High-Resolution Hurricane Vector Winds from C-Band Dual-Polarization SAR Observations

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ABSTRACT

This study presents a new approach for retrieving hurricane surface wind vectors utilizing C-band dual-polarization (VV, VH) synthetic aperture radar (SAR) observations. The copolarized geophysical model function [C-band model 5.N (CMOD5.N)] and a new cross-polarized wind speed retrieval model for dual polarization [C-band cross-polarized ocean surface wind retrieval model for dual-polarization SAR (C-2POD)] are employed to construct a cost function. Minimization of the cost function allows optimum estimates for the wind speeds and directions. The wind direction ambiguities are removed using a parametric two-dimensional sea surface inflow angle model. To evaluate the accuracy of the proposed method, two RADARSAT-2 SAR images of Hurricanes Bill and Bertha are analyzed. The retrieved wind speeds and directions are compared with collocated Quick Scatterometer (QuikSCAT) winds, showing good consistency. Results suggest that the proposed method has good potential to retrieve hurricane surface wind vectors from dual-polarization SAR observations.

1. Introduction

Large tropical storms form as typhoons in the Pacific Ocean and hurricanes in the Atlantic Ocean. Recent hurricanes such as “Superstorm” Sandy (2012) caused significant damage with intense rainfall and storm surges, as well as serious flooding. At least 286 people were killed along Sandy’s path in seven countries. Therefore, it is important to accurately forecast and monitor hurricane tracks and intensities, particularly for the protection of coastal residents and infrastructure. Better understanding of the hurricane surface wind fields is also essential.

The first applications of microwave remote sensing technology to hurricanes involved an airborne active scatterometer and passive radiometer during Hurricane Allen, demonstrating their potential for reliable measurements (Jones et al. 1981). Although scatterometers and radiometers can also observe the ocean surface by day or night, they can only provide coarse-resolution measurements, and thus their observations are not very suitable to probe high-resolution wind gradient variations between the hurricane eye and eyewall.
Yueh et al. (2003) examined the collocated Quick Scatterometer (QuikSCAT) winds and Special Sensor Microwave Imager (SSM/I) rain rates, and showed that the regions of high rain rate (>20 mm h⁻¹) have a lower normalized radar cross section (NRCS) than the neighboring areas, indicative of the attenuation effects of rain. Compared to these sensors, C-band synthetic aperture radar (SAR) is not only able to contribute fine-resolution sea surface wind field information but also is much less influenced by rain perturbations resulting from volume scattering and attenuation by raindrops in the atmosphere than the Ku-band sensors mentioned above (Tournadre and Quilfen 2003; Weissman and Bourassa 2011). Although SAR images of typhoons and hurricanes occasionally show dark spiral-shaped features due to extreme precipitation events (Reppucci et al. 2008, 2010), the advantages of C-band SAR make it a potentially excellent instrument to investigate mesoscale hurricane intensity and structure.

Great efforts have been devoted to extract hurricane surface wind fields using spaceborne SAR measurements. Horstmann et al. (2005) used a C-band RADARSAT-1 HH-polarized SAR image of Hurricane Ivan to investigate the feasibility of hurricane surface wind retrieval using conventional VV-polarized geophysical model functions (GMFs), such as C-band models 4 and 5 (CMOD4 and CMOD5, respectively). However, studies have shown that CMOD4 is inaccurate for high wind speed retrieval under extreme weather conditions (Migliaccio et al. 2003; Horstmann et al. 2005; Signell et al. 2010). In any case, whether CMOD4 or CMOD5 is used, ultimately, wind direction has to be determined prior to wind speed retrieval from SAR.

In Seasat imagery, linear features were first observed to be aligned with the direction of the wind on the scale of a few kilometers (Gerling 1986). Moreover, marine atmosphere boundary layer (MABL) rolls are frequently observed in SAR images as linear streaks (Alpers and Brummer 1994). These streaks are caused by the convergence or divergence of MABL rolls in the planetary boundary (Brown 2000). Therefore, wind direction can be estimated using the linear features associated with wind streaks, in combination with spectral analysis of the SAR image through a discrete Fourier transform (Vachon and Dobson 1996), or measurement of SAR image streaks via wavelet transform methods (Du et al. 2002), or by acquisition of the orthogonal of the most frequent gradient direction using the local gradient method (Koch 2004). However, these methods all produce wind direction with inherent 180° ambiguities, which can be resolved using the two-dimensional continuous wavelet transform technique to isolate wind-related cells and features, and to extract wind direction without the 180° ambiguity (Zecchetto and De Biasio 2002, 2008).

There can be alias features, such as oceanic or atmospheric internal waves, that produce similar linear features on the same spatial scales as wind rows. These nonwind streak features are not generally aligned with the local wind vectors and can therefore contaminate wind direction retrievals inferred directly from the SAR image. In hurricane wind regimes, although the wind direction dependence of the NRCS for CMOD5 is much weaker than that of CMOD4 (Horstmann et al. 2005), inaccurate wind directions are still able to cause serious errors in wind speed retrievals. To avoid the influence of inaccurate wind directions on wind speed retrieval, Shen et al. (2006) proposed an approach to determine hurricane wind vectors, assuming constant wind speeds and equal-distant wind directions in three neighboring subimage blocks of any specific concentric circle around the hurricane eye. However, this method needs to be modified in some circumstances, for example, for degraded hurricanes, which tend to gradually lose their circular structure, and for SAR images not containing the hurricane eye.

Saturation of the VV-polarized NRCS can be a problem for high wind retrieval from SAR. As wind speed increases, VV-polarized NRCS values also increase, eventually reaching a maximum and then starting to decrease for higher values of wind speeds. Thus, the VV-polarized NRCS experiences saturation under high wind conditions, which creates a wind speed ambiguity problem (multiple solutions) for SAR wind speed retrieval (Shen et al. 2009). Investigations from global positioning system (GPS) dropwindsonde observations and laboratory experiments, as well as airborne scatterometer measurements, suggest that sea surface roughness, and the air–water drag coefficient, approaches limiting values, and also suggest that the NRCS acquired at VV polarization does not continue to increase as winds increase beyond marginal hurricane strength (Powell et al. 2003; Donelan et al. 2004; Fernandez et al. 2006; Black et al. 2007). Bubble annulus experiments suggest that the bubble layer in saltwater impedes the transfer of momentum from the wind (Lundquist 1999). Altimeter observations also showed that the reflectivity is strongly impacted by foam layer and whitecap coverage (Quilfen et al. 2010; Toffoli et al. 2011). In addition to the possible effects of foam, sea spray is hypothesized to significantly influence the transfer of momentum, heat, and moisture in tropical cyclones (Kepert et al. 1999; Perrie et al. 2004a, b). A significant weakness of the wind speed retrieval using VV-polarized SAR images of hurricanes or typhoons is the CMOD5 saturation under high wind conditions. Shen et al. (2009) developed
a technique to remove the wind speed ambiguity based on the dominant hurricane wind structure. Reppucci et al. (2010) proposed a method to overcome the problem of saturation in the tropical cyclone wind regime, basing the technique on the combined use of SAR measurements for areas of wind speed of 20 m s\(^{-1}\) or less, and a parametric hurricane profile model (Holland 1980). However, hurricane vector wind retrievals from single-polarization SAR data are still a challenge, without assumptions on hurricane wind structure or external auxiliary wind information.

C-band cross-polarized ocean backscatter from \textit{RADARSAT}-2 fine quad-polarization SAR data has been documented as being insensitive to the wind direction or the radar incidence angle, and quite linear with respect to the wind speed (8–26 m s\(^{-1}\)), and thus can be used to directly retrieve wind speeds (Vachon and Wolfe 2011; Zhang et al. 2011). The dependence of cross-polarization returns on high wind measurements suggests that it may be ideal for hurricane surface wind retrievals (Hwang et al. 2010a,b). Recently, Zhang and Perrie (2012) proposed an empirical C-band cross-polarization ocean backscatter model (C-2PO) to retrieve high wind speeds, based on quad-polarization SAR measurements and collocated buoy observations. Although the C-2PO model is established from fine quad-polarization mode SAR data with a low noise floor, it may possibly apply to other imaging modes, for example, ScanSAR Wide. However, the user should exercise care when using this model to retrieve high winds from dual-polarization SAR imagery, because the noise floors for dual- and quad-polarization data are different. It is therefore necessary to develop a wind speed retrieval model based on dual-polarization SAR observations.

For hurricanes, wind speed and wind direction are of special interest to marine weather forecasters. Scatterometers can illuminate the sea surface at three different azimuth angles via three antennas, and thus the unique surface wind vector field can be obtained through multiangle observations. However, SAR has one antenna that only provides observations at one azimuth angle. It is difficult to acquire wind speed and direction without ambiguities, by means of individual angle measurements from SAR. Although fully polarimetric SAR measurements provide complementary directional information for the ocean surface wind fields (Zhang et al. 2012), the observed swaths are very small (25 km \(\times\) 25 km or 50 km \(\times\) 50 km), which are not suitable for monitoring hurricanes from space.

In VV polarization, the SAR-measured NRCS is a nonlinear cosine function with respect to wind speed and direction. For a given radar incidence angle and wind speed, one NRCS is associated with four relative wind directions over the range (0\(^\circ\)–360\(^\circ\)). In principle, wind directions can be acquired from the wind streaks and standard image processing techniques (Vachon and Dobson 1996; Du et al. 2002; Koch 2004; Zecchetto and De Biasio 2002, 2008). Though often successful, there are some errors that exist in wind directions from these methods. Moreover, the linear features from which wind directions are inferred from the SAR images are not always present, and they can sometimes be confused with oceanographic features on the same spatial scales (Monaldo et al. 2004). Scatterometers can provide wind direction observations over the open ocean but are contaminated by land signals near coastal regions (Yang et al. 2011b). Meteorological forecast models tend to produce physically reasonable wind direction estimates, but the disadvantage is that their spatial resolutions are generally limited to be far less than the SAR resolution. Moreover, global weather models do not necessarily include sufficient aspects of marine atmospheric boundary layer physics to resolve the finescale features observed by SAR (Li et al. 2011). Compared to single-polarization SAR, dual-polarization SAR can measure ocean backscatters with different scattering characteristics, which provides an opportunity to investigate hurricane wind vector retrievals. Therefore, the motivation of this study is to seek a feasible methodology to \textit{simultaneously} acquire wind speed and direction using dual-polarization SAR observations. The retrieved wind fields need to be evaluated using available data, from buoys, scatterometer measurements, and airborne stepped-frequency microwave radiometer (SFMR) data (Uhlhorn and Black 2003; Uhlhorn et al. 2007), and compared to winds from the National Oceanic and Atmospheric Administration’s (NOAA’s) Hurricane Wind Analysis System (H*Wind) data (Powell et al. 1998).

In this study, we aim to 1) present a new cross-polarized wind speed retrieval model based on observations, including SFMR and H*Wind data; 2) develop an approach to simultaneously retrieve wind speed and wind direction from two dual-polarization SAR images of Hurricanes Bill and Bertha; 3) remove wind direction ambiguities utilizing a parametric sea surface inflow angle model; and 4) assess the accuracy of the proposed hurricane wind vector retrieval method with collocated QuikSCAT winds.

2. Dataset

\textit{RADARSAT}-2 SAR has capability of provide single- (HH or VV or HV or VH), dual- (VV, VH or HH, HV), and quad-polarization (HH, HV, VH, VV) imaging
modes with different coverages. In this study, we focus on measurements from the dual-polarization (VV, VH) ScanSAR narrow and wide modes, because they provide wide swath (300 or 500 km) images, and are suitable for hurricane monitoring with large area coverage from space. The entire range of incidence angles for dual-polarization ScanSAR mode data is between 20° and 49°. For ScanSAR narrow mode, the pixel spacing is 25 m × 25 m, the resolution is 79.9–37.7 m × 60 m (range by azimuth), while for ScanSAR wide mode, the pixel spacing is 50 m × 50 m, the resolution is 160–72.1 m × 100 m (range by azimuth). The noise floor of the two modes is about 28 ± 2 dB (Slade 2009). We remove the speckle noise in the SAR image using a polarimetric SAR speckle filtering approach (Lee et al. 1999) with a nonoverlapping 7 pixel × 7 pixel moving window. This approach emphasizes the preserving of polarimetric properties, and statistical correlation between channels, not introducing cross talk, and not degrading the image quality.

We collected 648 RADARSAT-2 dual-polarization (VV, VH) SAR images for the time interval November 2008–March 2011, with 39 in situ National Data Buoy Center (NDBC) buoy observations in the Gulf of Alaska, and off the East and West Coasts of the United States. These buoys measured wind speed and direction, averaged over 8-min periods, and reported hourly wave parameters (significant wave height, dominant wave period and direction) and surface meteorological parameters (air temperature, sea surface temperature, dewpoint temperature, sea surface pressure). All buoy wind speeds measured at different anemometer heights were adjusted to a reference level of 10 m following Atlas et al. (2011). The spatial and temporal windows for the collocations are required to be less than 10 km and 30 min, respectively.

Buoys can measure ocean surface winds under low to moderate sea states, but they lose observational capabilities when wind speed approaches hurricane force. Hurricane surface winds have been estimated remotely using SFMR on board the NOAA hurricane research aircraft (Uhlhorn and Black 2003; Uhlhorn et al. 2007). The NOAA Hurricane Research Division's H*Wind (Powell et al. 1998) produces a gridded analysis by interpolating and smoothing wind speed observations from a vast array of marine, land, aircraft, and satellite platforms. H*Wind assimilates all of the available wind observations from a specific time period into a moving “storm relative” coordinate system that allows for the production of an objectively blended wind field.

In addition to collocations between SAR images and buoy observations mentioned above, we also collected SFMR and H*Wind data, which were collocated with SAR images of Hurricanes Earl and Ike acquired at 2259 UTC 2 September 2010 and 2356 UTC 10 September 2008, respectively. SFMR measurements over Hurricane Earl were obtained during 2230–2330 UTC 2 September 2010. SFMR can potentially provide along-track mapping of surface wind speeds at relatively high spatial (1.5 km) resolution. For Hurricane Ike, H*Wind data were acquired at 0130 UTC 11 September 2008. The spatial resolution of H*Wind data is 6 km. In total, the dataset consists of 1845 collocated pairs (buoy: 884, SFMR: 348, H*Wind: 613) of NRCS in VH polarization and wind speeds, which were used to develop the wind speed retrieval model for dual-polarization SAR.

Moreover, we collocated two RADARSAT-2 dual-polarization SAR images of Hurricanes Bill (2226 UTC 22 August 2009) and Bertha (1014 UTC 12 July 2008), with QuikSCAT wind data of these two hurricanes, acquired at 2254 UTC 22 August 2009 and 0942 UTC 12 July 2008, respectively. For Hurricanes Bill and Bertha, the time difference between SAR observations and QuikSCAT data are only 28 and 32 min, respectively. The collocation is based on the nearest distance criteria. We only choose those points where the distances between SAR retrievals and QuikSCAT measurements are smaller than 0.1° to validate the proposed dual-polarization SAR hurricane wind vector retrieval methodology.

In this study, QuikSCAT surface wind fields are obtained from the Remote Sensing Systems (RSS) website (ftp://ftp.ssmi.com/qscat/). QuikSCAT level 3 (L3) data consists of global grid values of meridional and zonal components of winds, measured twice a day in an approximately 0.25° × 0.25° resolution, which is suitable for scientific applications (Dunbar and Perry 2001; Callahan 2006). QuikSCAT level 2B (L2B) provides 12.5-km-swath winds. This kind of data is possibly associated with potential applications in coastal regions. The mission requirements for QuikSCAT have an accuracy of 2 m s⁻¹ rms in wind speed for the range 3–20 m s⁻¹, 10% rms for the range 20–30 m s⁻¹, and 20° rms in wind direction for wind speeds ranging from 3 to 30 m s⁻¹ (Dunbar et al. 2006). The original Ku-band GMF, Ku-2001, was developed for QuikSCAT wind vector retrieval (Wentz et al. 2001); validation data for winds higher than 20 m s⁻¹ were extremely limited. Analyses showed that high winds derived using the Ku-2001 GMF were significantly overestimated (Smith and Wentz 2003). Therefore, QuikSCAT ocean wind vectors were completely reprocessed based on the new GMF referred to as Ku-2011, which improves wind speed retrievals at high wind speeds (Ricciardulli and Wentz 2011). The Ku-2011 GMF was developed using wind speed data from the “WindSat” sensor with cross-calibrated multiplatform
data for wind direction (Atlas et al. 2011). WindSat is designed to demonstrate the capability of polarimetric microwave radiometry to observe ocean surface wind speeds. Meissner and Wentz (2009) developed a new algorithm for the WindSat winds and demonstrated that it has validity even in rain and storm conditions. The WindSat retrieval algorithms were trained with NOAA Hurricane Research Division (HRD) data, which are used as the optimum calibration for QuikSCAT wind speeds up to about 35 m s\(^{-1}\) (Ricciardulli and Wentz 2011). The Physical Oceanography Distributed Active Archive Center (PO.DAAC) provides both QuikSCAT L3 and L2B wind products, but these two kinds of data are processed with the Ku-2001 GMF. Although RSS only provides QuikSCAT L3 data, they are produced using the new Ku-2011 GMF. They are therefore more suitable for our study on high winds than those from PO.DAAC. Thus, we use QuikSCAT L3 winds instead of L2B winds to validate the proposed dual-polarization SAR vector wind retrieval algorithm.

3. Methodology, retrieved winds, and validation

a. Dual-polarization SAR wind vector retrieval

Figure 1 shows the relation between RADARSAT-2-measured VH-polarized NRCS (\(\sigma^0_{VH}\)) and collocated observed 10-m neural wind speed (\(U_{10}\)), from buoys, SFMR measurements, and H*Winds data. We find that \(\sigma^0_{VH}\) is not sensitive to the radar incidence angle or wind direction, but it is dependent on wind speed. This characteristic is very similar to that of the C-2PO model derived from fine quad-polarization SAR data (see Fig. 2, following Zhang and Perrie 2012). The intercepts of solid lines in Figs. 1 and 2 are different, which reveal that \(\sigma^0_{VH}\) from dual- and quad-polarization data have different relationships with \(U_{10}\). Previous studies have shown that the wind direction dependence on NRCS in VV polarization (\(\sigma^0_{VV}\)) under high winds became weaker than the dependence in moderate winds, but not for radar incidence angles (Horstmann et al. 2005). Moreover, \(\sigma^0_{VH}\) levels off as the wind speeds increase above hurricane force as shown in Fig. 1, which is possibly associated with \(\sigma^0_{VH}\) attenuation due to intense rainfall and related high sea-state processes. It should be noted that the C-2PO model is based on a dataset that includes only a few wind speeds above 20 m s\(^{-1}\), with a maximum wind of 26 m s\(^{-1}\). Although C-2PO has the potential for retrieval of high wind speeds, it needs further improvement by investigation of higher wind speed observations.

Airborne C-band dual-polarization (HH, VV) SAR observations over the ocean under moderate and high winds have exhibited the essential backscatter features of NRCS in copolarizations (Mouche et al. 2005; Sapp et al. 2013). However, the behavior of cross-polarized NRCS from spaceborne dual-polarization (VV, VH) SAR was not reported. Thus, we need to study cross-polarized SAR ocean surface backscatter characteristics especially under extreme weather conditions and to develop a wind vector retrieval algorithm for dual-polarization SAR.
In the present study, we incorporate SFMR-measured surface winds and H*Wind data. In total, there are 633 wind speeds above 20 m s\(^{-1}\), and the highest wind speed is 39.7 m s\(^{-1}\) as shown in Fig. 1, providing an opportunity to develop a high wind speed retrieval model for dual-polarization SAR observations. We use nonlinear least squares to derive a model relating \(\sigma^0_{\text{VV}}\) to \(U_{10}\) as follows:

\[
\sigma^0_{\text{VV}} = 0.332 \times U_{10} - 30.143.
\]

In Eq. (1), the units of \(\sigma^0_{\text{VV}}\) and \(U_{10}\) are decibels and meters per second, respectively. The correlation coefficient between observed \(\sigma^0_{\text{VV}}\) and simulated \(\sigma^0_{\text{VV}}\) with Eq. (1) is 0.93, and the relation is independent of external wind direction or radar incidence angles. Therefore, we have developed a C-band cross-polarized ocean surface wind retrieval model for dual-polarization SAR (C-2POD).

The wind speed range of the fit for C-2POD is 3.7–39.7 m s\(^{-1}\), whereas for C-2PO, the range is 2.0–26.0 m s\(^{-1}\). In addition to differences in the intercepts, between C-2POD and C-2PO models, as addressed previously, the slopes (angular coefficients) for the two models are different. They are 0.332 and 0.580, respectively. For example, if we assume the VH-polarized NRCS from dual-polarization SAR observation is −24 dB, and input this value into both the C-2POD and C-2PO models, the resulting wind speeds are 18.5 and 20.1 m s\(^{-1}\), respectively. It is evident that the C-2PO model overestimates wind speed. Thus, it is important to use C-2POD, instead of C-2PO, to retrieve wind speeds from dual-polarization SAR images.

Because dual-polarization SAR provides simultaneous co- and cross-polarized ocean backscatter with different scattering characteristics, we can potentially retrieve wind vectors. Therefore, to simultaneously retrieve wind speed and direction, we construct a cost function involving both the copolarized geophysical model function [C-band model 5.N (CMOD5.N)] and C-2POD. The cost function is

\[
J(i,j) = [\sigma^0_{\text{VV}}(i,j) - \sigma^0_{\text{VV}}(i,j)]^2 + [\sigma^0_{\text{HH}}(i,j) - \sigma^0_{\text{HH}}(i,j)]^2,
\]

where \(\sigma^0_{\text{VV}}\) and \(\sigma^0_{\text{HH}}\) are simulated and \(\sigma^0_{\text{VV}}\) and \(\sigma^0_{\text{HH}}\) are observed NRCS in VV and VH polarizations, respectively. Here, \(i\) and \(j\) are the line and column pixel locations, respectively, in the SAR image. For each pixel, we estimate \(\sigma^0_{\text{VV}}\) and \(\sigma^0_{\text{HH}}\) with the observed radar incidence angle and assumed wind direction and speed. Using a nonlinear least squares technique, along with simulated and observed NRCS in VV and VH polarizations, we minimize the cost function at each pixel by requiring that the partial derivatives with respect to wind speed and wind direction be zero. We thus obtain optimum estimates for wind speed, and direction, with associated ambiguities (multisolutions; e.g., \(\phi, \pi - \phi, \pi + \phi, 2\pi - \phi\)).

b. Wind direction ambiguity removal

Because of the friction between hurricanes and the ocean surface, the winds inside the hurricane rotate counterclockwise and the inflow angle is toward the storm’s center in the Northern Hemisphere. The average inflow angle is approximately 20° (Powell et al. 1996). Recent investigation by Zhang and Uhlhorn (2012) has shown that the mean inflow angle in hurricanes is in the range −22.6° ± 2.2° with 95% confidence. This result is obtained from analysis of near-surface (10 m) inflow angles using wind vector data from over 1600 quality-controlled global positioning system dropwindsondes deployed by aircraft on 187 flights in 18 hurricanes. They proposed an analytical parametric model for the surface inflow angle \(\alpha_{SR}\), which requires, as inputs, the storm motion speed, maximum wind speed, and radius of maximum wind, according to the relationship

\[
\alpha_{SR}(r^*, \theta, V_{\text{max}}, V_s) = A_{a0}(r^*, V_{\text{max}}) + A_{a1}(r^*, V_s) \times \cos[\theta - P_{a1}(r^*, V_s)] + \epsilon,
\]

where \(V_{\text{max}}\) and \(V_s\) are maximum wind speed and storm motion speed, respectively. The normalized radial distance \(r^*\) has a radius of maximum wind speed (\(r^* = r/R_{\text{max}}\)); \(\epsilon\) is model error; and \(A_{a0}\), \(A_{a1}\), and \(P_{a1}\) are functions that are described by Zhang and Uhlhorn (2012).

In this study, the model-estimated inflow angle can be used to select the “optimum wind direction” from the multiple of possible wind direction solutions. At each pixel location, the wind alias nearest to the counterclockwise tangential direction, less than the estimated inflow angle (toward the storm center), is chosen as the correct wind direction. To obtain the tangential direction at each pixel location, we use the approach of Du and Vachon (2003) to determine the location of the center of the hurricane eye. The maximum wind speed \(V_{\text{max}}\) is directly obtained from the C-2POD model. The maximum wind speed \(V_{\text{max}}\) can also be estimated via fitting of a parametric model for the tropical cyclone wind speed (Holland 1980) to the SAR measurements in the lower wind speed regime (Reppucci et al. 2010). Thus, the radius of maximum wind can be obtained by estimating the distance between the hurricane eye center and the maximum wind speed location. The storm motion speed can be acquired from National Hurricane Center (NHC) 6-hourly best-track data. Therefore,
the inflow angle is easily calculated using hurricane intensity and the motion parameters, using the parametric inflow angle model. SAR wind direction determination, among the possible aliases, is therefore easily accomplished, making use of the inflow angle at each pixel location.

c. Retrieved winds

Figures 3a and 3b show a RADARSAT-2 SAR image of Hurricane Bill in VV and VH polarizations, respectively. The cost function uses co- and cross-polarized wind speed retrieval models (CMOD5.N and C-2POD), as well as NRCS in VV and VH polarizations and radar incidence angles, to obtain the wind speed and direction, with ambiguities. Figure 3c shows the optimum wind speeds associated with the minimum cost function. Figure 4 shows wind speeds from the CMOD5.N model with overlaid interpolated wind directions from QuikSCAT. The wind speed resolutions for Figs. 3c and 4 are 1 km. Compared to scatterometer
winds, the advantage of high-resolution SAR is that it can image super hurricanes with very small eyes (~10 km) and analyze the wind gradient variations between the eye and eyewall regions. Moreover, the Advanced Scatterometer (ASCAT) on the Meteorological Operation-A (MetOp-A) satellite is able to provide ocean surface winds with an enhanced resolution up to 12.5 km, which is particularly suitable for observing large storm systems with fast-moving propagation speeds. Figure 3b clearly shows that the smaller values for \( s^0 \) are associated with lower wind speed—for example, in the hurricane eye area—while larger \( s^0 \) values are related to higher wind speeds in the eyewall region. This characteristic demonstrates that the cross-polarized SAR observations are not dependent on wind direction or radar incidence angle, but qualitatively vary linearly with wind speeds. It should be noted, as shown in Fig. 1, \( s^0 \) is not saturated when wind speeds are smaller than 30 m s\(^{-1}\) but levels off as the wind speeds increase above that value, above hurricane force winds, which is possibly caused by intense rainfall contamination and additional effects associated with severe sea states.

The resultant retrieved winds allow us to easily derive the hurricane intensity (maximum wind speed, \( V_{\text{max}} \)) and radius of maximum wind (\( R_{\text{max}} \)). They are 34.8 m s\(^{-1}\) and 40.1 km for Hurricane Bill, and 31.8 m s\(^{-1}\) and 47.5 km for Hurricane Bertha, respectively. The propagation motion speeds (\( V_s \)) of Hurricanes Bill and Bertha, as given by the NHC 6-hourly best-track data, are about 9.4 and 2.5 m s\(^{-1}\), respectively. To remove the ambiguities in the retrieved wind directions, the tangential direction and inflow angle at each pixel location have to be ascertained. The VH-polarized SAR image is used to determine the hurricane eye center (HEC) following Du and Vachon (2003). The HEC longitude and latitude are 62°22′11″W and 37°31′3″N for Hurricane Bill, and 62°31′28″W and 29°43′49″N for Hurricane Bertha. Thus, the tangential direction can be determined using a line between HEC and the pixel location. The locations of HEC and \( V_{\text{max}} \) for Hurricane Bill are indicated in Fig. 3c. The storm-relative inflow angles are calculated using the hurricane intensity, radius of maximum wind, and storm motion speed, using the parametric model of Zhang and Uhlhorn (2012). Figure 5 shows the estimated inflow angles. The mean value is −22.5°.

As mentioned previously, the wind alias closest to the counterclockwise tangential direction, less than the estimated inflow angle (toward the storm center), is selected as the optimum wind direction. Thus, we remove the ambiguity in the solutions and obtain the final unique wind directions, which are shown in Fig. 3d. Figures 6a and 6b show a corresponding RADARSAT-2 SAR image of Hurricane Bertha in VV and VH polarizations, respectively. Figure 6c shows the optimum wind speeds associated with the minimum cost function, and

FIG. 4. SAR-retrieved wind speeds from the CMOD5.N model and VV-polarized SAR image of Hurricane Bill as shown in Fig. 3a, with external wind directions from QuikSCAT. Color bar shows wind speeds (m s\(^{-1}\)) at \( U_{10} \).

FIG. 5. Storm-relative inflow angle (\( \alpha_{\text{SR}} \), deg) computed by the parametric model for Hurricane Bill motion speed of \( V_s = 9.4 \) m s\(^{-1}\), and intensities of \( V_{\text{max}} = 34.8 \) m s\(^{-1}\). Storm direction is toward the top of the figure.
the locations of HEC and $V_{\text{max}}$. We also use the CMOD5.N model and QuikSCAT-measured wind directions to obtain wind speeds, which are shown in Fig. 7. Again, to remove wind direction ambiguities, the inflow angles are calculated using $V_{\text{max}}$ and $R_{\text{max}}$ and the storm motion speed. Figure 8 shows the estimated inflow angles. The mean value is $-21.8^\circ$. Figure 6d shows the wind directions without ambiguities.

Since no available SFMR and H*Wind data can be collocated with SAR images of Hurricanes Bill and Bertha at 2226 UTC 22 August 2009 and 1014 UTC 12 July 2008, respectively, we use collocated SAR wind retrievals and QuikSCAT measurements to evaluate the accuracy of the proposed hurricane wind vector method. For Hurricane Bill, we compare the wind speeds from C-2POD and QuikSCAT in Fig. 9a. They show good consistency even for high wind speeds (>20 m s$^{-1}$). Figure 9b gives the wind speeds from C-2POD versus those from CMOD5.N. It is shown that CMOD5.N wind speeds are underestimated, compared to C-2POD values, which is possibly caused by saturation of the NRCS in VV polarization, under high wind conditions and inaccuracy in the external wind direction input. Figure 9c shows the SAR-retrieved wind directions versus QuikSCAT measurements. Rain has a significant impact on QuikSCAT wind speeds, but not on wind directions, except for very high rain rates (Ricciardulli and Wentz 2011). We quantitatively estimate the bias, and centered root-mean-square error (RMSE), based on the formula proposed by Koh et al. (2012). Compared to conventional RMSE, the centered RMSE is not dependent on the bias. We calculate the wind direction correlation following the vector correlation ($\rho_y^2$) approach (Crosby et al. 1993), where $\rho_y^2 = 2$ and $\rho_y^2 = 0$ are related to perfect correlation and zero correlation, respectively.

Figure 10 illustrates the comparisons for Hurricane Bertha. Overall, the results show that the SAR-retrieved

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**Fig. 6.** RADARSAT-2 dual-polarization SAR image acquired over Hurricane Bertha at 1014 UTC 12 Jul 2008 showing (a) VV polarization and (b) VH polarization, where the color bar shows $\sigma_0$ (dB) in VV polarization ($\sigma_{\text{VV}}$) and in VH polarization ($\sigma_{\text{VH}}$), respectively. (c) SAR-retrieved wind speeds. Color bar shows wind speeds (m s$^{-1}$) at $U_{\text{10}}$, and (d) SAR-retrieved wind directions without ambiguities. (RADARSAT-2 data and product 2009 MacDonald, Dettwiler and Associates Ltd., All Rights Reserved.) The locations of HEC and $V_{\text{max}}$ are indicated by the black plus sign (+) in panel (c).
wind vectors are comparable to the QuikSCAT winds. Since wind comparisons are made for SAR and QuikSCAT operating at different frequencies (C band and Ku band), apparent differences between SAR retrievals and QuikSCAT measurements can be found at individual points. The proposed dual-polarization SAR wind vector retrieval method still needs to be validated using additional SFMR measurements, H*Wind data, and reliable hurricane model results.

Although numerical simulations have shown that rain attenuation and scattering at the C band are one order of magnitude lower than at the Ku band (Tournadre and Quilfen 2003), we need to consider the modification of the NRCS by rain, for high rain rates and high winds. It was shown that heavy rainfall (35 mm h\(^{-1}\)) could induce serious wind speed retrieval bias (18.4 m s\(^{-1}\) for CMOD5.5 and 11.7 m s\(^{-1}\) for C-2PO) between SAR and SFMR (Zhang and Perrie 2012). Objectively, neither C-2POD nor CMOD5.N involve any rain parameter because of the lack of collocated high-resolution rain-rate data, and thus wind speed retrieval accuracies of the two models are affected by high rain rates. Future investigations will focus on correction of the NRCS in VV and VH polarizations for intense rainfall regions, which can potentially improve dual-polarization SAR wind vector retrievals in extreme wind conditions.

4. Discussion

Conventional C-band geophysical model functions (GMFs) for wind speed retrieval are generally derived from VV-polarized scatterometer measurements. Although wind speeds and directions are unknown and both are involved in the GMF, they can be derived from scatterometer observations at different azimuth angles. Compared to scatterometers, SAR only observes the ocean surface in one azimuth angle. Thus, it is difficult to simultaneously derive wind speeds and directions, combining SAR observations with GMFs, without ancillary or external wind information.

Saturation of the NRCS in VV polarization, under high winds, can cause wind speed ambiguities (multiplesolutions). As shown in Figs. 4 and 7, low wind speeds appear to occur in parts of the hurricane eyewall regions, which are caused by NRCS saturation. The comparisons between SAR retrievals and QuikSCAT measurements showed that high winds derived using CMOD5.N were underestimated (Figs. 9b and 10b). Moreover, the CMOD5.N model estimates include both wind speed and direction, and thus one can obtain wind direction before deriving wind speed (from the SAR imagery). Wind direction can also be obtained from the SAR image itself, scatterometer measurements, numerical weather prediction models, and buoy observations, but inaccurate wind direction from these sources inevitably yield wind speed retrieval errors from SAR images.

Dual-polarization (VV, VH) SAR can simultaneously measure ocean surface backscatter with different scattering characteristics, compared to single polarized SAR images (HH or VV or HV or VH). The NRCS in VV polarization is dependent on radar incidence angle and wind direction as well as wind speed, whereas NRCS in VH polarization is only dependent on wind speed. We can use NRCS in VH polarization to first retrieve wind speed. The resulting wind speed and the radar incidence
angle and NRCS in VV polarization are utilized to estimate wind direction. As a result, dual-polarization SAR observations provide a good opportunity to obtain wind vector measurements from space.

There are several important factors that affect the dual-polarization SAR wind vector retrieval accuracy. The NRCS calibration error is one of them. For high winds over 20 m s\(^{-1}\), the 0.5–1.0-dB NRCS calibration error will cause 3–8 m s\(^{-1}\) errors in wind speed (Yang et al. 2011a). Moreover, there is potential interchannel cross talk, which cannot be corrected, for dual-polarization data (Touzi et al. 2010). Investigation has demonstrated that the highest wind regions within hurricanes are usually accompanied by significant rain (Weissman and Bourassa 2011). Heavy rain contamination and additional effects associated with severe sea states can strongly dampen the co- (HH or VV) and cross-polarized (HV or VH) NRCS. Intense rainfall in high wind conditions can lead to NRCS attenuation (Powell 1990), and thus underestimation of high wind speeds (Tournadre and Quilfen 2003). Studies using scatterometer data have shown that for wind speeds above 30 m s\(^{-1}\) and rain rates exceeding 15 mm h\(^{-1}\), the error in the winds can be more than 10 m s\(^{-1}\) (Yang et al. 2004). Thus, the accurate retrieval of high wind speeds in intense rain areas has the potential to be improved only if the NRCS could be modified in these regions.

5. Conclusions

We have presented a method to simultaneously determine hurricane wind speed and direction with C-band
RADARSAT-2 dual-polarization SAR observations. Thus, a new cross-polarized wind speed retrieval model for dual polarization (C-2POD) is first developed by using SAR-observed NRCS in VH polarization, with collocated wind speeds from in situ buoys, airborne SFMR data, and H*Winds. This model and the VV-polarized geophysical model function CMOD5.N are used to construct a cost function. Optimum wind speeds and directions can be estimated when the cost function achieves its minimum. The hurricane inflow angles are further used to remove wind direction ambiguities. They are estimated utilizing a parametric model with inputs of maximum wind speed ($V_{\text{max}}$), storm motion speed ($V_s$), and radius of maximum wind ($R_{\text{max}}$). Here, $V_{\text{max}}$ and $R_{\text{max}}$ are derived from the retrieved wind speeds, and $V_s$ is from the NHC best-track data. Two dual-polarization SAR images of Hurricanes Bill and Bertha are used to evaluate the proposed approach. The retrieved winds are shown to be comparable to the collocated QuikSCAT data.

Compared to the CMOD5.N model (as shown in Figs. 9a and 10a), the proposed dual-polarization SAR wind vector retrieval algorithm not only improves the wind speed retrieval accuracy but also derives wind direction without ambiguity. Although we use reprocessed QuikSCAT data from the Ku-2011 GMF to validate our method, there are still some inherent wind speed errors present in the data, especially when wind speeds are above $35 \text{ m s}^{-1}$. Moreover, studies have shown that rain is one of the main sources of error in scatterometer winds (Draper and Long 2004; Nie and Long 2008; Allen and Long 2005; Weissman et al. 2013). The proposed
method is, therefore, in need of additional validation, using more SFMR hurricane surface wind measurement and other high-quality observations.

In this study, our estimate for the storm translational speed is based on the best-track data; we cannot determine storm motion from the SAR image itself. In the future, the Canadian RADARSAT Constellation Mission (RCM) will consist of three satellites in a low-Earth orbit, and thus provide observations of a given location in rapid succession. This will be very helpful for monitoring hurricane speed; two consecutive SAR images of hurricane locations in a couple of hours can be used to determine the hurricane eye centers and thus estimate the storm motion. Additionally, the hurricane intensity \( V_{\text{max}} \) and structure parameter \( R_{\text{max}} \) can also be calculated. These parameters and high-resolution surface wind field from dual-polarization SAR images are important for investigations of hurricane dynamics.

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