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NSCAT high-resolution surface wind measurements in Typhoon Violet

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Abstract. NASA scatterometer (NSCAT) measurements of the western Pacific Supertyphoon Violet are presented for revolutions 478 and 485 that occurred in September 1996. A tropical cyclone planetary boundary layer numerical model, which uses conventional meteorological and geostationary cloud data, is used to estimate the winds at 10-m elevation in the cyclone. These model winds are then compared with the winds inferred from the NSCAT backscatter data by means of a novel approach that allows a wind speed to be recovered from each individual backscatter cell. This spatial adaptive (wind vector) retrieval algorithm employs several unique steps. The backscatter values are first regrouped in terms of closest neighbors in sets of four. The maximum likelihood estimates of speed and direction are then used to obtain speeds and directions for each group. Since the cyclonic flow around the tropical cyclone is known, NSCAT wind direction alias selection is easily accomplished. The selected wind directions are then used to convert each individual backscatter value to a wind speed. The results are compared to the winds obtained from the tropical cyclone boundary layer model. The NSCAT project baseline geophysical model function, NSCAT 1, was found to yield wind speeds that were systematically too low, even after editing for suspected rain areas of the cyclone. A new geophysical model function was developed using conventional NSCAT data and airborne Ku band scatterometer measurements in an Atlantic hurricane. This new model uses the neural network method and yields substantially better agreement with the winds obtained from the boundary layer model according to the statistical tests that were used.

1. Introduction

Tropical cyclones are dangerous to ships at sea and to people and structures on land when they make landfall. At present, their hour-by-hour movement can be tracked by geostationary weather satellite visible and infrared images. Also crude estimates of their intensity can be determined by the method described by Dvorak [1975, 1984]; however, actual measurements of the winds near the surface in tropical cyclones are rare.

The use of satellite microwave scatterometers to obtain measurements of ocean surface winds in hurri-

canes and typhoons is well documented [Pierson *et al.*, 1978; Jones *et al.*, 1981; Black *et al.*, 1981; Liu *et al.*, 1997]. In general, three effects degrade satellite scatterometer wind retrievals in tropical cyclones. First, the relationship between the ocean's normalized radar cross section σ^0 and the surface wind vector is not well known at high wind speeds such as those in tropical cyclones. This relationship, known as the scatterometer geophysical model function (GMF), infers speeds that are too low for ocean surface winds greater than about 20 ms^{-1} . Second, the relatively low spatial resolution of satellite scatterometer measurements produces wind field distortions, especially in the high wind gradient regions of tropical cyclones. Thus low resolution results in incorrect scatterometer wind direction solutions as well as producing smoothed fields with reduced peak wind speeds. Third, the absence of coincident passive microwave observations eliminates the possibility for an atmospheric attenuation correction for moderate to heavy rain. Precipitation causes volume backscatter from rain droplets, it modifies the ocean surface reflectivity by impacting droplets, and it produces two-way atmospheric absorption [Jones and Zec, 1996]. This degradation is especially important near

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the region of peak winds for tropical cyclones where the effect is predominately attenuation. When future scatterometer observations are combined with the data from the Tropical Rainfall Measuring Mission (TRMM) [Simpson, 1988], it should be possible to understand the three-dimensional cloud structure and rainfall patterns of tropical cyclones. This information will permit determination of the effects of attenuation and rain backscatter on the ocean backscatter measurements.

To improve scatterometer wind retrievals in tropical cyclones, an adaptive geophysical algorithm [Jones *et al.*, 1996, 1997] is used to process NASA scatterometer (NSCAT) σ^0 measurements obtained during two passes over Typhoon Violet. The approach is to use scatterometer backscatter values with "a priori" knowledge of the spatial characteristics of the surface winds to obtain wind speed and direction values for every backscatter measurement. The algorithm methodology is described, and NSCAT inferred surface winds are presented with the objective that similar observations of tropical cyclones may be provided by next generation scatterometers (e.g., QuikSCAT and SeaWinds). These remotely sensed surface winds will provide useful data for forecasting and warning purposes.

2. NASA Scatterometer σ^0 and Ocean Wind Vector Measurements

2.1. The σ^0 Measurements

The NASA scatterometer, placed in orbit on board Japan's Advanced Earth Observing Satellite (ADEOS) in August 1996, measures the ocean backscatter σ^0 at multiple azimuths in a two-sided swath, and its four antenna beams illuminate each swath at three different azimuths. For each antenna the footprint on the ocean's surface is divided into 24 σ^0 measurements, which are the effective instantaneous fields of view (IFOVs). The

Figure 1. Typical alignment of the NASA scatterometer (NSCAT) instantaneous fields of view (IFOVs) that comprise a 25-km σ^0 cell. Arrows denote the relative azimuth directions for four antenna beams.

Figure 2. Typical spatial distribution of σ^0 IFOVs relative to a 50-km wind vector cell. Shaded circles represent the IFOV centers, and arrows denote the relative azimuth directions for four antenna beams.

fore and aft antennas are vertically polarized, and the middle azimuth antenna is dual polarized. Over each swath the σ^0 measurements from the four antennas are collected into 25-km cells as shown in Figure 1. Next, four 25-km cells (16 σ^0 's) are combined to form a wind vector cell (WVC), where a wind vector retrieval is produced. Thus the NSCAT geophysical product is vector winds located on 50-km centers; however, the inherent spatial resolution of NSCAT is that of each σ^0 measurement. The equivalent rectangle is approximately 8 km by 35 km, sampled on 25-km centers along and across the satellite track. Because the collocation of the IFOVs, from the different beams, is "imperfect," this causes an along-track sampling with about 7-km separation as shown in Figure 1. An example of the resulting NSCAT spatial sampling, relative to a 50-km WVC, is illustrated in Figure 2. A new wind retrieval algorithm is presented that takes advantage of this separation of individual σ^0 to obtain higher-resolution sampling of a tropical cyclone wind field in the approximately along track direction. This algorithm recovers better wind speeds where there are strong wind gradients.

2.2. Geophysical Model Function

For more than 2 decades, research has been conducted to relate satellite scatterometer backscatter (ocean σ^0) to the simultaneous ocean-surface wind vector. This research has led to the development of statistical relationships that are known as scatterometer geophysical model functions [Schroeder *et al.*, 1982; Long *et al.*, 1995]. After a scatterometer launch the GMFs are "tuned" to improve the correlations between near-simultaneous ocean σ^0 and surface neutral stability wind measurements [Liu and Tang, 1996]. The normal GMF tuning procedure is to group the σ^0 measurements according to incidence angles, surface wind speeds, and azimuth angles relative to wind direction.

From these groups, statistics are calculated and empirical relations are derived. Because of the relatively coarse temporal and spatial collocations of σ^0 and surface winds (typically $\pm 1/2$ hr and 25–50 km), satellite scatterometer GMFs are optimized for measuring synoptic-scale winds.

Shortly after the launch of ADEOS, scientists and engineers began to refine the prelaunch model function. This refinement required several months of observations and associated surface wind comparison data. The refined model function, called NSCAT 1 [Wentz and Smith, this issue; M. H. Freilich et al., manuscript in preparation, 1998] was used to reprocess all NSCAT data into winds starting in April 1997. Unfortunately, there were relatively few occurrences of ocean surface speeds beyond about 20–25 ms^{-1} in the NSCAT 1 comparison set of conventional winds (L. Zeng and R. A. Brown, Scatterometer observations at high wind speeds, submitted to *Journal of Applied Meteorology*, 1997). Further, no comparison surface wind data were available for any tropical cyclone. As a result, this NSCAT 1 GMF is an extrapolation from lower wind speeds, and it may be inaccurate at speeds greater than about 20 ms^{-1} .

Jones et al. [1998] have developed an improved geophysical model function for wind retrievals in tropical cyclones using a neural network. This new GMF, named neural network GMF (NNGMF), was developed using NSCAT σ^0 and a comparison data set of conventional winds (buoy and numerical weather model) augmented by airborne backscatter measurements and coincident surface wind vectors from aircraft flights into an Atlantic hurricane. These airborne data were obtained by two scatterometers, KUSCAT and NUSCAT, developed at the University of Massachusetts [Donnelly et al., this issue] and the Jet Propulsion Laboratory [Nghiem et al., 1995], respectively. NSCAT inferred surface winds for Typhoon Violet, presented below, show that the wind vector geophysical algorithm produces higher wind speeds when the NNGMF model is used.

2.3. Spatial Adaptive (Wind) Retrieval Algorithm

The spatial adaptive retrieval algorithm (SARA) is used to perform special geophysical wind retrieval processing for NSCAT observations of high-gradient wind conditions in tropical cyclones. A simplified algorithm block diagram is illustrated in Figure 3. This algorithm is similar to the NSCAT geophysical algorithm [Naderi et al., 1991], and like NSCAT, SARA utilizes a GMF in the wind retrieval process.

The basis of the wind retrieval is the maximum likelihood estimation (MLE) principle as applied to statistical parameter estimation [Pierson, 1989a, b]. This method maximizes the joint conditional probability of a set of σ_i^0 measurements given the surface wind vector. This is equivalent to finding the most likely wind speed and direction that produces the observed backscatter

Figure 3. Functional flow diagram for the spatial adaptive retrieval algorithm (SARA) wind retrievals in tropical cyclones.

values σ^0 . We assume that the “true” σ^0 is related to the wind vector by the model function σ_{mf}^0 . Thus, for a perfect GMF and an error-free backscatter measurement, $\sigma_i^0 = \sigma_{mf}^0$; and the conditional probability density p_i for a σ_i^0 measurement is given by

$$p_i(\sigma_i^0 | \sigma_{mf}^0) = \frac{1}{\sqrt{2\pi}\delta_i} \exp \left[-\frac{\frac{1}{2}(\sigma_i^0 - \sigma_{mf}^0)^2}{\delta_i^2} \right] \quad (1)$$

where δ_i^2 is the variance of the σ_{mf}^0 estimated from NSCAT instrument parameters. The likelihood function is the joint probability density J_{MLE} , defined as the natural logarithm of the product of the p_i s over the n measurements in the wind vector cell, given by

$$J_{MLE} = \sum_{i=1}^n \left[\left| \frac{(\sigma_i^0 - \sigma_{mf}^0)}{\delta_i} \right|^2 + \ln \delta_i \right]. \quad (2)$$

For NSCAT there are nominally 16 σ^0 for a 50-km wind vector cell and four σ^0 for a 25-km wind vector cell.

The NSCAT wind vector geophysical algorithm is implemented using an iterative procedure to minimize this likelihood function. In this procedure, “trial” wind speeds and directions are used to evaluate the corresponding GMF value F_i , and the likelihood value is calculated. Wind vector solutions are the trial speeds and directions that minimize the likelihood function. Because the GMF varies approximately as the cosine of twice the radar azimuth relative to the wind direction χ , multiple wind solutions are produced by the MLE. The number of solutions often ranges from two to four, depending upon the χ at which the measurements were made. These multiple solutions, called aliases or ambi-

guities, differ slightly in wind speed but vary in wind direction over the full range of 360° . For the case of two aliases they generally differ by approximately 180° .

The last step in the NSCAT geophysical algorithm is refinement of the retrieved wind direction known as wind direction alias removal. The most common NSCAT approach uses the wind solution ranking, by the inverse of the MLE residuals, and a median filter technique to select a single wind direction [Shaffer *et al.*, 1991].

For SARA, two wind retrieval spatial resolutions are used, namely, 25 km (SARA₂₅) and maximum resolution (SARA_{max}). SARA₂₅ differs from NSCAT 25-km wind retrievals in the σ^0 collocation approach and the wind direction alias selection. For SARA₂₅ collocation the backscatter values are combined using a nearest-neighbor grouping algorithm. The SARA₂₅ wind alias removal algorithm uses the a priori knowledge of wind direction in tropical cyclones. In the northern hemisphere the winds in tropical cyclones rotate counterclockwise, and the wind flow spirals inward toward the storm's center. For this paper a spiral with an inflow angle of 25° is used to approximate the tropical cyclone wind direction for purposes of selecting the "best SARA₂₅ wind direction" from the available solutions. Thus, at a particular location, the wind alias closest to the counterclockwise tangential direction less 25° (toward the center) is selected as the correct wind direction. It should be noted that this alias selection process is only weakly influenced by the assumed inflow angle; but it is strongly influenced by the selection of the location of the tropical cyclone center. The first estimate of the position of the cyclone eye is provided by time interpolation of the coordinates provided by the National

Figure 4. Example of σ^0 measurements when passing over the eye of Typhoon Violet, revolution 485. Adjacent IFOVs of antenna beam 6 correspond to circles for IFOV 12 and asterisks for IFOV 13. The tropical cyclone eye location corresponds to the minimum backscatter point.

Figure 5. Comparison of the spatial sampling of surface winds provided by SARA₂₅ (dashed arrows) and SARA_{max} (solid arrows) for revolution 485.

Hurricane Center or Joint Typhoon Warning Center. If the eye lies inside the NSCAT swath, its position may be refined using the values of σ^0 to define the point of minimum winds within the eye. An example is shown for revolution 485 in Figure 4. The rapid decrease in σ^0 for beam 6, cell 13 near 25° latitude corresponds to the eye location. The σ^0 cell 13 was selected because it exhibits the lowest backscatter for that beam. The optimum center location is the average of the minimum locations for the four antenna beams.

For maximum spatial resolution processing the SARA_{max} wind speed is obtained at the individual backscatter IFOV by using a modified MLE algorithm for a single σ^0 measurement. This approach utilizes an assumed direction and the measured σ^0 to determine wind speed. For the assumed wind direction, either the dealiased direction from SARA₂₅ processing or the wind direction from a tropical cyclone numerical wind model is used. This results in a wind field spatial sampling that is approximately 7 km along track by 25 km across track as illustrated in Figure 5. Here SARA_{max} wind vectors are displayed as solid arrows, and the SARA₂₅ wind retrievals are shown as dashed arrows.

2.4. Rain Editing Using "Goodness of Fit" Criterion

Given typical wide-area coverage of the spiral precipitation bands in tropical cyclones, it is likely that numerous satellite scatterometer σ^0 measurements are affected by rain. Unfortunately, the ADEOS satellite did not carry any instrument that would provide an independent assessment of precipitation that could be used for data editing. Consequently, in the SARA_{max} wind retrieval algorithm an objective evaluation is made using NSCAT σ^0 to estimate whether one or more measurements, within a 25-km grouping, are contaminated

by rain. This data quality control procedure, known as the “goodness of fit” (GOF) test, is used to set a “rain flag” that is used in data editing of SARA_{max} wind retrievals.

The basis of this test is an analytical study [Jones and Zec, 1966] that showed when a radar views the ocean’s surface through a homogeneous rain volume, the resulting backscatter is more isotropic than ocean backscatter without rain. An assessment of the extent of rain contamination on individual σ^0 measurements is made by examining the backscatter anisotropy given by σ^0 versus the relative azimuth of the four nearest neighbors within a 25-km grouping. The assumption is that the wind speeds and directions at these σ^0 locations are almost equal; therefore for σ^0 not contaminated by rain, the individual measurements should nearly match the corresponding theoretical GMF values using the same wind vector at each location. This approximation is believed to be reasonable, even in strong wind gradient conditions of tropical cyclones, because the distance between neighbors is less than 25 km.

The goodness of fit test uses the SARA_{max} wind speed and either the SARA₂₅ wind direction or the modeled direction to estimate the true surface wind vector at the individual σ^0 locations. Thus, by sequentially applying the same wind vector to every individual backscatter measurement, each σ^0 is tested for consistency with respect to its nearest neighbors. Because each SARA_{max} wind speed is independent, the GOF is repeated n times for each 25-km nearest neighbor grouping. For a σ_j^0 being evaluated, the corresponding residual is given as

$$r_j = \frac{1}{n} \sum_{i=1}^n \frac{(\sigma_i^0 - \sigma_{mf\,ij}^0)^2}{(\sigma_{mf\,ij}^0)^2} \quad (3)$$

where n is the number of σ^0 measurements within a 25-km cell, nominally $n = 4$; $(\sigma_{mf}^0)_{ij}$ is the GMF value evaluated at θ_i ; and χ_i and wind speed = (SARA_{max})_j.

After calculating residuals for every σ_j^0 measurement, a cutoff threshold is determined, such that a defined percentage of the data with the highest residuals is discarded. For this work the subjectively determined threshold resulted in 15% of the σ^0 being discarded. An example of the GOF editing of SARA_{max} wind retrievals for revolution 485 that passed over Typhoon Violet is presented in Figure 6. The left-hand panel depicts wind solutions from those σ^0 that passed the GOF. The right-hand panel shows those wind solutions where the GOF is failed. The spatial distribution of “failed solutions” is similar to the expected rain band structure about the typhoon eye. This gives credence to the assumption that they are contaminated by rain. Further, it is important that numerous measurements exist between these bands to allow the circulation of the cyclone to be defined (even close to the eye).

3. Typhoon Violet Description

During September 1996 the NSCAT observed Typhoon Violet in the tropical North Pacific Ocean. Analyses of this storm are in progress, but some preliminary results are presented that demonstrate the potential of the NSCAT surface wind measurements at the maximum resolution (SARA_{max}). SARA_{max} wind retrievals are compared with “surface truth” winds from a hurricane primitive equation, planetary boundary layer (PBL) surface wind model.

Violet first attained typhoon intensity on September 13 about 500 km east of Luzon, Philippines. The storm moved slowly northwestward and intensified rapidly over

Figure 6. Example of goodness of fit (GOF) data editing of SARA_{max} wind retrievals to remove measurements contaminated by rain. (left) SARA_{max} solutions where the GOF is passed and (right) wind solutions where the GOF is failed. NSCAT data are from Typhoon Violet obtained on revolution 485.

Table 1. Typhoon Violet Estimates of Intensity and Eye Diameter from JTWC

	Maximum Sustained Wind Speed, 1-min. Average*, m s^{-1}	Satellite/Radar Eye Diameter†, km
1400 UT, Sept. 19, 1996, revolution 478	46.4 (37.4)	147 (79)
0230 UT, Sept. 20, 1996, revolution 485	46.4 (37.4)	91 (49)
1330 UT, Sept. 20, 1996, revolution 492	43.8 (35.3)	134 (72)

*Numbers in parentheses are 1-hour averages.

†Numbers in parentheses are nautical mile values.

the next 3 days and attained supertyphoon intensity by 0000 UT on September 16 with peak winds estimated at 67 ms^{-1} (130 knots, Joint Typhoon Warning Center (JTWC) estimate) and minimum estimated central pressure of 910 mbar. During September 13 the center turned sharply northeastward and slowly filled over the next 10 days. This motion paralleled the northeast motion of Typhoon Tom located about 2000 km east of Violet. The interaction of the large-scale wind fields about Violet and Tom was viewed by NSCAT standard wind retrievals on September 21 and 22 as described by *Liu et al.* [1997].

The NSCAT passes that were available for analysis and the JTWC estimates of intensity and eye diameter are given in Table 1. The numbers in parentheses are estimates of the 1-hour average wind speed (meters per second) corresponding to the JTWC estimates, where the conversion is made using the tropical cyclone gust factor recommended by *Black* [1994]. During ADEOS revolution 478, NSCAT sampled the eye and about half of the storm's circulation on the right-side swath. During the next opportunity, revolution 485 (Figure 6), the typhoon was positioned almost midway across the right-side swath such that the eye and the circulation out to at least 300 km in all radial directions were sampled by NSCAT. During revolution 492 the center of the storm and its inner circulation were close to NSCAT nadir (along the ADEOS subtrack) and hence within the unsampled NSCAT measurement area between the swaths; consequently, revolution 492 is excluded from this preliminary analysis.

The filling and expansion of Violet during the time of the NSCAT passes suggest that the storm was beginning to undergo a transformation to extratropical storm structure. This factor complicates the specification of the wind field using models designed strictly for tropical cyclones; nevertheless, the untimely loss of ADEOS makes this data very valuable. Thus, in the absence of other data over well-documented "pure" typhoons or hurricanes, such a model is used to provide estimates of the field of wind directions needed for the SARA retrievals and estimates of the wind speed for comparison with the retrieved winds.

4. Tropical Cyclone Boundary Layer Models

Chow [1971] developed a model of the tropical cyclone planetary boundary layer that included the effects of storm translation and horizontal and lateral friction on the asymmetric wind field. This model numerically solved the primitive equations of motion applied to a vertically integrated PBL, often called a "slab model." For the steady state wind solution of a vortex, calculations are performed on a translating Cartesian grid described by a simple time-invariant pressure field in a coordinate system moving with the vortex center. Since its development, Chow's model has undergone considerable refinement [*Cardone et al.*, 1976, 1992] (also see *Thompson and Cardone* [1996] (hereinafter referred to as TC96)). Further, in numerous applications it has been shown to be a highly calibrated diagnostic tool for the specification of the surface wind field over a surface of prescribed roughness (including water) in a translating vortex. The meteorological model input variables are the PBL thermal stratification and depth, the vortex motion, and the two-dimensional PBL atmospheric pressure field.

The most critical model inputs are, of course, the center location, which places the model solution with respect to the center correctly in Earth coordinates, and the parameters of the axisymmetric part of the radial pressure profile. The latter includes central pressure, radius of maximum wind or pressure gradient, and peripheral pressure, all of which may be quite precisely specified from aircraft reconnaissance data. Unfortunately, aircraft reconnaissance of western North Pacific storms was terminated in 1986. It has continued in the North Atlantic, but NSCAT apparently did not sample a significant and well-documented Atlantic hurricane during its lifetime. When a tropical cyclone passes through a network of surface observing stations such as the buoy array in the U. S. Gulf of Mexico, these data can provide a viable substitute for the aircraft data. Unfortunately, Violet did not pass close to surface stations until the center approached to within about 110 km (60 nm) of Japan Meteorological Agency buoy 21 at 0600 UT on

Figure 7. Surface track for Typhoon Violet, September 20, 1996, from 1715 to 2103 UT. Surface winds are from *Thompson and Cardone* [1996] model corresponding to typhoon location at revolution 485 overflight.

September 21, more than 24 hours after revolution 485.

In the absence of reconnaissance data the error in the location of the center of circulation is at least 50 km (30 nm) if the center is estimated from satellite imagery [JTWC, 1997]. Between September 17 and 21, the JTWC typhoon track locations, which are based upon real-time warning fixes as shown in Figure 7, were used to model the storm history. An exception is that the position at 0300 UT, September 20 was displaced westward 15 min of longitude and southward 10 min of latitude. This provided a closer match between the modeled circulation center and the preliminary estimate of its location based on the 25-km NSCAT wind retrievals, which is the only use of the NSCAT data in the otherwise independent analysis of the wind field from the scant conventional data. The other critical

model profile parameter, radius of maximum wind, was estimated from the satellite eye diameter estimates by using an empirical ratio developed by *Shea and Gray* [1973] from analyses of a 1-year sample of aircraft reconnaissance data in western North Pacific typhoons.

5. Comparison of TC96 and SARA Winds

5.1. SARA₂₅ Wind Direction Results

For Typhoon Violet, NSCAT winds were produced using the SARA₂₅ algorithm that was run using both GMFs. To provide an independent comparison data set, the TC96 model, driven by conventional meteorological data, was also run for Violet over an elapsed time of approximately 36 hours from September 19 to 20, 1996.

Figure 8. Example of measured and modeled wind directions for Violet revolution 485, showing (left) SARA₂₅ using neural network geophysical model function (NNGMF) and (right) *Thompson and Cardone* [1996] model.

Wind vectors at 10 m elevation were interpolated to the individual NSCAT backscatter locations for revolutions 478 and 485, and direction comparisons were made with SARA₂₅ wind retrievals.

In general, the SARA₂₅ wind directions for the two GMFs are quite similar; but they differ slightly from the modeled wind directions. An example is presented in Figure 8 for Violet revolution 485. The modeled field is smoother as expected; but there are a few anomalous regions where the SARA₂₅ wind directions (Figure 8, left) step rather abruptly as the wind rotates about the cyclone center as in the regions at 27° N by 132° E and at 22° N by 133° E. Also, this effect is observed in the probability distribution functions (pdfs) of wind direction for these two wind fields (Figure 9). The SARA₂₅ direction distribution shown in Figure 9 (left) appears to “lock on” to certain wind directions, while the distribution for the TC96 wind field in Figure 9 (right) is more uniform. Apparently, the location of these lock on points is related to the radar look directions (relative azimuth χ) of the antennas, and this effect is most likely related to error in modeling the GMF anisotropy.

Figure 9. Histograms of measured and modeled wind directions for Violet revolution 485, showing (left) SARA₂₅ using NNGMF and (right) *Thompson and Cardone* [1996] model.

Statistical wind direction comparisons for Violet revolutions 478 and 485 are summarized in Table 2. Results are similar for both GMFs; therefore, in terms of retrieved wind directions, there is no preference.

5.2. SARA₂₅ Wind Speed Results

To improve the accuracy of the inferred tropical cyclone wind speeds, NSCAT wind retrievals were performed using the SARA_{max} algorithm and wind directions from the TC96 model. Also, the GOF test was performed to remove σ^0 that were contaminated by rain. Two different GMFs were used, NSCAT 1 and NNGMF; the results are described below.

A plot of SARA₂₅ wind barbs for revolution 478 using the NSCAT 1 GMF is presented in Figure 10. Figure (left), shows wind retrievals at the locations of the individual σ^0 , except for several regions where wind barbs are missing. First, the diagonal regions of missing wind barbs (between 26° N and 29° N and 24° N and 22° N) correspond to a NSCAT calibration frame where ocean measurements were not obtained. Next, the approximately elliptical regions of missing wind barbs (at 26.5° N and 28° N) correspond to the location of islands. Finally, there are regions near the typhoon eye (24.2° N by 132.3° E) without wind barbs that correspond to locations where the NSCAT σ^0 failed the GOF test. As discussed previously, the spatial pattern of these deleted σ^0 is in qualitative agreement with the location of spiral rainbands that usually surround the eye of a typhoon.

Figure (right), shows the spatially correlated wind speed differences for the TC96 wind speed minus SARA_{max} wind speed. North of the typhoon eye, the differences are generally negative and in the range of 0 to -5 ms^{-1} ; while, south of the eye, the differences are positive in the range of 0 to $+5 \text{ ms}^{-1}$. Since the wind directions north of the eye differ by 90° to 180° from those directions south of the eye, this behavior sug-

Table 2. Typhoon Violet Wind Direction Differences

	Revolution 478		Revolution 478	
	Mean, deg	Standard Deviation, deg	Mean, deg	Standard Deviation, deg
NSCAT 1 GMF	6.1	26.5	1.9	32.5
NNGMF	8.5	26.9	-4.3	38.8

Differences are *Thompson and Cardone* [1996] (TC96) model directions minus spatial adaptive retrieval algorithm (SARA_{max}) directions. GMF is geophysical model function, with NN denoting neural network.

gests a problem with the GMF anisotropy for NSCAT 1. Near the typhoon eye there are a number of locations where TC96 winds exceed SARA_{max} retrievals by 5 to 10 ms^{-1} (Figure 10, right, solid squares) and a few locations where they exceed SARA_{max} retrievals by $> 10 \text{ ms}^{-1}$ (shown as solid triangles). This demonstrates that scatterometer wind retrievals using the NSCAT 1 GMF significantly underestimate the high wind speeds.

The corresponding plot for revolution 478 of SARA_{max} wind retrievals using the NNGMF is presented in Figure 11. Overall, higher wind speeds are retrieved when using the NNGMF as demonstrated by the significant reduction in the number of solid sym-

bols in Figure 11, right, and there is better agreement with TC96 as in Figure 11 (right) than there was for the NSCAT 1 GMF in Figure 10 (right). For this case there are no apparent systematic wind speed differences with storm quadrant. Further, the mean speed differences appear to be unbiased because they are nearly randomly distributed within $\pm 5 \text{ ms}^{-1}$, except near the typhoon eye where SARA_{max} exhibits a larger variability of $\pm 10 \text{ ms}^{-1}$.

Wind speed statistics in terms of the means and standard deviations of speed differences between TC96 and SARA_{max} are shown for the two GMFs in Figure 12. The plotted points show the average over 5 ms^{-1} bins of the speeds retrieved using SARA_{max}, for the two GMFs,

Figure 10. SARA_{max} wind retrievals using NSCAT 1 model function and *Thompson and Cardone* [1996] (TC96) wind directions for Violet revolution 478, showing (left) SARA_{max} wind vectors and (right) wind speed differences between TC96 and SARA_{max}. Open triangles denote $< -10 \text{ m s}^{-1}$, open squares represent -10 to -5 m s^{-1} , and open diamonds denote -5 to 0 m s^{-1} . Solid symbols correspond to positive differences.

Figure 11. SARA_{max} wind retrievals using NNGMF model function and TC96 wind directions for Violet revolution 478, showing (left) SARA_{max} wind vectors and (right) wind speed differences between TC96 and SARA_{max}. Open triangle denote $< -10 \text{ m s}^{-1}$, open squares represent -10 to -5 m s^{-1} , and open diamonds denote -5 to 0 m s^{-1} . Solid symbols correspond to positive differences.

Figure 12. Comparison of the wind speeds recovered by SARA_{max} with corresponding tropical cyclone model speeds (TC96) for revolution 478. Symbols are mean values for 5 m s^{-1} bins: asterisks denote NNGMF model function and minuses represent NSCAT 1 model function. Vertical lines show the standard deviations of the SARA retrievals about the means.

paired with the corresponding average wind speeds from the TC96 model. The standard deviations of the wind speed differences are shown as vertical lines through the mean values. SARA_{max} wind speeds using the NSCAT 1 GMF are progressively lower than the TC96 model above 15 m s^{-1} . On the other hand, SARA_{max} wind speeds are in excellent agreement up to 30 m s^{-1} where they tend to saturate. Similar σ^0 saturations have been observed with airborne scatterometers in hurricanes [Donnley *et al.*, this issue; Yueh *et al.*, 1998]. The wind speed comparison results presented in Figure 12 are summarized in Table 3a.

Similar wind speed comparisons are presented for revolution 485 in Figures 13 to 15. For this Violet pass the comparisons are slightly degraded compared to revolution 478, but again, SARA_{max} retrieved wind speeds using the NNGMF are superior. Wind speed statistical comparisons are summarized in Table 3b.

6. Conclusions

The official NSCAT project 50-km wind vector product yields unrealistic winds in tropical cyclones. Most notably, NSCAT wind retrievals in tropical cyclones do

Table 3a. Typhoon Violet Revolution 478 Wind Speed Differences

Wind Speed Range, m s^{-1}	NSCAT 1 GMF		NNGMF	
	Mean, m s^{-1}	Standard Deviation, m s^{-1}	Mean, m s^{-1}	Standard Deviation, m s^{-1}
5 - 10	0.3	1.0	-0.2	1.2
10 - 15	2.0	2.1	0.7	3.9
15 - 20	3.6	2.0	1.0	2.9
20 - 25	5.6	2.0	0.5	3.5
25 - 30	6.8	3.1	-0.1	4.4
30 - 35	9.3	4.3	3.4	5.3
> 35	14.8	4.3	3.9	7.1

Differences are TC96 speed minus SARA_{max} speed.

Table 3b. Typhoon Violet Revolution 485 Wind Speed Differences

Wind Speed Range, m s^{-1}	NSCAT 1 GMF		NNGMF	
	Mean, m s^{-1}	Standard Deviation, m s^{-1}	Mean, m s^{-1}	Standard Deviation, m s^{-1}
5 - 10	-3.4	1.5	-2.2	2.6
10 - 15	2.2	1.6	-0.6	4.0
15 - 20	4.6	2.4	2.4	4.8
20 - 25	5.4	2.8	0.0	6.7
25 - 30	8.2	3.0	0.3	6.3
30 - 35	12.9	3.9	3.7	6.7
> 35	15.4	4.2	5.0	7.5

Figure 13. SARA_{max} wind retrievals using NSCAT 1 model function and TC96 wind directions for Violet revolution 485, showing (left) SARA_{max} wind vectors and (right) wind speed differences between TC96 and SARA_{max}. Open triangles denote $< -10 \text{ m s}^{-1}$, open squares represent -10 to -5 m s^{-1} , and open diamond denote -5 to 0 m s^{-1} . Solid symbols correspond to positive differences.

Figure 14. SARA_{max} wind retrievals using NNGMF model function and TC96 wind directions for Violet revolution 485, showing (left) SARA_{max} wind vectors and (right) wind speed differences between TC96 and SARA_{max}. Open triangles denote $< -10 \text{ m s}^{-1}$, open squares represent -10 to -5 m s^{-1} , open diamonds denote -5 to 0 m s^{-1} . Solid symbols correspond to positive differences.

not recover the expected peak surface wind speeds of greater than 30 m s^{-1} . A new wind retrieval algorithm, especially developed for tropical cyclones, has been employed to recover winds at the highest possible resolu-

tion. This spatial adaptive retrieval algorithm (SARA) when used with an improved geophysical model function (NNGMF) significantly improves NSCAT wind speed measurements. Results demonstrate that SARA_{max} winds are in excellent agreement with independent surface winds calculated using a numerical tropical cyclone model (TC96). Also, SARA₂₅ retrieved wind directions compare well with modeled directions, but they exhibit somewhat irregular flow patterns with abrupt wind direction steps. This is an area of future research.

The SARA_{max} algorithm has developed a goodness of fit test that detects the presence of significant rain. After application of this GOF test, contaminated wind retrievals are discarded, and the remaining wind measurements are improved. Refinement of this test is also an area of future research.

Figure 15. Comparison of the wind speeds recovered by SARA_{max} with corresponding tropical cyclone model speeds (TC96) for revolution 485. Symbols are mean values for 5 m s^{-1} bins: asterisks denote NNGMF model function and minuses represent NSCAT 1 model function. Vertical lines show the standard deviations of the SARA retrievals about the means.

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