SeaWinds on QuikScat

Special Product:

SeaWinds on QuikScat Normalized Objective Function Rain Flag

Product Description

Version 1.2

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Summary

A replica of the SeaWinds instrument planned for the ADEOS-II was launched on the dedicated QuikBird satellite to supply scatterometer data after the sudden termination of NSCAT data flow. This QuikScat instrument is a conical scanning Ku-band scatterometer. Like other Ku-band scatterometers before (SASS, NSCAT) it also overestimates ocean winds in rain-contaminated low-wind regions. This rain effect is great enough in tropical regions that a rain flag is necessary to reliably use the QuikScat data. This rain flag dataset has been produced from a rain detection algorithm that is based on an empirically normalized objective function. The algorithm flags wind vector cells where the measured backscatter cross section is in poor agreement with that calculated using the retrieved wind vector and the NSCAT-2 model function. This rain flagging method is effective only in the main section of the QuikScat swath where both H-pol and V-pol observations are present. This algorithm does an excellent job at flagging rain at low wind speeds.

Contents

1 Background

QuikScat obtains the surface wind vector over the ocean by measuring the radar signal returned from the sea surface. The sea surface radar cross-section, σ_0, is measured for several different azimuth angles and for both horizontally and vertically polarized radiation. The wind vector is retrieved by fitting these measurements to the NSCAT-2 geophysical model function that describes the expected σ_0 as a function of wind speed, wind direction relative to the look angle, and the incidence angle. The presence of rain in the atmosphere through which the radar signal is traveling affects the measured σ_0. This occurs in three ways:

1. The radar signal is attenuated by the rain as it travels to and from the earth's surface. This reduces the measured σ_0.
2. The radar signal is scattered by the raindrops. Some of this scattered power returns to the instrument. This increases the measured σ_0.
3. The roughness of the sea surface is increased because of splashing due to the raindrops. This increases the measured σ_0

A simple expression for the measured cross-section σ_{meas} that includes these effects is shown here.

$$\sigma_{meas} = \sigma_{scat}(R) + \tau(R)^2 \left[\sigma_{wind} + \sigma_{splash} \left(R/h \right) \right] \tag{1}$$

In this equation, R is the rain column rate (rain rate times column height h), σ_{scat} is the contribution due to scattering from rain drops, τ is the one-way attenuation due to the rain, σ_{wind} is the contribution due to surface roughness caused by wind, and σ_{splash} is the contribution due to surface roughness caused by raindrops. Although this equation is somewhat simplified, it describes the important effects of rain on scatterometry.

At low wind speeds, where σ_{wind} is small, the additional scattering effects dominate, and σ_{meas} is greater than σ_{wind}. Eventually, as the wind speed increases, σ_{wind} becomes large enough that the attenuation effect becomes important and begins to cancel the effect of the scattering terms.

At low wind speeds and not too high rain rates, it is relatively easy to detect when a QuikScat measurement is affected by rain. For low winds, the horizontally polarized cross-section σ_H is significantly (~3 dB) smaller than the vertically polarized cross section σ_V. The contribution to the measured σ_0 by rain-scattered signal is either polarization independent (for small, spherical rain drops) or has a larger horizontally polarized component (for large, flattened rain drops). When the rain-scattered return is added to the sea-surface return, σ_H is too large compared to σ_V to be consistent with any wind speed and direction.

For very high winds, the magnitude of σ_{wind} for both polarizations is also much larger, and the scattering component of σ_{meas} becomes less important. Under these conditions, the presence of rain modifies σ_H and σ_V, but usually not by so much that they become inconsistent with any wind vector. Instead, the wind vectors are typically changed in magnitude and rotated towards a direction perpendicular to the satellite track. The $\sigma_{H,wind}$ to $\sigma_{V,wind}$ ratio in the model function is maximized when the retrieved vector is aligned perpendicular to the satellite track. Note that the same effect can occur even for low wind speeds, if both σ_H and σ_V are increased by the rain so much that they are consistent with a strong, cross-swath wind. These effects make it difficult to impossible to use the σ_H to σ_V ratio to detect rain at high values of σ_0.

Rain is more highly variable over short distances than is wind. For each 25 km wind vector cell, typically more than 12 egg measurements are used to retrieve the wind vector. It is possible that in rainy instances, these eggs, which may be separated by more the 25 km, will view significantly different rain rates. Eggs that are viewing the sea surface from the same direction and with the same polarization, and would therefore usually measure similar values of σ_0, might show significant variation. This, too, can form a component of a rain detection algorithm.

2 ENOF Rain Flag Algorithm

We have developed a rain detection algorithm that is simple, and sensitive to both the σ_H to σ_V ratio, and to high variability within a wind vector cell. The algorithm is based on an empirically normalized objective function (ENOF), which is defined for each wind vector cell, and is given by the equation (2) below.

$$ENOF = \frac{1}{N}\sum_{i=1}^{N}\frac{\left(\sigma_{i,MEAS} - \sigma_{i,NSCAT2}\right)^2}{W_i} \qquad (2)$$

Here, $\sigma_{i,meas}$ is the measured σ_0 for each observation in the cell, and $\sigma_{i,NSCAT-2}$ is the value of σ_0 calculated for each observation, using the retrieved wind vector and the NSCAT-2 model function. W_i is a weighting function that represents the “expected” or “typical” contribution of the ith measurement to the overall variance, and the sum is over the N observations used to retrieve the wind vector for the cell. W_i is chosen, using the procedure described below, so that if the ENOF is greater than one, the fit of the measured σ_0’s to the model function is significantly worse than is typical. Note that this procedure is sensitive both to cases where σ_H is too large to σ_V, and to cases where there is large variability between σ_{meas} that should be the same, i.e. when measured at the same angle and polarization.

Choosing the weights W_i so that the ENOF will be large in the presence of rain is somewhat complicated. Formally, W_i is a function of the true wind speed, the wind direction relative to the observation azimuth angle, the incidence angle, and the polarization. Due to the two-beam conical scanning geometry of QuikScat, we can replace the dependence on the incidence angle and polarization with a dependence on beam index. Previous work has indicated that the expected variance is not a strong function of relative wind direction. We do expect some dependence of W_i on the azimuth and polarization diversity in the wind vector cell, since it will be easier for the retrieval process to return a wind that fits the model function when fewer polarizations are measured, or when there is not much variation in measurement azimuth angle. We absorb this dependence into a dependence on cross-swath wind-vector cell number.

The largest problem occurs because we do not know the true wind speed. Using the retrieved wind speed is not acceptable because the typical effect of rain is to increase all σ_0 measurements, yielding a retrieved wind speed that is much higher than the true wind speed. This in turn would give us a much too large value for W_i, and we would be less sensitive to rain-induced increases in variance. Instead of using the retrieved wind, we use a rain-desensitized proxy for wind speed to describe the wind speed dependence. We have constructed a simple wind-speed retrieval regression based on a rain-desensitized average σ_0 given by

$$\bar{\sigma}_{0,rain-desensitized} = \bar{\sigma}_V - 0.5\bar{\sigma}_H(1.0 - 0.05\bar{\sigma}_H)\,, \qquad (3)$$

where $\bar{\sigma}_V$ and $\bar{\sigma}_H$ are the averaged V-Pol and H-Pol σ_0's for all observations in the cell. The idea is that since the presence of rain often increases σ_H more than σ_V , by subtracting away part of σ_H we can construct an average σ_0 that is less sensitive to increases due to rain. At high winds, and therefore large values of σ_0, the value of σ_H approaches that of σ_V, so we reduce the degree to which σ_H is subtracted. This average σ_0 is then used in a polynomial regression of the following form to retrieve a pseudo wind speed.

$$W_{PSEUDO} = a_{1/2}\sigma_0^{\ 1/2} + a_1\sigma_0 + a_2\sigma_0^{\ 2} + a_3\sigma_0^{\ 3} + a_4\sigma_0^{\ 4}\,. \qquad (4)$$

The coefficients $a_{1/2} - a_4$ are chosen by fitting to the full NSCAT-2 model function.

We then use this pseudo wind speed to divide the measurements into bins by polarization, cross-swath cell number, and wind speed. Only QuikScat measurements for which a 3 x 3 pixel area of SSM/I measurements centered on the QuikScat measurement both were measured within 60 minutes and were rain free were used. All rain-free collocated measurements for QuikScat revs 900-999 were used. For each bin, a histogram of squared-difference deviations was calculated, and the value of the 95th percentile was used for a first-guess value for W_i. The idea is that any measurement for which the squared difference exceeds this value is of suspect quality. The 95th percentile was used, rather than the mean, to help account for variations in the width of the distribution of squared-difference deviations for different cells, wind speeds, and polarizations. A surface plot of the Logarithm of the 95th percentile as a function of pseudo wind speed and cell number is shown in Figure 1a (H-Pol) and 2a (V-Pol). Since the unsmoothed values were noisy, especially at high wind speed where there was not much data in the 100 orbits used to determine W_i, we performed a series of smoothing steps to obtain the surfaces shown in Figures 1d and 2d.

The values of W_i shown in Figures 1 and 2 are used to compute the values of the ENOF for each wind vector cell. The only task that remains is to select a threshold. ENOFs above this threshold have a significant chance of being contaminated by rain. We have chosen a threshold that flags approximately 7.5% of the wind vector cells when applied globally, an ENOF value of 45.

3 Preliminary Rain Flag Validation

To estimate the performance of the rain flag, we compared our rain flag to SSM/I columnar rain densities. Only SSM/I measurements that occurred within 30 minutes of QuikScat measurements were used. We chose to compare our flag to columnar rain, since rain scattering and attenuation is directly related to the product of the path length of the scatterometer signal through the rain and the density of the rain. This product is directly proportional to the SSM/I rain column.

First, we show two example applications of the rain flag in Figures 3 and 4, one low wind example where the rain flag works well and a high wind example where it fails. Each figure consists of 4 plots. The upper left plot (a) contains the wind vectors from the ECMWF global analysis color-coded by wind speed. The upper right plot (b) shows the QuikScat wind vectors color-coded by SSM/I rain column. Green indicates light rain with a rain column between 0.0 and 3.0 km mm/hr and red indicates heavier rain, with rain above 3.0 km mm/hr, black indicates no rain, and blue indicates no collocated SSM/I data. The lower left plot (c) shows the QuikScat wind vectors color-coded using the ENOF rain flag. Vectors with ENOF values above 45 are shown in red, those below are shown in blue. The lower right plot (d) shows the QuikScat vectors color-coded by SSM/I liquid cloud water. Vectors colored red are found in regions of cloud greater than 0.15 mm.

In Figure 3, note that we have effectively flagged most of the vectors that SSM/I has measured to be in regions of moderate to heavy rain, except in the outer swath region, where only V-Pol observations are available. In the Southern part of the region, we have flagged many vectors where SSM/I reports no rain, but where they are adjacent to rainy regions. We believe that many of these vectors are in fact influenced by rain and are not flagged in error. The vectors are in many cases obviously wrong (wind speed much too high, and pointing cross-swath), and are typically in regions where SSM/I reports significant cloud cover, as shown in Figure 3d. There is also a significant number of isolated vectors that are flagged as rain. Since they often occur in regions of low cloud cover, these are probably "false alarms" or vectors misclassified by the rain algorithm. This may be caused by random noise in the σ_0 measurements. These could easily be removed using a spatial filtering technique that requires one or more nearest neighbors to be flagged in order for the cell to remain flagged. We have demonstrated the effectiveness of such a flag, but it is not implemented at this time.

The rain flag is quite successful in this low wind case, removing most if not all of the vectors that are clearly influenced by rain. It is much easier to see the effects of rain in regions of low wind speed due to the low sea-surface σ_0's, and to the low σ_H to σ_V ratio. Performance similar to that illustrated here is exhibited in the low wind, high rain tropical convergence regions in the Pacific, Atlantic and Indian Oceans. This is very encouraging, since it is in these regions that the QuikScat wind vectors disagree most strongly with modeled winds and wind speeds retrieved by SSM/I.

In the second example, Figure 4, the rain flag algorithm is much less successful at identifying regions of rain. Here, the rain is associated with a mid-latitude storm located southeast of the southern tip of Africa. As can be seen in Figs. 4a and 4b, there are large regions of the storm with high wind speed and high rain rate. None of these regions are flagged as having rain by the ENOF rain flag, even though there are some QuikScat vectors that appear to be affected by rain, such as the vectors pointing cross-swath near 65 E, 50S. We also see similar failure of the rain flag algorithm in the high winds of tropical cyclones.

Performance metrics are used to further evaluate the detection algorithm. An SSM/I rain column threshold $R_{SSM/I}$ of 5 km mm/hr was used to determine which cells contain rain. We then evaluated the performance of the algorithm as a function of this threshold. The results we discuss here only consider data in wind vector cells 10-66, where both H-Pol and V-Pol measurements are available.

We primarily use two metrics to determine the success of our rain flag algorithm. These are summarized below.

Misclassification Rate: The percent of cells containing rain as determined by SSM/I, i.e. cells with an SSM/I rain column above $R_{SSM/I}$, but that

	are not flagged by our rain algorithm. In other words, the percent of raining wind vector cells that are missed.
False Alarm Rate	The percent of cells for which SSM/I indicates **no** rain, but that are flagged by our rain algorithm. The idea is that if SSM/I indicates any rain at all, it is OK for the algorithm to flag it as rain. Note that the False Alarm Rate does not depend on $R_{SSM/I}$.

Ideally, we would like both the misclassification rate and the false alarm rate to be as small as possible. In Fig. 5, we plot the misclassification rates as a function of rain column threshold for QuikScat revs 1550-1850. As the rain-column threshold increases, the misclassification rate falls from 35% at 3 km mm/hr to about 20% at 10 km mm/hr. The false alarm rate is 5.5%. Use of the spatial filtering technique described above, improves the misclassification rate as shown by the dashed line. When we separate the data into three wind speed bins, we find the lowest misclassification rates occur for the lowest wind speed bin, from 3 m/s to 8 m/s. The dotted-dashed line shows that at these winds, we are misclassifying less than 10% of the wind vectors for columnar rain rates above 5 km mm/hr. For winds from 8 m/s to 15 m/s, the misclassification rate increases to about 30%, and to 65-75% for winds above 15 m/s. This confirms what we saw in the examples above – the rain flag works well for low wind speeds, but misses many instances of rain for high wind speeds.

The use of the ENOF rain flag to exclude rain-contaminated wind vector cells significantly improves the agreement of QuikScat wind vectors with those produced by general circulation models, such as those used by NCEP and ECMWF for weather forecasting and data assimilation. In the table below, we report the RMS wind speed difference and the RMS wind direction difference between QuikScat and ECMWF when different methods of rain flagging are used. These statistics were obtained by averaging collocated QuikScat-SSM/I observation over QuikScat revs 1550-1850.

	NO RAIN FLAG	RAIN FLAGGED WITH ENOF (7.5%)	RAIN FLAGGED WITH SSM/I
RMS Wind Speed Difference	2.22	1.72	1.63
RMS Wind Direction Difference	25.5	23.4	23.3

The SSM/I rain flag used to produce these statistics is very conservative. If the closest SSM/I cell to the QuikScat observation, or any of its 8 nearest-neighbors shows any rain, the observation is discarded. Use of the ENOF flag improves the agreement with the ECMWF model nearly as much as using this conservative SSM/I rain flag. This result is very encouraging, indicating that the ENOF rain flag removes erroneous wind vectors almost as effectively as SSM/I collocated rain measurements, but does not require an SSM/I collocated measurement.

In summary, we are best able to identify rain at low winds where it is most needed. The rain flag classifies approximately 80% of SSM/I rain for low winds, an SSM/I rain column threshold of 3 km mm/hr, and a false alarm rate of approximately 6%.

4 Data Product Contents and File Format

These rain flag data are provided in Binary format by orbit for revs 430 through 3099. Like the L2B data product, rain flag data are in 1624 rows of 76 wind vector cells. Each data file contains the ENOF rain flag values for the WVCs matching the L2B data set.

The value of the flag is the empirically normalized sum of the squared differences between the measured sigma_0's, and those calculated using the selected wind vector in the model function. The data are stored as single byte unitless values between 0 and 250. In our opinion, values above 45 indicate a significant probability of rain contamination. Where no rain flag was calculated, the value is set equal to 255. There should be no data with values of 251, 252, 253, or 254.

The file naming scheme is: QS_ENOFflagRRRRR.dat, where RRRRR is the 5 digit rev number. These overlay files for revs 430 through 3099 are available from the PO.DAAC. The rain flag is incorporated into the QuikScat L2B data files for rev 3100 onward.

5 Points of Contact

Questions concerning data distribution should be directed to the PO.DAAC. Issues related to data quality or processing should be directed to Carl Mears or Deborah Smith.

5.1 PO.DAAC: Data Distribution Issues - Contact Information

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Homepage: http://www.ssmi.com

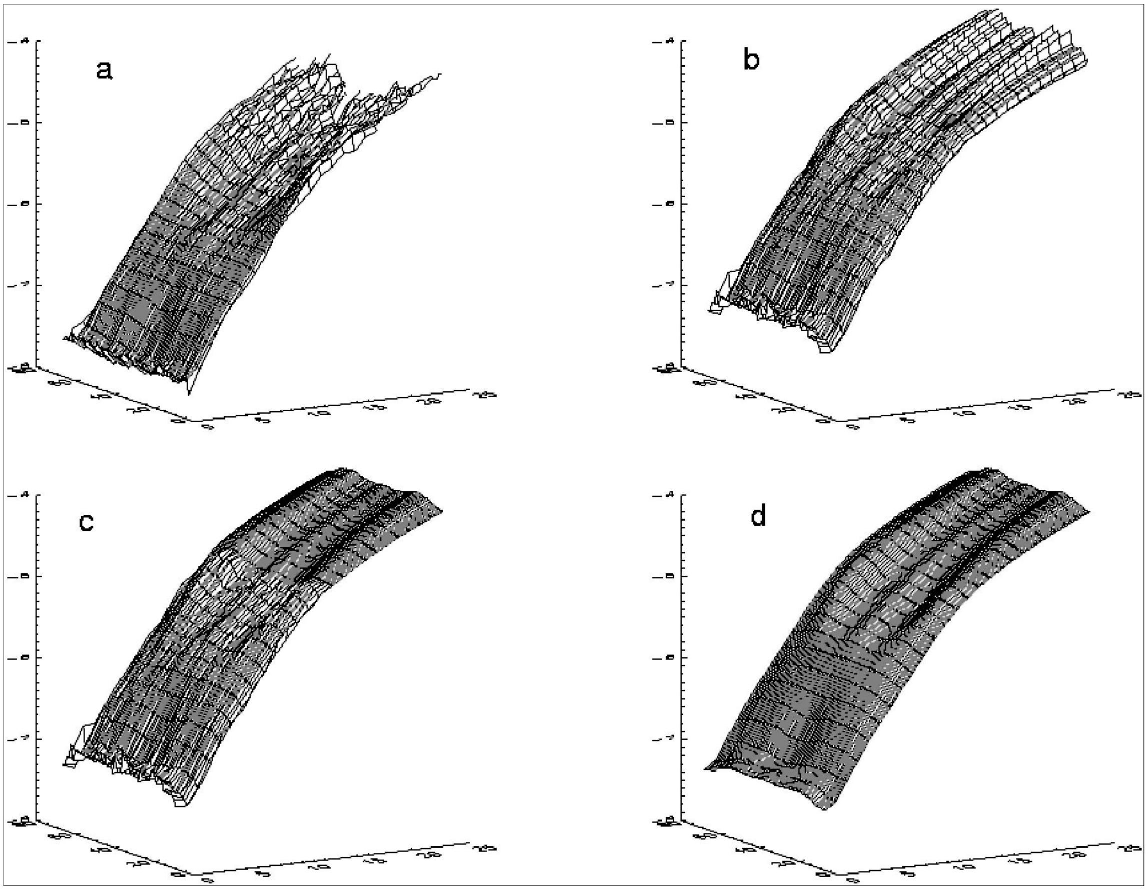

Figure 1. This is a surface plot of the Logarithm of W_i as a function of Pseudo Wind speed and cross-swath cell index. In (a) is the unsmoothed statistic. In (b), we have fit a power law for the data from 13 m/s to 18 m/s, and used it to replace the data above 18 m/s. In (c) we have smoothed the fit parameters in the cross-swath direction. In (d), we have smoothed the data below 18 m/s. In all cases, the smoothing procedure also enforces symmetry with respect to the center of the swath.

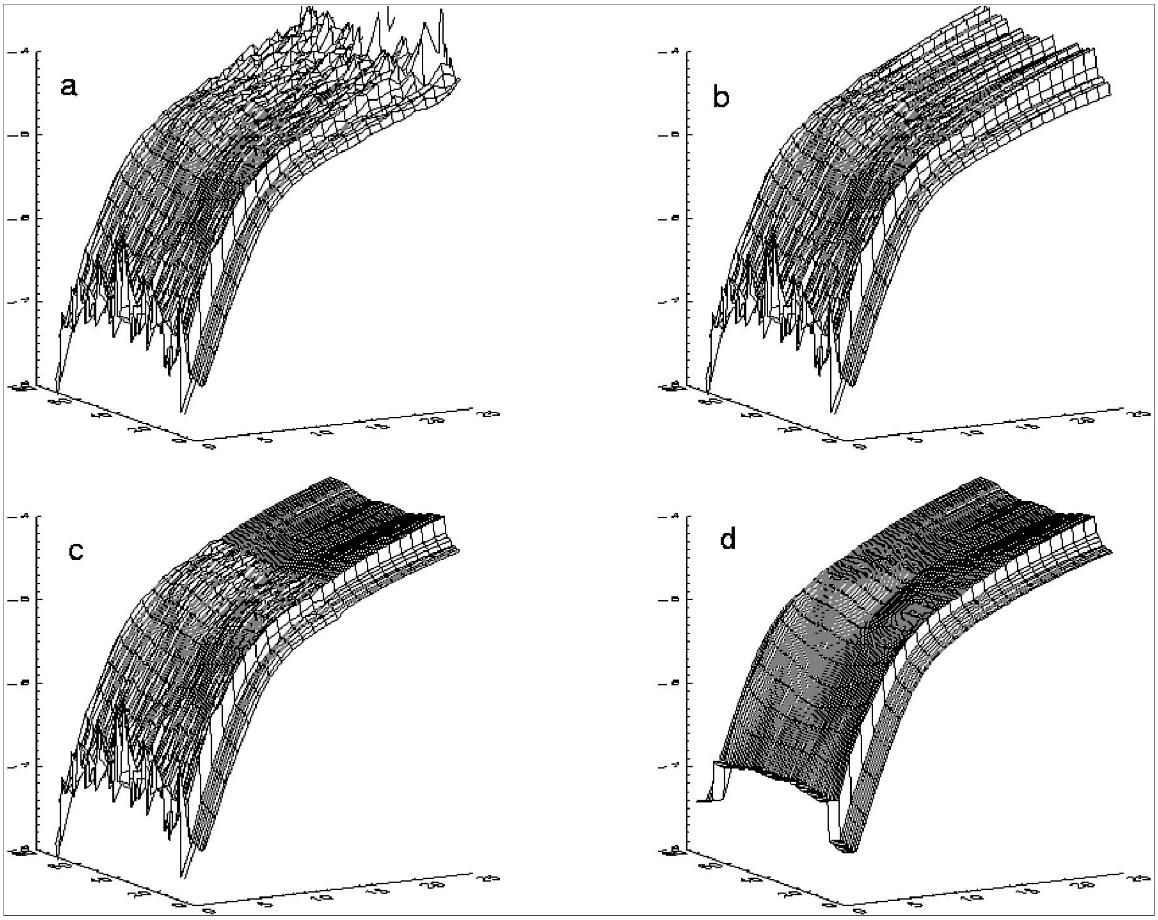

Figure 2. These plots are the same as in Figure 1, except they are for V-Pol measurements. Note the marked decrease in expected variance as we move from the mid-swath region, where both V-Pol and H-Pol measurements are present, to the far-swath region, where only V-Pol measurements are present. This strongly suggests that the measurements with the same polarization contain correlated errors that are not present for comparisons between measurements with different polarizations.

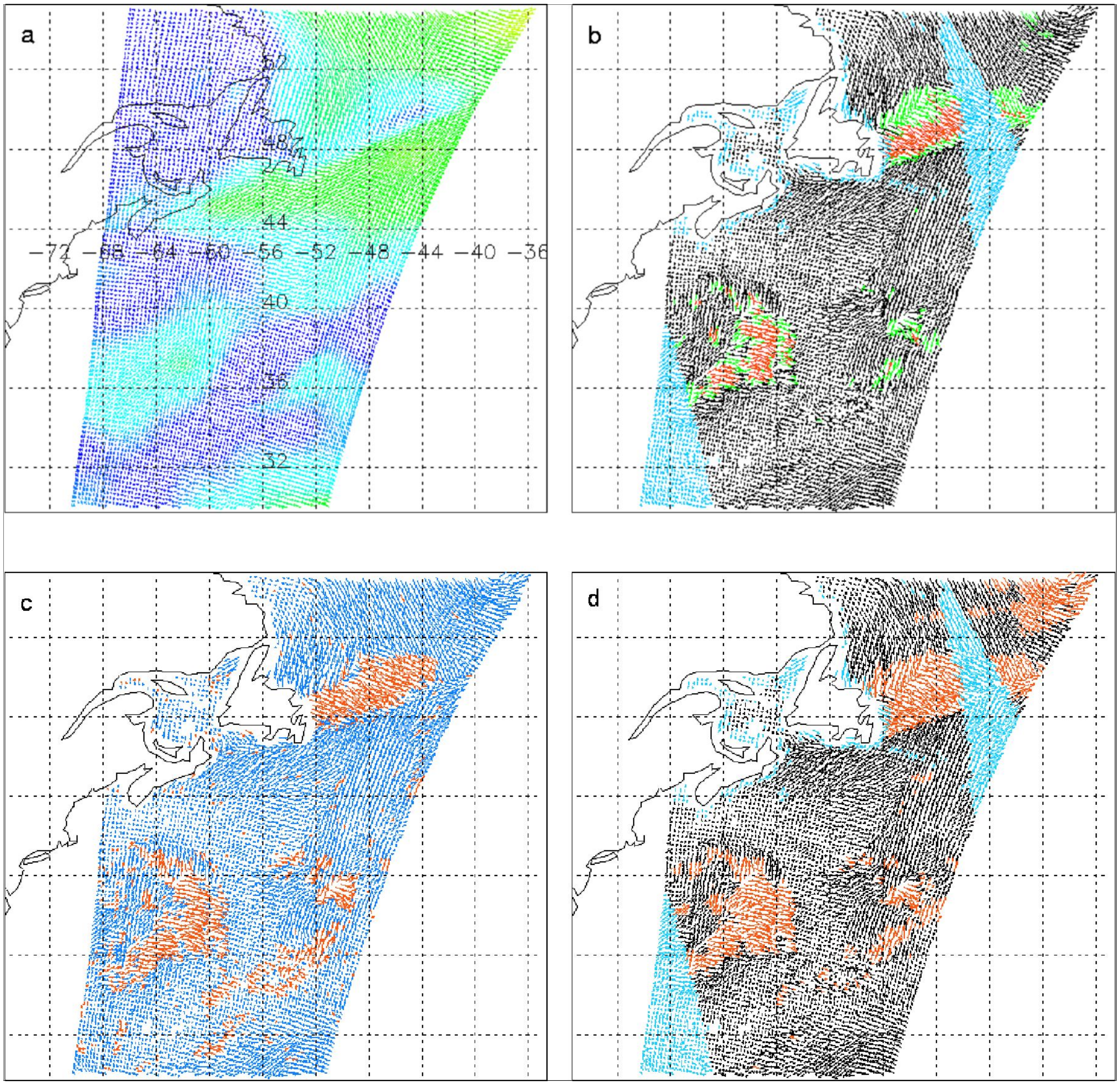

Figure 3. This is an example of the ENOF rain flag working well. In Fig 3a, we show ECMWF global analysis wind vectors for comparison, color-coded by wind speed. In Fig3b, we show QuikScat wind vectors color-coded by SSM/I rain column. Black vectors indicate no SSM/I rain, green vectors indicate rain between 0.0 and 3.0 km mm/hr, and red vectors indicate rain column above 3.0 km mm/hr. Blue vectors indicate no SSM/I data. In Fig 3c, we plot QuikScat vectors color coded by ENOF rain flag with a threshold of 45. Red vectors indicate rain and blue vectors indicate no rain. Note the excellent correspondence with Fig3b, except in the far swath region. In Figure 3d, we plot QuikScat vectors, color-coded by SSM/I cloud water. Red vectors indicate cloud water above 0.15 mm. Note that the is significant cloud water in many of the regions flagged by the ENOF Flag as rain, but not flagged by SSM/I as rain.

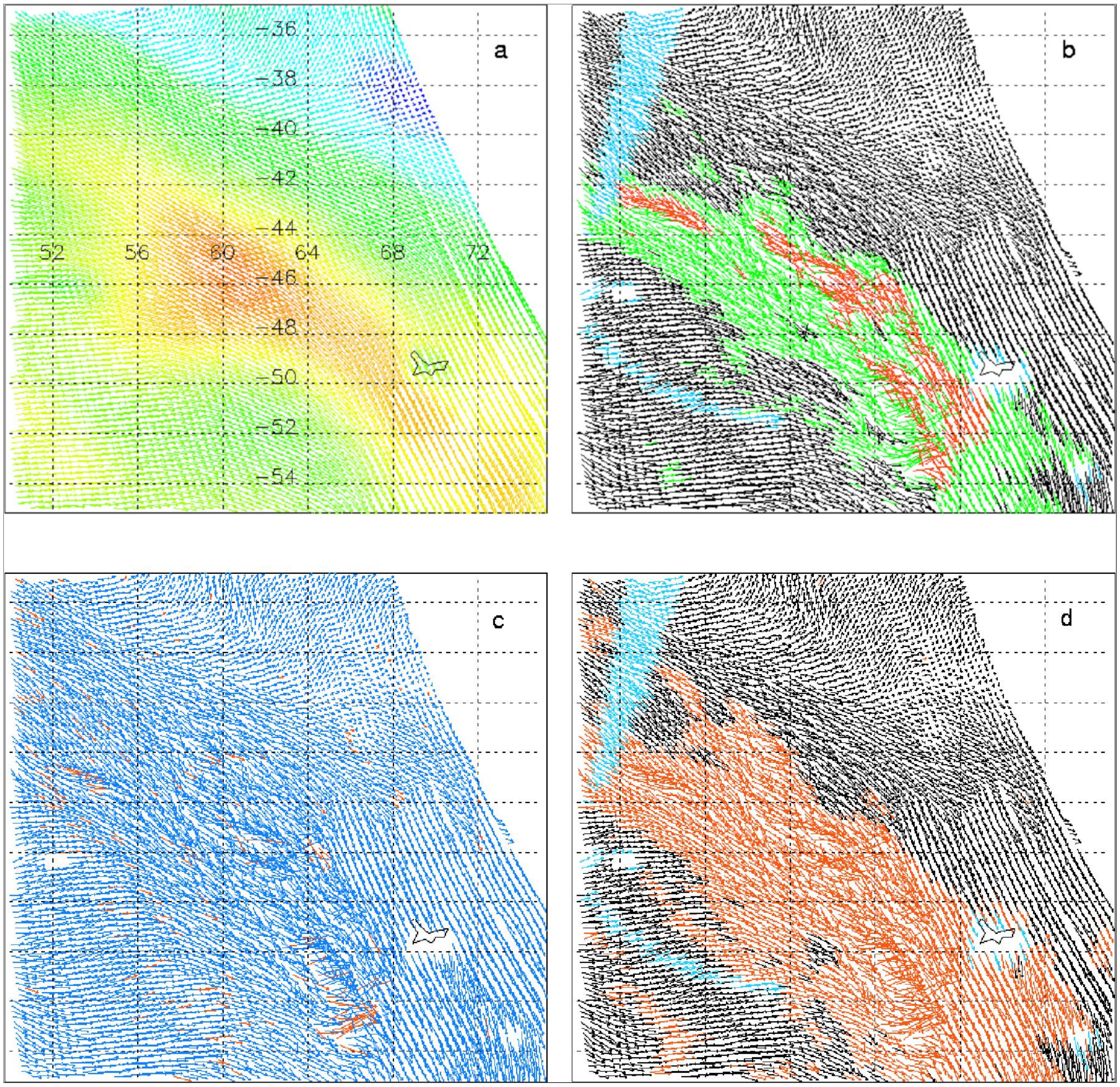

Figure 4. This is an example of poor performance of the ENOF rain flag. In Fig 4a, we show ECMWF global analysis wind vectors for comparison, color-coded by wind speed. In Fig 4b, we show QuikScat wind vectors color-coded by SSM/I rain column. Black vectors indicate no SSM/I rain, green vectors indicate rain between 0.0 and 3.0 km mm/hr, and red vectors indicate rain column above 3.0 km mm/hr. Blue vectors indicate no SSM/I data. In Fig 4c, we plot QuikScat vectors color coded by ENOF rain flag with a threshold of 45. Red vectors indicate rain and blue vectors indicate no rain. Note that the rain flag misses nearly all the rain measured by SSM/I, except in a relatively low-wind region near 65E, 52S. In Figure 3d, we plot QuikScat vectors, color-coded by SSM/I cloud water. Red vectors indicate cloud water above 0.15 mm.

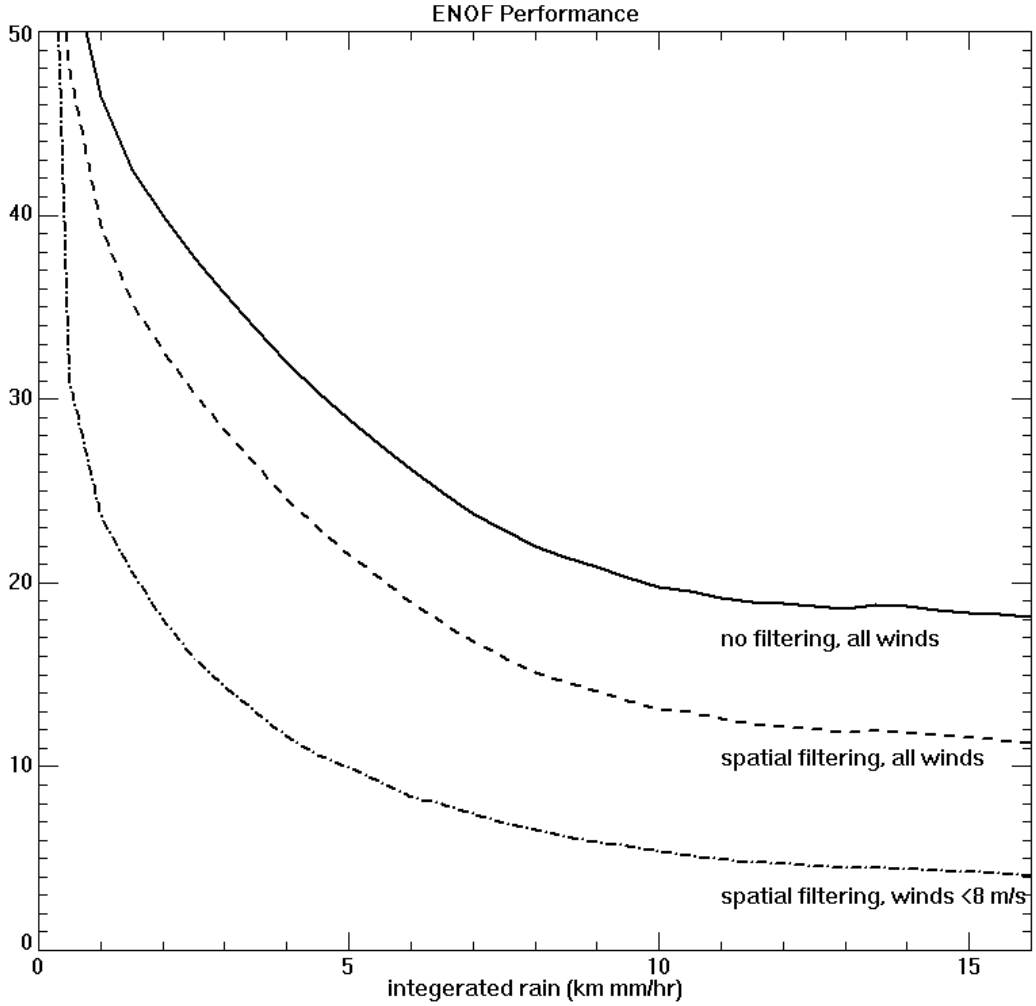

Figure 5. This plot shows the Misclassification rate as a function of SSM/I rain column for an ENOF threshold value of 45. The solid line represents the performance of the data provided within this dataset. The dashed line represents the performance of the data using a nearest neighbor spatial filtering technique to remove isolated flagged wind vectors. This algorithm performs best at low wind speeds as shown by the dotted-dashed line representing the misclassification rate of spatially filtered wind speeds below 8 m/s. Low winds are most affected by rain within the signal path. Using this rain flag, we can remove greater than 90% of these erroneous wind vectors when the rain column is greater than 5 km mm/hr. The false alarm rates for each curve are 5.5, 6.1 and 6.6 respectively.