Improved Tropical Cyclone Observations by Scatterometers, using SAR learning

Weicheng Ni, Ad Stoffelen, Kaijun Ren, Jur vogelzang

weicheng.ni@zju.edu.cn
Contents

1. Background and Aim of Research
2. SAR and ASCAT Wind Speed Reconciliation
3. Tropical Cyclone Resolution Enhancement for ASCAT Winds
4. Results and Discussion
## Difference between SAR and Scatterometer

<table>
<thead>
<tr>
<th>SAR</th>
<th>Scatterometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Resolve winds to scales of 1 km</td>
<td>1 20-km true spatial resolution</td>
</tr>
<tr>
<td>2 Narrow swath and sporadic</td>
<td>2 Large coverage, short revisit time</td>
</tr>
<tr>
<td>3 Complex scheduling issues</td>
<td>3 Abundant data</td>
</tr>
</tbody>
</table>

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: 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.
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.
2DVAR Cost Function

**Background Term**

\[ J_b = \delta x^T B_{l,l}^{-1} \delta x \]

\[ J_b = \delta \hat{\xi}^T B_{\hat{\psi},\hat{\psi}}^{-1/2} B_{\hat{\psi},\hat{\psi}}^{-1/2} \delta \hat{\xi} \]

where: 

\[ B_{\hat{\psi},\hat{\psi}} \approx \begin{pmatrix} B_{\hat{\chi},\hat{\chi}} & 0 \\ 0 & B_{\hat{\psi},\hat{\psi}} \end{pmatrix} \]

**Gaussian Assumption:**

\[ B_{\hat{\psi},\hat{\psi}}^{-1/2}(p, q) = \sqrt{\frac{\pi}{2}} \frac{1 - v^2}{1 - \nu^2} e^{-\frac{1}{2} \pi^2 R^2_{\varphi}(p^2 + q^2)} \]

\[ B_{\hat{\chi},\hat{\chi}}^{-1/2}(p, q) = \sqrt{\frac{\pi}{2}} \nu \epsilon_t R^2_{\chi} e^{-\frac{1}{2} \pi^2 R^2_{\chi}(p^2 + q^2)} \]

**Observation Term**

\[ J_o = \sum_{m=1}^{N_{obs}} \sum_{k=1}^{K} \left( \frac{(\delta \tilde{u}_m - \delta l_{m,k})^2}{\sigma^2_i} + \frac{(\delta \tilde{v}_m - \delta t_{m,k})^2}{\sigma^2_i} - 2 \ln P_k \right)^{-4}^{-1/4} \]

**Parameters of interest:**

\( R_{\psi}, R_{\chi}, \nu^2, \epsilon_l, \epsilon_t, \sigma_l, \sigma_t \)
SAR and ASCAT Wind Speed Reconciliation

Parameters of interest:
\( R_\psi, R_\chi, \nu^2, \varepsilon_l, \varepsilon_t, \varepsilon_u, \varepsilon_v \)

How to determine background and observation errors?

Idea: Determine \( \varepsilon_o, \varepsilon_b \) using Triple Collocation analysis method.

System 1
SAR

System 2
ASCAT

System 3
ECMWF IFS

Wind Triplet

Triple Collocation Analysis

\[
\begin{align*}
\sigma_1^2 &= C_{11} - C_{13}(c_{12} - a_2r)^2, \\
\sigma_2^2 &= C_{22} - C_{23}(c_{12} - a_2r)^2, \\
\sigma_3^2 &= C_{33} - C_{23}(c_{12} - a_2r)^2,
\end{align*}
\]

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

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

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.

Figure 4. Same as Figure 3 but for adjusted ASCAT CMOD7 winds.
Tropical Cyclone Resolution Enhancement

- **TC Distribution.**

![Map of TC distribution](image)

- **TC Impact Region.**

![Diagram of TC impact region](image)

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.

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.

### Observation and Background 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

<table>
<thead>
<tr>
<th>TC Category</th>
<th>SAR</th>
<th>ASCAT</th>
<th>ECMWF</th>
<th>Number of Point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\varepsilon_l(m/s))</td>
<td>(\varepsilon_t(m/s))</td>
<td>(\varepsilon_l(m/s))</td>
<td>(\varepsilon_t(m/s))</td>
</tr>
<tr>
<td>Weak</td>
<td>2.78</td>
<td>2.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.71</td>
<td>1.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>2.53</td>
<td>2.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.90</td>
<td>1.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong</td>
<td>2.10</td>
<td>2.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.96</td>
<td>1.70</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Observation Errors**

**Background Errors**
Tropical Cyclone Resolution Enhancement

Length Scale \((R_\phi, R_\chi)\)

**Length scale of Stream Function \((R_\phi)\)**

- \(R_\phi\) versus RMW?

**Length scale of Velocity Potential \((R_\chi)\)**

- \(R_\chi\) versus Asymmetry Scale?

---

**Figure 7.** Impacts of \((R_\phi, R_\chi)\) in 2DVAR analyses.
Quality of Analysis with respect to \((R_\psi, R_\chi)\)

\[ V_{RMS} = \left\{ \frac{1}{N} \left[ \sum_{i} \left( \nu_{SAR}^{(i)} - \nu_{2DVAR}^{(i)} \right)^2 \right] \right\}^{1/2} \]

Eq. (3)

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

\[ - - \nu^2 = 0.25 \]

Figure 8. 2DVAR analysis qualities for TC Teddy under different \((R_\psi, R_\chi)\) parameter settings:

(a-c) \(\nu^2 = 0.25\); (d-f) \(\nu^2 = 0.5\).
Statistical Results

- TC features are retrieved from SAR observations.
- $R_\phi$ values increase linearly along with TC RMW.
- The fitting curve between $R_\chi$ and TC asymmetry scales resembles a family of rectangular hyperbolas.

Figure 9. The relationships between the optimal $(R_\phi, R_\chi)$ values and TC characteristics.
2DVAR Batch Grid and Innovation Estimation

- (1) 2DVAR batch grid
  Interpolate ECMWF forecasts into 1.8 km grids.

- (2) Innovation ($\delta x$) 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.

**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.
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.
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.
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.

**Figure 14.** Morphological analysis regarding 2DVAR SR products

**Figure 15.** Spatial variance estimates from different wind products under different TC category.
**Background**: The blurring effects in scatterometers remain a huge issue, which impedes the research of dynamical behaviour 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 analysis 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!