10.5 OPERATIONAL EVALUATION OF QUIKSCAT OCEAN SURFACE VECTOR WINDS IN TROPICAL CYCLONES AT THE TROPICAL PREDICTION CENTER/NATIONAL HURRICANE CENTER

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1. INTRODUCTION

The mission of Tropical Prediction Center/National Hurricane Center (TPC/NHC) is to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather, and by increasing the understanding of these hazards. One of the most significant challenges in accomplishing this mission is the scarcity of data over the oceans that make up the TPC/NHC area of responsibility, which for tropical cyclones (TCs) comprises the North Atlantic basin (including the Gulf of Mexico and Caribbean Sea) and the eastern North Pacific basin (east of 140ºW). Remotely-sensed ocean surface vector winds from the SeaWinds scatterometer onboard the QuikSCAT satellite, operated by the National Aeronautics and Space Administration (NASA), help to fill some of the data gaps. These data have become an important analysis and forecast tool at TPC/NHC since becoming available in near real time in 2000.

SeaWinds onboard QuikSCAT is an active Ku-band scatterometer operating at 13.4 GHz that estimates ocean surface vector winds by measuring the return of backscatter due to centimeter-scale ocean surface waves (e.g., Hoffman and Leidner 2005). QuikSCAT nominally provides wind retrievals with a horizontal resolution of 25 km, and post-processing techniques have resulted in 12.5-km retrievals being available in near real time (NRT) since 2003. The QuikSCAT data available at TPC/NHC are processed at the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) using the NRT retrieval process described by Hoffman and Leidner (2005). These data are displayed on the NOAA/National Centers for Environmental Prediction (NCEP) Advanced Weather Interactive Processing System (N-AWIPS) workstations used by forecasters at TPC/NHC, allowing them to overlay various data types (e.g., satellite imagery, conventional surface observations, etc.) with QuikSCAT.

The swath of data provided by QuikSCAT is 1800 km wide, making it possible at times to sample the entire circulation of a TC in one overpass. However, at low and middle latitudes, QuikSCAT can only provide a maximum of two passes per day over a given TC. The gaps between QuikSCAT swaths exceed 550 km equatorward of 20ºN latitude and are near 1000 km at the Equator, which can result in all or part of a TC going unsampled for 24 h or more. Data acquisition and processing results in a delay of approximately 1.5–3 hours between the collection of raw data by the satellite and receipt of the 25-km QuikSCAT wind retrievals on the forecaster's workstations. The 12.5-km data is delayed an additional 45–60 minutes. These delays can limit the accuracy of TPC/NHC analyses and forecasts, especially in situations when other observations are sparse (e.g., when reconnaissance aircraft are not flying into the system).

One of the primary limitations of QuikSCAT wind data is contamination due to the effects of rain, particularly in TCs where strong winds are most often found in regions of deep convection and high rainfall rates. Previous research (e.g., Chelton and Freilich 2005; Chelton et al. 2006) has shown that rain can increase the retrieved wind speed due to reflection of the satellite's emitted beam off of the raindrops, and/or from roughening of the sea surface due to raindrop impacts. Rain can also decrease the retrieved wind speed by attenuating the wind-induced backscatter signal from the ocean surface. The sign of the retrieved wind speed bias due to rain varies with both the rain rate and the actual wind speed near the ocean surface. In TCs, it has been found that rain tends to artificially inflate the retrieved QuikSCAT wind speeds when actual winds are less than 30–40 kt. Conversely, rain tends to cause underestimates in retrieved wind speeds when the actual winds are stronger than 30–40 kt (Edson et al. 2002, Edson 2004). In other words, properly interpreting QuikSCAT retrievals in rain requires some knowledge of the actual wind speeds that are already occurring. This bias reversal near 30–40 kt is especially unfortunate, as it straddles the intensity threshold (34 kt) between a tropical depression and a tropical storm, which can complicate decisions on both storm

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classification and the issuance of tropical storm watches and/or warnings.

The lack of an independent measure of rain rate on the QuikSCAT platform makes operational interpretation of rain effects on the QuikSCAT wind retrieval very difficult. TPC/NHC forecasters often ignore the empirical rain flag (Huddleston and Stiles 2000; Hoffman and Leidner 2005), because in rain-free areas the retrieval still tends to flag high wind speeds, and in rainy areas rain-flagged retrievals can provide reasonable wind speed estimates when actual wind speeds exceed 30–40 kt. Instead, forecasters subjectively assess the impact of rain on the retrieved QuikSCAT wind speed. This assessment is usually made by examining geostationary satellite imagery near the time of the QuikSCAT pass, which provides some indication of where deep convection is occurring, although with great uncertainty given the unavailability of explicit rain rate information. Occasionally, microwave imagery from other platforms is used to assess rain impacts, but that imagery is rarely coincident with a QuikSCAT overpass.

The automated QuikSCAT wind vector retrieval is chosen from among up to four possible wind directions, or "ambiguities", at each location in the measurement swath. The automated solution is chosen by an ambiguity removal filter (Hoffman and Leidner 2005), but the choice of the "wrong" ambiguity often results in the wind solution being 180º out of phase with the actual wind direction, and this type of error often occurs in patches or lines. Ambiguity removal error can also impact the wind speed solution, since each directional ambiguity has a slightly different wind speed. Errors in ambiguity removal severely limit the ability of QuikSCAT to properly identify or locate closed circulations such as those associated with TCs. Therefore, TPC/NHC forecasters often manually analyze all the possible wind solutions in the QuikSCAT swath (i.e., the "ambiguities") to subjectively locate a circulation center and then utilize the wind speeds associated with the "correct" ambiguities. In fact, it is becoming common practice at TPC/NHC, for determining wind speeds and directions in a QuikSCAT swath over a TC, to manually analyze the ambiguities without even considering the automated vector solution.

Despite its limitations, QuikSCAT data are heavily used at TPC/NHC for TC analysis, underscoring the tremendous need for remotely sensed wind data. One objective measure of the frequency of QuikSCAT use is how often the data are mentioned in TPC/NHC's tropical cyclone discussion (TCD) products. These discussions are issued for each active TC with every routine 6-h forecast package, and for occasional "special" advisory issuances. TCDs from 2003–2006 (2006 data through 29 September) were examined for any mention of QuikSCAT. The use of QuikSCAT was then sorted by three analysis parameters: intensity (maximum sustained surface wind), center fixing/identification, and wind radii. Each TCD where QuikSCAT was used for TC analysis was placed into one or more of the three categories, since some TCDs mentioned that QuikSCAT was used for analyzing two or all three of the parameters.

The frequency of Atlantic basin TCDs containing references to QuikSCAT steadily increased from around 10% in 2003 to over 20% in 2006, while remaining between 15% and 18% in the eastern North Pacific (Fig. 1). The use of QuikSCAT has been effectively greater, since at most two QuikSCAT passes are available per day over a given TC. This means that only two of the four routine daily forecast cycles (and their accompanying TCDs) could have new QuikSCAT data to consider. Additionally, in some cases, QuikSCAT could have been used in the forecast process and not mentioned in the TCD. If one considers only the one-half of all TCDs for which new QuikSCAT data could have been available, the "effective" frequency of references to QuikSCAT in those TCDs at TPC/NHC has reached 35–40% in both basins.

When QuikSCAT was mentioned in TCDs from 2003–06, the data was most often used to make some judgment about the current intensity of the TC (62%), and less frequently for center fixing/identification (21%) and wind radii analysis (17%) (Fig. 2).

Details on the application of QuikSCAT in the analysis of these three parameters are provided in the next section. Section 3 describes an updated NRT retrieval algorithm that aims to slightly improve the rain flagging and the data quality near the edge of the QuikSCAT swath. Finally, based on operational experiences with the benefits and limitations of QuikSCAT, section 4 describes the need for a next-generation satellite capable of measuring ocean surface vector winds in all weather conditions encountered in TCs.

2. TC ANALYSIS APPLICATIONS

a.) Center fixing/identification

As mentioned earlier, errors that occur in the directional ambiguity removal process can significantly reduce, and in some cases eliminate, the ability of QuikSCAT to provide TC center fixes via the automated wind vector solution. This limitation is likely due to (i) the effects of Global Forecast System (GFS) model forecasts of TC structure and location (since the GFS is used in the ambiguity removal process), and (ii) rain contamination that results in retrieved wind directions oriented perpendicular to the track of the satellite (Chelton and Freilich 2005). These errors in ambiguity removal at just a few locations can often result in the QuikSCAT wind solution misplacing or even failing to identify the center of a TC.

Therefore, TPC/NHC forecasters sometimes perform a manual analysis of all the possible wind solutions (i.e., an “ambiguity analysis”) in an attempt to determine if a surface circulation exists and, if so, where it is located. The forecasters analyze streamlines on a plot of the ambiguities (the plotting convention of the ambiguities points *toward* the direction the wind is blowing, opposite of the standard meteorological convention), working inward toward a suspected center and remaining consistent with adjacent ambiguities that correspond to a cyclonic circulation. The starting point of the analysis is chosen, if possible, in a region where either the wind direction is known from other observations and/or where points in the QuikSCAT swath show only two potential wind directions (i.e., two-way ambiguities), implying less uncertainty in the wind direction. An example of a manual ambiguity analysis is shown in Fig. 3 for a QuikSCAT pass over Tropical Storm Helene in the eastern Atlantic at 0800 UTC 14 September 2006.

The automated QuikSCAT solution shows a broad center near 12.5ºN and 34.8ºW (Fig. 3a) well south and west of the 0600 UTC NHC best track position of Helene at 13.2ºN, 33.8ºW. A manual analysis of the data (Fig. 3b) is begun northeast of the suspected center, in a region of two-way ambiguities, where the easterly ambiguity (wind from the east) is chosen given that an easterly wind would be expected north and east of the suspected center location, as suggested by a time series of geostationary satellite imagery (not shown).

West of 35ºW, the ambiguities allow for a turn in the streamlines toward the south, and a turn back to the east is required north of 13ºN due to the lack of northerly ambiguities in this region. The westerly ambiguities are followed to near 34ºW where a turn to the north and then the west is required due to the lack of southerly ambiguities along a row of points extending from 13.6ºN, 35.0ºW to 13.7ºN, 34.0ºW. These two-way ambiguities strongly suggest that the center of Helene is located south of this location. Following the easterly ambiguities, a turn to the south can occur no farther west than 34.8ºW, due to the lack of northerly ambiguities west of this longitude. As a result, a center can be closed off near 13.3ºN, 34.6ºW.

This ambiguity analysis indicates a much better-defined surface circulation than that suggested by the automated QuikSCAT solution, and the ambiguity analysis places the center farther to the north, closer to the NHC best track position at this time. These analyses are particularly valuable in tropical depressions and tropical storms, where the cyclone center is often not well-defined or easily identified in geostationary satellite imagery. Adjustments in TC center location are vital to determining (i) the organization of the cyclone (i.e., how close the center is to any deep convection) and therefore its intensity, and (ii) the precise forward motion of a TC, which is used to initialize track model guidance, making the location of the TC center critical to the entire forecast process. These ambiguity analyses are also helpful in identifying if a closed surface circulation exists, which is part of the process of determining whether or not a TC has formed.

Performing this type of ambiguity analysis can take several minutes and, depending on forecaster workload, cannot be performed on every QuikSCAT overpass. Additionally, this manual analysis involves subjective interpretation and can still result in uncertainty in the exact center location. Complete elimination of ambiguity removal errors would require a fundamentally different and enhanced type of measurement from a future satellite that does not suffer from such directional uncertainties near circulation centers.

b.) Intensity

To quantify the utility of QuikSCAT in TC intensity estimation, error statistics were computed for the maximum wind of the automated QuikSCAT solution against the NHC best track intensity for all available passes over TCs during the 2005 Atlantic season. This sample included 172 25-km and 147 12.5-km passes over Atlantic TCs. QuikSCAT maximum wind speeds were extracted from retrievals that were placed on grids (0.25º horizontal spacing for the 25-km retrievals and 0.125º for the 12.5-km retrievals). These maxima were then compared to the NHC best track intensity at the time closest to the applicable QuikSCAT overpass. The average biases of the QuikSCAT maximum wind speeds were then calculated for tropical depressions, tropical storms, and hurricanes binned by category on the Saffir-Simpson Hurricane Scale (Fig. 4).

While the NHC best track intensity estimates are more uncertain when aircraft reconnaissance data are unavailable, identical bias calculations were performed on a sub-sample of 69 25-km and 64 12.5-km QuikSCAT passes where aircraft reconnaissance data were available within 3 h of the QuikSCAT pass time. These results (not shown) are nearly identical to those of the larger sample presented below, and suggest that any additional uncertainty in the NHC best track intensity data when aircraft reconnaissance data are not available does not affect this evaluation of the skill of QuikSCAT in estimating TC intensity.

In 34 passes over Atlantic tropical depressions, the 25-km QuikSCAT maximum wind had an average bias of +12.1 kt (Fig. 4). This result strongly suggests that rain contamination severely inflates QuikSCAT wind speed maxima at this stage of development.

This bias was even more pronounced in the 12.5-km QuikSCAT product (+21.9 kt in 29 overpasses).

The bias was not as large for tropical storms. In 77 passes over Atlantic tropical storms during 2005, the 25-km QuikSCAT maximum wind had an average bias of +1.0 kt, while the 12.5-km maximum wind compared less favorably with an average bias of +8.3 kt in 62 overpasses (Fig. 4). Some of the reduced bias was due to cancellation of fairly large positive and negative errors, as the mean absolute error (MAE) values were 7.0 kt for the 25-km retrievals, and 11.0 kt for the 12.5-km retrievals, for TCs of tropical storm intensity.

The magnitude of the bias of the 25-km solution reversed sign and substantially increased in magnitude to –15.3 kt in 35 overpasses of Category 1 hurricanes (Fig. 4). The increased resolution of the 12.5-km product usually results in a greater retrieved wind speed, resulting in a bias of only –4.5 kt in 33 passes over Category 1 hurricanes with this data. At Category 2 intensity, the magnitude of the low biases increased for both datasets, to –30 kt for the 25-km data and –11 kt for the 12.5-km data, although the number of passes at this intensity was much smaller.

The limitations of using QuikSCAT for intensity analysis are especially evident in major hurricanes. The 25-km QuikSCAT maximum wind had average biases of –34.8, –51.8, and –71.0 kt in Category 3, 4, and 5 hurricanes, respectively (Fig. 4). Corresponding average biases for the 12.5-km retrievals were –29.4, –37.0, and –55.0 kt. Attenuation of the backscattered surface signal by rain, the limited horizontal resolution of the instrument, and saturation of the non-raining backscatter signal at wind speeds greater than about 90 kt (e.g., Fernandez et al. 2006), make it impossible for QuikSCAT to measure the maximum wind speed in the inner core of a major hurricane.

QuikSCAT data is sometimes used for determining the NHC best track intensity, which makes a direct comparison between QuikSCAT and the best track intensity somewhat problematic. Therefore, a comparison was also made between the QuikSCAT maximum wind and the Dvorak current intensity estimates from TPC's Tropical Analysis and Forecasting Branch (TAFB). Results of this comparison (not shown) revealed biases in QuikSCAT intensity estimates that are quite similar to those presented above.

Overall, these results demonstrate that QuikSCAT has limited utility in intensity estimation for tropical depressions, since the backscattered surface signal produced by relatively weak winds is often overwhelmed by rain effects. In moderate to strong tropical storms and some Category 1 or 2 hurricanes, the backscatter signal due to the surface wind increases to the point where it likely does reach the satellite and can provide some useful information on intensity. However, due to some attenuation of the surface backscatter signal by rain, QuikSCAT wind speed estimates at these intensity ranges still exhibit large variability. Intensity estimation by QuikSCAT is severely low-biased and essentially impossible for major hurricanes, due to a combination of limited horizontal resolution, signal saturation at very high wind speeds, and rain attenuation. Examples of QuikSCAT passes over TCs of varying intensity are presented next to highlight the utility and shortcomings of QuikSCAT in TC intensity analysis.

A QuikSCAT pass over Tropical Depression 16 (later Hurricane Ophelia) just prior to 0000 UTC on 7 September 2005 illustrates the limited utility of QuikSCAT intensity estimates at this stage of development (Fig. 5). The NHC best track intensity of the depression at this time was 30 kt. However, rain-contaminated QuikSCAT vectors in the area of cold cloud tops north and east of the center show wind maxima of 40–45 kt in the 25-km data (Fig. 5) and 56 kt in the 12.5-km data (not shown). A NASA Tropical Rainfall Measuring Mission (TRMM) overpass at 2126 UTC 6 September shows estimated rain rates exceeding 1 in hr^{-1} northeast and east of the center (Fig. 6), strongly suggesting that rain contamination inflated the QuikSCAT wind speeds in these areas.

Later, a QuikSCAT pass over Tropical Storm Ophelia at 1116 UTC 9 September (Fig. 7a), when the intensity was 55 kt, shows a 56-kt wind maximum very close to where the NOAA Stepped-Frequency Microwave Radiometer (SFMR) retrieved a wind maximum of 58 kt only a short time later (Fig. 7b). At this time, it is possible that the actual surface wind speeds in Ophelia had reached a magnitude where the backscatter returned to the QuikSCAT instrument due to the surface wind was no longer being significantly contaminated by rain. However, this interpretation is not straightforward, since an independent measurement of rain rate is not available from QuikSCAT, and since the influence of rain on the QuikSCAT retrieved wind speed varies with both the rain rate and the actual wind speed.

Finally, a QuikSCAT pass over Hurricane Katrina (Fig. 8) at 1128 UTC 28 August 2005 shows a wind maximum of only 75 kt, while Katrina had maximum winds of 145 kt derived from aircraft reconnaissance data. This example clearly demonstrates the limitations of QuikSCAT intensity estimates in major hurricanes.

c.) Wind radii

Another important operational parameter for TCs is a measure of the size of the system as depicted by wind radii. TPC/NHC defines the wind radii as the largest extent of particular wind speeds in each of the four quadrants of the cyclone. While the utility of QuikSCAT for intensity analysis is limited in major hurricanes, it can still be quite useful in the analysis of

34-kt and occasionally 50-kt wind radii in most tropical storms and hurricanes, especially since these wind areas can extend beyond the region of heavy rainfall in the inner core of the TC. Wind radii information from QuikSCAT is particularly valuable for TCs that are not sampled by aircraft reconnaissance, since the radii are critical for determining the location and timing of tropical storm and hurricane watches and warnings.

For example, the same QuikSCAT pass over Katrina (Fig. 8) that only showed a maximum wind of 76 kt demonstrates the utility of QuikSCAT in wind radii analysis. A gridded isotach field generated from the 25-km QuikSCAT winds (Fig. 8b) shows a well-defined 34-kt wind radius around the cyclone that agrees closely with several ship, buoy, and reconnaissance observations (not shown) over the Gulf of Mexico that day. For TCs not sampled by aircraft reconnaissance and over the open ocean, where ship and buoy observations are sparse, QuikSCAT is often the most reliable measure of wind radii available to TPC/NHC forecasters.

In addition to the TC analysis applications described above, QuikSCAT data have been assimilated into global analyses at NCEP and the European Centre for Medium-Range Weather Forecasting (ECMWF) since 2002 (Hoffman and Leidner 2005). These data have improved the analysis of 10-m winds (Chelton and Freilich 2005, their Fig. 11) and somewhat improved forecasts of 10-m winds and sea-level pressure in the NCEP and ECMWF global models.

3. NEW NRT RETRIEVAL ALGORITHM

A new QuikSCAT NRT retrieval algorithm based on changes made to the science-quality retrieval algorithm at NASA's Jet Propulsion Laboratory has been developed and is currently being tested in parallel. Improvements in the experimental retrievals that are relevant to TPC/NHC's use of QuikSCAT include the following:

1) A new rain "impact" flag that only flags vectors where the wind retrieval is deemed to be impacted by rain effects, rather than flagging all vectors where the presence of rain is merely suspected.

2) A modified backscatter-wind relationship based on wind speeds data from SSM/I measurements. For winds in the 32–60 kt range, the retrieved wind speeds will increase on average by about 6%.

3) Improved wind retrieval quality on the edge of the QuikSCAT swath, including an additional row of vectors on the swath edge.

4) A modified land mask for the 12.5-km QuikSCAT retrieval that will provide wind retrievals to within 20 km of the coast instead of 25 km.

To evaluate the changes in the experimental NRT retrieval, QuikSCAT data from 2003 were re-processed at NESDIS using the new NRT retrieval for evaluation by users. Passes over 2003 Atlantic TCs were examined at TPC for TC intensity and center fixing applications, comparing the results of the experimental NRT processing to the current operational NRT retrievals. The same was done for passes over Atlantic and eastern North Pacific TCs during a portion of the 2006 hurricane season.

Sixty-four passes using the re-processed data from 2003 were examined. In this dataset the QuikSCAT wind maximum showed an average increase of 5–10 kt in passes where the old QuikSCAT maximum wind was 55 kt or greater (Fig. 9a). Compared to NHC best track intensities, the mean absolute error (MAE) of the maximum winds from the experimental NRT retrievals decreased by 0.7 kt compared to the operational NRT retrieval and the average bias was reduced by 3.4 kt.

Similar trends are seen in the 88 passes analyzed from 2006 (Fig. 9b), although a larger number of passes showed a wind speed increase in the new algorithm of 10 kt or more when the old NRT maximum was in the 50–70 kt range. The increase in the retrieved wind speed of 5–10 kt is not sufficient to overcome the extreme low bias of QuikSCAT seen in hurricanes at Category 2 intensity or higher. Additionally, this change in the backscatter-wind relationship means that rain-contaminated wind maxima will have an even larger bias in weak TCs. Therefore, the experimental NRT QuikSCAT retrieval algorithm will still be unable to accurately depict intensity throughout the TC lifecycle.

The new "impact" rain flag in the experimental NRT retrieval should result in only about 2% of the vectors being flagged compared to 5–8% of the vectors with the operational rain flag. This will reduce the over-flagging of wind vectors in regions where no rain is present, which often occurs if actual wind speeds exceed about 15 kt (e.g., Hoffman et al. 2004). This change could potentially improve the TC center fixing utility of the automated solution, since rain-flagged vectors that were left out of the first step of the ambiguity removal process may now be included. To examine this possibility, the center fixes from the automated solution of the operational and experimental QuikSCAT NRT retrieval algorithms were compared to the linearly-interpolated NHC best track position for 54 passes over 2003 Atlantic TCs. It should be noted that this comparison is not independent if the automated QuikSCAT solution was used in determining the best track location of the TCs in the sample; however, in most cases a manual analysis of QuikSCAT ambiguities is used for determining center location, rather than the center fix provided by the automated solution.

The results of this comparison were mixed, with some experimental NRT passes showing improvement over the operational NRT fix, while others showed degradation (Fig. 10). While some overpasses showed changes in the center fix location of 10–20 nm or more, 72% showed a difference of 10 nm or less between the retrieval algorithms. On average, the experimental NRT retrieval fixes were actually 3 nm worse than the operational fixes compared to NHC best track data. These results strongly suggest that even with the new retrieval algorithm, automated QuikSCAT solutions will not be able to provide reliable center fixes for TCs. Therefore, TPC/NHC forecasters will need to continue to utilize manual ambiguity analysis to identify and locate TC circulation centers, largely ignoring whether or not the data have been rain-flagged by the NRT algorithm.

Any improvement in the quality of the QuikSCAT retrievals along the edge of the swath is beneficial to TPC/NHC, since overpasses (especially in the deep Tropics) frequently capture only a portion of the TC circulation. The extra row of wind vector solutions will provide additional data, and higher quality wind retrievals along the swath edge will increase the utility of the data. An example of this improvement is seen in a QuikSCAT pass over Tropical Depression Nine around 0845 UTC 28 September 2006 (Fig. 11). The center of the cyclone was located on the south side of the deep convection (not shown), and the wind direction in the experimental NRT wind solution (Fig. 11b) looks much more realistic along the edge of the swath when compared to the operational retrieval (Fig. 11a). The experimental retrieval shows more southwesterly flow south and east of the center and more easterly flow north of the center. In contrast, the operational retrieval has nearly uniform south to south-southeast flow along the edge of the swath, resulting in a lower wind speed northeast of the center when the easterly ambiguities are chosen instead of the southerly ones (not shown). The automated wind solution will not always be as reasonable as in this example, so TPC/NHC forecasters will in most cases still need to perform a manual ambiguity analysis, which will also benefit from the new extra data along the edge of the swath.

4. BEYOND QUIKSCAT

Evaluation of QuikSCAT winds continue at TPC/NHC along with evaluation of data from the WindSat polarimetric radiometer to determine if passive radiometry can provide wind speed and direction information of a quality comparable to that obtained with the relatively well-understood scatterometry approach.

The availability of QuikSCAT data has demonstrated both the utility and the limitations of ocean surface vector winds in the operational environment at TPC/NHC. QuikSCAT helps to partially fill an immense data void in surface wind observations over the open oceans, and it can provide useful information in the analysis of TCs, as evidenced by its frequent mention in NHC TCDs. However, the experience with QuikSCAT has revealed significant limitations with the data for TC analysis purposes.

The major limitations of QuikSCAT from the TPC operational perspective include the following:

1) the inability to resolve maximum winds in the inner core of most hurricanes due to limited horizontal resolution, instrument signal saturation, and attenuation by rain;

2) rain contamination and the resulting biases in retrieved wind speeds;

3) the lack of collocated rain rate data to determine the influence of rain on the retrieved wind solution;

4) an incomplete understanding of the influence of rain on the backscatter returned to the satellite;

5) ambiguity removal errors that make QuikSCAT-derived TC center locations unreliable and make difficult the determination of whether a circulation center exists in incipient systems;

6) the low frequency of passes over any given region (at most two passes per day with a single satellite) and the largest gaps between swaths in the Tropics;

7) the time lag between the satellite overpass and data receipt at TPC/NHC.

It is our hope that by describing the benefits and shortcomings of the current platform, future platforms will be designed to build upon the strengths of QuikSCAT and address the problems and needs outlined here and elsewhere in the literature (e.g., Hoffman and Leidner 2005; Chelton et al. 2006; Von Ahn et al. 2006). To facilitate this effort, the TPC/NHC requirements for a next-generation sensor for retrieval of ocean surface vector winds from satellite are outlined as follows:

1) a greatly reduced or even non-existent sensitivity to rain, and a resulting capability to provide reliable wind speed and direction retrievals regardless of rain rate (no rain, light rain, or heavy rain);

2) the capability to accurately measure all sustained wind speeds encountered in tropical cyclones, from zero up to 165 kt (the greatest maximum sustained wind speed in the best track database), which compared to QuikSCAT would presumably require an increase in horizontal resolution (to about 1–4 km) and an increased sensitivity of the raw measurement to extreme wind speeds;

3) the capability to measure wind direction to within 10–20º, which is particularly necessary for more

accurate position fixing of the center of a TC, and/or for determining if a closed circulation center exists at all (a key factor in determining whether or not tropical cyclogenesis has occurred);

4) more timely data availability; reduce time of data receipt to a few minutes following the time of data collection by the satellite;
5) multiple satellites to provide more continuous monitoring of systems, especially in the deep Tropics; increase frequency of retrievals over each fixed location in the TPC areas of responsibility to every 1–3 hours.

Currently, one of the most daunting operational forecasting challenges at TPC/NHC is to predict the future intensity and structure of TCs. An increase in the accuracy and spatial and temporal coverage of ocean surface vector wind data in real time would improve the analysis of the initial state of the TC wind field. Also, these data would provide an improved initialization of TC structure in numerical models, and a spatially continuous analysis against which to judge operational model forecasts of TC structure. Together, these improvements in the quality of TC wind field analysis would lead to more accurate and timely forecasts, watches, and warnings for the public.

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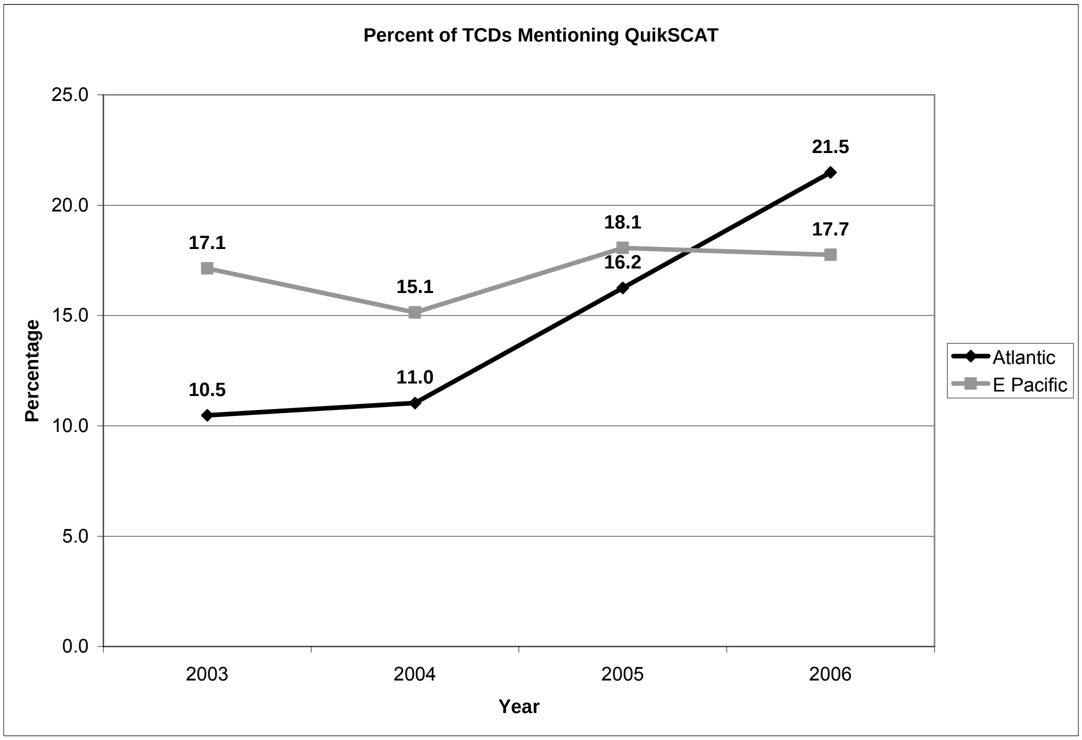

Figure 1. **Trend in percentage of NHC tropical cyclone discussions (TCDs) mentioning QuikSCAT in the Atlantic and eastern North Pacific basins. 2006 season data through 29 September.**

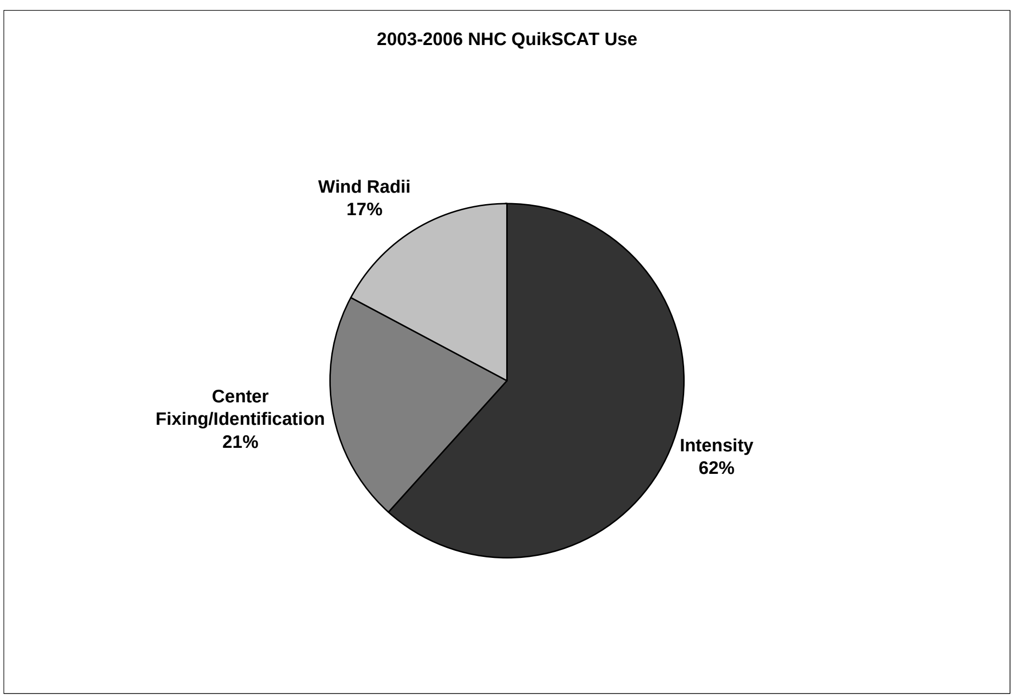

Figure 2. **Use of QuikSCAT based on NHC TCDs from 2003–2006 in the Atlantic and eastern North Pacific basins sorted into categories of intensity, center fixing/identification, and wind radii analysis. 2006 season data through 29 September.**

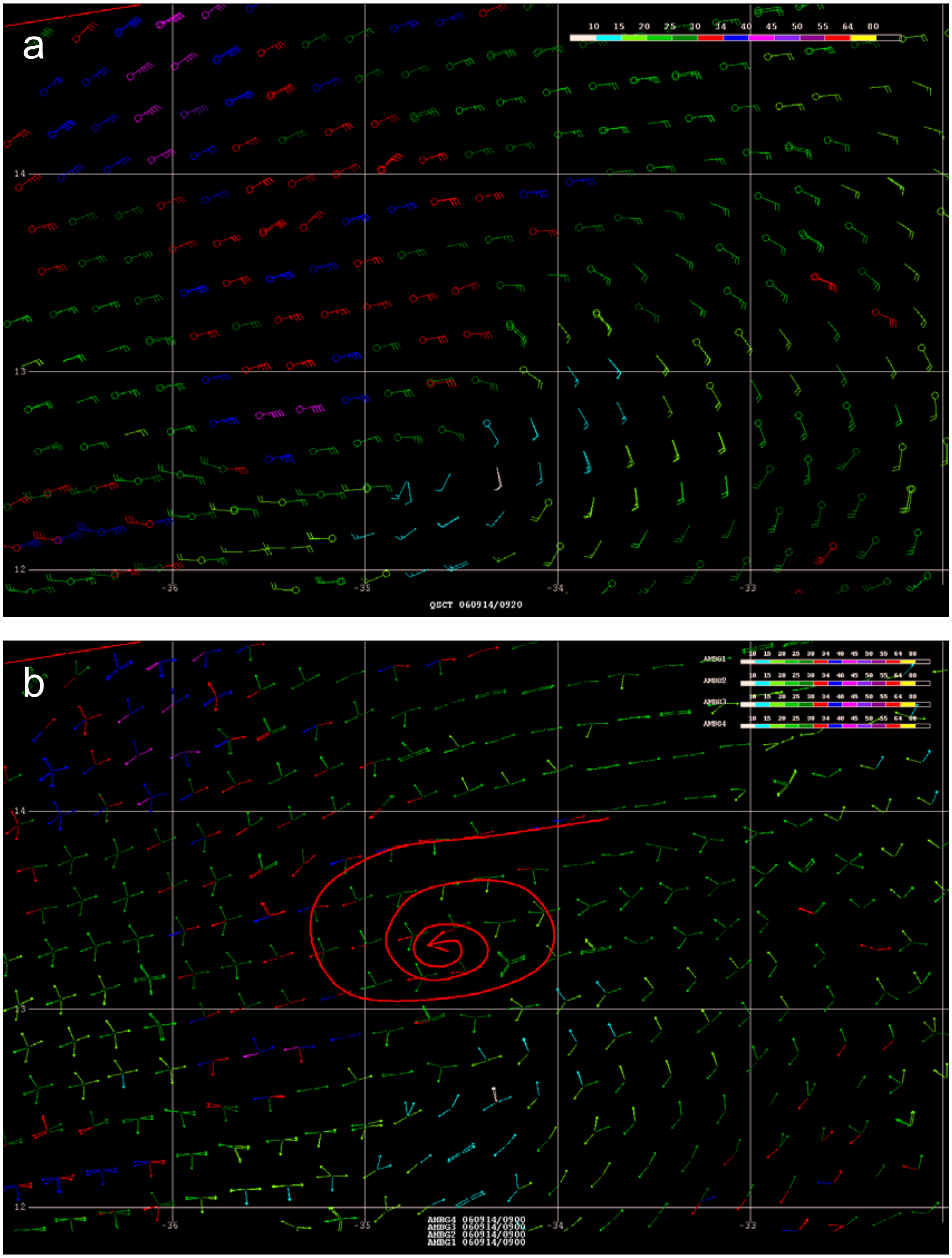

Figure 3. (a) Automated QuikSCAT solution in a pass over Tropical Storm Helene at 0800 UTC 14 September 2006 showing a broad center near 12.5°N, 34.8°W. (b) Manual analysis of QuikSCAT ambiguities (red streamline) showing the center of Helene farther northeast near 13.3°N, 34.6°W. Ambiguities are plotted opposite of standard meteorological convention (arrows point toward the direction the wind is blowing).

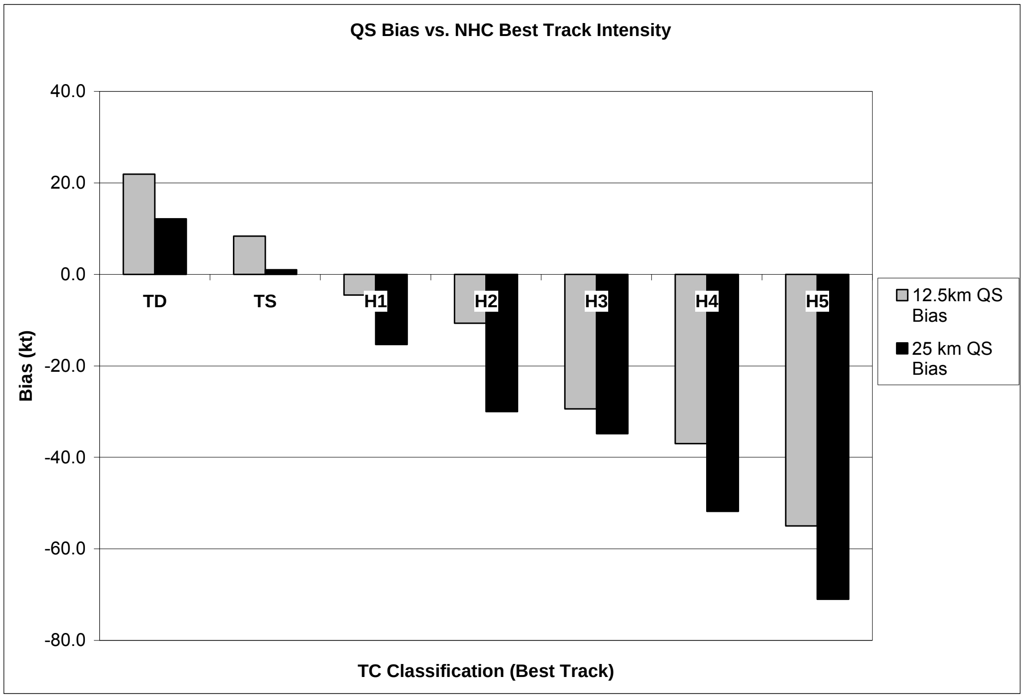

Figure 4. Average bias of QuikSCAT maximum wind compared to nearest 6-h NHC best track intensity in passes over 2005 Atlantic basin tropical cyclones, binned by TC intensity category (tropical depression, tropical storm, and hurricanes in each Saffir-Simpson Hurricane Scale category.

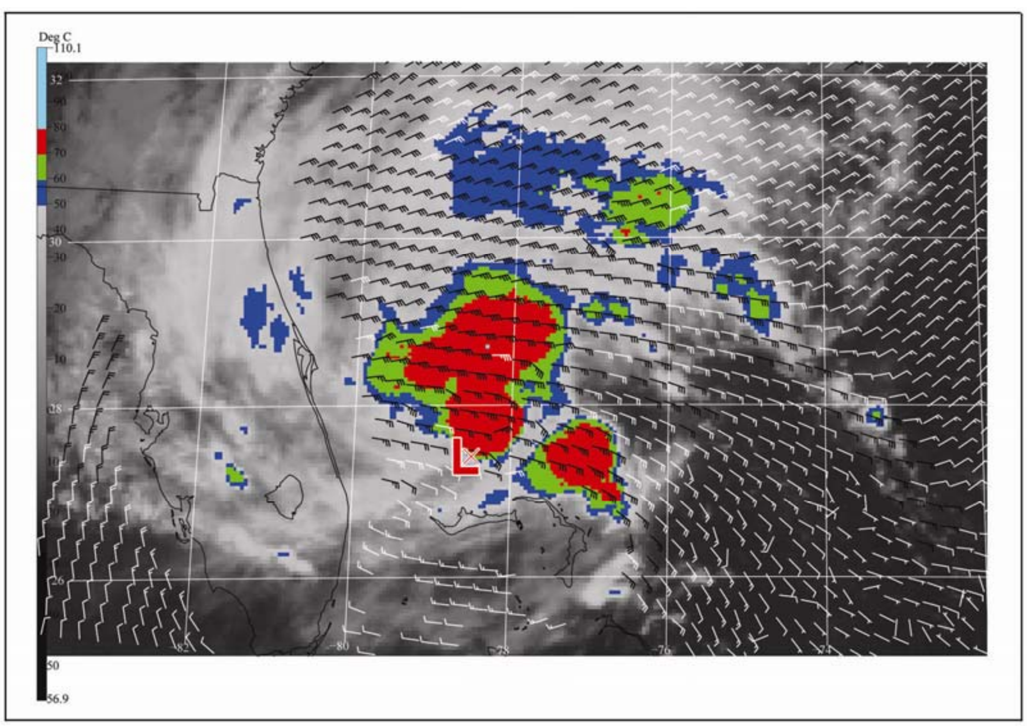

Figure 5. QuikSCAT automated 25-km wind solutions (barbs, kt) from 2316 UTC 6 September 2005 over Tropical Depression 16 (later Ophelia) with 2345 UTC *GOES-12* enhanced infrared satellite image. Black wind barbs are flagged for possible rain contamination. "L" indicates the 0000 UTC 7 September NHC best track position of the depression.

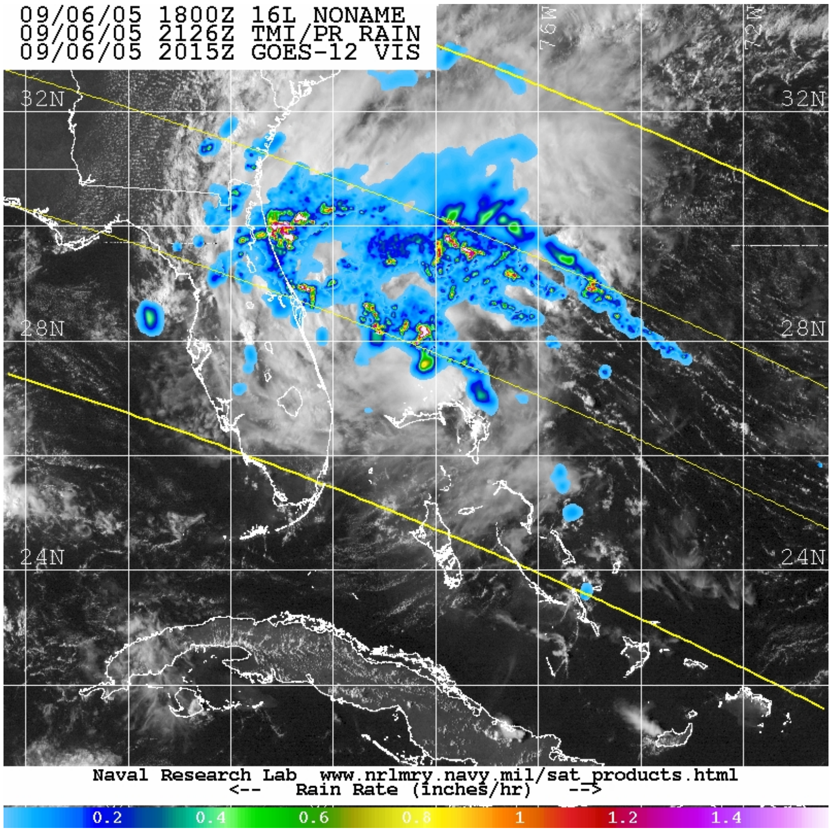

Figure 6. TRMM rain rate (color-filled contours, inches per hour) valid at 2126 UTC 6 September 2005 over Tropical Depression 16. Image courtesy of the Naval Research Laboratory TC web page.

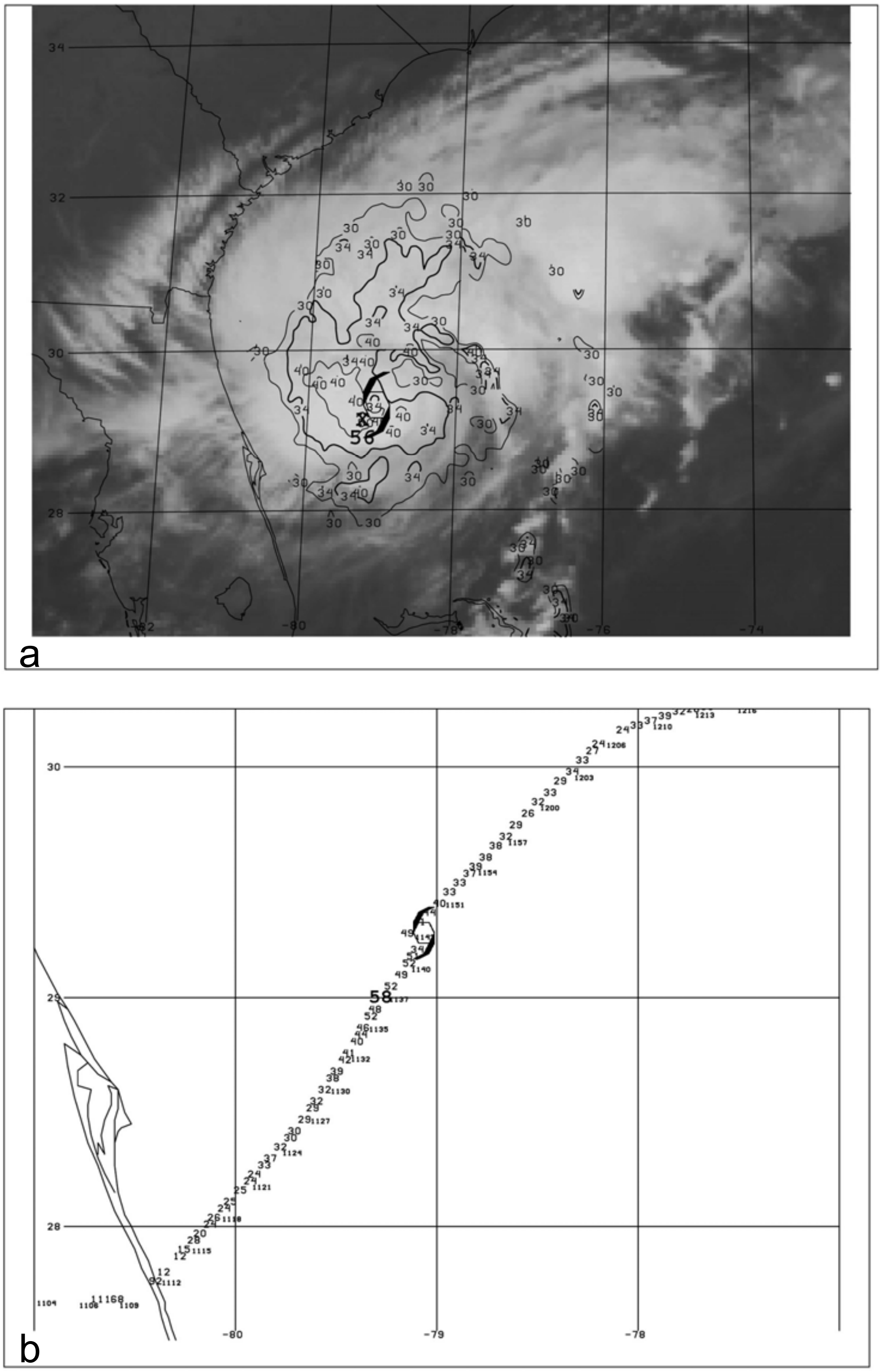

Figure 7. (a) Infrared *GOES-12* imagery from 1145 UTC 9 September 2006 and isotachs from 12.5-km QuikSCAT automated wind solution (contours) from 1127 UTC 9 September over Tropical Storm Ophelia. Maximum wind location is indicated by "X". (b) Surface wind speed (kt, large numerals) from the NOAA Stepped-Frequency Microwave Radiometer (SFMR) with time of observation (UTC, small numerals) indicated. The maximum wind measured by the SFMR around 1200 UTC was 58 kt near 29.0°N, 79.3°W. The tropical storm symbol indicates the approximate 1200 UTC NHC best track position of Ophelia.

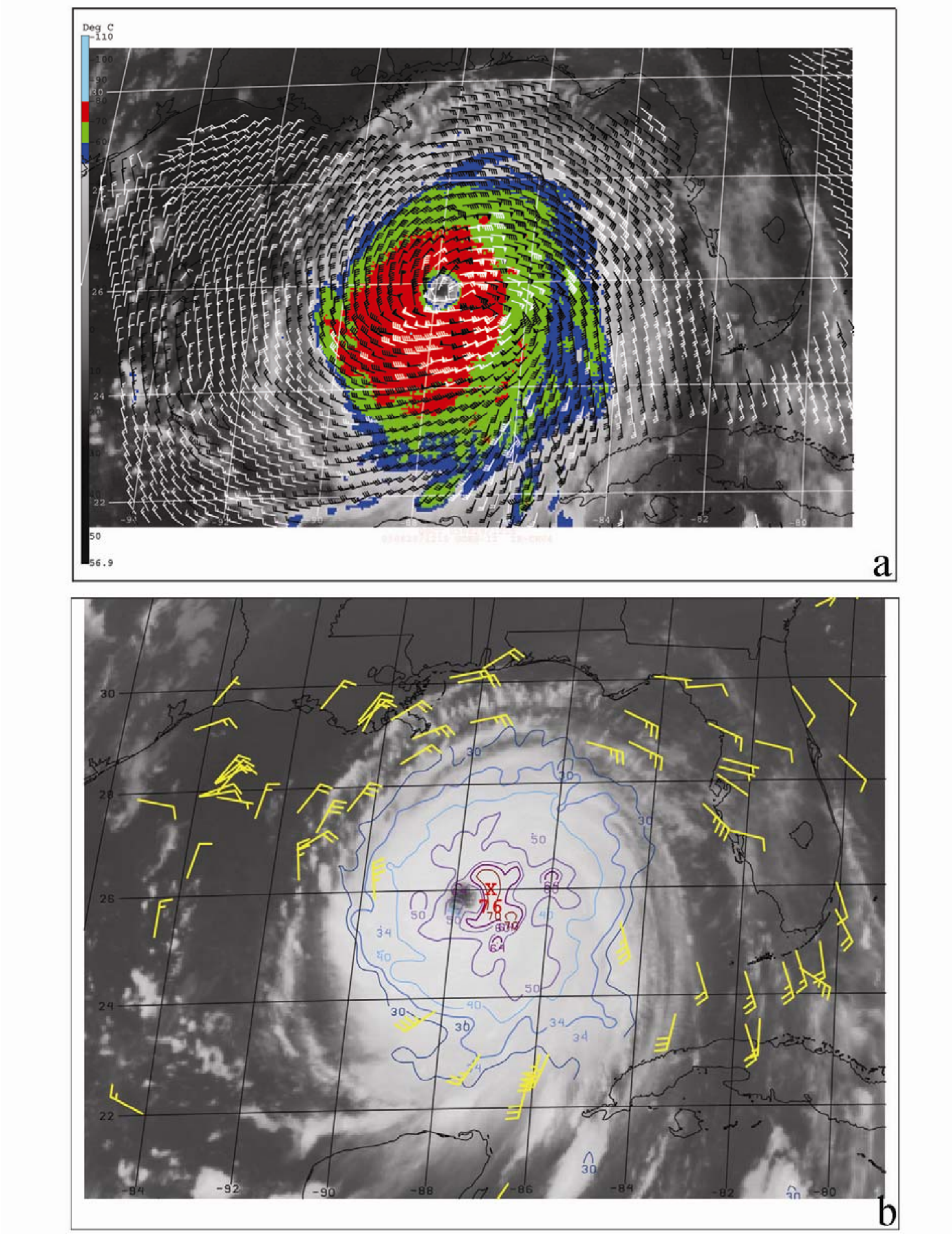

Figure 8. (a) QuikSCAT automated 25-km wind solutions (barbs, kt, black barbs are flagged for rain) from 1127 UTC 28 August 2005 over Hurricane Katrina with 1145 UTC *GOES-12* enhanced infrared image, and (b) isotachs (color contours, kt) from 25-km automated QuikSCAT winds at 1127 UTC 28 August 2005 over Hurricane Katrina with 1200 UTC ship and buoy wind observations (barbs, kt) and 1145 UTC *GOES-12* infrared image.

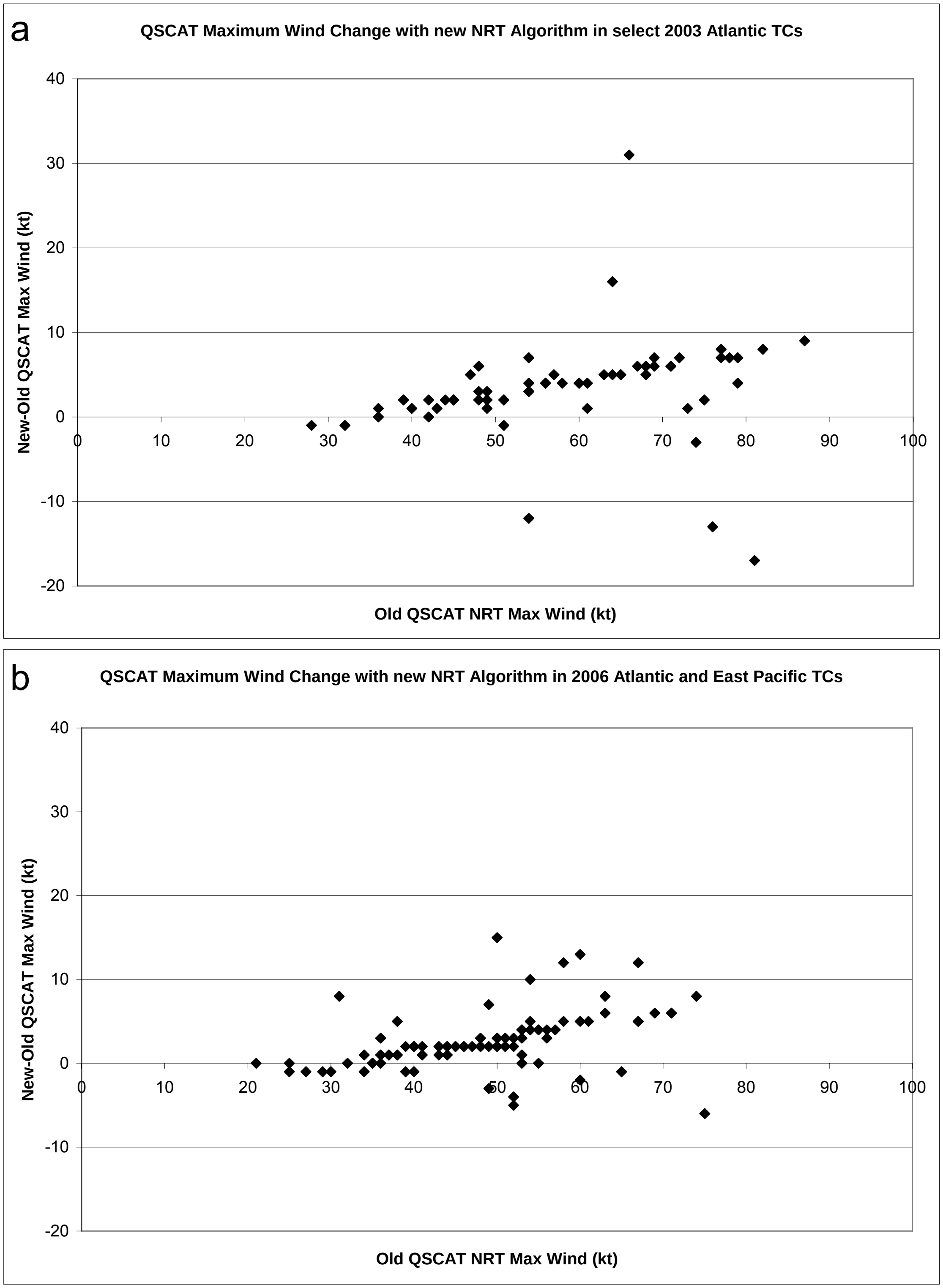

Figure 9. (a) Change in QuikSCAT maximum wind (kt) with experimental NRT retrieval compared to operational NRT retrieval maximum wind for 64 passes over 2003 Atlantic TCs; (b) as in (a) except for 88 passes over eastern North Pacific and Atlantic TCs in 2006.

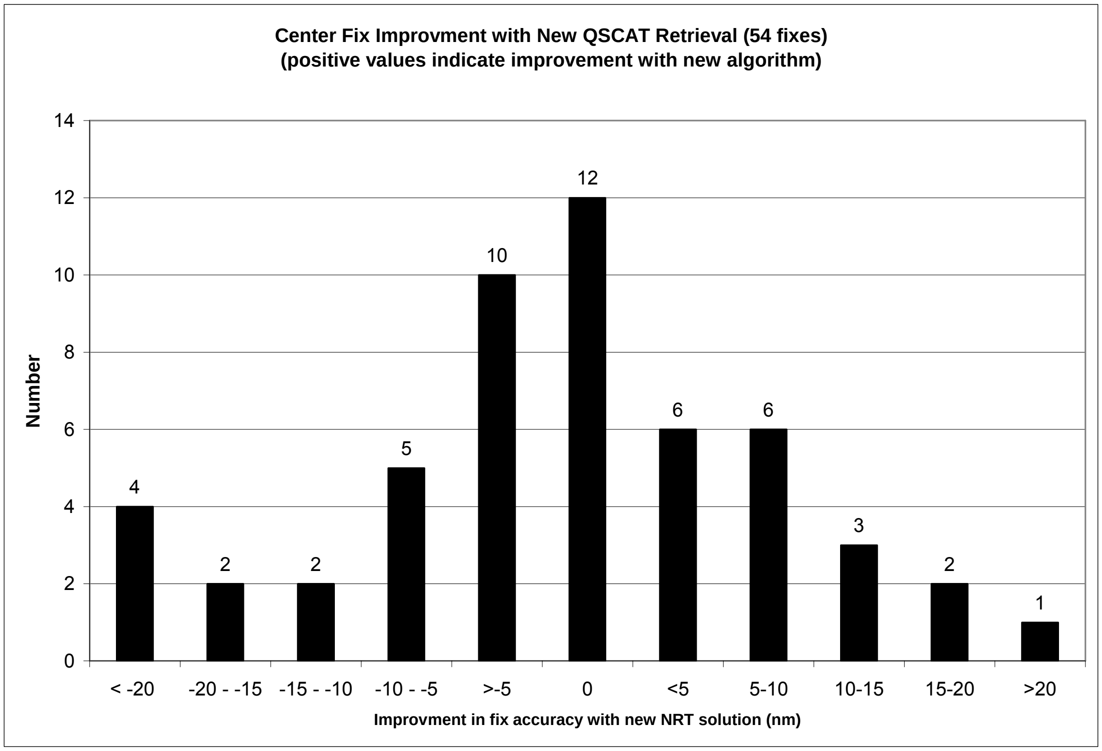

Figure 10. Distribution of improvement/degradation in TC center fix accuracy (nm) with experimental NRT retrieval compared to interpolated NHC best track for 54 passes over 2003 Atlantic TCs.

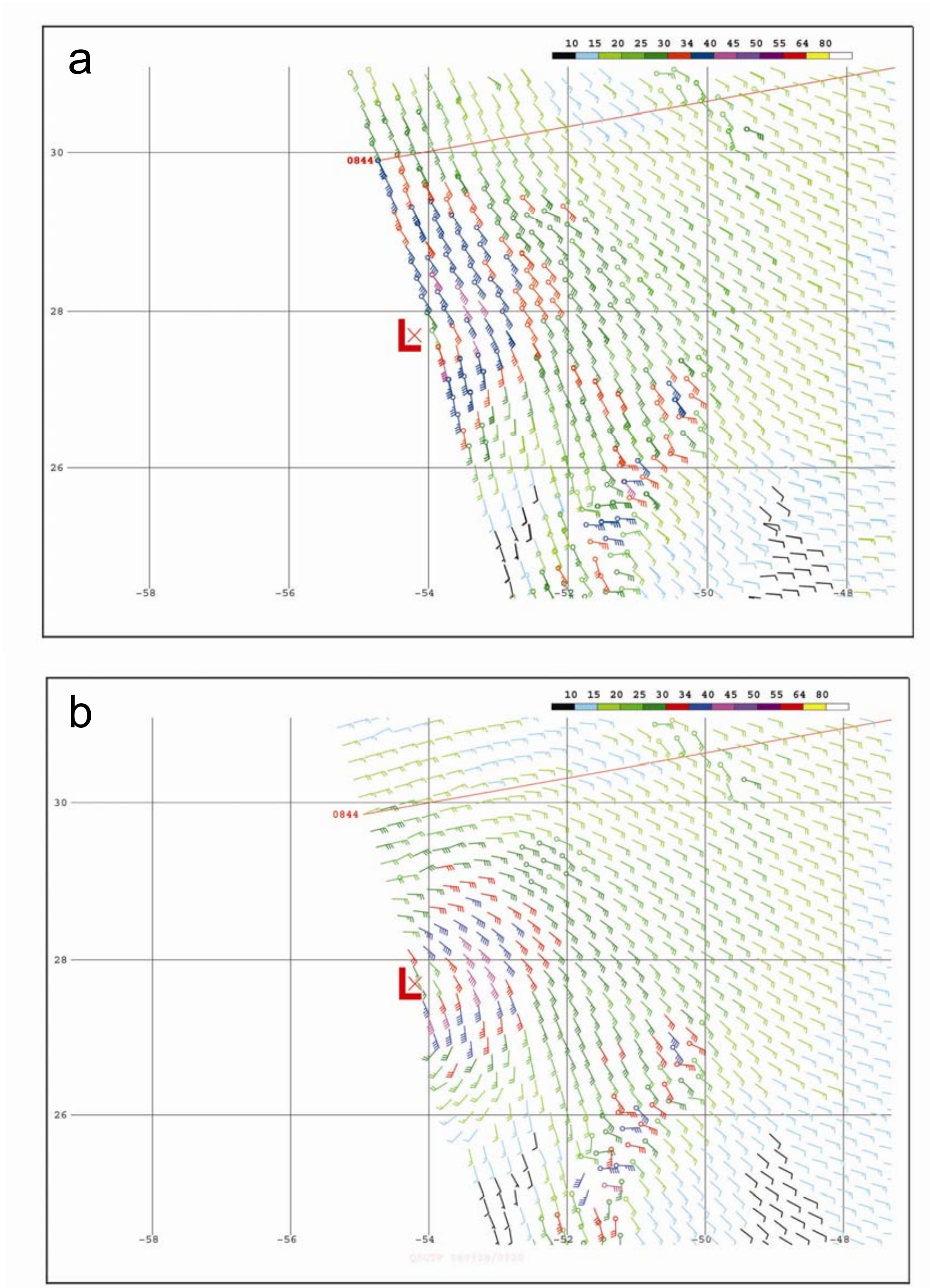

Figure 11. (a) QuikSCAT overpass with operational automated retrieval over Tropical Depression 9 at 0842 UTC 28 September 2006; (b) as in (a) except from experimental retrieval. "L" indicates the approximate 0900 UTC position of the depression.