the contribution to TC forecasts.

- **Aim**: A novel SR method taking advantage of the 2DVAR scheme is provided, running 2DVAR analyisi method with **SR structure functions empirically trained on SAR data** for different classes of TCs.

- **Validation**: Validation studies demonstrate that the SR products possess the **correct small-scale properties** of TC inner-core structures, while preserving consistency at large scales with original ASCAT winds.

Thanks!