Effects of Rain on CFOSAT Scatterometer Measurements

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Abstract
The Ku-band scatterometer onboard China France Oceanography Satellite (CFOSAT) observes the sea surface with two conically scanning fan beams. Compared to the prior Ku-band pencil beam scatterometers, this innovative observing mechanism provides more independent backscatter measurements at varying incidence and azimuth angles, as such it brings challenges for the sea surface wind inversion, particularly under rainy conditions. In this paper, the rain effects on the CFOSAT SCATterometer (CSCAT) are investigated using the collocated numerical weather prediction (NWP) wind data and the Global Precipitation Measurement (GPM) microwave imager (GMI) rain data. Similar to the prior Ku-band or C-band scatterometers, the sensitivity of CSCAT radar backscatter to rain substantially varies with wind speed, radar polarization and incidence angle. However, due to the complex observation geometries, rain effects on the CSCAT retrieved winds is more complex than that of prior scatterometers, which may lead to a remarkable underestimation of CSCAT wind speed at high winds and heavy rain conditions. A simple simulation method is used to clarify the relation between the retrieved wind speed and the dependency of radar rain effects on the incidence angle. It is found that the backscatter measurements at low incidence angles, which are generally underestimated at high winds and heavy rainy conditions, have a larger influence on the wind inversion minimization, leading to much lower retrieved wind speeds than those of ECMWF and the pencil beam scatterometer (e.g., Haiyang-2B scattometer). Under low and moderate rain conditions though, a more compensated effect between low and high incidence angle measurements is found, leading to generally unbiased CSCAT high winds, in contrast to the generally underestimated pencil-beam scatterometer winds.
Key words: CFOSAT; Scatterometer; Backscatter; Rain effects; Wind quality
1. Introduction

Over the last four decades, numerous satellite scatterometers have been designed to infer mesoscale sea surface wind vectors over the global ocean. Generally, spaceborne scatterometers provide accurate sea surface wind information, which is then used in a variety of applications, such as ocean forecasting, numerical weather prediction (NWP), and air-sea interaction studies. However, experience with past scatterometer missions has proven that rain is the most significant factor in distorting the normalized radar cross-section (or backscatter) measurements from wind-induced gravity-capillary waves, notably for the Ku-band systems, e.g., the National Aeronautics and Space Administration scatterometer (NSCAT) and the SeaWinds-like pencil beam scatterometers, leading to poor-quality retrieved winds (Jones and Zec, 1996; Portabella and Stoffelen, 2001; Stiles and Yueh, 2002). Consequently, assessment of the rain impact on scatterometer measurements is an essential prerequisite for the above mentioned applications of scatterometer winds.

Rain is known to distort the wind-related backscatter signal through the following three major aspects. First, rain striking the sea surface creates rings, stalks and crowns (Bliven et al., 1997), which change the roughness of sea surface and increase the radar backscatter, as compared with the backscattering from rain-free environment. Second, raindrops scatter part of the incident radar energy back to the sensor (volume scattering), and thus increase the power backscattered to the scatterometer (Ulaby et al., 1981). Third, the rain layer acts like an attenuator for the portion of microwave signal traveling towards sea surface, as well as the sea surface reflected energy returning back towards the receiver. Over the last 20 years, various methods have been proposed to deal with the rain effects in scatterometry with the object of acquiring high-quality sea surface winds. Few attempts have been carried out to model both the rain- and the wind-induced radar
backscatters (Draper and Long, 2003; Nie and Long, 2008) in order to retrieve both parameters simultaneously. Besides, some studies propose to correct for the rain-induced backscattering signal before the wind inversion (Hilburn et al., 2006; Weissman and Bourassa, 2008). However, it is difficult to resolve separately the three effects of rain from the scatterometer backscatter measurements, since the radar beam filling by rain is generally inhomogeneous (Tournadre and Quilfen, 2003), while high-resolution rain data are usually not available to most of the scatterometer missions. Consequently, a more practical approach is to flag the rain-contaminated winds for the operational use of scatterometer data (Huddleston and Stiles, 2000; Portabella et al., 2012; Lin et al., 2015a; Xu and Stoffelen, 2020). To date, the rain flagging is an essential procedure of the scatterometer wind quality control (QC).

In practice, the scatterometer winds are retrieved from a set of backscatter measurements at multiple azimuths, incidences, and polarizations (Stoffelen and Portabella, 2006). This is a highly nonlinear procedure, so it is not straightforward to assess the impact of rain on scatterometer winds even though the rain effects on the radar backscatter measurements are well addressed. As a result, the impact of rain on scatterometer winds, as well as the rain flagging, needs to be elaborated for each and every satellite scatterometer. Specifically, the new concept of Ku-band scatterometer onboard the China-France Oceanography satellite (CFOSAT, launched in October 2018) observes the sea surface using two slowly-rotating fan beams (Lin and Dong, 2011; Lin et al., 2019), resulting in more complicated observation geometries than the past fixed fan beam scatterometers (Figa-Saldaña et al., 2002) and/or rotating pencil-beam scatterometers (Naderi et al., 1991; Spencer et al., 1997; Liu et al., 2020). This further complicates the assessment of rain impact on the CFOSAT SCATterometer (CSCAT) winds, and as such the QC methods developed
for the prior Ku-band scatterometers, e.g., NSCAT, SeaWinds, and Haiyang-2 satellite scatterometers, may be not applicable to the rain flagging of CSCAT data.

This paper investigates the rain impact on CSCAT backscatter measurements as well as on the retrieved wind vectors, with the objective of improving the wind inversion and the quality control for the rotating fan beam scatterometer. Section 2 presents the different types of wind and rain data used in this study. In Section 3, the accuracy of European Centre for Medium-Range Weather Forecasts (ECMWF) winds, which are used as the key reference data, is evaluated using the collocated rain and buoy data. Section 4 elaborates on the effects of rain on the CSCAT backscatter ($\sigma^0$) measurements. The rain impact on the CSCAT winds, particularly at high winds, is presented in Section 5, together with a simulation approach that is used to show the relationship between the retrieved CSCAT wind speed and the sensitivity of the radar backscatter to rain. Finally, conclusions and outlooks are summarized in Section 6.

2. Data

To study the impact of rain on CSCAT $\sigma^0$ and retrieved winds, the CSCAT level 2 (L2) data of 25-km grid resolution, including L2A $\sigma^0$ values and L2B retrieved winds, are collocated with both the European Centre for Medium-Range Weather Forecasts (ECMWF) winds and the Global Precipitation Measurement (GPM) microwave imager (GMI) rain data. The L2B winds are retrieved using a multiple solution inversion scheme in combination with two-dimensional variational ambiguity removal, in order to achieve a spatially consistent wind field (Liu et al., 2020). Note that, the quality flag associated with the wind product is not used in this study, with the objective of keeping all the rain-contaminated data for the further analysis. The matched ECMWF winds are acquired by interpolating three ECMWF 3-h forecast winds on a 0.125° grid spatially and temporally to the CSCAT observing location and time, respectively. The collocated
GMI data are less than 30 minutes and 25 km distance from the CSCAT acquisitions. The total amount of collocations, from January 2019 to October 2020, is about 11.5 million, among which 10.2 million (88.7%) under rain-free condition and 1.3 million (11.3%) under various rainy conditions.

The ECMWF 10-m real winds (U10) are used as reference in the following sections. However, the scatterometer $\sigma^0$ is actually directly related to the gravity-capillary ocean waves driven by the surface wind stress, and modulated by air density variations. A recent study indicates that the winds retrieved from scatterometer backscatter measurements better represent 10-m stress-equivalent winds (U10S) than U10 or 10-m neutral equivalent wind (U10N) (Kloe et al., 2017). The primary difference between U10 and U10S is that the latter is independent of the actual atmospheric stratification (it is referenced to a neutrally stratified atmosphere) and accounts for air density variations. Nonetheless, the averaged difference between U10 and U10S is almost negligible (less than 0.2 m/s), although it can be locally significant (Stoffelen et al., 2020). Moreover, the main objective of this paper is to analyze the general tendency of $\sigma^0$ changes as a function of wind speed and rain rate, so the conceptual difference between ECMWF and CSCAT winds is ignored in this study.

3. Evaluation of ECMWF winds

The sensitivity of CSCAT $\sigma^0$ measurements to rain is estimated at different ECMWF wind speed regions. The main concern of such estimation is the accuracy of ECMWF winds under various rainy conditions. Therefore, the statistics of ECMWF reference are firstly evaluated using an ancillary data set that consists of six years of ECMWF winds collocated with moored buoy data and Tropical Rainfall Measuring Mission’s (TRMM) Microwave Imager (TMI) rain data. Similar to the collocations of ECMWF and CSCAT data, the ECMWF model wind output is
interpolated spatially and temporally to the TMI acquisitions. The buoy wind speed at a given
anemometer height has been converted to 10-m equivalent-neutral winds using the Liu-Katsaros-
Businger (LKB) model (Liu et al., 1979).

Table 1 illustrates the mean value (i.e., bias) and the standard deviation (SD) of the difference
between ECMWF and buoy wind speed. Moreover, a linear regression model (i.e., \( w_{\text{buoy}} = a + b \times w_{\text{ECMWF}} \)) is used to examine the trends of ECMWF high winds under different rainy conditions.

As expected, the SD value increases remarkably with the rain rate, since ECMWF does not well
resolve the sea surface wind variability under rainy conditions (Lin et al., 2015a; Lin et al.,
2015b). Whereas the sensitivity of wind speed biases (e.g., \(<w_{\text{ECMWF}} - w_{\text{buoy}}>)\) to rain is much
smaller than that of SD errors. Particularly, the linearity relationship between ECMWF and buoy
winds barely changes with the rain rate above 3 mm/h. Moreover, the Ku-band rain-induced
wind speed biases (Portabella and Stoffelen, 2001) are well beyond the estimated ECMWF wind
speed bias increase under rainy conditions as shown in Table 1 and in Portabella et al. (2012).

Consequently, the ECMWF wind speed is used as reference in the following sections, despite it
largely unresolves sea surface variability and is somewhat biased low (notably at low winds)
under rainy conditions.

<table>
<thead>
<tr>
<th>Rain rate (RR, mm/h)</th>
<th>0</th>
<th>0 &lt; RR &lt; 1</th>
<th>1 ≤ RR &lt; 3</th>
<th>3 ≤ RR &lt; 6</th>
<th>RR ≥ 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of data (%)</td>
<td>88.7</td>
<td>8.5</td>
<td>1.9</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Bias (m/s)</td>
<td>-0.40</td>
<td>-0.66</td>
<td>-0.85</td>
<td>-1.17</td>
<td>-1.67</td>
</tr>
<tr>
<td>SD (m/s)</td>
<td>1.35</td>
<td>2.19</td>
<td>2.59</td>
<td>2.79</td>
<td>3.21</td>
</tr>
<tr>
<td>(a)</td>
<td>-0.02</td>
<td>-0.11</td>
<td>-0.27</td>
<td>0.15</td>
<td>0.62</td>
</tr>
<tr>
<td>(b)</td>
<td>1.07</td>
<td>1.12</td>
<td>1.18</td>
<td>1.16</td>
<td>1.15</td>
</tr>
<tr>
<td>Number</td>
<td>151399</td>
<td>8400</td>
<td>3311</td>
<td>1319</td>
<td>719</td>
</tr>
</tbody>
</table>
4. Rain effects on CSCAT $\sigma^0$

In general, rainfall leads to a loss of anisotropy in the radar backscatter signal, which in turn will degrade the quality of the wind direction retrieval. This aspect has already been well documented (e.g., (Stiles and Yueh, 2002; Portabella et al., 2012)), and as such it is not highlighted here. This section mainly examines the dependence of CSCAT backscatter on wind speed, incidence angle and radar polarization for different rain rates. A simplified model is considered in the following analysis, in which the rain effects are categorized into two types, namely attenuation (denoted as $\alpha$) and intensification (denoted as $\sigma^0_{\text{int}}$), respectively (Stiles and Yueh, 2002; Nie and Long, 2007). The latter is mainly due to the combined effect of rain splashing ($\sigma^0_{\text{splashing}}$) and volume scattering ($\sigma^0_{\text{volume scattering}}$), i.e.,

$$\sigma^0_{\text{int}} = \alpha \sigma^0_{\text{splashing}} + \sigma^0_{\text{volume scattering}}$$  \hspace{1cm} (1)

As such, the measured backscatter coefficient ($\sigma^0_{\text{m}}$) can be expressed as (Stiles and Yueh, 2002; Nie and Long, 2007),

$$\sigma^0_{\text{m}} = \alpha \sigma^0_{\text{wind}} + \sigma^0_{\text{int}}$$  \hspace{1cm} (2)

where $\sigma^0_{\text{wind}}$ is the wind-induced radar backscatter coefficient, which can be estimated from the rain-free scatterometer measurements, or simulated through the scatterometer geophysical model function (GMF) using the collocated sea surface wind information (e.g., from ECMWF model output) and the observation geometry as input parameters. According to the above phenomenological model, one may infer that $\alpha \in (0, 1)$ and $\sigma^0_{\text{int}} > 0$. 

Fig. 1 illustrates the averaged CSCAT $\sigma^0$ as a function of ECMWF wind speed for different incidence angles and rain rates (see the legends in each panel). Similar to prior Ku-band scatterometers (Stiles and Yueh, 2002; Draper, 2004), rainfall generally increases the CSCAT backscattering signal at low and medium wind speeds ($w < 10$ m/s), implying that the intensification effect dominates the total backscattering power. Whereas rain decreases the backscatter coefficients at high wind speeds ($w > 15$ m/s), in which case the attenuation effect becomes a dominant factor. The sensitivity of CSCAT backscatter coefficients to wind speed and rain rate also shows a remarkable dependency on both the incidence angle and the polarization.

For instance, at low wind speeds ($w < 5$ m/s), the rain-induced increase in the CSCAT backscatter coefficients generally becomes larger as the incidence angle increases, which may be explained by Eq. (3) (Donelan and Pierson Jr, 1987),

$$\lambda_B = \frac{\lambda}{2 \sin \theta}$$  \hspace{1cm} (3)

where $\theta$ is the observing incidence angle, $\lambda$ and $\lambda_B$ are the wavelengths of microwave signal and Bragg resonant wave, respectively. That is, the resonant wavelength decreases as the incidence angle increases, such that the rain splashing effect (e.g., changes of sea surface roughness) is more remarkable for the larger incidence angles (i.e., shorter resonant wavelength). As such, at low winds, rain-induced backscatter intensification is greater for larger incidence angles. In contrast, the rain-induced backscatter attenuation effect, dominant under high wind conditions, is significant for VV polarization, and for the HH polarization only at lowest incidence angles (see also Fig. 2). In other words, the rain-related underestimation of CSCAT backscatter coefficients appears at relatively low wind speeds (~ 10 m/s) for the backscatter measurements at lowest incidence angles.
Fig. 1. The mean CSCAT backscatter coefficients as function of ECMWF wind speed for the vertically-polarized (VV, upper panels) and the horizontally-polarized beams (HH, lower panels) respectively. The incidence angles and the rain rates are indicated in the legends.

Fig. 2 illustrates the sensitivity of CSCAT backscattering signal to the incidence angle for various rain rates and wind speed conditions (see the legends). Note that the mean backscatter under rainy conditions is normalized by that of the rain-free conditions and then displayed in log scale. It is clear that the HH beam is much more sensitive to rain than the VV beam, showing in particular a larger rain intensification effect at low and medium wind speeds. At high winds \( w \geq 15 \text{ m/s} \) and rainy conditions, the mean VV backscatter is smaller than the rain-free backscatter over all the incidence angles, while the HH backscatter is larger for \( \theta > 40^\circ \). As an example, Table 2 illustrates the specific \( \sigma^0 \) changes induced by rain at two different incidence angles for both VV
and HH beams. Again, it shows that the rain effects on the HH beam are more complicated than on the VV beam.

![Graph showing CSCAT backscatter coefficients normalized by the rain-free values as a function of the incidence angle for different wind speeds and rain rates.](image)

**Fig. 2.** The mean CSCAT backscatter coefficients normalized by the rain-free values as a function of the incidence angle. The wind speed and rain rate are indicated in the legends.

**Table 2.** The concrete $\sigma^0$ changes induced by rain at two different incidence angles for $w \approx 14$ m/s

<table>
<thead>
<tr>
<th>Rain rate (RR, mm/h)</th>
<th>$\theta = 30^\circ$</th>
<th>$\theta = 50^\circ$</th>
<th>$\theta = 30^\circ$</th>
<th>$\theta = 50^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VV (dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR &lt; 2</td>
<td>-0.11 dB</td>
<td>-0.19 dB</td>
<td>-0.15 dB</td>
<td>0.07 dB</td>
</tr>
<tr>
<td>2 \leq RR &lt; 4</td>
<td>-0.28 dB</td>
<td>-0.38 dB</td>
<td>-0.12 dB</td>
<td>0.78 dB</td>
</tr>
<tr>
<td>4 \leq RR &lt; 6</td>
<td>-0.49 dB</td>
<td>-0.60 dB</td>
<td>-0.71 dB</td>
<td>1.56 dB</td>
</tr>
<tr>
<td>RR \geq 6</td>
<td>-1.17 dB</td>
<td>-0.57 dB</td>
<td>-1.17 dB</td>
<td>2.97 dB</td>
</tr>
<tr>
<td>HH (dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta = 30^\circ$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta = 50^\circ$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This section summarizes the CSCAT backscatter change with the incidence angle, the wind speed, as well as the polarization under rainy conditions. The main objective is to better understand the impact of rain on the CSCAT wind retrieval, and to improve the wind quality control method over rainy areas. Considering the complex viewing geometry of CSCAT (Liu et al., 2020), it is possible that some of the measurements within the same wind vector cell (WVC) are dominated by the rain attenuation effect (e.g., low incidence angle), while others are dominated by the rain intensification effect (e.g., high incidence angle, HH beam), particularly at high wind conditions (see Table 2). This mix of rather different rain effects on WVC backscatter measurements is quite specific of the CSCAT viewing geometry and its impact on wind retrievals is further examined in section 5.

5. Rain effects on CSCAT-derived winds

5.1 General assessment

ECMWF winds are used as reference in order to characterize the impact of rain on the CSCAT retrieved winds. Fig. 3 shows the two-dimensional histograms of CSCAT wind speed and direction versus ECMWF winds for various rain conditions. The statistical scores, e.g., correlation coefficient (CC), bias, standard deviation (SD) and the number of collocations (Num), are shown in the upper-left corner of each panel. As expected, both bias and SD values increase with rain rate. For sea surface winds below 10 m/s, the retrieved CSCAT wind speed is significantly overestimated (w.r.t. ECMWF winds) under rain conditions. This is in line with the results in Section 4, i.e., the rain intensification effect dominates at low and medium wind speeds. However, for high winds (above 15 m/s), the CSCAT retrieved winds are generally in good agreement with those of ECMWF, even for collocated GMI rain rates up to 6 mm/h. According to Fig. 2, the rain-induced $\sigma^0$ changes are relatively smaller for low incidence angles. As such,
one would expect a relatively small rain impact on CSCAT winds provided that the low incidence angle backscatter measurements dominate the WVC inversion cost function, as proven in the following simulation. This would imply that CSCAT may provide rather unbiased high winds under rainy conditions, in contrast with the generally underestimated high winds by the Ku-band pencil-beam scatterometers, which generally operate at $\theta > 44^\circ$.

Fig. 3. 2-D histograms of CSCAT wind speed (upper panels) and direction (lower panels) versus the collocated ECMWF winds for rain free (left), $2.5 < RR < 3.5$ mm/h (mid), $RR \geq 6$ mm/h (right), respectively.

Fig. 4 illustrates the CSCAT wind speed bias (w.r.t. ECMWF reference) as a function of the averaged CSCAT and ECMWF wind speed and the cross-track position (CTP) under different rainy conditions, respectively. Fig. 4a shows again the general good agreement between CSCAT and ECMWF high wind speeds for rain rates below 6 mm/h. However, a large discrepancy is noticeable under heavy and extreme rain condition (e.g., $RR > 6$ mm/h), as indicated by the
magenta curve. This is probably due to substantial volume scattering effects, such that the radar backscatter signal mostly comes from the rain layer rather than from the sea surface, and no wind information can be retrieved from the scatterometer observations. Fig. 4b shows that the wind speed bias increases rapidly as rain rate, notably for the outer-swath WVCs (CTP > 300 km). This is also in line with Fig. 2, since the outer swath is generally observed at high incidence angles. Moreover, a more compensated effect between low and high incidence angle measurements is found for the WVCs close to the satellite nadir track (CTP < 300 km), leading to relatively flat bias for a given rain category.

![Fig. 4. Bias of CSCAT wind speed (compared to ECMWF winds) as a function of (a) the averaged CSCAT and ECMWF wind speed and (b) the cross-track position. Curves in different colors indicate different rain rates, as shown in the legend.]

5.2 Test case: Super Typhoon Maysak

Nevertheless, Figs. 3 and 4 indicate that the high wind speed retrieved from CSCAT may be significantly underestimated due to the rain contamination. To further understand the characteristics of CSCAT-derived high winds, which are of great interest to the community of marine disaster monitoring, the super Typhoon Maysak observed by both CSCAT and HY-2B scatterometer (HSCAT) is analyzed in this section. Fig. 5 shows the CSCAT wind vectors,
together with collocated GMI rain data superimposed. Qualitatively, the retrieved winds are spatially consistent, though the rain contamination is remarkable nearby the eyewall. Fig. 6 shows the wind speed, the inversion residual (namely maximum likelihood estimator, MLE), as well as the bias w.r.t. ECMWF winds, for both CSCAT (upper panels) and HSCAT (lower panels). It shows that both CSCAT and HSCAT wind speeds are significantly underestimated (w.r.t. ECMWF speeds) under extreme rain conditions (RR >12 mm/h, nearby the eyewall), and the corresponding MLE values are larger than in the other regions, indicating as expected a poor wind retrievals. Note though that substantial differences between CSCAT and HSCAT retrievals are seen in the region highlighted by the black rectangle, where a remarkable underestimation of CSCAT wind speed is shown, while HSCAT winds are more in agreement with those of ECMWF. As aforementioned, the rain attenuation effect dominates the backscatter measurements at relatively low incidence angles, yet the rain intensification effect prevails over the measurements at high incidence angles.

Fig. 5. Super Typhoon Maysak observed by CSCAT (arrows) on September 1st 2020, at 10:40 UTC. The collocated GMI rain data (11:00 UTC) are shown in color (see legend).
**Fig. 6.** The scatterometer wind speed (left), the inversion residual (middle) and the speed bias w.r.t. ECMWF winds (right), from CSCAT (upper panels) and HSCAT (lower panels), respectively. The black rectangles indicate an area of substantial differences between CSCAT and HSCAT retrievals.

A simulation approach is carried out to investigate how the complex rain effects impact wind retrieval. To simplify the analysis, two views acquired at different incidence angles (i.e., $\theta \approx 30^\circ$ and $50^\circ$) are used in the simulation. The inversion cost function is written as,

$$
\text{MLE} = \sum_{i=1}^{2} \left( \frac{\sigma_{m,i} - \sigma_{s,i}}{k_{p,i} \sigma_{m,i}} \right)^2
$$

(4)

where $\sigma_{m,i}$ is the $i$th backscatter measurement, and $\sigma_{s,i}$ is the backscatter simulated with the NSCAT-4 GMF (Wentz and Smith, 1999; KNMI Scatterometer Team, 2021) for a range of possible wind solutions. The normalized measurement errors ($k_{p,i}$) are assumed to be 0.1 for both views. The other parameters used in the simulation and/or comparison are retrieved from the
CSCAT L2A and L2B data (corresponding to the observations in the black box in Fig. 6), as shown in Table 3. Note though that no noise is applied to the simulated sigma0 measurements for the sake of simplicity. Fig. 7 illustrates the inversion results of ideal measurements (rain free, upper panels) and rain-contaminated measurements (lower panels), respectively. The latter use the model in Eq. 2, according to the sensitivities indicated in Fig. 2.

Table 3. Two views acquired from the CSCAT L2 data. For the sake of comparison, the ECMWF wind vector values as well as the simulated \( \sigma_0 \) values are shown.

<table>
<thead>
<tr>
<th>View</th>
<th>Incidence angle</th>
<th>Azimuth angle</th>
<th>ECMWF wind</th>
<th>Simulated ( \sigma_0 ) (dB)</th>
<th>Measured ( \sigma_0 ) (dB)</th>
<th>Changes by rain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.7°</td>
<td>15°</td>
<td>14.6 m/s</td>
<td>-14.6</td>
<td>-14.3</td>
<td>+ 0.3 dB</td>
</tr>
<tr>
<td>2</td>
<td>30.0°</td>
<td>49°</td>
<td>243°</td>
<td>-5.4</td>
<td>-6.0</td>
<td>- 0.6 dB</td>
</tr>
</tbody>
</table>
Fig. 7. Illustration of the inversion results with ideal measurements (rain free, upper panels) and rain-contaminated measurements (lower panels), respectively. The left panels show the wind vector solution space of view 1 (black curve) and 2 (red curve) separately, and the right panels show the corresponding inversion residuals (i.e., MLE values). The green markers indicate the ambiguous solution closest to the ECMWF wind input.

The black and red curves in Fig. 7(a) and (c) indicate separately the wind vector solution space for views 1 and 2, in which the intersections of these two curves are actually the retrieved ambiguous wind solutions. Fig. 7(b) and (d) present the contributions (i.e., inversion residuals) of both views to the inversion cost function. Apparently, the ideal simulation without rain leads to an accurate result. The ambiguous solution closest to the ECMWF background wind is exactly the same as the model input values. However, the backscatter measurements with rain contamination not only lead to a lower retrieved wind speed (~13 m/s) than the ‘true’ value, but also produce a bias in the wind direction retrieval. According to the right panels of Fig. 7, the MLE curves of view 2 (red) are generally steeper (i.e., they have larger amplitude or modulation) than those of view 1, indicating that the overall cost function is mostly shaped by the measurement at lower incidence angle, and as such, it has a larger influence on the minimization process, i.e., on the wind retrieval.

In practice, the number of views for each CSCAT WVC varies from 4 to 16, and thus the impact of rain on wind retrieval is more complicated than that of the simplified simulation (with only two views) shown above. Nonetheless, the fundamental process of rain impact on the backscatter measurements and the retrieved winds can be summarized with what is shown in Fig. 2 and Fig. 7(c).

6. Conclusions

The innovative observing mechanism of CSCAT presents unprecedented challenges but also opportunities for retrieving high-quality wind fields under rainy conditions. In this paper, the
impact of rain on the CSCAT backscatter measurements is firstly evaluated based on the collocated CSCAT-ECMWF-TMI data set. Since we are mainly concerned with the rain-induced changes of total backscatter coefficients, the rain effects are simply grouped into two categories, e.g., attenuation and intensification, respectively. As such, the sensitivity of $\sigma^0$ changes to the two rain effects are examined for various incidence angles, wind speeds, radar polarizations, as well as rain rates. Under rainy conditions, the rain attenuation effect is more remarkable for backscatter measurements at lower incidence angles and/or higher wind speed conditions, particularly for the VV beam. In contrast, the rain intensification effect is dominant in the $\sigma^0$ measurements at higher incidence angles and/or lower wind speeds, notably for the HH beam. In other words, under rainy conditions, when the wind-induced $\sigma^0$ is small (large), the rain intensification (attenuation) effect dominates the changes of the overall $\sigma^0$ value.

Generally, the rain impact on the scatterometer-derived winds can be inferred from the rain-induced $\sigma^0$ changes, using ECMWF winds as reference. For instance, the retrieved wind speed is significantly overestimated (w.r.t. ECMWF) for wind speeds below 10 m/s and rain rates above 2 mm/h. Moreover, the retrieved wind errors increase with rain rate. However, the complicated viewing geometry of CSCAT implies that some of the $\sigma^0$'s measurements within a certain WVC may be attenuated by rain, while the others may be intensified by rain. Hence, a specific Typhoon case is used to verify how the complex rain-induced $\sigma^0$ changes impact the CSCAT wind retrieval, as compared to the retrieval of a pencil-beam scatterometer like HSCAT. A significant underestimation of the CSCAT wind speed is shown, while HSCAT winds are in better agreement with ECMWF winds. Such underestimation is attributed to the complicated viewing geometry of CSCAT and the varying rain effects on the backscatter measurements at different incidence angles. Finally, a simple simulation is carried out to show that, for high wind
conditions, the rain attenuation effects on the lower incidence angle measurements dominate over
the rain intensification effects on the higher incidence angle measurements, leading to
underestimation of the CSCAT retrieved winds for heavy and extreme rain conditions (above 6
mm/hr).

In summary, rain is a major factor in degrading the CSCAT wind quality, similar to prior Ku-
band pencil-beam scatterometers. Nevertheless, CSCAT high wind speed retrievals are generally
unbiased for low and moderate rain conditions (up to 6 mm/h), due to the compensated rain
effects between low and high incidence angle measurements for the inner-swath WVCs. Following the results in Sections 4 and 5, one may further improve the CSCAT wind retrieval
quality by using the backscatter measurements that are less sensitive to rain instead of using all of
the available views. Finally, the quality control of the CSCAT retrieved winds should also be
improved by taking the backscatter sensitivities to rain into account.

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List of Figure Captions

Fig. 1. The mean CSCAT backscatter coefficients as function of ECMWF wind speed for the vertically-polarized (VV, upper panels) and the horizontally-polarized beams (HH, lower panels) respectively. The incidence angles and the rain rates are indicated in the legends.

Fig. 2. The mean CSCAT backscatter coefficients normalized by the rain-free values as a function of the incidence angle. The wind speed and rain rate are indicated in the legends.

Fig. 3. 2-D histograms of CSCAT wind speed (upper panels) and direction (lower panels) versus the collocated ECMWF winds for rain free (left), $2.5 < RR < 3.5 \text{ mm/h}$ (mid), $RR \geq 6\text{ mm/h}$ (right), respectively.

Fig. 4. Bias of CSCAT wind speed (compared to ECMWF winds) as a function of (a) the averaged CSCAT and ECMWF wind speed and (b) the cross-track position. Curves in different colors indicate different rain rates, as shown in the legend.

Fig. 5. Super Typhoon Maysak observed by CSCAT (arrows) on September 1st 2020, at 10:40 UTC. The collocated GMI rain data (11:00 UTC) are shown in color (see legend).

Fig. 6. The scatterometer wind speed (left), the inversion residual (middle) and the speed bias w.r.t. ECMWF winds (right), from CSCAT (upper panels) and HSCAT (lower panels), respectively. The black rectangles indicate an area of substantial differences between CSCAT and HSCAT retrievals.

Fig. 7. Illustration of the inversion results with ideal measurements (rain free, upper panels) and rain-contaminated measurements (lower panels), respectively. The left panels show the wind vector solution space of view 1 (black curve) and 2 (red curve) separately, and the right panels show the corresponding inversion residuals (i.e., MLE values). The green markers indicates the ambiguous solution closest to the ECMWF wind input.