Abstract
The scatterometer SeaWinds on QuikSCAT measures ocean winds via the relationship between the wind and the normalized radar backscatter cross-section ($\sigma^0$) from the ocean surface. Scattering and attenuation from falling rain droplets along with ocean surface perturbations due to rain change the backscatter signature of the waves induced by near-surface winds. A simple model incorporates the effects of rain on ocean $\sigma^0$. Colocated data from the precipitation radar (PR) aboard the Tropical Rainfall Measuring Mission (TRMM) satellite is used to simulate the effects of rain as seen by SeaWinds. PR-derived backscatter, atmospheric rain attenuation, and rain rates are averaged over the SeaWinds footprint. The enhancement in backscatter from rain striking the ocean surface is estimated as a function of rain rate using a least-squares technique. QuikSCAT $\sigma^0$ values are simulated from the PR-derived parameters and numerical weather prediction model winds using the simple backscatter model. The simple model introduced accurately estimates (within 3 dB) the measured QuikSCAT $\sigma^0$ values. The use of a rain model in the wind estimation process can potentially significantly enhance wind retrieval in the presence of rain.

1 INTRODUCTION
SeaWinds on QuikSCAT, a spaceborne scatterometer launched in 1999 by NASA, provides daily coverage of instantaneous ocean vector winds. Scatterometer wind retrieval is possible due to the relationship between $\sigma^0$ of the ocean surface and the wind speed and direction. The value of $\sigma^0$ can be influenced, however, by other geophysical parameters. Rain is one of the main environmental factors that significantly modifies $\sigma^0$. Rain affects the backscatter values in three ways: First, the electromagnetic signal scatters from the falling hydrometeors. Second, the signal is attenuated by the rain both before and after scattering from the ocean surface. Third, rain striking the surface of the water causes rings, stalks, and waves from which the signal additionally scatters. The interaction of rain with the surface of the water also alters the wind-induced capillary wave field, further changing the backscatter directional dependence.

In this paper, a simple model is given for the backscatter from the ocean during rain. Data from the precipitation radar (PR) on board the Tropical Rainfall Measuring Mission (TRMM) satellite is collocated with SeaWinds on QuikSCAT data. The TRMM PR data, along with numerical weather prediction model winds are used to simulate QuikSCAT $\sigma^0$ values. Using a least-squares technique, the effect on backscatter of the rain striking the ocean is estimated. The simple model introduced accurately estimates (within 3 dB) the measured QuikSCAT $\sigma^0$ values. The use of a rain model in the wind estimation process can potentially significantly enhance wind retrieval in the presence of rain.

2 DATA
2.1 SeaWinds on QuikSCAT
SeaWinds on QuikSCAT is a scanning pencil-beam scatterometer. In order to accurately infer the wind, the SeaWinds instrument employs a dual-beam design. The outer (v-pol) beam has a 3dB footprint of 37 × 52 km and the inner (h-pol) beam has a 3dB footprint of 34 × 44 km. The SeaWinds footprints are spaced about 22 km apart in the along-track and 15 km (inner beam) or 19 km (outer beam) apart in the along-scan directions. The satellite sub-track is segmented into a grid of (approximately) 25 × 25 km wind vector cells.

The wind is related to $\sigma^0$ through the empirically determined geophysical model function (GMF). The GMF is a function of wind speed, relative azimuth direction, polarization, and incidence angle. The wind at each wvc is inferred by inverting the GMF using a maximum likelihood technique.

2.2 TRMM Precipitation Radar
The TRMM satellite, launched in 1997 as a joint project between the U.S. and Japan, provides a data set of instantaneous midlatitude rainfall estimates. The TRMM satellite orbits at a low inclination angle (35°) with a swath width of approximately 200 km. The PR on board TRMM is a Ku-band scatterometer with a footprint of approximately 5 × 5 km, a much finer sampling than SeaWinds. The PR provides rain reflectivity measure-
ments and rain estimates in 3 spatial dimensions. Standard PR data products used in this report include unadjusted reflectivities ($Z_m$), integrated rain rates ($R$), and path integrated attenuation or PIA ($\Delta \sigma^o$) from the 2A25 data product.

3 SIMPLE MODEL FOR $\sigma^o$

Three main rain-related mechanisms influence radar backscatter over the ocean. These mechanisms include attenuation from atmospheric water, volume scattering from rain droplets, and rain-induced disturbances on the water surface. Combining these influences using a simple phenomenological model, the radar backscatter as observed by the scatterometer during rain can be represented by

$$\sigma_m = (\sigma_w + \sigma_{sr})\alpha + \sigma_r$$

where $\sigma_m$ is the measured $\sigma^o$ from space, $\sigma_w$ is the wind-induced radar backscatter, $\sigma_{sr}$ is the surface backscatter due to rain striking the water, $\alpha$ is the two-way atmospheric attenuation, and $\sigma_r$ is volume scattering due to falling rain droplets.

In the model, we assume that $\sigma_w$ and $\sigma_{sr}$ linearly combine to form a net backscatter surface return. Although this relationship does not fully represent the complicated nature surface scattering from wind and rain produced ocean waves, it has been shown that surface rain generally augments $\sigma^o$ due to wind.\(^1\) Thus, for this first order analysis, we assume a linear relationship.

3.1 Determining Model Parameters

Data from the TRMM PR and numerical weather prediction (NWP) model fields allow us to calculate values for $\sigma_{w}$, $\alpha$, and $\sigma_r$. In order to make the notation tractable, where a quantity is calculated for both PR and QuikSCAT resolutions, the symbol is primed (') if it has the resolution of the PR, and is unprimed if it has the resolution of QuikSCAT. Also, parentheses in the subscripts of symbols is used to indicate the source of the data used to estimate that parameter.

The Level 2B QuikSCAT wind data includes collocated estimates of the wind from the National Centers for Environmental Prediction (NCEP). These wind fields are interpolated to the same grid as the SeaWinds 25 $\times$ 25 km wind product. For each QuikSCAT $\sigma^o$ value, the nearest-neighbor NCEP wind vector is projected through the GMF ($M$) to produce an expected value for the wind-induced backscatter ($\sigma_w$) at a measurement point, i.e.

$$\sigma_w(NCEP) = M(u(NCEP), X(NCEP), \theta, \text{pol})$$

where $u(NCEP)$ is the NCEP model wind speed, $X(NCEP)$ is the relative azimuth angle of the NCEP wind direction, $\theta$ is the incidence angle of the QuikSCAT measurement, and pol is the polarization.

Although NCEP provides an estimate of the non-rain wind $\sigma^o$, $\sigma_w(NCEP)$ has some error ($\epsilon$) due to the low resolution, prediction errors, and model-function inaccuracies. This $\sigma^o$ error is location-dependent. Because NCEP is very low resolution, we assume that $\epsilon$ is spatially correlated. Further, since each collocation region covers only a few hundred wind vector cells, we assume that $\epsilon$ is constant over the collocation region. For each collocation region $\langle n \rangle$, we represent the error by the symbol $\epsilon_n$. Thus, the effective wind $\sigma^o$ for each rain-contaminated region is: $\sigma_w = \sigma_w(NCEP) + \epsilon_n$. The error parameter $\epsilon_n$ is estimated in Section 3.3.

The two-way atmospheric attenuation factor ($\alpha$) is calculated from the PIA estimates in the TRMM 2A25 data sets,

$$\alpha_i(\text{PR}) = 10^{-\frac{\Delta \sigma^o}{20}}$$

The PIA estimate is formed from an MLE technique given TRMM 2A21 PIA estimate from a surface reference method, and a Hitschfeld-Bordan method.\(^2\) For each QuikSCAT observation, the collocated values of $\alpha_i(\text{PR})$ are weighted-averaged over the 6dB SeaWinds footprint,

$$\alpha(\text{PR}) = \frac{\sum_{i=1}^{N} G_i \alpha_i(\text{PR})}{\sum_{i=1}^{N} G_i}$$

where $N$ is the number of TRMM measurements falling under the one SeaWinds footprint, $G_i$ is the SeaWinds antenna gain pattern value (in normal space) at the position of the $i$th TRMM measurement, and $\alpha_i(\text{PR})$ is the $i$th PIA value. Values for $\alpha$ where there is no rain detected are set to one.

Estimates for the volume-scattering rain cross-section ($\sigma_r$) are calculated from unadjusted reflectivities ($Z_m$) obtained from the TRMM 1C21 data set. The actual reflectivity of the atmospheric rain ($Z_e$) is related to the unadjusted reflectivity through the equation,

$$Z_m(r) = Z_e(r) \alpha(r) \text{ mm}^6 \text{m}^{-3}$$

where $r$ is the range, and $\alpha(r)$ is the path integrated two-way attenuation at range $r$. The volume backscattering coefficient can be found from,

$$\sigma_{vr}(r) = 10^{-10} \frac{\pi^5}{\lambda_0} |K_w|^2 Z_e(r) \text{ m}^2 \text{m}^{-3}$$

where $\lambda$ (cm) is the electromagnetic wavelength, and $|K_w|^2$ is a coefficient related to the absorption properties of water (assumed to be 0.9). The quantity $\sigma_{vr}$ is radar backscatter cross-section per unit volume. The volume backscattering cross-section observed by the satellite ($\sigma_{vrr}$) is attenuated by the two-way attenuation factor, $\alpha(r)$ and is equal to

$$\sigma_{vrr}(r) = \sigma_{vr}(r) \alpha(r)$$
Figure 1: Calculated values of $\sigma_r$ plotted against corresponding QuikSCAT observed $\sigma_0$ values for a set of collocated inner-beam measurements.

$$
\sigma_r = 10^{-10} \frac{\pi^2}{\lambda_0^2} |K_w|^2 Z_e(r) \alpha(r)
$$

(7)

$$
\sigma = 10^{-10} \frac{\pi^2}{\lambda_0^2} |K_w|^2 Z_m(r).
$$

The total atmospheric rain backscatter as seen by the PR $(\sigma_r'(PR))$ is $\sigma_{v,p}$ integrated through the PR antenna beam to the lowest no-surface-clutter range $(r_{ne})$.

$$
\sigma_r'(PR) = \int_{0}^{r_{ne}} \sigma_{v,p}(s) ds \ \text{m}^2/\text{m}^2
$$

(8)

$$
\approx \sum_{s=1}^{N_{ne}} \sigma_{v,p}(s) \Delta r \ \text{m}^2/\text{m}^2
$$

(9)

where $\Delta r$ is the vertical range resolution of the PR and $N_{ne}$ is the lowest no-surface-clutter range bin. All valid $\sigma_r'(PR)$ values are weighted-averaged over the SeaWinds footprint,

$$
\sigma_r(PR) = \frac{\sum_{i=1}^{N} G_i \sigma_{r_i(PR)}}{\sum_{i=1}^{N} G_i}
$$

(10)

where $\sigma_{r_i(PR)}$ is the $i^{th}$ PR rain backscatter value. Values for $\sigma_{r_i(PR)}$ where there is no rain detected are set to zero.

The calculated values of $\sigma_r(PR)$ are plotted against corresponding QuikSCAT measured backscatter values $(\sigma_{m(QSCAT)})$ in Figure 1, demonstrating that falling rain accounts for up to 1/3 (-5 dB) of the total backscatter.

Since the PR is nadir-looking and SeaWinds operates at relatively high incidence angles, the values of $\alpha(PR)$ and $\sigma_r(PR)$ may be slightly underestimated for SeaWinds geometry because the SeaWinds beam has a longer path to the surface from the rain top. In addition, TRMM PR and SeaWinds measurements are only collocated at the ocean surface. Thus, for decreasing range, the TRMM and SeaWinds beams become increasingly misaligned. This effect may alter our estimate of SeaWinds $\alpha$. Also, temporal changes in rain profiles between the TRMM observation and SeaWinds observation times introduces additional errors.

To ameliorate the effects of misalignment, we perform the remaining analysis on 3 subsets of the data which involve differing levels of correlation between the QuikSCAT $\sigma_0$ values $(\sigma_{m(QSCAT)})$ and the PR rain rate averaged over the SeaWinds footprint $(R(PR))$. Examining the correlation coefficients between $R(PR)$ and $\sigma_{m(QSCAT)}$ for each collocation set, we find natural breaks in the values around 0.4 and 0.1 (see Fig. 2). Subset 1 is all data within the collocation sets with correlation coefficients greater than 0.4. Subset 2 is all data within collocation sets with correlation coefficients greater than 0.4. Subset 3 is all the collocation data.

3.2 Modeling $\sigma_r$ and $\alpha$

Both $\sigma_r$ and $\alpha$ are inherently related to the rain rate by power-law models in the TRMM processing. They can be expressed as: $-\sigma_r(PR)(\text{dB}) = c R_d(PR)$ and $\sigma_r(PR) = e R_f(PR)$. The parameters $c$, $d$, $e$, and $f$ are calculated by taking the logarithm of both sides of these equations and using linear least squares estimation on the PR data (see Figure 3). Table 1 gives the values obtained by this method. Both $\sigma_r$ and $\alpha(\text{dB})$ are linear functions of rain rate.

Table 1: Values of the parameters $c$, $d$, $e$, $f$ in the equations $-\alpha = c R_d$ and $\sigma_r = e R_f$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$c$</th>
<th>$d$</th>
<th>$e$</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.05</td>
<td>1.0</td>
<td>0.0003</td>
<td>1.0</td>
</tr>
</tbody>
</table>
3.3 Modeling $\sigma_{sr}$

Unfortunately, a relationship for the surface enhancement due to rain ($\sigma_{sr}$) cannot be extracted from either TRMM or SeaWinds data alone. However, an estimate of this parameter can be obtained by solving Eq. (1) for $\sigma_{sr}$. After adding appropriate subscripts, we obtain

$$
\sigma_{sr}^{(CALC)} = \alpha_{(PR)}^{-1}(\sigma_{m(QSCAT)} - \sigma_{r(PR)}) - (\sigma_{w(NCEP)} + \epsilon_n).
$$

Supposing that $\sigma_{sr}$ has a power-law dependence on the rain rate,\(^3\) we conclude that $aR_{(PR)}^{b} = \sigma_{sr}^{(CALC)}$.

The only unknown on the right hand side of Eq. 11 is the error parameter $\epsilon_n$. We estimate parameter to be the mean difference between $\sigma_{m(QSCAT)}$ and $\sigma_{w(NCEP)}$ for all observations where $R_{(PR)}$ is between 0 and 0.7 mm/hr in a given collocation region. The threshold of 0.7 mm/hr is the lower bound for the sensitivity of the TRMM PR rain measurements.\(^3\) The observations below the threshold are practically unaffected by the rain, but are located near the heavier rain-contaminated regions, allowing for a fairly good approximation of the average error over the area containing rain.

Since $\sigma_{sr}^{(CALC)}$ can take on negative values, a non-parametric estimation technique with an Epanechnikov kernel is used to give averaged values of $\sigma_{sr}^{(CALC)}$ at discrete bins of $R_{(PR)}$. Next, using non-linear least-squares estimation, values for $a$ and $b$ are estimated as the best least-squares fit to the averaged values. In order to ensure robustness, all values of $\sigma_{sr}^{(CALC)}$ that are further than 2 standard deviations from the model estimate are discarded and the estimation process is performed again.

### Table 2: VALUES OF $a$ AND $b$ WHERE $\sigma_{sr} = aR_{(PR)}^{b}$

<table>
<thead>
<tr>
<th>subset</th>
<th>$a_{hpol}$</th>
<th>$b_{hpol}$</th>
<th>$a_{vpol}$</th>
<th>$b_{vpol}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1.86 \times 10^{-3}$</td>
<td>0.67</td>
<td>$0.50 \times 10^{-3}$</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>$2.20 \times 10^{-3}$</td>
<td>0.75</td>
<td>$1.74 \times 10^{-3}$</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>$2.18 \times 10^{-3}$</td>
<td>0.76</td>
<td>$1.46 \times 10^{-3}$</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Estimates of $a$ and $b$ are given in Table 2 for each collocation subset. The h-pol data is not very sensitive to the subset used. The v-pol data is more sensitive to the subset. We use the results from subset 1 in Section 4.

### 4 VISUALIZATION OF THE MODEL

The full wind/rain $\sigma^o$ model is now parameterized by the wind $\sigma^o$ and the rain rate as

$$
\sigma_m = (\sigma_w + aR)^b 10^{-\left(\sigma_m \epsilon_n + \epsilon_n\right)} + eR^b.
$$

This model is calculated for a range of rain rates and plotted against $\sigma_{w(NCEP)}$ in Figure 4 for all h-pol observations. The data follows the model closely, helping validate the simple approach taken in this paper. The standard deviation of the error between the calculated and measured $\sigma_{QSCAT}$ values is less than 2 dB for both h-pol and v-pol data sets. Also, over 90% of all calculated measurements are within 3 dB of the measured QuikSCAT values.

### 5 CONCLUSIONS

Examining the shape of the curves in Figure 4, we notice three regimes. Below a threshold in $\sigma_w$, the signal from the rain dominates, making the $\sigma_m$ not very sensitive to the wind. In this regime, the rain almost completely corrupts the wind information. Above a higher threshold in $\sigma_w$, the measured backscatter follows $\sigma_w$ very closely, indicating that the wind signal dominates. In between these two thresholds, the contributions from wind and rain are on the same order of magnitude. By incorporating a rain rate parameter into the wind retrieval process, wind estimates may potentially be improved in this "middle" regime. In addition, rain rate may be inferred from the scatterometer signal in both the middle regime and the regime where the rain signal dominates.

### References


Figure 4: Wind/Rain model versus $\sigma_w(NCEP)$ plotted with QuikSCAT $\sigma^o$ data.