The Operational Use of QuikSCAT Ocean Surface Vector Winds at the National Hurricane Center

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ABSTRACT

The utility and shortcomings of near-real-time ocean surface vector wind retrievals from the NASA Quick Scatterometer (QuikSCAT) in operational forecast and analysis activities at the National Hurricane Center (NHC) are described. The use of QuikSCAT data in tropical cyclone (TC) analysis and forecasting for center location/identification, intensity (maximum sustained wind) estimation, and analysis of outer wind radii is presented, along with shortcomings of the data due to the effects of rain contamination and wind direction uncertainties. Automated QuikSCAT solutions in TCs often fail to show a closed circulation, and those that do are often biased to the southwest of the NHC best-track position. QuikSCAT winds show the greatest skill in TC intensity estimation in moderate to strong tropical storms. In tropical depressions, a positive bias in QuikSCAT winds is seen due to enhanced backscatter by rain, while in major hurricanes rain attenuation, resolution, and signal saturation result in a large negative bias in QuikSCAT intensity estimates.

QuikSCAT wind data help overcome the large surface data void in the analysis and forecast area of NHC's Tropical Analysis and Forecast Branch (TAFB). These data have resulted in improved analyses of surface features, better definition of high wind areas, and improved forecasts of high-wind events. The development of a climatology of gap wind events in the Gulf of Tehuantepec has been possible due to QuikSCAT wind data in a largely data-void region.

The shortcomings of ocean surface vector winds from QuikSCAT in the operational environment at NHC are described, along with requirements for future ocean surface vector wind missions. These include improvements in the timeliness and quality of the data, increasing the wind speed range over which the data are reliable, and decreasing the impact of rain to allow for accurate retrievals in all-weather conditions.

1. Introduction

The mission of the National Hurricane Center (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 large portions of the NHC's areas of responsibility (Fig. 1), which for tropical cyclones (TCs) include the North Atlantic basin (including the Gulf of Mexico and Caribbean Sea) and the eastern North Pacific basin (east of 140°W). In addition, NHC has responsibility for marine analyses, forecasts, and warnings in the portions of the tropical North Atlantic and eastern Pacific Oceans. Remotely sensed ocean surface vector wind (OSVW) data from the SeaWinds scatterometer on board the National Aeronautics and Space Administration (NASA) Quick Scatterometer

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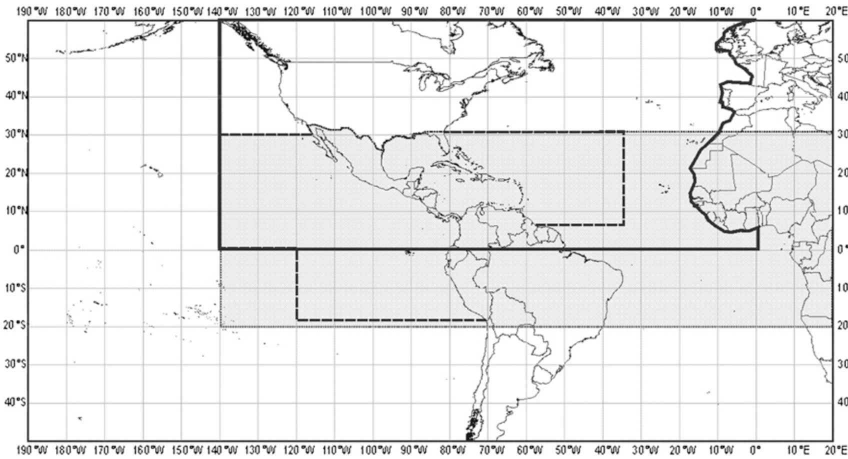

FIG. 1. Map showing NHC's area of responsibility for TCs (outlined by thick black line), marine forecasts (outlined by dashed black line), and surface analysis (shaded area).

(QuikSCAT) satellite, a near-polar-orbiting research satellite launched in June 1999, have helped fill some of these data gaps. QuikSCAT wind retrievals have become an important tool for analysis and forecasting at NHC since becoming available in near–real time in 2000. These retrievals are utilized frequently by NHC's Hurricane Specialists Unit in the analysis and forecasting of TCs, and are also used by NHC's Tropical Analysis and Forecast Branch (TAFB) in the issuance of marine forecasts and warnings, as well as in surface analyses.

The utility of QuikSCAT winds in the analysis and forecasting of extratropical cyclones and marine weather in the mid- and high latitudes at the Ocean Prediction Center (OPC) is documented by Von Ahn et al. (2006), while Chelton et al. (2006) and Atlas et al. (2001) describe the utility of scatterometer winds in general marine forecasting applications. Our purpose is to expand on those works by highlighting the strengths and weaknesses of QuikSCAT wind data as applicable to the operational forecasting mission at NHC, with an emphasis on TC applications. Section 2 provides a brief description of the QuikSCAT instrument, data availability, and the general characteristics of the data. Sections 3 and 4 describe the application, evaluation, and benefits of QuikSCAT data in NHC analyses, forecasts, and warnings. Examples of QuikSCAT's utility for TCs are presented in section 3, while section 4 focuses on utilization by TAFB. Section 5 identifies some important limitations of QuikSCAT for operational use at NHC. Section 6 examines other current and potential sources of satellite OSVW data and lists National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS) requirements for future satellite retrievals of these data. A summary is provided in section 7.

2. QuikSCAT overview

Hoffman and Leidner (2005) provide a description of the QuikSCAT platform that includes details beyond the brief summary provided here. SeaWinds on board QuikSCAT is an active microwave pencil-beam scanning radar (scatterometer), operating at 13.4 GHz (Ku band), that estimates 10-m wind speed and direction by measuring the return of backscatter due to centimeter-scale capillary waves on the ocean surface and assuming a neutral stability profile to adjust the wind to the standard 10-m height. QuikSCAT nominally provides surface wind retrievals with a unique vector every 25 km, although postprocessing techniques have resulted in 12.5-km retrievals being available in near–real time since 2003. In addition, techniques for even finer-resolution retrievals are under development (e.g., Long 2006). QuikSCAT provides retrievals in swaths that are 1800 km wide, resulting in coverage of about 90% of the global oceans each day, although the overall coverage is least in the deep tropics, where gaps between adjacent swaths approach 1000 km. Reliable retrievals of wind speeds up to about 90 kt (46.3 m s^{-1}) [equivalent to category 2 on the Saffir–Simpson hurricane scale (e.g., Simpson 1974)] can be produced in rain-free areas (e.g., Fernandez et al. 2006), but this is not possible in most TCs. The retrievals are impacted by moderate to heavy rain, but winds of tropical storm force can sometimes be estimated from QuikSCAT in rainy conditions with careful forecaster interpretation.

The QuikSCAT data available at NHC are processed at NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) using the near-real-time (NRT) retrieval process described by Hoffman and

Leidner (2005). These data are displayable at the NOAA/NWS/National Centers for Environmental Prediction (NCEP) Advanced Weather Interactive Processing System (N-AWIPS) workstations used by forecasters at NHC. This capability is critical in allowing forecasters to overlay and carefully analyze QuikSCAT retrievals with other data types (e.g., geostationary satellite imagery, conventional surface observations, numerical weather prediction model output fields, etc.).

The design of the QuikSCAT instrument results in up to four possible wind solutions, or ''ambiguities,'' in each wind vector cell (WVC) over which the retrieval is performed. An ambiguity removal filter chooses a solution (hereafter the ''automated'' solution) from among the ambiguities in each WVC (Hoffman and Leidner 2005). The ambiguity removal filter utilized in the NESDIS NRT retrievals is initialized with a 6–9-h forecast 10-m wind field from the NCEP Global Forecast System (GFS) model. Both the automated solutions and the ambiguities are displayable in N-AWIPS at NHC, which is important since the ambiguities are often manually analyzed by a forecaster to properly interpret the QuikSCAT retrievals, especially in TCs.

3. Operational benefits of QuikSCAT for TC analyses and forecasts

QuikSCAT data are heavily used at NHC for TC analysis, especially when aircraft reconnaissance data are not available, which is usually the case for systems in the eastern half of the Atlantic basin and anywhere in the eastern North Pacific basin. The frequent use of QuikSCAT by hurricane specialists at NHC underscores the tremendous operational need for remotely sensed surface wind data in the TC environment. Applications of QuikSCAT in operational TC analysis and forecasting include center identification, center location, intensity estimation, and wind radii analysis; examples of each of these applications are provided below. At the end of this section, we summarize our estimates of how often NHC forecasters use QuikSCAT for each of these applications.

a. Center location and identification

Tropical cyclone center locations derived from the automated QuikSCAT wind solutions are often unreliable, showing large positional errors or the absence of a closed circulation altogether. Therefore, forecasters at NHC perform a manual analysis of all the possible wind solutions (i.e., an ''ambiguity analysis'') in an attempt to locate the surface circulation or determine if one exists. This manual procedure is essentially a streamline analysis that is performed by examining all of the possible ambiguities, working inward toward a suspected center and attempting to choose ambiguities that correspond to a closed cyclonic circulation.[1] The starting point for the analysis is chosen, if possible, in a region where either the wind direction is known from other observations, or at points in the QuikSCAT swath that show only two or three potential wind directions (i.e., two- or three-way ambiguities), implying less uncertainty in the wind direction.

Real-time ambiguity analysis at NHC is often used in tropical depressions and tropical storms, where the surface circulation is often not well defined and may not be easily identified in visible or infrared satellite imagery. This is a critical issue, because identifying the presence of a closed surface circulation is a requirement for initiating advisories on a TC. Also, accurately specifying the initial location of the circulation center is vital to determining the organization and intensity of the cyclone [i.e., the location of the center relative to the deep convection, to which Dvorak satellite intensity estimates (Dvorak 1975) are very sensitive], and the forward motion of the cyclone, which greatly influences the short-term official track forecast and is used to initialize model track guidance. In addition, the manual analysis is necessary for properly obtaining a TC intensity estimate from QuikSCAT, because the wind speeds vary slightly among each of the ambiguities at each WVC.

The utility of the manual ambiguity analysis for determining if a circulation center exists has been manifested in specific operational decisions. One such example occurred in a pass at 1035 UTC 25 August 2008 in the Caribbean Sea over what was classified as Tropical Depression 7 shortly thereafter. The automated QuikSCAT solution showed the signature of an open wave at the surface, with the flow curving from the southeast to the northeast roughly along 68°W (Fig. 2a). However, manual analysis of the ambiguities showed that a closed surface circulation existed in the vicinity of 14.6°N, 68.7°W (Fig. 2b); this was a critical piece of information used in initiating advisories on Tropical Depression 7 (which later became Hurricane Gustav) at 1500 UTC that day (Pasch and Roberts 2008). The presence of a circulation is also supported by 37-GHz color composite imagery from the U.S. Navy's WindSat radiometer at around 1055 UTC that day (Fig. 2c). Based in part on evidence from QuikSCAT, advisories were initiated on the depression, and associated tropical storm watches and warnings were issued about 3 h prior to the arrival of aircraft reconnaissance into the system.

[1] The plotting convention of the ambiguities is *toward* the direction the wind is blowing, opposite of the standard meteorological convention.

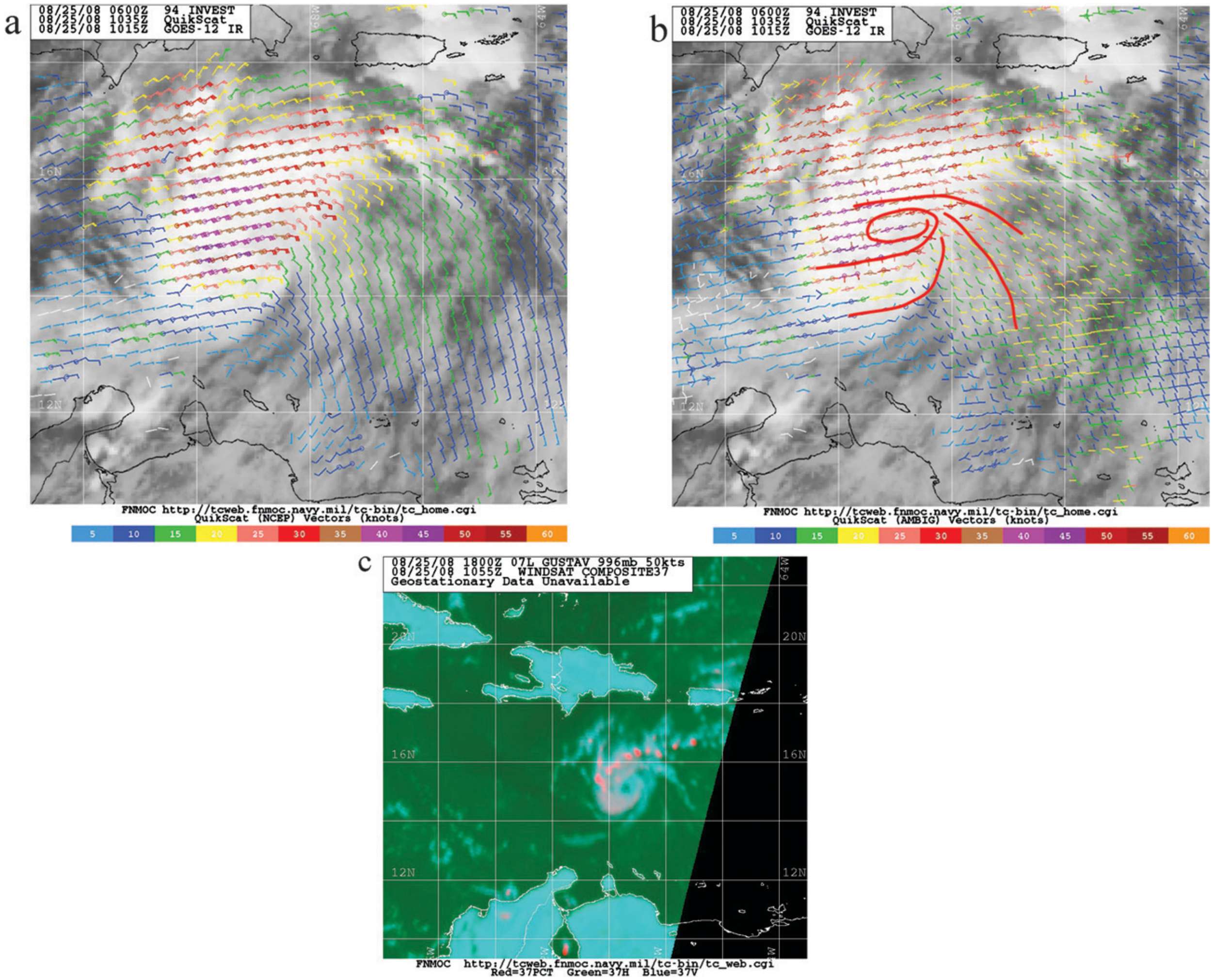

FIG. 2. (a) Automated QuikSCAT solution in a pass over what was later classified as Tropical Depression 7 (and later Hurricane Gustav) at 1035 UTC 25 Aug 2008 with 1015 UTC *Geostationary Operational Environmental Satellite-12* (*GOES-12*) infrared satellite imagery. (b) Manual analysis of QuikSCAT ambiguities (red streamline) suggests that a closed surface circulation exists near 14.6°N, 68.7°W that is not apparent in the automated solution. Advisories on the depression were initialized in part because of the circulation identified in this QuikSCAT pass. (c) WindSat 37-GHz color composite imagery at 1055 UTC 25 Aug 2008 showing a circulation evident slightly to the west of that indicated in the QuikSCAT ambiguity analysis. [Images courtesy of the U.S. Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC).]

This use of manual ambiguity analysis has been beneficial in many other cases as well. For example, manual analysis of a QuikSCAT pass early on 3 August 2004 (not shown) suggested that a closed circulation had formed in association with a tropical wave about 450 mi east of the Windward Islands. Based on these data, NHC initiated advisories on a tropical depression (which eventually became Tropical Storm Bonnie) a little sooner than would otherwise have been the case, since aircraft had not yet investigated the system (Avila 2004). In another case, QuikSCAT ambiguities at 1300 UTC 11 November 2006 over Tropical Depression 20-E in the eastern Pacific (not shown) revealed that the circulation might no longer be closed, and that the system was probably not producing winds of tropical storm force (Knabb 2006). Without the QuikSCAT data, NHC would likely have incorrectly upgraded the disorganized depression to a tropical storm based on Dvorak intensity estimates, which would have been unfortunate, especially since the cyclone dissipated later that same day. Other examples of center locations determined by manual ambiguity analysis are provided by Edson (2004).

b. Intensity

QuikSCAT wind retrievals can provide valuable information on the intensity of tropical depressions [maximum 1-min 10-m wind less than 34 kt (17.5 m s^{-1})] and especially tropical storms [maximum wind of 34–63 kt (17.5–32.4 m s^{-1})], but not on the intensity of most hurricanes [maximum wind of 64 kt (32.9 m s^{-1}) or greater]. Even in tropical storms, however, interpretation of the data can be quite complicated, due to the impact of rain on the QuikSCAT retrieved wind speed (see section 5a for further discussion of this issue). An additional complication is the variability in retrieved wind speeds among the ambiguities at each WVC, which often ranges between 5 (2.6 m s^{-1}) and 10 kt (5.1 m s^{-1}). This section provides some examples of how QuikSCAT can be used for intensity estimation, in part by comparing QuikSCAT with other datasets (particularly aircraft reconnaissance).

Automated solutions (12.5-km resolution) from a QuikSCAT pass at 1113 UTC 13 September 2005 over Tropical Storm Ophelia (Beven and Cobb 2006) show a maximum wind speed of 54 kt (27.8 m s^{-1}) about 60 n mi northeast of the 1200 UTC best-track (Jarvinen et al. 1984) position of the cyclone (Fig. 3). The maximum flight-level wind measured by aircraft, after reduction from 700 mb to the surface by the standard 0.9 factor (e.g., Franklin et al. 2003), was 59 kt (30.4 m s^{-1}) at around 1300 UTC, located 65 n mi northeast of the center, only 10 n mi from the QuikSCAT maximum (Fig. 4). This relatively close agreement between QuikSCAT and the aircraft data exemplifies that QuikSCAT retrievals in tropical storms, despite the presence of rain, can still provide useful information on intensity, which is especially useful for systems not sampled by aircraft. As will be shown later in section 5, however, interpretation of QuikSCAT data in these situations is often not straightforward.

QuikSCAT can occasionally provide intensity information for some hurricanes, particularly those undergoing extratropical transition (ET; e.g., Jones et al. 2003), when rainfall rates near the TC core begin to decrease, reducing the contamination effects of rain from the wind retrievals. For example, as Hurricane Helene (2006) was undergoing ET, a QuikSCAT pass over the cyclone at 0916 UTC 23 September indicated that maximum winds had increased to 80 kt (41.2 m s^{-1}) and were located within a convection-free area in the southwestern quadrant of the cyclone (Fig. 5). These QuikSCAT data prompted NHC to issue a "special" advisory on Helene that updated the current and forecast intensities of the cyclone (important to mariners trying to avoid hazardous conditions in the path of Helene). Without QuikSCAT data, it is unlikely that this secondary peak in Helene's intensity (Brown 2006) would have been observed. It is important to emphasize, however, that this Helene case was unusual for a system still designated as a TC, and that QuikSCAT cannot measure the maximum winds in most hurricanes, for reasons described in more detail later in section 5.

c. *Wind radii*

The 1800-km-wide swath of retrieved winds from QuikSCAT can be useful in determining the radial extent of 34-kt (17.5 m s^{-1}) and occasionally 50-kt (25.7 m s^{-1}) winds, for which NHC provides analyses and 3-day forecasts in each full advisory package.[2] Wind radii information from QuikSCAT is particularly valuable for TCs not sampled by aircraft reconnaissance. Accurate wind radii analyses and forecasts are a critical factor in determining the size and timing of tropical storm and hurricane watch and warning areas, and they provide guidance to mariners seeking to avoid hazardous wind conditions associated with a TC.

Figure 6a shows a QuikSCAT pass that captured the entire circulation of Hurricane Katrina (2005) around 1200 UTC on 28 August 2005. A gridded isotach field generated from the 25-km QuikSCAT wind retrievals (Fig. 6b) shows a well-defined 34-kt wind radius around the cyclone that agrees closely with several ship and buoy observations located in this region and with aircraft reconnaissance data from that day (not shown). This level of agreement between QuikSCAT and surface and reconnaissance observations in a heavily sampled cyclone such as Katrina gives NHC forecasters a relatively high level of confidence in QuikSCAT observations of outer wind radii in hurricanes where no other data are available.

d. *Frequency of use*

In an attempt to quantify the utility of QuikSCAT in operational TC analysis and forecasting at NHC, we counted how often QuikSCAT data were mentioned in NHC's TC discussion (TCD) products. One TCD is issued for each active TC with every routine 6-hourly forecast package, and for occasional "special" advisories. TCDs from 2000 to 2007 were examined for any mention of QuikSCAT, and during this period the percentage of Atlantic TCDs in which QuikSCAT was mentioned steadily increased to 22% in 2006, but with a slight decrease to near 18% in 2007 (Fig. 7). Some of the higher numbers from 2005 and 2006 might be due to the fact that more cyclones formed farther east in the Atlantic basin in those seasons, outside the range of aircraft reconnaissance, increasing the need for the QuikSCAT information. The mention of QuikSCAT in eastern North Pacific TCDs remained between 15% and

[2] NHC defines a wind radius as the *maximum* extent of the stated wind speed in each quadrant of the TC. Such winds do not necessarily extend out that far everywhere in the quadrant.

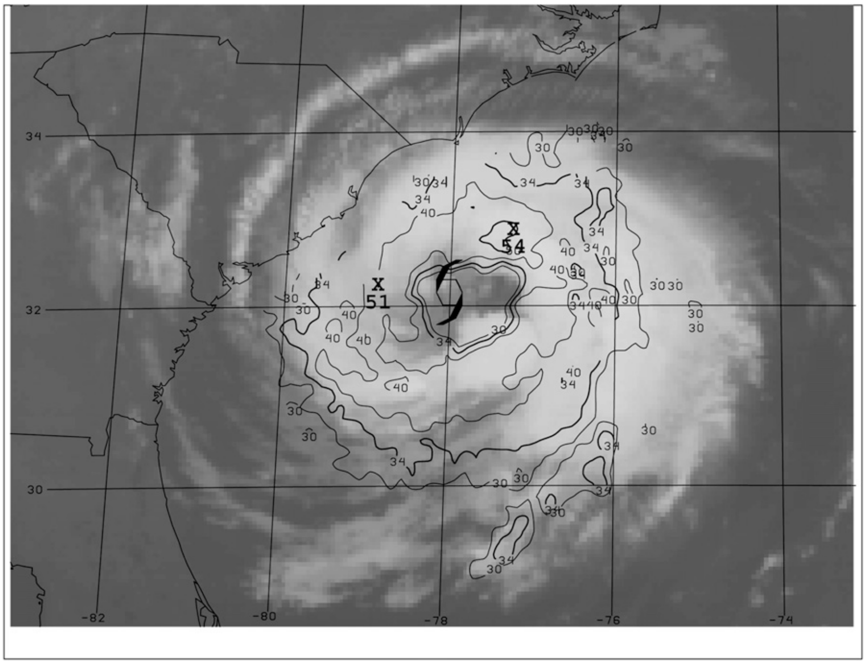

FIG. 3. Isotachs (kt) from 12.5-km QuikSCAT winds valid at 1113 UTC 13 Sep 2005 and *GOES-12* image valid at 1115 UTC. Tropical storm symbol indicates the approximate 1200 UTC 13 Sep NHC best-track position of Ophelia.

19% from 2001 through 2006 and increased to near 27% in 2007. The effective use of QuikSCAT in TCDs is greater than the percentages would indicate in both basins, 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. In addition, in some cases QuikSCAT could have been used in the analysis and forecast process and not mentioned in the TCD, but those uses cannot be quantified. 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 NHC is now 40%–50% in both basins.

The specific applications of QuikSCAT, based on mentions in the TCDs, were sorted by the three analysis parameters discussed in the previous sections: intensity (maximum sustained surface wind), center fixing/identification, and wind radii. Each TCD in which QuikSCAT was mentioned 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. During the 5-yr period from 2003 to 2007 in both basins, QuikSCAT was mentioned most often when describing its use in making some judgment about the current intensity of the TC (62%), and less frequently for center fixing/identification (21%) and wind radii analysis (17%). There was some variability in the mention of QuikSCAT across seasons and basins, likely due to year-to-year variations in the locations and intensities of TCs. For example, the use of QuikSCAT data for wind radii analysis has been mentioned more often in TCDs for major hurricanes than for cyclones of weaker intensities. During 2003, however, no major hurricanes occurred in the eastern North Pacific basin (Beven et al. 2005), and that year QuikSCAT's use in wind radii analysis was mentioned only 4% of the time in eastern North Pacific TCDs. Interestingly, during the 5-yr period, the use of QuikSCAT for intensity analysis was mentioned in the Atlantic basin (64% of TCD mentions) more often than in the eastern North Pacific (55%), despite the presence of more frequent aircraft reconnaissance in the Atlantic. All 33 of the TCD mentions of QuikSCAT for intensity estimation during the 2007 in the Atlantic basin were for tropical depressions and tropical storms, highlighting the deficiency of QuikSCAT for hurricane intensity estimation.

4. Operational benefits for marine analysis and forecasting in the tropics

NHC's TAFB disseminates surface analyses and marine forecasts and warnings for an area of responsibility of approximately 12 million (n mi)^2 that includes

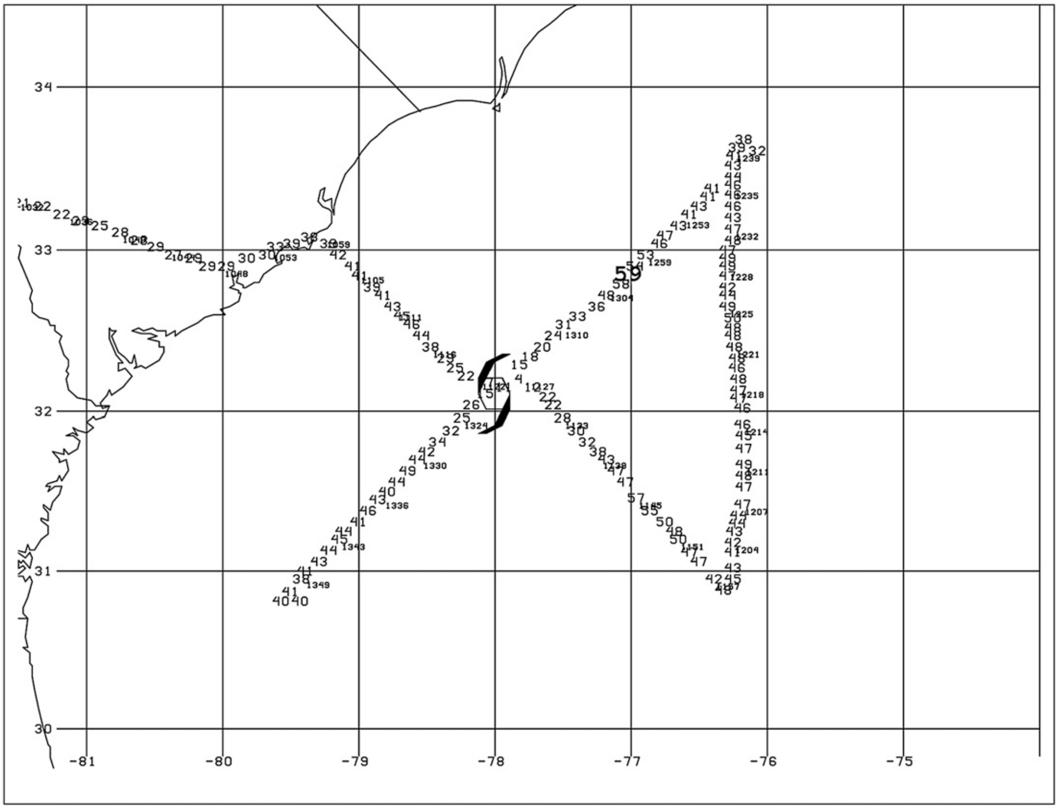

FIG. 4. Peak flight-level winds multiplied by a scaling factor of 0.9 from U.S. Air Force Reserve aircraft reconnaissance (kt, large numerals) and time of observation (UTC, small numerals) from 1030 through 1350 UTC 13 Sep 2005 in Tropical Storm Ophelia. The maximum scaled flight-level wind of 59 kt was found near 32.8°N, 77.1°W. The tropical storm symbol indicates the approximate 1200 UTC NHC best-track position of Tropical Storm Ophelia.

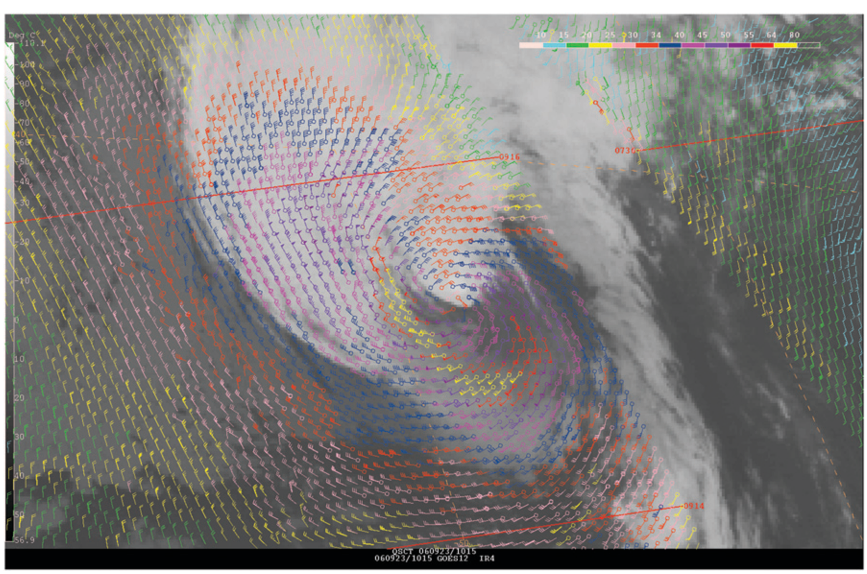

FIG. 5. Automated 12.5-km QuikSCAT solution in a pass over Hurricane Helene at 0916 UTC 23 Sep 2006 and *GOES-12* infrared image from 1015 UTC.

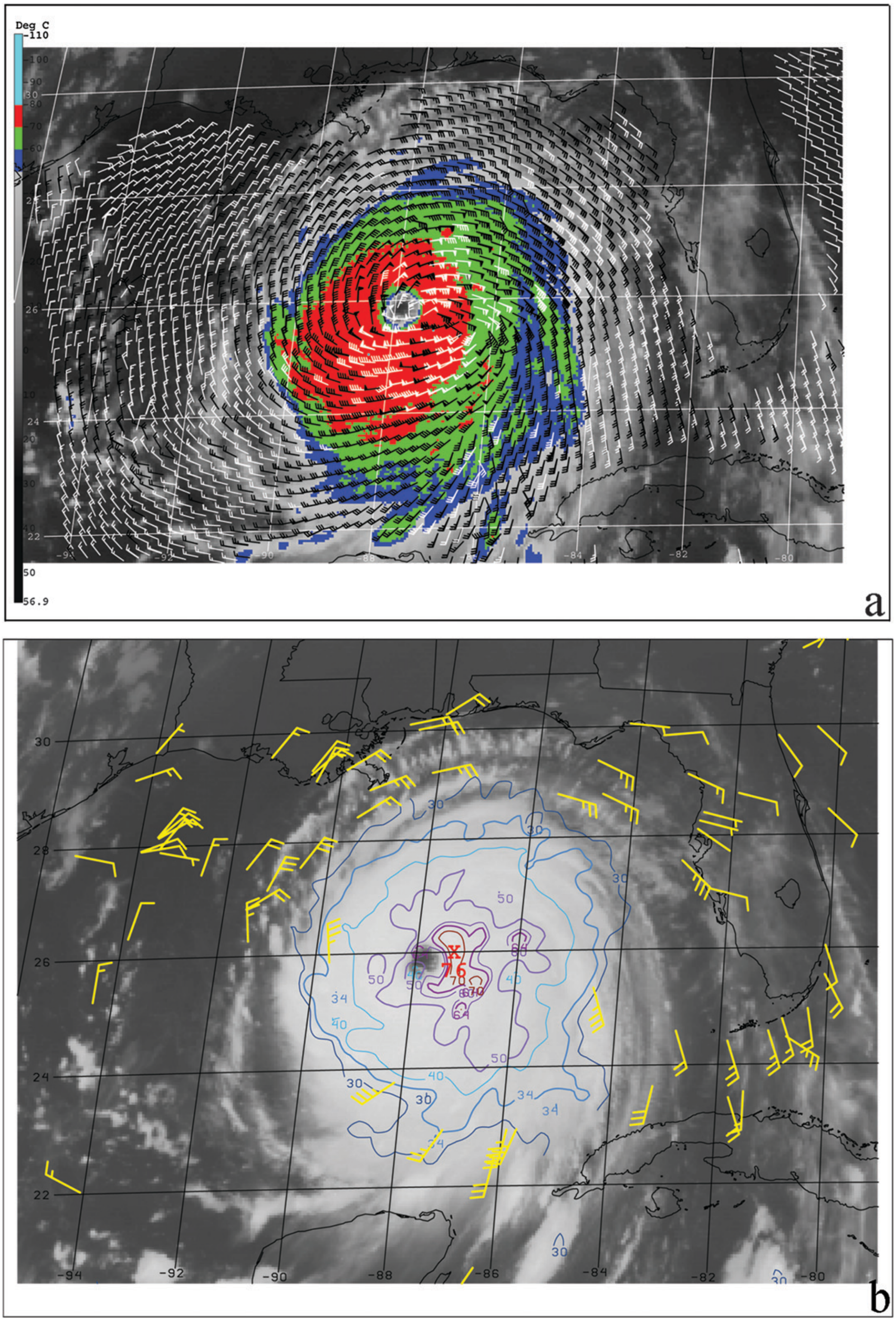

FIG. 6. (a) QuikSCAT winds (barbs, kt) from 1127 UTC 28 Aug 2005 over Hurricane Katrina with 1145 UTC *GOES-12* infrared image and (b) isotachs (color contours, kt) from 25-km QuikSCAT winds at 1127 UTC 28 Aug 2005 over Hurricane Katrina with 1200 UTC ship and buoy wind observations (kt). Black wind barbs in (a) are flagged for possible rain contamination.

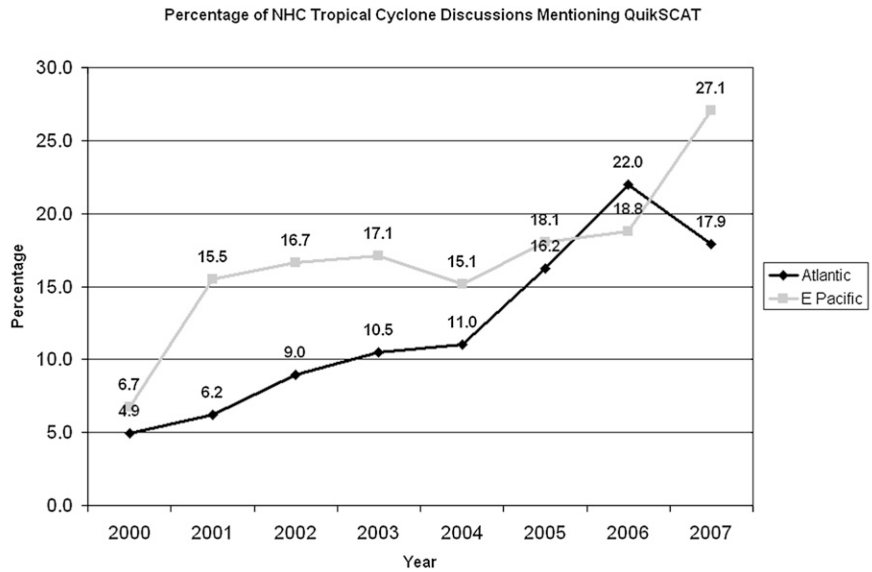

FIG. 7. Trend in percentage of NHC TCDs mentioning QuikSCAT from 2000 through 2007 in the Atlantic and eastern Pacific basins.

the Atlantic Ocean from the equator to 31°N west of 35°W, and the eastern Pacific Ocean from 20°S to 30°N east of 140°W (Fig. 1). Away from areas of rain contamination, QuikSCAT wind data have had a very positive impact on the analysis of synoptic surface features such as fronts, troughs, high and low pressure centers, and tropical waves, since the locations and characteristics of such features are vital to marine weather forecasts and warnings in the tropics.

The relatively wide range of retrievable wind speeds from QuikSCAT allows forecasters to frequently detect winds of gale force [34–47 kt (17.5–24.2 m s^{-1})] and storm force [48–63 kt (24.7–32.4 m s^{-1})] for the issuance of marine forecasts and warnings. Widespread convection in the tropics, however, leads to frequent overestimation by QuikSCAT of wind speeds that are actually less than gale force, requiring careful forecaster interpretation of the data. Rain contamination also complicates the interpretation of QuikSCAT wind direction retrievals in areas of the most interesting and potentially dangerous weather associated with convectively active tropical waves, fronts, or cyclones. Rain contamination issues are discussed in more detail below in section 5a.

a. *Gulf of Tehuantepec gap wind events*

QuikSCAT winds have greatly improved the monitoring and forecasting of gap wind events, particularly those that occur during the cold season (October–March) in the Gulf of Tehuantepec, an area adjacent to the Pacific coast of southeastern Mexico. The structural characteristics of these events are described by Steenburgh et al. (1998), who examined a case in which winds were estimated to have reached about 50 kt (25.7 m s^{-1}). Prior to the availability of QuikSCAT data in 1999, TAFB forecasters had to rely on occasional ship observations in an attempt to observe the intensity of these wind events and to issue and verify gale or storm warnings in this region (Cobb et al. 2003). Based on QuikSCAT data from the cold seasons of 1999–2000 through 2006–07, 143 wind events reaching at least gale force have been documented in the Gulf of Tehuantepec, with 44 of those events reaching storm-force magnitude (Brennan et al. 2007). On average, 12.4 gale-force events (winds reaching gale but not storm force) occur per cold season in the Gulf of Tehuantepec, with an average of 5.5 storm-force events per season. Even hurricane-force Tehuantepec events are occasionally detected by 12.5-km QuikSCAT retrievals, including hurricane-force events occurring in mid-November 2007 and early January 2008.

The 1800-km-wide QuikSCAT swath is ideal for identifying the extent of gale- and storm-force winds in Tehuantepec events. A 12.5-km QuikSCAT overpass at 1212 UTC 12 February 2006, during a Tehuantepec wind event, shows a few 55-kt (28.3 m s^{-1}) barbs and a large area of winds of at least 50 kt (25.7 m s^{-1}) offshore of the Mexican coast (Fig. 8a). These retrieved winds are slightly stronger than those from the 25-km QuikSCAT data, which show only a few 50-kt (25.7 m s^{-1}) barbs (Fig. 8b). Confidence in the automated QuikSCAT wind solutions in these events is high since rain contamination is not a factor, due to the large-scale subsidence caused by cold-air advection. Elsewhere in the TAFB areas of responsibility, QuikSCAT has been useful in identifying small-scale high-wind events in other passes, straits, gaps, and in climatologically favored areas such as along the Caribbean coast of Colombia (not shown).

b. Intertropical convergence zone

In an effort led by TAFB, the position of the intertropical convergence zone (ITCZ) was introduced into the NWS unified surface analysis (e.g., Berg et al. 2007) in 2004. This change was motivated by the utility of QuikSCAT in identifying the trade wind confluence over large areas that is not always revealed by convection. QuikSCAT even clearly depicts the broad double-ITCZ structures (Fig. 9) often observed over the eastern Pacific during boreal spring (e.g., Zheng et al. 1997; Lietzke et al. 2001).

5. Limitations of QuikSCAT in NHC operations

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

1) the inability to resolve the maximum winds in the inner core of most hurricanes due to insufficient retrieval resolution, instrument signal saturation (which limits the maximum retrievable wind speed, even in rain-free conditions), and attenuation by rain;
2) positive and negative biases in retrieved wind speeds, caused by rain contamination, that are difficult to distinguish and quantify without other collocated wind data;
3) the lack of collocated rain rate data to determine the influence of rain on the retrieved wind solution;
4) ambiguity removal errors that make automated QuikSCAT-derived TC center locations unreliable, which make the determination of whether a circulation center exists in incipient systems difficult, and that require the forecaster to manually analyze the ambiguities;
5) the low frequency of passes over any given region or weather system (at most two passes per day with a single satellite) and the largest gaps between swaths in the tropics; and
6) the time lag between the satellite overpass and data receipt at NHC.

Some specifics about these limitations are discussed in the remainder of this section.

a. Rain effects on QuikSCAT wind retrievals

1) Overview

The Ku-band frequency of QuikSCAT is sensitive to the effects of rain contamination that can limit the utility of QuikSCAT data, particularly in TCs where strong winds are often found in regions of deep convection and high rainfall rates. The effects of rain on QuikSCAT retrievals (e.g., Chelton and Freilich 2005; Chelton et al. 2006) can increase or decrease the amount of backscatter returned to the satellite via the following mechanisms:

1) creating additional backscatter from reflection of the satellite's emitted beam off of the raindrops themselves (i.e., ''volume backscatter''), and/or from roughening the sea surface due to the impact of the raindrops, contributing to a higher retrieved wind speed; and/or
2) attenuation of the wind-produced backscatter signal from the ocean surface by raindrops, contributing to a lower retrieved wind speed.

The sign of the bias due to rain in the QuikSCAT wind speed solution varies with both the actual wind speed and the rain rate. The impact of rain on the retrieved wind speed is directly proportional to the rain rate, but it is inversely proportional to the true wind speed near the ocean surface, since rain degrades the retrieval more severely at low wind speeds (Portabella and Stoffelen 2001; Weissman et al. 2002; Hoffman et al. 2004; Chelton et al. 2006). For example, when rain rates increased to more than 1 mm h^{-1}, Weissman et al. (2002) found a positive bias in QuikSCAT wind speeds compared to buoy observations, especially in weak wind speed conditions where rain becomes the primary scattering mechanism. At wind speeds less than about 10 m s^{-1}, volume backscatter from rain and increased ocean surface roughness result in a positive retrieved wind speed bias due to rain; when wind speeds exceed about 15 m s^{-1}, attenuation of the ocean surface backscatter due to rain results in a negative bias in the retrieved wind speed (Stiles and Yueh 2002). Edson et al. (2002) and Edson (2004) found similar biases in QuikSCAT passes over TCs, where rain tends to increase the retrieved QuikSCAT wind speed when the actual winds are less than 15–20 m s^{-1} (30–40 kt), while rain tends to decrease the retrieved wind speeds when the actual winds are stronger than 15–20 m s^{-1}. Since this change in retrieval bias occurs near the threshold of tropical storm intensity, it is often challenging to make operational decisions based on QuikSCAT regarding whether or not a TC has become a tropical storm, and/or how far winds of tropical storm force extend from the circulation center.

2) Operational interpretation of rain impacts

An example of the challenges involved with interpreting the effects of rain on QuikSCAT wind speeds is

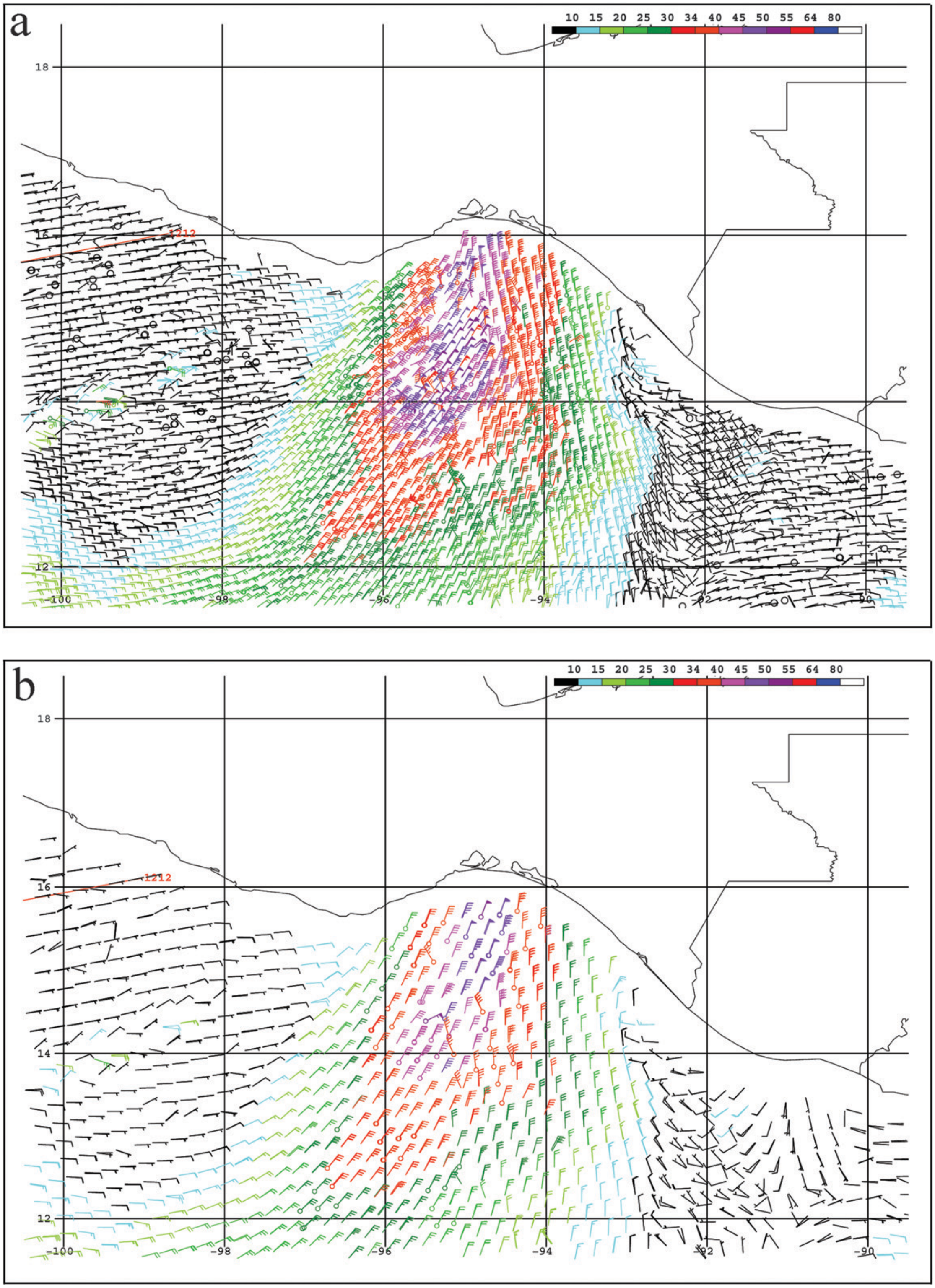

FIG. 8. QuikSCAT (a) 12.5- and (b) 25-km retrievals (kt) from 1212 UTC 12 Feb 2006 over the Gulf of Tehuantepec. Black wind barbs indicate retrieved wind speeds of less than 10 kt.

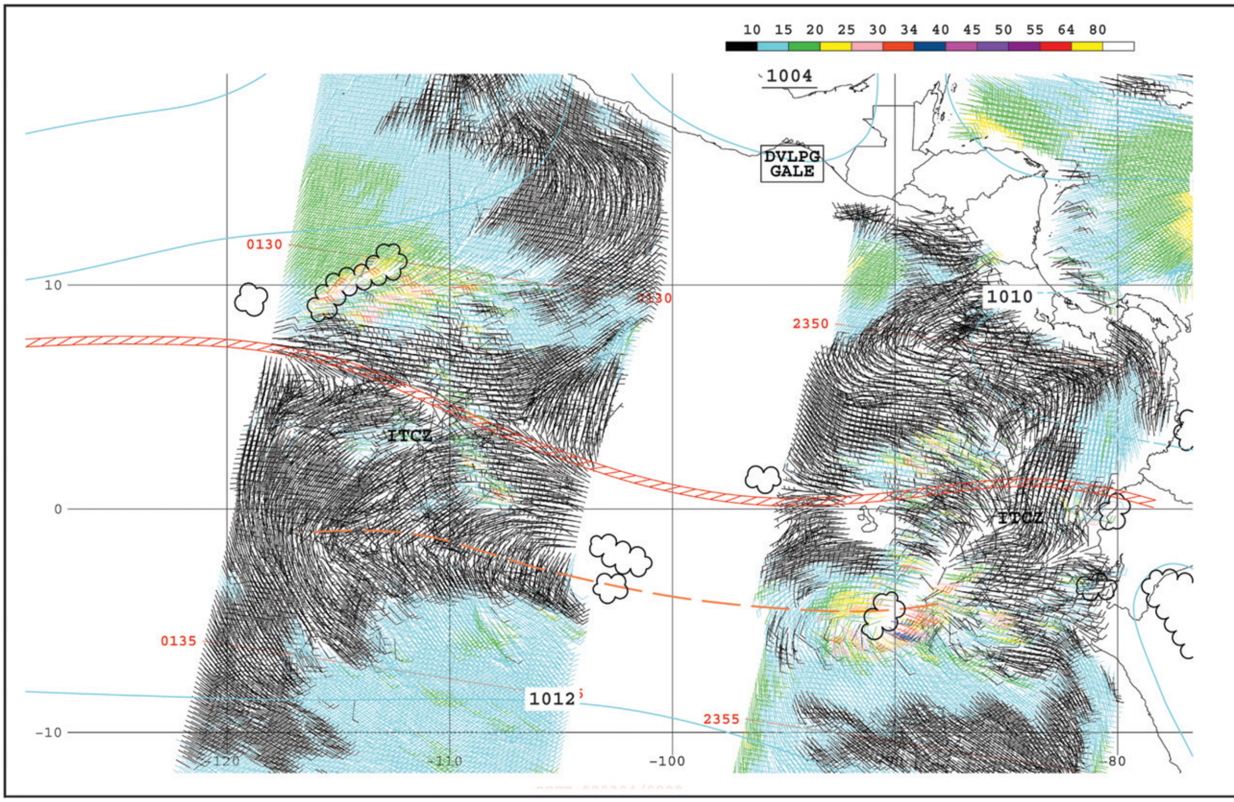

FIG. 9. TAFB surface analysis valid at 0000 UTC 4 Mar 2008 overlaid with 25-km QuikSCAT wind retrievals. A double-ITCZ structure is seen in the convergent areas on either side of the equator in both QuikSCAT retrieval swaths. The northern ITCZ is depicted by the cross-hatched line, while the southern ITCZ is indicated with a trough symbol. Black wind barbs indicate retrieved wind speeds of less than 10 kt.

provided by the pass over Tropical Storm Zeta (2005) shown in Fig. 10. This QuikSCAT pass from 0752 UTC 30 December 2005 occurred when Zeta was a marginal tropical storm according to the NHC best track (Knabb and Brown 2006). Winds from the 25-km QuikSCAT product show multiple wind maxima exceeding 34 kt in the northeast quadrant of the cyclone, and the 34-kt (17.5 m s^{-1}) wind radius in this quadrant of the storm could be 50 n mi or 150 n mi depending on how one judges the validity of these QuikSCAT retrievals. An overpass from the Tropical Rainfall Measuring Mission (TRMM) satellite (e.g., Kummerow et al. 1998) in this area around 0831 UTC indicates rain rates of 5–13 mm h^{-1} (0.2–0.5 in. h^{-1}) northeast of the cyclone center in the vicinity of the QuikSCAT wind maxima (Fig. 11), suggesting that the outermost wind maximum at a radius of about 150 n mi could be inflated due to rain contamination.

To assess the impact of rain on the QuikSCAT wind solution, NHC forecasters often overlay QuikSCAT vectors on nearly concurrent geostationary satellite imagery using N-AWIPS workstations (Fig. 12). Also, other near-polar-orbiting platforms [e.g., TRMM, Special Sensor Microwave Imager (SSM/I)] occasionally provide rain-rate information in close time proximity to the QuikSCAT pass, but this method of evaluating the effect of rain on QuikSCAT wind retrievals is imprecise and time consuming. Therefore, a highly desirable capability of any future scatterometer missions would be to obtain collocated rain-rate information or, preferably, to obtain backscatter measurements that are much less sensitive to the effects of rain.[3]

The lack of an independent measurement of rain rate on the QuikSCAT platform prompted the development of an empirical multidimensional histogram (MUDH) rain flag to identify vectors potentially contaminated by the effects of rain (Huddleston and Stiles 2000; Hoffman and Leidner 2005). The design of the rain flag, however,

[3] The ASCAT scatterometer, which was launched in October 2006 on board the METOP satellite, operates in the C band. This wavelength is less sensitive to rain but provides lower spatial resolution wind retrievals than QuikSCAT, limiting its ability to retrieve high wind speeds.

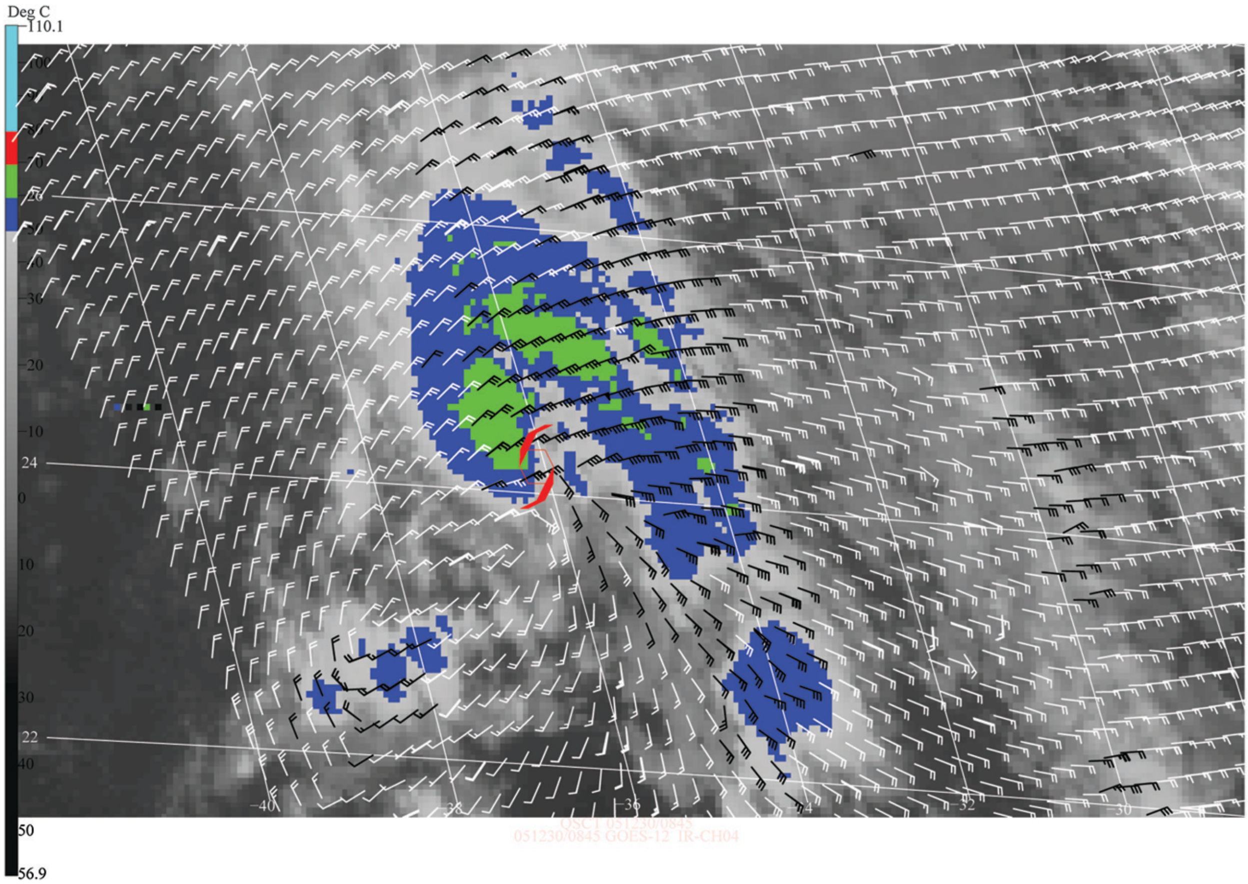

FIG. 10. The 25-km wind retrieval from the QuikSCAT pass over Tropical Storm Zeta at 0752 UTC 30 Dec 2005 with *GOES-12* imagery from 0815 UTC. The tropical storm symbol indicates the 0600 UTC NHC best-track position of Zeta. Black wind barbs are flagged for possible rain contamination.

can result in light rain rates escaping detection and the overflagging of wind vectors in regions where no rain is present if wind speeds exceed about 10 m s^{-1} (Hoffman et al. 2004; Milliff et al. 2004; Chelton et al. 2006). These issues force operational forecasters to subjectively assess the impact of rain on the retrieved QuikSCAT wind speeds, which can be very difficult in an operational setting, especially without collocated rain-rate information. Even if the rain rate was known, the reliability of the QuikSCAT wind speeds would still be uncertain since determining the effect of rain requires some a priori knowledge of the true near-surface wind speed.

b. *Skill of QuikSCAT wind retrievals for TC intensity analysis*

To quantify the skill of QuikSCAT in TC intensity estimation, error statistics were computed comparing the QuikSCAT maximum wind speed estimate (derived from the automated solution, not from an ambiguity analysis) to the NHC best-track intensity for all available QuikSCAT passes over TCs in the Atlantic basin during 2005 and the Atlantic and eastern North Pacific basins during 2006 and 2007 (475 and 428 retrievals at 25 and 12.5 km, respectively, were examined). Maximum wind speeds were extracted from 0.25° (0.125°) gridded isotach fields generated from the 25-km (12.5 km) retrievals. Figure 13 shows the average bias of the QuikSCAT maximum wind speed compared with the NHC best-track intensities for tropical depressions, tropical storms, and hurricanes binned by category using the Saffir–Simpson hurricane scale.

While NHC best-track intensity estimates are more uncertain when aircraft reconnaissance data are unavailable, identical bias calculations were performed on subsamples of 69 and 64 QuikSCAT passes at 25 and 12.5 km, respectively, from 2005 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

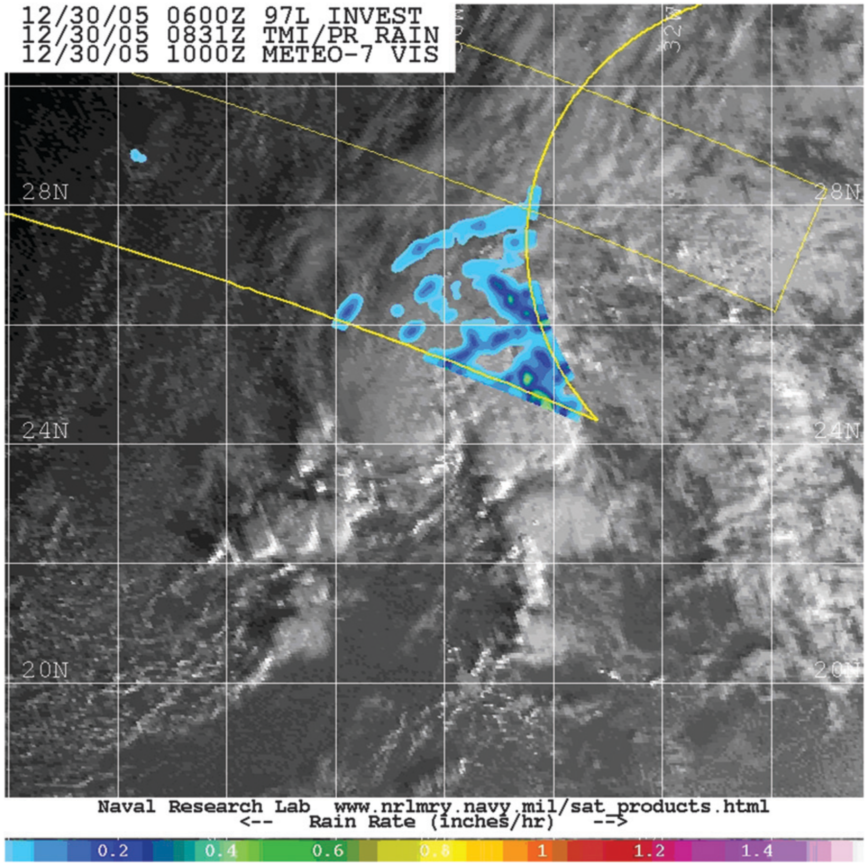

FIG. 11. Rainfall rate (color fill, h^{-1}) from the TRMM satellite valid at 0831 UTC 30 Dec 2005 over Tropical Storm Zeta. (Image courtesy the Naval Research Laboratory.)

are not available does not affect this evaluation of the skill of QuikSCAT in estimating TC intensity.

In addition, QuikSCAT data are sometimes themselves 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 subjective Dvorak current intensity estimates from TAFB for the 2005 sample. Results of this comparison (not shown) revealed biases in QuikSCAT intensity estimates that are quite similar to those presented below.

1) TROPICAL DEPRESSIONS

In 127 passes over tropical depressions, the 25-km QuikSCAT maximum wind had an average bias of +11.2 kt (+5.8 m s^{-1}) when compared to the NHC best-track intensity; this strongly suggests that rain contamination severely inflates QuikSCAT wind speed maxima at this stage of development (Fig. 13). The bias was even larger in the 12.5-km QuikSCAT product [+18.8 kt (+9.7 m s^{-1}) in 117 overpasses]. Figure 14 shows a QuikSCAT pass over Tropical Depression 16 (later Hurricane Ophelia) just prior to 0000 UTC 7 September 2005. While the NHC best-track intensity of the depression was 30 kt (15.4 m s^{-1}) at this time (when the depression was being sampled by aircraft reconnaissance), rain-contaminated QuikSCAT vectors in the area of cold cloud tops north and east of the center show wind maxima of 45 kt (23.2 m s^{-1}) in the 25-km retrieval (Fig. 14) and 56 kt (28.8 m s^{-1}) in the 12.5-km retrieval (not shown). A TRMM overpass at 2126 UTC 6 September shows estimated rain rates exceeding 25 mm h^{-1} northeast and east of the center (Fig. 15), strongly suggesting that rain contamination was inflating the QuikSCAT wind speeds in these areas. The 25–35-kt (12.9–18 m s^{-1}) QuikSCAT winds near the center of the depression (where rain rates are lower) are in better agreement with the Dvorak and best-track intensity values [both 30 kt (15.4 m s^{-1})] at that time.

This case suggests that the erroneous inflation of QuikSCAT maximum wind values is often quite severe in tropical depressions, since at this stage of development the backscatter signal from relatively weak surface

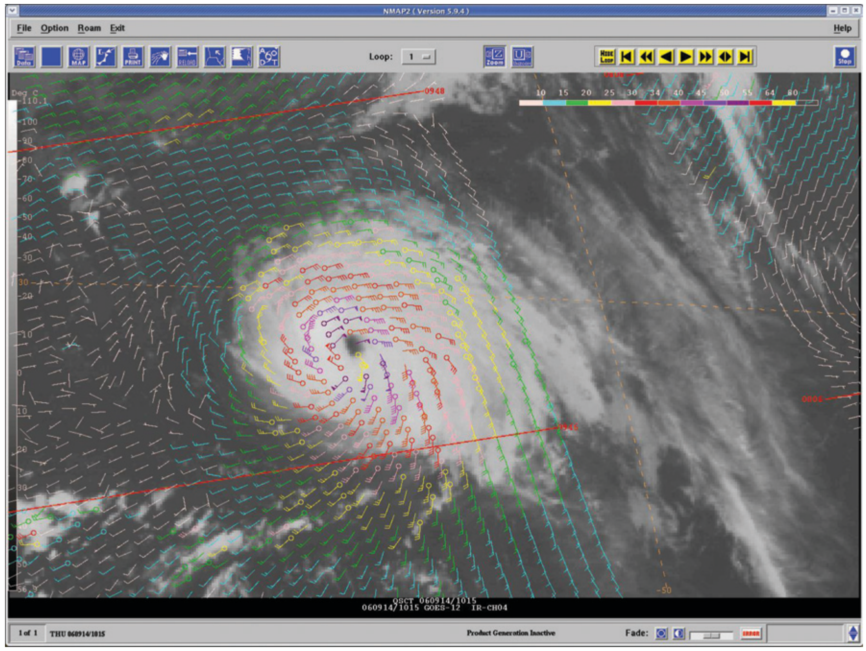

FIG. 12. Overlay of 25-km QuikSCAT wind barbs (kt) and *GOES-12* infrared satellite imagery on an N-AWIPS workstation showing Hurricane Gordon at 1015 UTC 14 Sep 2006. Wind barbs with circles at the base are flagged for possible rain contamination.

wind speeds can be overwhelmed by the effects of rain. Interpretation of these higher retrieved winds is not straightforward, however, since in areas of convection, stronger surface winds would normally be expected due to enhanced vertical momentum transport.

2) TROPICAL STORMS AND CATEGORY 1–2 HURRICANES

QuikSCAT winds have frequently shown utility for estimating intensity in tropical storms, with the data

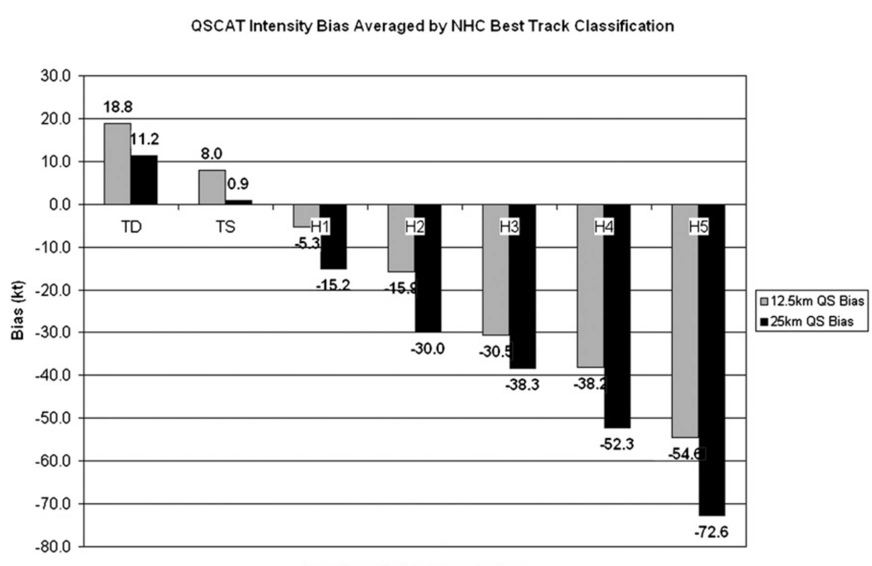

FIG. 13. Bar graph showing average bias (kt) of the QuikSCAT maximum wind compared to the nearest 6-h NHC best-track intensity in passes over 2005–06 Atlantic and 2006 eastern Pacific basin tropical cyclones sorted by NHC best-track classification [tropical depression (TD); tropical storm (TS); and Saffir–Simpson hurricane scale category, H1–H5).

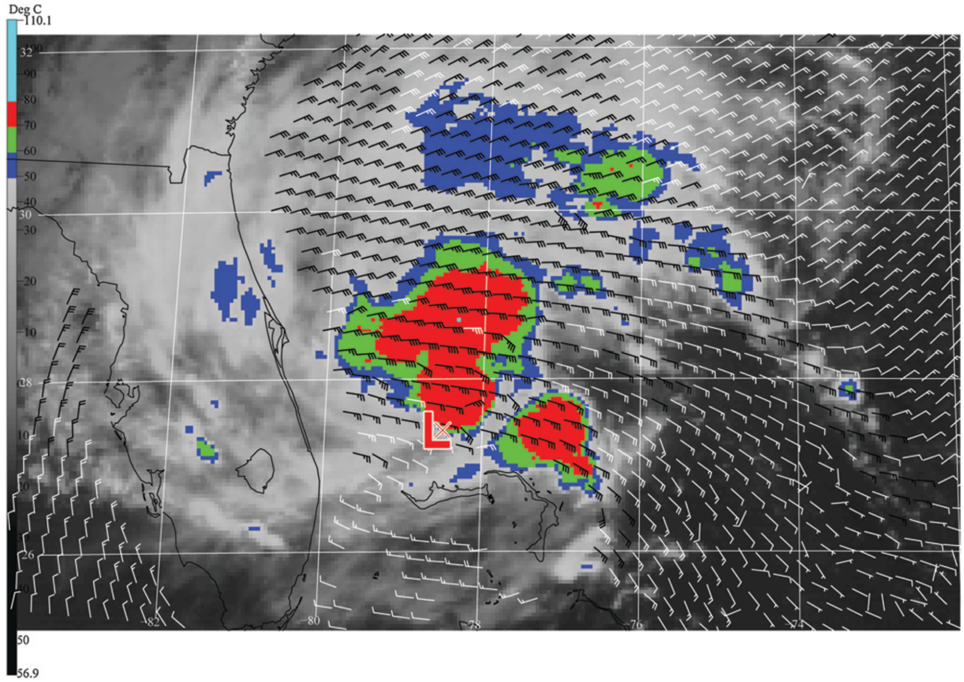

FIG. 14. QuikSCAT winds (barbs, kt) from 2316 UTC 6 Sep 2005 over Tropical Depression 16 (later Ophelia) with 2345 UTC *GOES-12* infrared satellite image. Black wind barbs are flagged for possible rain contamination. The L indicates the 0000 UTC 7 Sep NHC best-track position of the depression.

being much less useful for intensity in category 1 and 2 hurricanes [maximum sustained winds of 64–95 kt (32.9–48.9 m s^{-1})]. In 202 passes over tropical storms during 2005–07, the 25-km QuikSCAT maximum wind had an average bias of +0.9 kt (+0.4 m s^{-1}) when compared to the NHC best-track intensity (Fig. 13). The 12.5-km maximum wind compared less favorably with a bias of +8.0 kt (+4.1 m s^{-1}) in 180 passes. While the average bias for tropical storms was significantly less than in depressions, some of this reduced bias was due to the cancellation of some fairly large positive and negative errors, as evidenced by the mean absolute error (MAE) values of 6.8 kt (3.5 m s^{-1}) for the 25-km QuikSCAT data and 10.4 kt (5.4 m s^{-1}) for the 12.5-km data.

For category 1 hurricanes, the 25-km QuikSCAT maximum wind had an average bias of −15.2 kt (−7.8 m s^{-1}) in 82 overpasses; the 12.5-km QuikSCAT maximum wind had an average bias of −5.3 kt (−2.7 m s^{-1}) in 73 overpasses (Fig. 13). At category 2 intensity, the magnitude of the biases increased to −30.0 kt (−15.4 m s^{-1}) for the 25-km data and −15.9 kt (−8.2 m s^{-1}) for the 12.5-km data, although the number of passes at this intensity was much smaller (23 and 20 passes for the 25- and 12.5-km retrievals, respectively). Overall, these bias results suggest that QuikSCAT has some skill in estimating the intensity of tropical storms, with skill decreasing markedly for hurricanes of category 1 or 2 intensity. Ophelia was in a location that resulted in numerous QuikSCAT overpasses at or near a time when aircraft reconnaissance was sampling the cyclone. A comparison of the 12.5- and 25-km QuikSCAT maximum winds with the maximum flight-level reconnaissance winds (adjusted to the surface using a 90% reduction factor) and surface wind estimates from the NOAA Stepped-Frequency Microwave Radiometer (SFMR; Uhlhorn and Black 2003) is shown in Fig. 16. The absolute differences between the 12.5-km QuikSCAT maximum winds and the maximum flight-level winds (adjusted to the surface) are 7 kt (3.6 m s^{-1}) or less for seven of the nine passes shown. These passes occurred when the best-track intensity of Ophelia was between 55 and 65 kt (28.3 and 33.4 m s^{-1}). As the best-track intensity and adjusted flight-level winds increase to above 70 kt (36.0 m s^{-1}), the spread between reconnaissance winds and maximum QuikSCAT winds increases. Overall, the 12.5-km maxima compare more favorably to the adjusted flight-level wind maxima than the 25-km maxima, except for a pass near 0000 UTC 14 September. More detailed comparisons of a pass with aircraft-based data are given below.

The maximum 12.5-km QuikSCAT wind in a pass over Ophelia at 1116 UTC 9 September agrees closely with the maximum SFMR surface wind speed measured only a short time later. The 12.5-km QuikSCAT wind

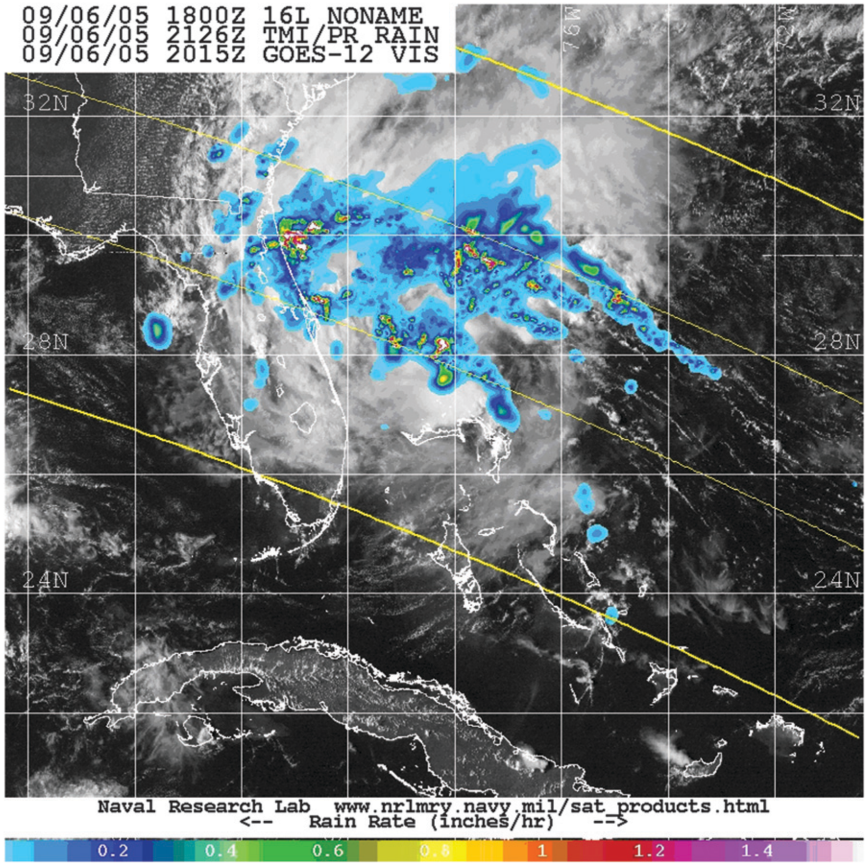

FIG. 15. As in Fig. 11 but valid at 2126 UTC 6 Sep 2005 over Tropical Depression 16 (later Ophelia). (Image courtesy of the Naval Research Laboratory.)

maximum of 56 kt (28.8 m s^{-1}) was located 13 n mi SSW of the 1200 UTC best-track center position of Ophelia (Fig. 17). The SFMR maximum surface wind of 58 kt (29.8 m s^{-1}) was found 20 n mi SSW of the center at 1137 UTC (Fig. 18), very close to the location of the QuikSCAT maximum wind. While a TRMM pass at 1522 UTC (Fig. 19) indicates high rain rates in the vicinity of the highest QuikSCAT winds, it is possible that the surface wind speeds had reached a threshold where the backscatter returned to the QuikSCAT instrument due to the wind was no longer being significantly contaminated by rain. Overall, these results highlight the utility of QuikSCAT for intensity estimation in tropical storms and its increasing limitations once the systems strengthen into hurricanes.

3) MAJOR HURRICANES

The limitations of QuikSCAT in intensity estimation are especially evident in major hurricanes [maximum sustained winds greater than 95 kt (48.9 m s^{-1})]. When compared to the NHC best-track intensities for major hurricanes, the 25-km QuikSCAT maximum winds had average biases of −38.3 (−19.7 m s^{-1}), −52.3 (−26.9 m s^{-1}), and −72.6 kt (−37.3 m s^{-1}) in category 3, 4, and 5 hurricanes, respectively (Fig. 13). Corresponding average biases for the 12.5-km retrievals were −30.5 (−15.7 m s^{-1}), −38.2 (−19.7 m s^{-1}), and −54.6 kt (−28.1 m s^{-1}). For example, the 25-km QuikSCAT retrieval in a pass over Hurricane Katrina (Fig. 6a) at 1127 UTC 28 August 2005 shows a maximum wind speed of 76 kt (39.1 m s^{-1}) in the 25-km data at a time when the best-track intensity of the storm as inferred from aircraft reconnaissance data was 145 kt (74.6 m s^{-1}). These bias signals are quite strong, in spite of the relatively small number of QuikSCAT passes over major hurricanes analyzed in this study. For the 25-km QuikSCAT retrievals, 15, 20, and 5 passes were analyzed for category 3, 4, and 5 hurricanes, respectively. For the 12.5-km retrievals, the corresponding numbers of passes analyzed were 14, 19, and 5.

It is obvious that in major hurricanes, rain contamination, the horizontal resolution of the data, and saturation of the backscatter signal at wind speeds greater than about 90 kt (46.3 m s^{-1}), even in nonraining

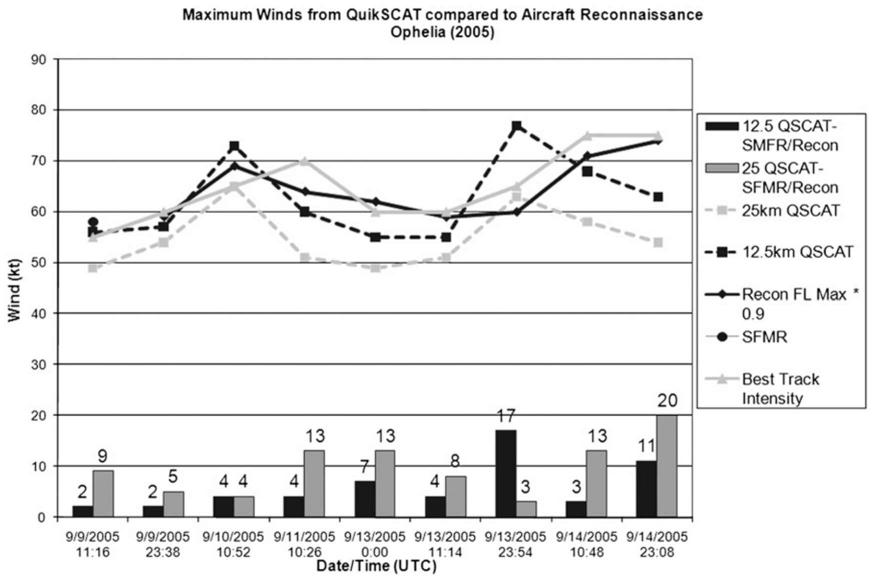

FIG. 16. Comparison of 25- and 12.5-km QuikSCAT maximum winds (light and dark dashed lines, respectively) to the maximum flight-level winds from aircraft reconnaissance adjusted to the surface by a reduction factor of 0.9 (solid dark line) as well as the maximum wind from the SFMR (dark circle) in Ophelia. Light solid line indicates final NHC best-track intensity. Bar graphs depict the absolute difference between the QuikSCAT and flight-level winds or SFMR. Dates and times of QuikSCAT passes are indicated along the *x* axis.

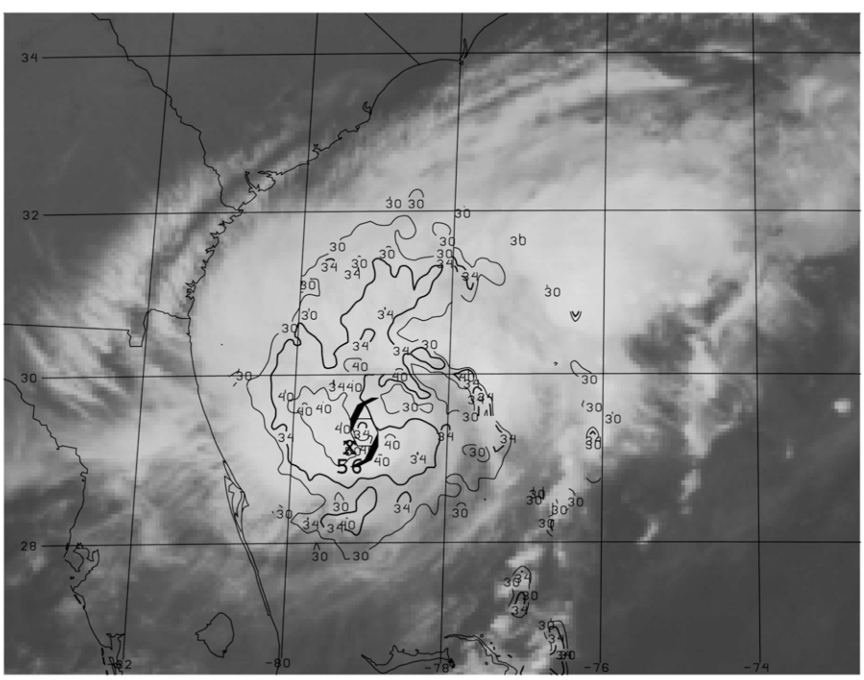

FIG. 17. Infrared *GOES-12* imagery from 1145 UTC 9 Sep 2006 and isotachs from 12.5-km QuikSCAT winds (contours) from 1127 UTC 9 Sep over Tropical Storm Ophelia. Maximum wind location is indicated by an X and tropical storm symbol shows the approximate 1200 UTC 9 Sep 2006 NHC best-track position of Ophelia.

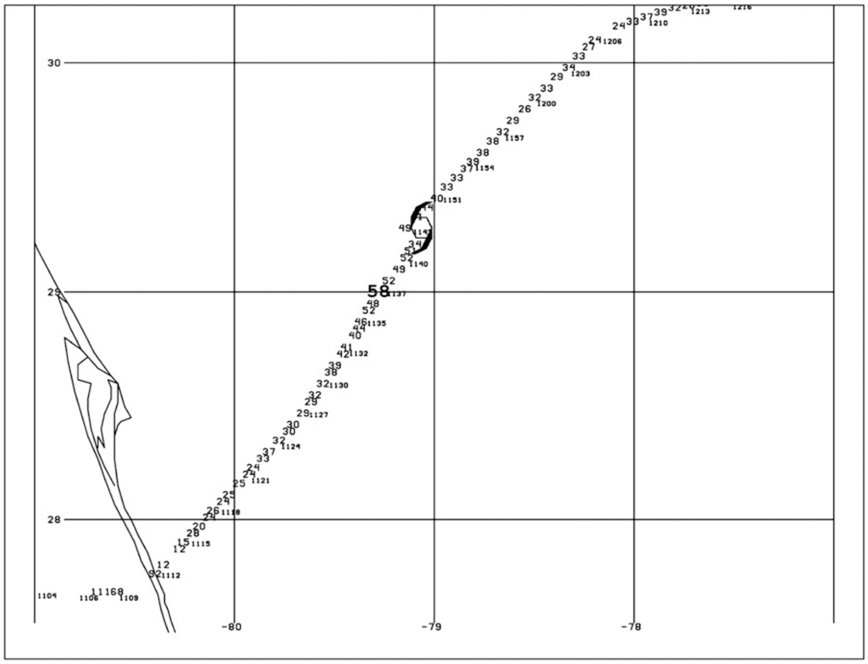

FIG. 18. Surface wind speed (kt, large numerals) from the SFMR and time (UTC, small numerals) of an observation in Tropical Storm Ophelia around 1200 UTC 9 Sep 2006. The maximum wind measured by the SFMR around 1200 UTC was 58 kt near 29.0°N, 79.3°W. The tropical storm symbol indicates the approximate 1200 UTC NHC best-track position of Ophelia.

conditions (e.g., Fernandez et al. 2006), make it impossible for QuikSCAT to measure the maximum wind speed in the inner core. Future scatterometer instruments must be able to measure hurricane-force winds (up to and including category 5 strength) in heavy rain conditions to be useful in the analysis of the intensity of major hurricanes.

c. Ambiguity removal errors

At WVCs in the QuikSCAT swath, the ambiguity closest to the median of the wind vectors in the neighboring 7 × 7 area of WVCs is chosen with multiple passes of a median filter designed to eliminate individual vectors that are inconsistent with their neighbors. As a result of this spatial continuity constraint, errors in ambiguity selection often occur in patches or lines. The choice of the ''wrong'' ambiguity often results in the chosen wind direction being 180° out of phase with the actual wind, and can also impact the wind speed solution, though often not as severely. These errors often degrade the ability of QuikSCAT to identify or locate closed circulations, such as those associated with TCs.

The choice of the wrong ambiguity in just a few locations can result in the automated QuikSCAT wind solution misplacing or failing to identify the center of a TC due to the spatial consistency constraint in the ambiguity removal technique.

These errors in ambiguity removal are likely due to

1) poor depictions of TC structure and location in the GFS model that is used to initialize the ambiguity removal filter and
2) rain contamination resulting in a wind direction oriented across the track of the satellite (Chelton and Freilich 2005).

To quantify the robustness of QuikSCAT in identifying TC centers and then to determine the degree of accuracy in those centers that were identified, 25-km NRT QuikSCAT wind vector solutions for 213 passes over TCs during the 2002 eastern North Pacific and 2003 Atlantic seasons were analyzed. If a discernible center was identified in the automated wind solution field, the location of that fix was compared to the interpolated position taken from the NHC best track.

Only 88 (41%) of the passes examined identified a circulation center. The likelihood of resolving a center increased with the intensity of the TC. QuikSCAT identified a center in only 30% of the tropical depressions, while nearly 70% of the category 3 hurricanes had

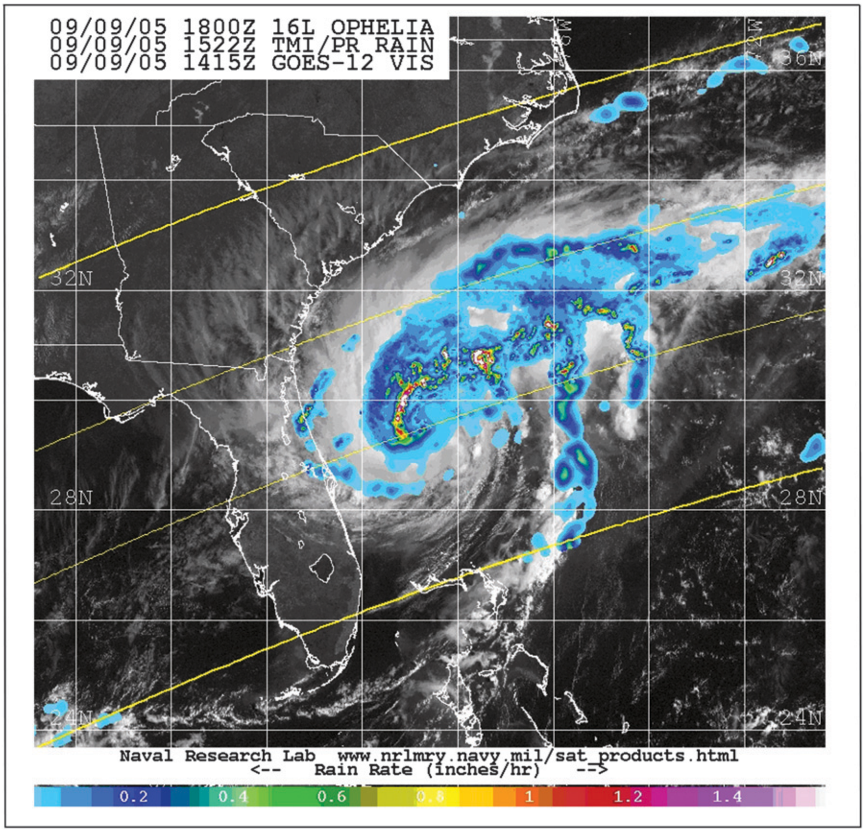

FIG. 19. As in Fig. 11 but valid at 1522 UTC 9 Sep 2005 over Tropical Storm Ophelia.

a center in the automated wind solution (Fig. 20). This result was expected since higher surface winds create stronger backscatter at the ocean surface, increasing the chances of a proper ambiguity solution. In addition, the background GFS forecast wind field used in the ambiguity removal processes would be more likely to contain a closed circulation for a stronger TC. The fact that QuikSCAT often does not identify a circulation center in weaker systems is especially unfortunate, as it is in those cases that an accurate center location is most needed, since there is no distinct eye.

Figure 21 shows the range and azimuth error for all center fixes that were identified. There is a discernible directional bias toward the southwest in the automated QuikSCAT solutions compared to the interpolated NHC best-track position. It is believed that this bias is due to deficiencies in the ambiguity selection algorithm rather than a physical limitation of the scatterometer itself. As noted above, a QuikSCAT pass directly over the TC often results in the selection of across-swath wind barbs (usually wind blowing from the east) near the TC core due to rain contamination, resulting in QuikSCAT resolving a center to the southwest of the true center location (Fig. 2a). Although QuikSCAT identified centers in only 30% of the tropical depressions, the position errors for those center fixes are smaller (~23 n mi average) than for any other category (Fig. 22). In contrast, the average error is nearly twice as large (45 n mi) in category 3 hurricanes.

Performing a manual ambiguity analysis (section 2a) requires considerable time, and depending on forecaster workload, cannot be performed on every QuikSCAT pass. In addition, subjective interpretation of the ambiguities is required by the forecaster, which can still result in uncertainty in the exact center location. As a result, even by performing ambiguity analyses, NHC forecasters are unable to fully overcome the limitations of QuikSCAT in TC center identification/fixing. 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.

d. *Coverage gaps*

The swath of data provided by QuikSCAT is 1800 km wide, making it possible for the entire circulation of a

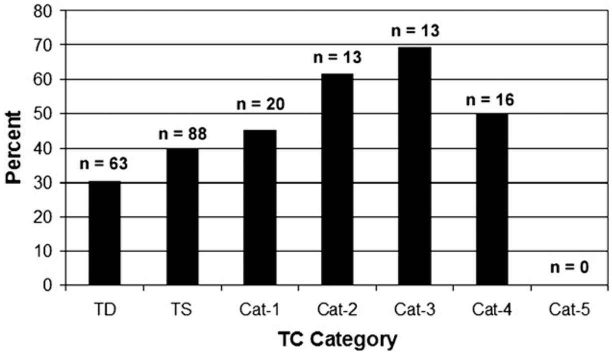

FIG. 20. Percentages of QuikSCAT passes from 2002 for the eastern Pacific and 2003 for the Atlantic hurricane seasons that revealed a circulation center in the wind solution field, by storm category. The numbers on top of each bar represent the total number of passes in each category.

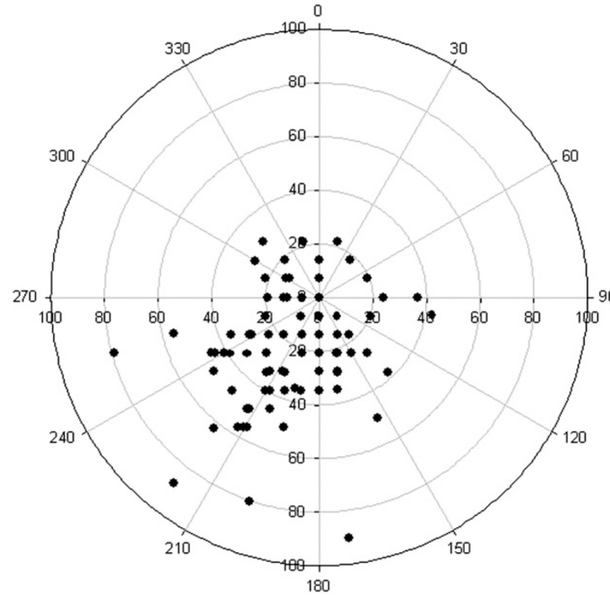

FIG. 21. Locations of the QuikSCAT center fixes from the 2002 eastern Pacific and the 2003 Atlantic hurricane seasons relative to the interpolated NHC best-track position. Units along the azimuth are degrees and radial units are nautical miles.

TC and large portions of the TAFB forecast area to be sampled in a single overpass. At low and midlatitudes, however, the single scatterometer is limited to a maximum of two passes over any given location each day. Gaps between adjacent QuikSCAT swaths (which exceed 550 km equatorward of 20° latitude and 1000 km at the equator) can result in all or part of a TC or other phenomena going unsampled. If the feature of interest is moving at a speed similar to the daily zonal progression of the QuikSCAT swaths, the feature could go unsampled by QuikSCAT for a day or more.

e. *Data latency*

Data acquisition and processing times result in a delay of approximately 1.5–3 h between the raw satellite observation and the availability of the 25-km QuikSCAT wind retrievals on forecaster workstations; the 12.5-km data are delayed an additional 45–60 min. These delays limit the utility of QuikSCAT data in NHC analyses and forecasts and can limit the accuracy of NHC products, especially in areas where other wind observations are sparse. For example, for TCs in the eastern North Pacific basin, QuikSCAT passes that occur between 1200 and 1300 UTC do not typically become available until about the time the 1500 UTC advisory package is released, often preventing these data from being incorporated into the analysis and forecast process until the next advisory cycle.

6. Beyond QuikSCAT

QuikSCAT has been in orbit well beyond its 3–5-yr life expectancy. The instrument continues to function, but is gradually showing more signs of its age, and is now operating on a backup transmitter. Currently, there are two other satellite platforms providing OSVW retrievals: the U.S. Navy's WindSat (a polarimetric radiometer, a passive system) and the European Space Agency's Advanced Scatterometer (ASCAT, an active system). Both WindSat and ASCAT have limitations, however, in the quality and quantity of the data they provide, which will still result in a net reduction of satellite OSVW capability for NHC forecasters after the loss of QuikSCAT.

NHC conducted a preliminary evaluation of WindSat retrievals during the 2006 hurricane season. Results of this evaluation suggest that WindSat is unable to reliably retrieve wind speeds above tropical storm strength,

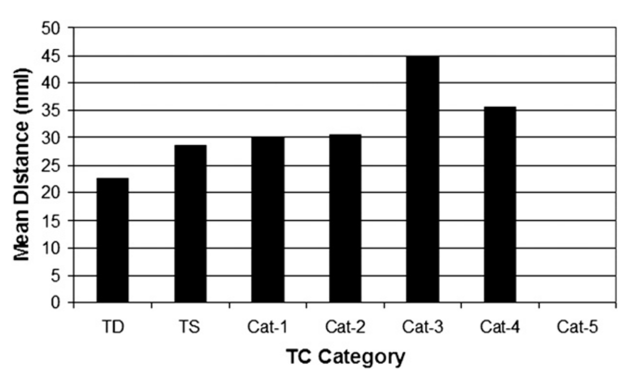

FIG. 22. Mean distance (n mi) by tropical cyclone category of center location error from the NHC best-track position interpolated to the QuikSCAT pass time.

leading to a large negative intensity bias for TCs exceeding an intensity of about 50 kt (25.7 m s^{-1}) (Brennan and Knabb 2007). This represents a significant reduction in capability from what has been available from QuikSCAT (section 5b). The inability of WindSat to reliably retrieve wind speeds as strong as those from QuikSCAT is likely due to its lower resolution (50 km for wind retrievals) and the impact of high cloud liquid water values typically found in regions of strong winds in TCs. It is clear to NHC that passive-only measurements of OSVW in TCs are fundamentally less reliable than active-only measurements; therefore, WindSat OSVW retrievals are not utilized by NHC in operational TC analysis. NHC forecasters do, however, frequently view conventional passive microwave imagery (primarily 37 GHz) of TCs from WindSat via Web sites operated by the U.S. Navy.

In 2007, a preliminary evaluation of wind retrievals from ASCAT, launched by the European Space Agency in October 2006, was conducted in operations at NHC. NHC's TC and marine forecasters are now routinely viewing ASCAT data on a daily basis in the course of their operational shifts. The use of a C-band scatterometer on ASCAT results in wind retrievals that are less sensitive to rain, but ASCAT has less coverage (two parallel 550-km-wide swaths) and lower resolution (the highest-resolution ASCAT retrievals available are at 25 km) compared to QuikSCAT. The impacts of ASCAT on NHC operations are not expected to ever be as significant as QuikSCAT, because of the substantially reduced data coverage arising from the narrower swaths and an increased frequency at which ASCAT fails to sample weather systems of interest. Using the data that are available, ASCAT preliminarily appears to reliably retrieve surface wind speeds of about 25–30 kt (12.9–15.4 m s^{-1}) or less (below tropical storm or gale force) in all weather conditions in NHC areas of responsibility (Cobb et al. 2008). ASCAT appears to have a low wind speed bias, which increases with increasing wind speed for wind speeds exceeding about 25–30 kt (12.9–15.4 m s^{-1}), representing a degradation in capability in tropical storms as compared to QuikSCAT.

WindSat, ASCAT, and even QuikSCAT do not meet NHC's operational needs for satellite OSVW. In an effort to acquire satellite OSVW measurements that do meet these needs and those of the rest of the NWS and NOAA, operational NOAA users defined their requirements for a next-generation OSVW mission at a workshop held at NHC in June 2006 (Chang and Jelenek 2006):

1) A greatly reduced or even nonexistent sensitivity to rain, resulting in the 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 TCs, from 0 up to 165 kt (the greatest maximum sustained wind speed in the NHC best track database). Compared to QuikSCAT, this capability would presumably require an increase in horizontal resolution (to about 1–4 km to be comparable with geostationary imagery) and an increased sensitivity of the raw measurement to extreme wind speeds.
3) Elimination of the directional ambiguity problem. This is necessary, particularly 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, specifically reducing the time of data receipt to a few minutes or less following the time of data collection by the satellite.
5) Increasing the frequency of retrievals over each fixed location in the NHC areas of responsibility to every 1–3 h by using multiple satellites to provide more continuous monitoring of systems, especially in the deep tropics.

Subsequent to the formulation of these requirements, the National Academy of Sciences released a decadal survey in January 2007 that recommended NOAA undertake a next-generation ocean vector winds mission (XOWVM; National Research Council 2007). XOWVM would take a significant step toward meeting the operational requirements outlined above and result in a substantial improvement over the quality of OSVW retrievals currently available from QuikSCAT. XOWVM would greatly enhance the analysis, warning, and forecasting of TCs, particularly those not sampled by aircraft reconnaissance, which includes the majority of TCs globally. Even in TCs sampled by aircraft [e.g., Hurricane Katrina (2005) near landfall], there can still be considerable uncertainty in the cyclone's intensity (Knabb et al. 2005), and a satellite such as XOWVM would supplement aircraft reconnaissance for the analysis of cyclone intensity and size. In addition, XOWVM would improve the analysis, forecasting, and warning of other intense marine storms such as hurricane-force extratropical cyclones as well as other marine wind events.

7. Summary

The availability of QuikSCAT wind retrievals has demonstrated both the utility and the limitations of

OSVW in the operational environment at NHC. An evaluation of these wind data at NHC has shown promise, especially in terms of providing a spatially consistent wind field over the tropical oceans, which are typically void of dense surface observations. QuikSCAT can provide useful information in the analysis of TCs, and this is borne out by its frequent mention in NHC tropical cyclone discussions. There are significant limitations of the data, however, especially in the automated solution, which make interpretation of the data difficult and time consuming. For center location/identification in TCs, the automated solution is often unreliable, particularly in tropical depressions, whose centers are often most difficult to identify and locate using conventional satellite data. The shortfalls of the automated solution often require a time-consuming manual analysis of the directional ambiguities to identify and/or locate the center of a TC.

These trends are reinforced in a comparison of the maximum retrieved wind speeds in QuikSCAT passes over TCs to the NHC best-track intensity during 2005–07. A strong positive bias was seen in the QuikSCAT maximum wind in tropical depressions. In these cases, the effects of rain contamination often render QuikSCAT wind maxima of limited use in determining if a TC has intensified from a depression to a tropical storm. However, NHC forecasters might have more confidence that a system has become a tropical storm when QuikSCAT winds just outside of rain areas approach tropical storm strength.

A minimum in the bias of QuikSCAT intensity estimates is seen in strong tropical storms. As wind speeds in a TC increase to hurricane force, however, the utility of QuikSCAT maximum wind estimates rapidly diminishes. For major hurricanes, the QuikSCAT maximum wind has a very large negative bias, as the effects of rain, resolution limitations, and signal saturation combine to limit the instrument's ability to retrieve wind speeds of major hurricane intensity.

The QuikSCAT-retrieved wind speed is often useful in analyzing the 34-kt (17.5 m s^{-1}) and occasionally 50-kt (25.7 m s^{-1}) wind radii in TCs, especially when the 34-kt wind radii extend outside areas of convection. For tropical storms with areas of 34-kt QuikSCAT winds embedded within convection, however, the interpretation of the data for wind radii analysis is less straightforward. This problem occurs because the sign of the wind speed bias due to rain in QuikSCAT retrievals reverses near the 34-kt wind threshold and interpretation is hindered by the lack of rain-rate information from the QuikSCAT platform.

QuikSCAT data have been particularly valuable in forecasting and analysis in the TAFB areas of responsibility where conventional surface wind information is sparse. QuikSCAT wind data have improved the analysis of surface features such as fronts, cyclones, and the ITCZ, and have resulted in the more accurate identification of wind warning areas. This is particularly true in the case of gap wind events such as those in the Gulf of Tehuantepec, where a climatology of gale- and storm-force wind events has been constructed based largely on QuikSCAT observations, improving forecasts and warnings in these areas.

The limitations of QuikSCAT winds are also evident in weather forecast and analysis applications in the tropics, where the strongest winds are typically accompanied by rainfall that can degrade the quality of QuikSCAT wind retrievals. The impact of rain and the uncertainty introduced by directional ambiguity greatly complicates the interpretation of these winds by forecasters in the time-constrained operational forecast environment.

Future OSVW research at NHC will include continued evaluation of OSVW data from the European ASCAT scatterometer on board the Meteorological Operational Satellite Programme's (METOP) satellite in NHC operations. Also, a joint NOAA–NASA study is currently under way to evaluate QuikSCAT replacement options, including a next-generation satellite OSVW mission that could come much closer to meeting NHC's operational requirements.

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REFERENCES

Atlas, R., and Coauthors, 2001: The effects of marine winds from scatterometer data on weather analysis and forecasting. *Bull. Amer. Meteor. Soc.,* **82,** 1965–1990.

Avila, L. A., 2004: Tropical cyclone report: Tropical Storm Bonnie, 3–13 August 2004. National Hurricane Center, Miami, FL, 10 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL022004_Bonnie.pdf.]

Berg, R., J. Clark, D. Roth, and T. Birchard, 2007: The National Weather Service unified surface analysis. Preprints, *22nd Conf. on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction,* Park City, UT, Amer. Meteor. Soc., 6A.4. [Available online at http://ams.confex.com/ams/pdfpapers/124199.pdf.]

Beven, J. L., and H. D. Cobb III, 2006: Tropical cyclone report: Hurricane Ophelia, 6–17 September 2005. National Hurricane Center, Miami, FL, 10 pp. [Available online at: http://www.nhc.noaa.gov/pdf/TCR-AL162005_Ophelia.pdf.]

——, L. A. Avila, J. L. Franklin, M. B. Lawrence, R. J. Pasch, and S. R. Stewart, 2005: Eastern North Pacific hurricane season of 2006. *Mon. Wea. Rev.,* **133,** 1403–1414.

Brennan, M. J., and R. D. Knabb, 2007: Preliminary operational evaluation of WindSat ocean surface vector winds at the Tropical Prediction Center/National Hurricane Center. Preprints, *14th Symp. on Meteorological Observation and Instrumentation,* San Antonio, TX, Amer. Meteor. Soc., 6.3. [Available online at http://ams.confex.com/ams/pdfpapers/117228.pdf.]

——, H. D. Cobb III, and R. D. Knabb, 2007: Observations of Gulf of Tehuantepec gap wind events from QuikSCAT: An updated event climatology and operational model evaluation. Preprints, *22nd Conf. on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction,* Park City, UT, Amer. Meteor. Soc., 8A.4. [Available online at http://ams.confex.com/ams/pdfpapers/124096.pdf.]

Brown, D. P., 2006: Tropical cyclone report, Hurricane Helene, 12–24 September 2006. National Hurricane Center, Miami, FL, 12 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL082006_Helene.pdf.]

Chang, P. S., and Z. Jelenek, 2006: NOAA Operational Ocean Surface Vector Winds Requirements Workshop report. National Hurricane Center, Miami, FL, 52 pp. [Available online at http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/SVW_workshop_report_final.pdf.]

Chelton, D. B., and M. H. Freilich, 2005: Scatterometer-based assessment of 10-m wind analyses from the operational ECMWF and NCEP numerical weather prediction models. *Mon. Wea. Rev.,* **133,** 409–429.

——, ——, J. M. Sienkiewicz, and J. M. Von Ahn, 2006: On the use of QuikSCAT scatterometer measurements of surface winds for marine weather prediction. *Mon. Wea. Rev.,* **134,** 2055–2071.

Cobb, H. D., III, D. P. Brown, and R. Molleda, 2003: Use of QuikSCAT imagery in the diagnosis and detection of Gulf of Tehuantepec wind events 1999–2002. Preprints, *12th Conf. on Satellite Meteorology and Oceanography,* Long Beach, CA, Amer. Meteor. Soc., JP4.1. [Available online at http://ams.confex.com/ams/pdfpapers/54957.pdf.]

——, R. Knabb, P. S. Chang, and Z. Jelenak, 2008: Preliminary assessment of the utility of ASCAT ocean surface vector wind (OSVW) retrievals at the Tropical Prediction Center/National Hurricane Center. Preprints, *28th Conf. on Hurricanes and Tropical Meteorology,* Orlando, FL, Amer. Meteor. Soc., 15B.4. [Available online at http://ams.confex.com/ams/pdfpapers/137882.pdf.]

Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.,* **103,** 420–430.

Edson, R. T., 2004: Tropical cyclone analysis techniques from QuikSCAT NRCS, wind and ambiguity data and microwave imagery. Preprints, *26th Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Meteor. Soc., P1.8. [Available online at http://ams.confex.com/ams/pdfpapers/75828.pdf.]

——, M. A. Lander, C. E. Cantrell, J. L. Franklin, P. S. Chang, and J. D. Hawkins, 2002: Operational use of QuikSCAT over tropical cyclones. Preprints, *25th Conf. on Hurricanes and Tropical Meteorology,* San Diego, CA, Amer. Meteor. Soc., P1.26. [Available online at http://ams.confex.com/ams/pdfpapers/35317.pdf.]

Fernandez, D. E., J. R. Carswell, S. Frasier, P. S. Chang, P. G. Black, and F. D. Marks, 2006: Dual-polarized C- and Ku-band ocean backscatter response to hurricane force winds. *J. Geophys. Res.,* **111,** C08013, doi:10.1029/2005JC003048.

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting,* **18,** 32–44.

Hoffman, R. N., and S. M. Leidner, 2005: An introduction to the near-real-time QuikSCAT data. *Wea. Forecasting,* **20,** 476–493.

——, C. Grassotti, and S. M. Leidner, 2004: SeaWinds validation: Effect of rain as observed by East Coast radars. *J. Atmos. Oceanic Technol.,* **21,** 1364–1377.

Huddleston, J. N., and B. W. Stiles, 2000: Multidimensional histogram (MUDH) rain flag. Product description, Version 3.0. Jet Propulsion Laboratory, Pasadena, CA, 8 pp.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis, 1984: A tropical cyclone data tape for the North Atlantic Basin, 1886-1983: Contents, limitations, and uses. NOAA Tech. Memo. NWS NHC 22, Coral Gables, FL, 21 pp.

Jones, S. C., and Coauthors, 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Wea. Forecasting,* **18,** 1052–1092.

Knabb, R. D., 2006: Tropical Depression Twenty-E discussion number 2. [Available online at http://www.nhc.noaa.gov/archive/2006/ep20/ep202006.discus.002.shtml.]

——, and D. P. Brown, 2006: Tropical cyclone report: Tropical Storm Zeta, 30 December 2005–6 January 2006. National Hurricane Center, 10 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL312005_Zeta.pdf.]

——, J. R. Rhome, and D. P. Brown, 2005: Tropical cyclone report: Hurricane Katrina, 23–30 August 2005. National Hurricane Center, 43 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf.]

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.,* **15,** 809–817.

Lietzke, C. E., C. Deser, and T. H. Vonder Haar, 2001: Evolutionary structure of the eastern Pacific double ITCZ based on satellite moisture profile retrievals. *J. Climate,* **14,** 743–751.

Long, D. G., 2006: High resolution vector retrieval from SeaWinds scatterometer data. Preprints, *14th Conf. on Satellite Meteorology and Oceanography/14th Conf. on Interaction of the Sea and Atmosphere,* Atlanta, GA, Amer. Meteor. Soc., J4.2. [Available online at http://ams.confex.com/ams/pdfpapers/101367.pdf.]

Milliff, R. F., J. Morzel, D. B. Chelton, and M. H. Freilich, 2004: Wind stress curl and wind stress divergence biases from rain effects on QSCAT surface wind retrievals. *J. Atmos. Oceanic Technol.,* **21,** 1216–1231.

National Research Council, cited 2007: Earth science and applications from space: National imperatives for the next decade and beyond. The National Academies Press. [Available online at http://www.nap.edu/catalog/11820.html.]

Pasch, R. J., and D. P. Roberts, cited 2008: Tropical Depression Seven discussion number 1. [Available online at http://www.nhc.noaa.gov/archive/2008/al07/al072008.discus.001.shtml.]

Portabella, M., and A. Stoffelen, 2001: Rain detection and quality control of SeaWinds. *J. Atmos. Oceanic Technol.,* **18,** 1171–1183.

Simpson, R. H., 1974: The hurricane disaster potential scale. *Weatherwise,* **27,** 169–186.

Steenburgh, W. J., D. M. Schultz, and B. A. Colle, 1998: The structure and evolution of gap outflow over the Gulf of Tehuantepec, Mexico. *Mon. Wea. Rev.,* **126,** 2673–2691.

Stiles, B. W., and S. Yueh, 2002: Impact of rain on spaceborne Ku-band scatterometer data. *IEEE Trans. Geosci. Remote Sens.,* **40,** 1973–1983.

Uhlhorn, E. W., and P. G. Black, 2003: Verification of remotely sensed sea surface winds in hurricanes. *J. Atmos. Oceanic Technol.,* **20,** 99–116.

Von Ahn, J. M., J. M. Sienkiewicz, and P. S. Chang, 2006: The operational impact of QuikSCAT winds at the NOAA Ocean Prediction Center. *Wea. Forecasting,* **21,** 523–539.

Weissman, D. E., M. A. Bourassa, and J. Tongue, 2002: Effects of rain rate and wind magnitude on SeaWinds scatterometer wind speed errors. *J. Atmos. Oceanic Technol.,* **19,** 738–746.

Zheng, Q., X.-H. Yan, W. T. Liu, W. Tang, and D. Kurz, 1997: Seasonal and interannual variability of atmospheric convergence zones in the tropical Pacific observed with ERS-1 scatterometer. *Geophys. Res. Lett.,* **24,** 261–263.