Evaluation of Hurricane Ocean Vector Winds from WindSat

Ian S. Adams, Student Member, IEEE, Christopher C. Hennon,
W. Linwood Jones, Fellow, IEEE, and Khalil Ahmad, Student Member, IEEE

Abstract-The ability to accurately measure ocean surface wind vectors from space in all weather conditions is important in many scientific and operational usages. One highly desirable application of satellite-based wind vector retrievals is to provide realistic estimates of tropical cyclone intensity for hurricane monitoring. Historically, the extreme environmental conditions in tropical cyclones (TC) have been a challenge to traditional space-based wind vector sensing provided by microwave scatterometers. With the advent of passive microwave polarimetry, an alternate tool for estimating surface wind conditions in the tropical cyclone has become available. This paper evaluates the WindSat polarimetric radiometer's ability to accurately sense winds within TCs. Three anecdotal cases studies are presented from the 2003 Atlantic Hurricane season. Independent surface wind estimates from aircraft flights and other platforms are used to provide surface wind fields for comparison to WindSat retrievals. Results of a subjective comparison of wind flow patterns are presented as well as quantitative statistics for point location comparisons of wind speed and direction.
I. INTRODUCTION

The measurement of global ocean surface wind vector (wind speed and direction), using microwave remote sensing techniques from polar orbiting satellites, provides vital environmental information for both scientific and operational applications. From a scientific standpoint, ocean vector wind data is critical to support basic research in global climate change, air-sea interaction, ocean and atmospheric circulation, and a variety of meteorological and oceanographic research topics. Operationally, these data are essential for short-term weather and ocean wave forecasts/warnings, ship routing, marine operations, hurricane analysis, etc. Also there are significant military applications of the wind vector, which affects a broad range of naval operations including strategic ship movement and positioning, aircraft carrier operations, aircraft deployment, underway replenishment, and littoral operations.

Historically, the use of radar scatterometers on spacecraft to measure the ocean surface wind vectors is well-established, with over 35 years of research and development [1]. Space-borne scatterometers, such as NASA’s NSCAT and SeaWinds instruments and the European Space Agency’s Active Microwave Instrument on ERS-1 and ERS–2, have observed global ocean winds continuously since the early 1990’s. However, there have never been a sufficient number of these sensors simultaneously operational, in the proper orbits, to satisfy the revisit and
coverage requirements necessary for full utilization in operational meteorological applications. At best, scatterometers observe ~ 90% of the ice free oceans daily with a revisit time that ranges from 12 to 24 hours, which is far from desired temporal sampling.

Further, the use of satellite passive microwave radiometry also has a strong heritage for remote sensing of atmospheric and oceanic environmental parameters. Over the past 15 years, a series of seven Special Sensor Microwave/Imagers (SSM/I) have successfully operated on the Defense Meteorological Satellite Program (DMSP) satellites. Typically, there are two or more SSM/I’s operating simultaneously in morning and evening sun-synchronous orbits. They have provided reliable passive microwave data for retrieving atmospheric and ocean environmental parameters such as integrated atmospheric water vapor and cloud liquid water, ocean surface wind speed, and sea ice concentration and type [2, 3]. Historically, the ocean surface wind direction is one parameter that has not been provided by microwave radiometers; however, analysis of SSM/I data has revealed a wind direction dependence (anisotropy) in the polarized ocean brightness temperatures, which has been confirmed by modeling and aircraft measurements [4, 5]. These empirical observations have provided the motivation for the WindSat experiment.

WindSat is the world’s first passive microwave polarimetric radiometer. It was launched on the polar, sun-synchronous, low-earth-orbit satellite Coriolis in January 2003. The objective of WindSat is to demonstrate the “proof of concept” of a new microwave polarimetric radiometry
technique for measuring the ocean surface wind vector (speed and direction) from space. A significant part of this new research has been the definition of the wind direction signatures and the associated retrieval algorithm [6, 7]. In late 2004, the first preliminary oceanic wind vector results (environmental data records version 1.5.1) were released to the science community. One important potential application for WindSat wind vectors is tropical cyclone (TC) analysis. Since TCs form and spend most of their lifetime over the data-poor oceans, surface wind vector data can make a vital contribution to identifying surface circulations and determining maximum surface wind speeds and radii. SeaWinds scatterometer data have been used at TC forecast centers worldwide for several years with some success. Unfortunately, SeaWinds retrievals experience a dramatic loss in accuracy in the presence of moderate and heavy rainfall – a common condition in TCs. Thus, our primary motivation for this paper is to provide a preliminary assessment on alternative passive WindSat surface wind vector retrievals in TC environments.

This paper provides a brief description of the WindSat Project's version-0 wind retrieval algorithm [7] and presents unique evaluations of wind vector retrievals in the high cloud liquid water/precipitation environment of a hurricane. Both wind speed and wind direction comparisons will be made with an experimental tool known as H*Wind that performs surface wind analyses given a large of amount of heterogeneous data. To complement this surface wind analysis, rain rates were derived using WindSat brightness temperatures with a modified version
of the TMI 2A12 heritage rain algorithm. Effects of rain on the derived wind speeds and directions are discussed.

Because WindSat is a proof of concept mission for the passive microwave measurement of wind direction, we feel the proper question to answer is “Do any WindSat retrieved direction aliases agree closely with the surface wind direction analysis?” Thus, the objective of this paper is to evaluate the ability of WindSat to retrieve realistic wind directions and to assess the suitability of the present geophysical model function in a tropical cyclone environment.

II. OCEANIC WIND VECTOR RADIOMETER POLARIMETRIC SIGNATURES

The microwave ocean brightness temperature (Tb) observed by a satellite radiometer depends upon a number of ocean surface and atmospheric geophysical variables, as well as measurement geometry. Fortunately, these Tb signatures are functions of the observing radiometer frequency (wavelength) and polarization, which permits the separation of these effects during the multi-frequency radiometer geophysical retrieval process [8]. For this paper, we are only concerned with the Tb signatures for the ocean surface wind vector, which will be described next in very simplified terms. For a more complete discussion, the reader is referred to the paper by Jenelak et al., in this special issue [6].
As discussed in Gaiser et al. [9], recent advances in polarimetric radiometry modeling and measurements have demonstrated that usable wind direction information can be obtained by combining the vertical and horizontal polarizations with the cross-correlation of the two [10-15]. The cross-correlation terms represent the third and fourth parameters of the modified Stokes vector [16], defined as

\[
I_s = \begin{bmatrix}
I \\
Q \\
U \\
V
\end{bmatrix} = \begin{bmatrix}
T_v \\
T_h \\
T_{45} - T_{-45} \\
T_{lc} - T_{rc}
\end{bmatrix} = \begin{bmatrix}
\frac{\langle E_v E_v^* \rangle}{2 \Re \langle E_h E_h^* \rangle} \\
\frac{\langle E_h E_h^* \rangle}{2 \Re \langle E_v E_v^* \rangle} \\
2 \Im \langle E_v E_v^* \rangle \\
2 \Im \langle E_h E_h^* \rangle
\end{bmatrix}.
\]

In this definition, \(T_v, T_h, T_{45}, T_{-45}, T_{lc}\) and \(T_{rc}\) represent brightness temperatures (radiances) at vertical, horizontal, plus 45\(^0\), minus 45\(^0\), left-hand circular and right-hand circular polarizations respectively. In principle, the Stokes vector provides a full characterization of the electromagnetic signature of the ocean surface, which is sufficient to uniquely determine the wind direction.

Of these Stokes parameters, the most useful for wind direction measurement are the 3\(^{rd}\) (implemented by the difference between the \(\pm45^\circ\) polarization channels) and the 4\(^{th}\) (implemented by the difference between the left and right-hand circular polarization channels). On WindSat, there are three channels, 10.7 GHz, 18.7 GHz and 37 GHz, that make polarimetric measurements. An example of the 18.7 GHz 3\(^{rd}\) Stokes signature, known as the geophysical model function (GMF), versus wind speed and direction is given in Fig. 1 [6]. From this figure,
it is shown that the 3rd Stokes parameter is anisotropic with the relative wind direction. This relative wind direction is defined as the difference between the wind direction and the azimuth look of the radiometer antenna, where a relative azimuth equal zero corresponds to the wind blowing toward the radiometer antenna. The 3rd Stokes can be modeled as a Fourier series of relative wind direction where the dc Fourier term is zero, and the anisotropic signature is predominantly the sum of the first and second harmonics, the coefficients of which are functions of wind speed.

The 4th Stokes parameter, shown in Fig. 2, is also anisotropic with relative wind direction. This parameter is basically second harmonic with a small first harmonic component, both of which have amplitudes which increase with wind speed. Both the 3rd and 4th Stokes signatures are relatively weak as environmental radiometric signals go; but, fortunately, they are very robust in that they are highly immune to the influences of atmospheric absorption and emission caused by water vapor and cloud liquid water. These atmospheric signals are common-mode and cancel during the subtraction of the ±45° and left and right-hand circular polarizations. Unfortunately the effect of heterogeneous precipitation is less certain because there are an extremely limited number of observations of the 3rd and 4th Stokes parameters in the presence of rain. This may have influenced the evaluation results presented herein for hurricane wind direction measurements, which usually are accompanied by strong bands of precipitation. This will be discussed further in the following section.
III. WINDSAT WIND VECTOR RETRIEVAL

To aid in the understanding of the wind vector evaluation results presented later, a brief description of the WindSat (version-0) wind vector retrieval algorithm [7] is discussed in this section, and a simplified flow chart presented in Fig. 3. The first step in the wind retrieval process is to process the four frequency, vertically and horizontally polarized WindSat Tb’s. This algorithm is similar to that implemented for SSM/I [8] to solve for four relevant environmental variables (not including wind direction). An important part of the retrieval process is the use of a forward radiative transfer model (RTM) that provides the relationship between the measured Tb’s (over oceans) as a function the sea surface and atmospheric environmental parameters. Of these environmental parameters, the four that can be retrieved are: sea surface temperature (SST), surface wind speed (WS), integrated atmospheric water vapor (WV), and integrated cloud liquid water (CLW). The geophysical retrieval algorithm inputs the measured Tb’s and solves for the unknown environmental parameters using regression relationships with the coefficients found from the forward RTM. The algorithm involves an iterative procedure that sequentially solves first for the CLW (using the 18.7, 23.8 and 37.0 GHz), then WV (using same channels), next WS (10.7, 18.7, 23.8 and 37.0 GHz), and finally SST (using only 10.7 GHz). After solving for the four parameters, the entire process is repeated several times until the retrievals converge to a stable value. It should be noted that this
environmental retrieval algorithm is not designed for high winds > 20 m/s nor any environmental retrievals in rain.

For the wind direction retrieval, the 3rd and 4th Stokes parameters for the 10.7, 18.7 and 37 GHz polarimetric channels are used as inputs with the wind speed retrieved above. Relative wind directions are varied and the modeled 3rd and 4th Stokes parameters, \((T_{U,V})_{\text{mod}}\), calculated. For each relative wind direction trial, the square of the difference between the measured and the modeled parameters \([T_{U,V}]_{\text{meas}},\;\text{and}(T_{U,V})_{\text{mod}}\) are calculated and summed for all frequencies. Values of relative wind direction that minimized the sum of these terms (cost function) for all frequencies were outputted as “possible solutions”. Because of the harmonic nature of the geophysical model functions (Figs. 1 and 2), multiple possible wind directions (called wind direction aliases) can result. It should be noted that this environmental retrieval algorithm is not designed for high winds > 20 m/s nor any environmental retrievals in rain.

For microwave scatterometer wind direction retrievals, the retrieval process is similar; but because of differences in the radar backscatter GMF, the distribution of aliases is much different than that for passive microwave polarimetry. For scatterometer wind retrievals, the number of aliases range from two to four with the two most probable directions being roughly 180° apart. For WindSat, however, the most frequent number of aliases is two or three, and the directional difference of aliases are rarely 180° apart. These WindSat aliases are ranked by the “goodness
of fit”, which is proportional to the inverse of the cost function. After ranking, the aliases subjected to a multi-pass median filter to produce a single selected vector. The alias selection skill, which is defined as the percentage of the selected directions that are closest to the true direction, is quite high (typically > 85%).

IV. SURFACE WIND ANALYSIS (H*WIND)

As mentioned previously, verification of TC surface wind fields are inherently challenging due to the dearth of data available for these systems. Fortunately, a reasonable analysis is possible when reconnaissance aircraft fly missions through the storm. Since the 1990s, these data have been processed through the H*Wind [17] analysis system. H*Wind is a software tool that provides an objective analysis of the (TC) surface wind field by assimilating all available surface observations, as well as aircraft and remotely sensed data, into a common framework that also allows for limited human quality control. The H*Wind algorithms, graphical user interface, and databases were developed over a number of years at the National Oceanographic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) and have been used for post-storm analysis and to experimentally support operational TC analysis. All data included in an analysis are transformed into a storm relative coordinate system. In this paper, the storm centers are linearly interpolated from the surrounding ‘best track’ fixes from the National Hurricane Center (NHC).
A. Wind Speed Validation Set

Caution has to be used when applying an H*Wind analysis for wind speed validation purposes. Due to a lack of data at any one time, H*Wind is not a snapshot of the wind field; rather, it is an assimilation of observations that have been collected during a three to six hour period of observations. Furthermore, much of the storm circulation remains unobserved even by including data over such a time window. Since the wind field structure of a typical TC is highly variable in both space and time, a significant error range in the analysis field is introduced. Typical wind speed errors in an H*Wind analysis are estimated to be 10%-20% [18], although that will vary depending on the quantity and quality of data that are available as well as the degree of quality control employed by the analyst. In particular, H*Wind maximum wind values are usually lower than the actual intensity of the TC due to under sampling of the TC circulation and the smoothing performed by the objective analysis.

In this paper, we were careful to choose two cases, where the TC was well sampled around the WindSat pass time, out of the possible six partial or complete WindSat passes over Atlantic TCs during the six-month data window. We selected Fabian (3 September 2147 UTC) and Isabel (17 September 1129 UTC) as suitable candidates for a wind speed comparison. In Table 1, the times of the WindSat passes are shown along with the observations incorporated into each H*Wind analysis. An additional WindSat overpass of Isabel (14 September 1040 UTC) was used for
validation of wind direction, but it was determined that there were not sufficient observations to warrant the inclusion of that pass in the wind speed comparison.

For the two aforementioned passes, the amount of data available for each pass was sufficient for a reasonable wind speed analysis. During the WindSat overpass, both storms had an Air Force Reconnaissance Aircraft (AFRES) in the circulation taking flight level wind measurements and releasing Global Positioning Satellite (GPS) dropsondes (which provide vertical profiles of several variables, including wind speed and direction from flight level to just above the surface). All wind data are transformed to a uniform one-minute average and 10 m height. The AFRES flight level winds were reduced to 10 m wind values via a planetary boundary layer model [19]. The Geostationary Orbiting Environmental Satellite (GOES) low-level cloud drift winds were reduced through methodology developed by Dunion and Velden [20]. Other data sources include the Stepped-Frequency Microwave Radiometer (SFMR) wind speeds [21], moored and drifting buoy measurements, QuikSCAT (rain flagged vectors excluded) and a few ship observations. A plot of the data coverage for each storm is shown in Figs. 4 and 5.

B. Wind Direction Validation Set

Since a typical H*Wind analysis contains a large amount of data that lack surface wind direction information (e.g. AFRES flight level winds, SFMR), surface directional analyses are found from an empirical modification of those observations. The result is an idealized, symmetric circular
flow that contains an inflow component to account for surface frictional effects. It is quite probable that a TC with a true asymmetric wind field will be represented as a symmetric storm in an H*Wind analysis, unless there is a significant amount of surface directional data available to modify the analysis. All three cases in this paper for which directional comparisons were made were represented by H*Wind as almost wholly idealized circular flows at the surface. Thus, the wind direction validation presented in Section VI is not a comparison to an observed surface wind direction. However, we believe that the comparison is valid to a first approximation since surface wind flows in strong hurricanes tend to approximate idealized flows very closely...at least over scales similar to the WindSat resolution.

V. METHODOLOGY

A. Rain Algorithm

Auxiliary TC rain fields are provided using a preliminary WindSat rain algorithm (version-0) to augment the surface wind field validation dataset. This algorithm is a modified version of the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) oceanic rainfall algorithm, which was originally developed at the Colorado State University [22, 23] for the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). The TMI 2A12 algorithm employs a multi-channel, physically-based rainfall retrieval procedure that uses cloud-resolving models to produce a large set of possible cloud profiles (over a wide range of likely
raining conditions) along with their respective passive microwave brightness temperatures. Once a database of profiles and associated brightness temperatures is established, the retrieval employs a Bayesian inversion approach to estimate rainfall on a pixel-by-pixel basis, given the set of measured brightness temperatures.

The WindSat algorithm uses four frequencies: 10.7, 18.7, 23.8, and 37 GHz. For all channels, vertically and horizontally polarized measurements are used, except for the 23.8 GHz where only the vertical polarization is used. To separate the rainfall into convective and stratiform components, the AMSR-E retrieval algorithm utilizes measurements from the 37 GHz and the high resolution 85 GHz frequency channels. Since WindSat does not have an 85 GHz channel, its algorithm depends only on the emission characteristics of the 37 GHz channel to make an assessment of the convective/stratiform nature of the rainfall.

To estimate rain rates, we used WindSat Intermediate Data Product (IDR) brightness temperatures. Since these Tb’s are measured at variable resolutions (see Table 2), we used a nearest neighbor interpolation to resample each channel (10.7 to 37 GHz) at 12.5 km spacing to allow the highest possible resolution for the rain map. Further, to co-register wind retrievals and the rain, IDR Tb’s were interpolated to the same geolocations provided in the respective EDR data products. This allows us to provide rain estimates at each EDR wind vector location for further analysis.
Improving the WindSat algorithm rain type classification capabilities will be a major topic for future investigation. Even though the preliminary WindSat rain algorithm has yet to be validated, Fig. 6 provides a subjective comparison between near simultaneous WindSat and an SSM/I (available from Naval Research Lab Monterey [24]) rain images for Hurricane Isabel. The collocation time is approximately 9 minutes, thereby minimizing any spatial and temporal differences between the two images. Locations of relative rain intensity agree well, allowing us to identify regions of significant rainfall, which may have an effect on wind vector retrievals.

B. Analysis Techniques

As previously discussed, the WindSat environmental data records (EDR’s) are based on Tb measurements at 4 frequencies with up to 6 polarizations at each frequency (see Table 2 for radiometer configuration) [25]. Since each channel is of different location and resolution, the measurements must be resampled and averaged to a common size for wind vector retrieval. This analysis uses the WindSat EDR data product, version 1.5.1 processing, in which Tb’s have been averaged to the 6.8 GHz footprint size and have been resampled at every 4\textsuperscript{th} 37 GHz location, for a spacing of about 12.5 km.

Since H*Wind analysis files are derived at a high resolution—on the order of 6 km—we needed to convert this wind analysis to a resolution equivalent to WindSat for meaningful comparisons.
Using a nearest neighbor interpolation, all H*Wind points within a radius of 25 km of the WindSat wind vector locations were weighted, inversely proportional to distance, and then averaged. Considering the inverse distance weighting, this produced an effective resolution of about 25 km at the EDR spacing of approximately 12.5 km.

Customarily, within the (scatterometer) ocean vector winds scientific community, the evaluation of remotely sensed wind directions is performed globally using the “selected” wind direction alias compared with the independent “surface truth” dataset. In this manner, both the combined effect of direction retrieval accuracy and the wind direction alias selection skill are evaluated. However, for the evaluation of WindSat directions in TCs, we choose not to adopt this philosophy and will evaluate the accuracy of the “closest” WindSat wind alias to the H*Wind direction. Considering the immaturity of the WindSat version-0 geophysical model function, especially for high winds and a highly attenuating atmosphere environment in TCs, we believe that it is unfair to penalize the wind direction measurement accuracy based upon poor wind alias selection skill.

The H*Wind surface wind analysis typically covers a region of ± 400 – 500 km surrounding the hurricane center, and wind direction differences are calculated at each EDR location. For the wind direction evaluation, we define WindSat retrieval direction differences as “closest” WindSat direction minus the corresponding H*Wind direction. The relative azimuth, X, is
defined as wind direction minus the WindSat antenna azimuth look direction, where $X = 0^\circ$ is a wind blowing toward the antenna.

C. WindSat Hurricane Passes

Three Atlantic hurricanes are used for this anecdotal case study. As discussed in Section IV, two were chosen because of the availability of coincident aircraft measurements of surface winds at the time of the WindSat pass. The selected storms are Fabian (3 September 2003 2147 UTC) and Isabel (17 September 2003 1129 UTC), for which a wind speed and directional analysis was performed. A third pass, Isabel on 14 September 1040 UTC, is also used for directional analysis. Because of the lack of sufficient wind speed data near this time, the magnitude of the wind vectors was not considered for this pass. As discussed in Section IV, this does not preclude a feasible directional analysis.

VI. RESULTS

A. Wind Directions

Subjective evaluations of WindSat wind flow patterns are made by examining the both the WindSat and H*Wind images for the three hurricane cases described above, given in Figs. 7 – 9. In each image, the wind direction is shown as a unit length vector with the WindSat closest direction shown in gray and the H*Wind analysis direction shown in magenta. For clarity of
presentation, the EDR’s have been thinned with only about 25% of the locations plotted. Also the WindSat rain rate is plotted as a color-scaled background with rain rates less than 0.3 mm/hr shown in white.

Fig. 7 shows the wind comparisons for the Isabel pass on 17 September 1129 UTC. It should be noted that there are wind retrievals in all regions of the storm. This has not been the case for conventional microwave radiometer retrievals in rain, where no parameters except rain rate are retrieved. Thus it is apparent that 3rd and 4th Stokes parameters exist even in the presence of rain; but the question is “Are the retrievals sensible?”. In this example, there is generally good agreement between the flow patterns of WindSat and H*Winds for wind directions outside areas of intense rain. However, within the rain areas, there are apparent systematic differences in the wind directions. By closer visual inspection, the direction differences are much greater in the raining regions, especially those areas with moderate to high rains. This same behavior is apparent for WindSat's pass over Isabel on 14 September, shown in Fig. 8. Wind directions within the moderate-to-high rain areas display large differences; additionally, there appears to be a systematic problem in the western region of the storm, outside of any rain. This behavior is even more obvious in Fig. 9, where, we find large systematic differences in the rain-free regions east and southeast of the center. In general, the WindSat directional retrievals in those areas are not physically realizable. Also, as expected, wind directions are highly erroneous in rain regions.
A quantitative evaluation is presented in Fig. 10, which shows a composite statistical analysis of the three hurricanes mentioned previously. For all data (Fig. 10a) there is a slight bias of -4.3° and the rms difference of 25.7°, which is consistent with the expected global performance of WindSat wind direction retrievals. This result is somewhat misleading because the hurricane force winds and the moderate to high rain rates occupy only about 10% of the total comparison region; so the majority of points are outside of this difficult region. In Fig. 10b, only locations where the rain rate < 4 mm/hr are included, and the RMS difference decreases to 22.0°. In Fig. 10c, wind direction retrievals are significantly affected by the presence of rain rates > 4 mm/hr, with differences in these high rain regions being 39.2°. In particular, results shown in Fig. 10d, a scatter diagram of the rms wind direction difference versus rain rate, exhibit a strong linear correlation. Detailed statistics are available in Table 3.

While the histograms described above show good results for wind directional retrievals for non-raining regions, there are other statistical metrics presented in Fig. 11, which indicate probable deficiencies in the model function. In the wind direction algorithm, solutions are found in terms of the relative wind direction $X$, and then from the measurement geometry (antenna azimuth relative to north), the wind direction is calculated. Insight can be found by examining relative differences between the distribution of relative directions from: (1) the measurement geometry and the independent estimates of wind directions and (2) the closest retrieved $X$’s. Such polar
plots are presented in Fig. 11 showing the relative wind direction histograms for the H*Wind directions and for the closest WindSat alias. It is noted that there are “spikes” in the WindSat distribution, which are indicative of the algorithm “locking-in” to certain preferred directions. However, similar features are not observed in the H*Winds histogram. Experience in the scatterometer ocean vector wind science community has shown that such histogram anomalies are excellent indicators of problems associated with the geophysical model function [26]. Because these spikes appear both in the all data (including rain) and non-rain histograms, it is believed that they are not the result of rain; rather they are probably the result of an improper anisotropy signature of the 3rd and 4th Stokes GMF.

B. Wind Speeds

Radiometric windspeed retrievals in a hurricane environment are severely disadvantaged considering that the WindSat geophysical model function has not been fully developed for wind speeds above 20 m/s, nor have the effects of rain been included in algorithm development. Unlike the wind directions, WindSat retrievals of wind magnitudes are quite poor over the majority of the hurricane area. Since the wind speed retrieval uses the conventional (non-polarimetric) channels, one would expect similar results as the heritage SSM/I algorithm (see Fig. 12). Note that SSM/I does not retrieve wind speeds in the region of moderate-to-high rain. For WindSat, the presence of rain over-powers the measured Tb’s and the resulting wind retrievals have large residuals of rain in them.
This can be seen in wind contour comparisons of WindSat retrievals and H*Wind wind speeds shown in Fig. 13. The WindSat wind speed difference contours shown in the lower panel strongly resemble the rain map. Fig. 13 shows the WindSat wind speed (top), H*Wind wind speed analysis (middle), and the difference between the two (bottom, WindSat – H*Wind) for Hurricane Fabian (left, 3 September 2147 UTC) and Hurricane Isabel (right, 17 September 1129 UTC). This figure immediately suggests that heavy rainfall is overwhelming any surface signal in the core and rainband areas of the TCs. For the Fabian case, WindSat maximum retrieved winds exceed 70 m/s – far higher than the official intensity estimate provided by the NHC near that time (55 m/s at 1800 UTC and 57.5 m/s at 4 September 0000 UTC). When AFRES data are available, the NHC intensities are determined primarily from flight level winds and are generally considered reliable.

Furthermore, both cases feature a wind speed difference pattern that is spatially correlated to a large degree with areas of heavy rain (see Figures 7 and 9 for comparison). For example, differences of 20-30 m/s in the Fabian pass (Fig. 13e) are found near 23°N 83°W – collocated with a large area of 27+ mm/hr rainfall (Fig. 9). Rainband patterns are clearly evident as well in both cases. Curiously, a large negative bias area is found to the south and southeast of each system. Although an exact cause cannot be determined with any certainty, we point out that rain
is light or absent in those areas. Fig. 14 reveals a strong relationship between rain rate and the wind speed difference. Both show increasing wind speed difference with increasing rain rate.

More WindSat passes over TCs must be reviewed to determine if this is a persistent pattern in the retrievals. Around the periphery of each system, there is a larger degree of agreement between WindSat and the H*Wind analysis, particularly within the wind speed range of 10-20 m/s. However, if the egregious differences seen in these two cases are evident in other cases, WindSat surface wind speed retrievals will not be usable in the any rainy area of TCs, unless suitable correction algorithms can be developed.

VII. CONCLUSION

This paper evaluates WindSat wind vector performance in a few year 2003 Atlantic hurricanes by comparison with independent surface wind field estimates using the H*Wind software analysis tool. Unfortunately, for hurricanes, there is no realizable “surface truth”; but H*Wind provides a useful tool for compositing a rather diverse collection of spatially and temporally distributed estimates of surface wind magnitude and a few directions. So with all of its limitations, H*Wind is the best that is available; and even though the WindSat comparisons are largely qualitative, they are nonetheless very useful.
The comparison results for wind speeds demonstrate that the version-0 algorithm does not perform well. This is not a surprise, because it was never intended to. This algorithm was developed for “non-precipitating atmospheres and at ocean surface winds < 20 m/s”. The vertically and horizontally polarized Tb’s are strongly affected by heavy cloud cover and precipitation in and around TCs; so it is doubtful that the wind speed retrieval will ever improve. However, the fact that the 3\textsuperscript{rd} and 4\textsuperscript{th} Stokes signals exist in this environment provides hope that a new algorithm might be developed to retrieve both wind speed and direction from these parameters.

Concerning wind directions, the comparisons are much better. The magnitude of the 3\textsuperscript{rd} and 4\textsuperscript{th} Stokes anisotropic signal increases with wind speed, which helps. Outside of the immediate vicinity of the hurricanes, the wind flow patterns look reasonable, except for a few random regions where the WindSat retrieval and H*Wind diverge. The reasons for this are not understood; but since the wind direction algorithm uses “bogus” WindSat wind speed retrievals, this may influence the results. This needs further investigation. Within a few 100’s km of the storm center, at locations with precipitation > 4 mm/hr (as inferred by an experimental WindSat rain algorithm), the wind direction differences increase with rain rate. This is clearly a failure of the algorithm; nevertheless there are some successes where reasonable wind directions retrievals are made between the intense spiral rain bands, even in regions of heavy clouds.
Finally, a few comments should be made to put Windsat wind retrievals in hurricanes into proper perspective. Despite the less than desired performance, the authors are encouraged with the limited successes. We feel that future developments, aimed at wind vector in retrievals in hurricanes, will likely improve. After all, the scatterometer remote sensing community has been investigating this special application for decades with only limited success – it’s a really tough problem that requires persistence and innovative approaches to advance.

ACKNOWLEDGMENT

The authors would like to thank Dr. Richard Knabb (Tropical Prediction Center) for sound editing advice and Dr. Mark Powell (Hurricane Research Division) for answering many H*Wind questions. Many thanks to Dr. Chris Kummerow for help in applying the AMSR-E rain algorithm to WindSat.
References


Table 1. Observation platforms used by H*Wind to produce the analyses fields for Fabian and Isabel (2003).

<table>
<thead>
<tr>
<th>Observation</th>
<th>Fabian 3 Sep. 2003 2147 UTC</th>
<th>Isabel 17 Sep. 2003 1129 UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number Obs</td>
<td>Time Frame</td>
</tr>
<tr>
<td>AFRES</td>
<td>134</td>
<td>18:00 – 20:22</td>
</tr>
<tr>
<td>SFMR</td>
<td>701</td>
<td>18:00 – 23:20</td>
</tr>
<tr>
<td>Moored Buoy</td>
<td>0</td>
<td>18:00 – 00:00</td>
</tr>
<tr>
<td>Drifting Buoy</td>
<td>12</td>
<td>18:00 – 00:00</td>
</tr>
<tr>
<td>GOES</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Ship</td>
<td>11</td>
<td>18:18 – 00:00</td>
</tr>
</tbody>
</table>
Table 2. WindSat instrument configuration.

<table>
<thead>
<tr>
<th>Band, GHz</th>
<th>Polarizations</th>
<th>Bandwidth, MHz</th>
<th>Earth Incidence Angle, degrees</th>
<th>Horizontal Spatial Resolution, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>V, H</td>
<td>125</td>
<td>53.5</td>
<td>40 x 60</td>
</tr>
<tr>
<td>10.7</td>
<td>V, H, ±45, L, R</td>
<td>300</td>
<td>49.9</td>
<td>25 x 38</td>
</tr>
<tr>
<td>18.7</td>
<td>V, H, ±45, L, R</td>
<td>750</td>
<td>55.3</td>
<td>16 x 27</td>
</tr>
<tr>
<td>23.8</td>
<td>V, H</td>
<td>500</td>
<td>53.0</td>
<td>12 x 20</td>
</tr>
<tr>
<td>37.0</td>
<td>V, H, ±45, L, R</td>
<td>2000</td>
<td>53.0</td>
<td>8 x 13</td>
</tr>
</tbody>
</table>
Table 3. Wind Direction Error Statistics.

<table>
<thead>
<tr>
<th></th>
<th>Fabian</th>
<th>Isabel 09/14</th>
<th>Isabel 09/17</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Data</td>
<td>Mean</td>
<td>-6.3</td>
<td>-4.07</td>
<td>-1.27</td>
</tr>
<tr>
<td></td>
<td>STD</td>
<td>30.01</td>
<td>20.35</td>
<td>25.73</td>
</tr>
<tr>
<td>Rain &lt; 4 mm/hr</td>
<td>Mean</td>
<td>-8.79</td>
<td>-3.01</td>
<td>-0.19</td>
</tr>
<tr>
<td></td>
<td>STD</td>
<td>27.28</td>
<td>17.71</td>
<td>16.38</td>
</tr>
<tr>
<td>Rain &gt; 4 mm/hr</td>
<td>Mean</td>
<td>7.01</td>
<td>-13.44</td>
<td>-3.81</td>
</tr>
<tr>
<td></td>
<td>STD</td>
<td>39.07</td>
<td>34.71</td>
<td>39.78</td>
</tr>
</tbody>
</table>
Fig.1 Example of measured and modeled 3$^{rd}$ Stokes wind direction geophysical model function at 18.7 GHz from [6].
Fig. 2 Example of measured and modeled $4^{\text{th}}$ Stokes wind direction geophysical model function at 18.7 GHz from [6].
Fig. 3  NOAA NESDIS Wind Wind Vector Retrieval Algorithm Version-0 Flow Chart.
Fig. 4  Observations assimilated into the H*Wind system for Hurricane Fabian, 2147 UTC 3 September. Data were collected from 1800 UTC through 0000 UTC on 4 September. The location of Fabian at this time is shown as a circle in the inner box. Yellow is SFMR from NOAA P-3 aircraft. Red barbs are flight level winds reduced to surface vector from Air Force C-130. Light blue (near core) corresponds to GPS Dropsondes (surface values). Pink is QuikSCAT non-rain flagged winds. See Table 1 for an expanded listing of specific data sources utilized.
Fig. 5 Observations that were assimilated into the H*Wind system for Hurricane Isabel at 1129 UTC 17 September. Data were collected from 0757 UTC through 1449 UTC. The location of Isabel at this time is shown as a circle in the inner box. Red barbs are flight level winds reduced to surface vector from Air Force C-130. Light blue (near core) corresponds to GPS Dropsondes (surface values). Pink is QuikSCAT non-rain flagged winds. See Table 1 for an expanded listing of specific data sources utilized.
Fig. 6 Rain rates for Hurricane Isabel, September 14, morning. SSM/I (a) 25 km resolution at 1049 UTC [24], Windsat (b) 12.4 km resolution at 1040 UTC. SSM/I image courtesy of NRL/Monterey.
Fig. 7 Windsat (gray) and H*Wind (magenta) wind directions, 17 September 1129 UTC with Windsat rain rate background. Majority of errors are visible in the moderate-to-high rain areas.
Fig. 8 Windsat (gray) and H*Wind time interpolated wind directions, 14 September 1040 UTC with Windsat rain rate background. Large errors are present northeast and northwest of the eye outside of the raining region.
Fig. 9 Windsat (gray) and H*Wind (magenta) wind directions, 03 September 2147 UTC with Windsat rain rate background. Large errors are present east and southeast of the eye outside of the raining region.
Fig. 10 Statistical Analysis of overall Windsat performance for three hurricane passes from 2003 hurricane season. (a) is the wind direction error all data, (b) corresponds to rain rates less than 4 mm/hr and (c) is wind direction error for rain rates above 4 mm/hr. Panel (d) shows a strong linear correlation between the magnitude of the wind direction error and rain rates. Xs are absolute mean direction difference, with vertical lines denoting standard deviation of each bin. Linear fit to the data is also plotted.
Fig. 11  Relative wind direction polar histogram for closest wind direction aliases and H*Wind analysis. Hurricane Isabel, 14 September 1040 UTC.
Fig. 12  SSMI Wind Speed Retrieval (left panel) and WindSat wind field. Hurricane Isabel, 14 September 1040 UTC.
Fig. 13 Hurricane Wind Speed Comparison. Left column is Fabian, 3 September, 2147 UTC. Right column is Isabel, 17 September, 1129 UTC. First row is Windsat wind speeds, second row is H*Wind and third row is windspeed difference.
Fig. 14 Hurricane Wind Speed Difference vs. Rain Rate. (a) is Fabian, 03 September 2147 UTC and (b) is Isabel, 17 September 1129 UTC. Black Xs are mean wind speed differences for 5 mm/hr rain bins, and vertical lines denote standard deviations. Linear fit is also plotted.