Can synthetic aperture radars be used to estimate hurricane force winds?

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[1] We compare wind fields retrieved from a RADARSAT-I synthetic aperture radar (SAR) image acquired over Hurricane Ivan on September 10, 2004 using the C-band geophysical model functions Cmod4 and its newest version Cmod5. Cmod4 has previously been shown to yield very good wind field estimates under low and moderate wind conditions. Wind directions obtained from streaks imaged by the SAR, that are well aligned with the mean surface wind direction are used to invert both algorithms to obtain estimates of the wind speed on scales of 1 km. These estimates are compared with predictions from a high-resolution tropical cyclone model as well as local in situ estimates.

[2] It is found that the SAR wind speeds using Cmod5 agree reasonably well, while those from Cmod4 significantly under predict the measured wind speeds near the hurricane eye wall that reach values as high as 60 m s⁻¹. Citation: Horstmann, J., D. R. Thompson, F. Monaldo, S. Iris, and H. C. Graber (2005), Can synthetic aperture radars be used to estimate hurricane force winds?, Geophys. Res. Lett., 32, L22801, doi:10.1029/2005GL023992.

1. Introduction

[3] The ability of space borne microwave radars to measure the wind vector near the surface of the ocean relies on the fact that the wind field generates surface roughness that increases with wind speed. For radar backscatter at moderate incident angles (20° to 60°), the normalized radar cross section (NRCS) is proportional to the spectral density of the surface roughness on scales comparable to the radar wavelength. For this mid-incidence regime and wind speeds below 20 m s⁻¹, the NRCS is typically largest when the wind blows directly toward the radar and decreases to a minimum when the wind direction is orthogonal to the radar look direction. Another smaller maximum in NRCS occurs when the wind blows directly away from the radar.

[4] The relation between the near-surface wind vector and NRCS can be described by an equation of the form

\[ \sigma_0 = a(\theta) u^s \left( 1 + b(u, \theta) \cos \Phi + c(u, \theta) \cos 2\Phi \right) \]  

(1)

where \( \sigma_0 \) represents NRCS, \( u \) represents wind speed, \( \Phi \) represents the relative angle between the radar look and wind direction, and \( \theta \) is the nadir incidence angle. The quantities \( a(\theta), b(u, \theta), c(u, \theta) \) are empirical parameters determined by measured data.

[5] Equation (1) shows that \( \sigma_0 \) is an exponential function of wind speed and a harmonic function of its direction. Note that a specific NRCS value cannot be associated with a unique wind speed and direction pair. However, if wind direction is known a priori, it is possible to use equation (1) to estimate wind speed. An approach convenient for operational applications is to use predicted wind directions from operational meteorological models [Monaldo et al., 2002]. Another method is to estimate the wind direction directly using linear features in the SAR image itself [Horstmann et al., 2002]. Both approaches have proven successful for moderate wind speed regimes.

[6] In hurricanes, the surface roughness structure grows more complicated not only because of the addition of more wave breaking and surface foam, but also because of the more complex structure of the long wave field (cross seas) generated at previous times when the hurricane was at a different location. It is, therefore, likely that conventional empirical geophysical model functions (GMFs) developed using data for moderate wind conditions may also begin to break down.

[7] In the following sections, we briefly describe some of the salient aspects of SAR wind retrieval schemes and the results of applying these in the high wind regimes observed in Hurricane Ivan. We will show that the newly-developed Cmod5 GMF [Hersbach, 2003] outperforms the commonly used Cmod4 [Stoffelen and Anderson, 1997] in this high wind speed case study. In particular, we will show using NRCS measurements from a SAR image collected over Hurricane Ivan that the dependence of NRCS on the relative angle between the radar look direction and the local wind directions weakens, and perhaps disappears altogether, at very high wind speeds, and that such dependence is better modeled by the Cmod5 GMF.

2. SAR Wind Retrieval

2.1. Wind Direction Estimation

[8] The most popular method for SAR wind direction retrieval is based on the imaging of linear features aligned along the wind direction [Gerling, 1986]. Most of these features are associated with wind streaks and marine atmospheric boundary layer (MABL) rolls, which are visible in SAR images at scales greater 200 m. To retrieve the orientation of these linear features, several methods have been developed [Gerling, 1986; Vachon and Dobson, 1996; Lehner et al., 1998; Horstmann et al., 2002; Wackerman et al., 2004] of which the Local Gradient (LG)-Method yields the smallest residuals, with a typical error of 18°.
In the present study we use the LG-Method [Horstmann et al., 2002; Koch, 2004] to retrieve SAR wind direction. In this approach, a SAR image is sequentially smoothed and reduced to resolutions of 100, 200, and 400 m. The resulting three SAR images retain spatial scales greater than 200, 400, and 800 m. From each of these images, local directions defined by the normal to the local gradient (to within a $180^\circ$ ambiguity), are computed. In the next step, pixels associated with land, surface slicks, and sea ice, are masked and excluded from further analysis. From all of the retrieved directions, only the most frequent directions in a predefined grid cell are selected. These resulting wind directions typically vary by only a few degrees, except for cases where additional features are present in the SAR image, e.g., ocean surface waves or artifacts from the original SAR processing. The $180^\circ$ directional ambiguity can be removed if wind shadowing, which is often visible in the lee of coastlines is present. If such features are not present in the image other a priori information, e.g., weather charts, atmospheric models or in situ measurements are used to remove ambiguities.

2.2. SAR Geophysical Model Functions

With the wind direction in hand, we can use the NRCS measured by the SAR to retrieve the wind speed using GMFs. For C-band, VV-polarization NRCS, there are a number of popular model functions, for which the coefficients and exact model form have been determined empirically. The most commonly used C-band model function is the Cmod4 [Stoffelen and Anderson, 1997] and the most recently developed is Cmod5 [Hersbach, 2003]. Each of these GMFs is directly applicable for wind speed retrieval from C-band VV polarized SAR images [e.g., Vachon and Dobson, 1996; Lehner et al., 1998; Horstmann et al., 2003]. For wind speed retrieval from C-band SAR images acquired at HH-polarization (i.e., the configuration for RADARSAT-1 images), no similar well-developed GMF exists. To meet this deficiency a hybrid model function is used that consists of one of the prior mentioned VV-polarization GMF and a C-band polarization ratio (PR) [Thompson et al., 1998; Horstmann et al., 2000]. The PR is defined as the ratio of HH-polarization NRCS to VV-polarization NRCS. The nature of the PR is an active area of research and several different PR’s have been proposed in literature [Thompson et al., 1998; Mouche et al., 2005]. The PR proposed by Thompson et al. [1998] neglects wind speed and wind direction dependence but nevertheless showed good results when utilized for wind speed retrieval from RADARSAT-1 SAR imagery [Monaldo et al., 2002].

Comparisons of C-band SAR retrieved wind speeds, using the Cmod4 at low to moderate wind speeds (up to 20 m s$^{-1}$) resulted in errors of $\sim 2$ m s$^{-1}$ [Monaldo et al., 2002; Horstmann et al., 2003]. It is also well known that the Cmod4 underestimates the wind speeds at high winds (>20 m s$^{-1}$) when applied to SCAT and SAR data [Donnelly et al., 1999; Katsaros et al., 2002; Horstmann et al., 2003]. The Cmod5 algorithm was specifically designed to provide better estimates of the NRCS at higher wind speeds [Hersbach, 2003]. Differences between Cmod4 and Cmod5 for low to moderate wind speeds are relatively minor. At high wind speeds (>25 m s$^{-1}$) however, the differences become quite significant. In particular, the NRCS from Cmod4 continues to increases monotonically with wind speed for all incident angles, while that predicted by Cmod5 increases much more slowly with wind speed and for lower incident angles (depending on the wind vector), can even reach a maximum value and decrease with further increase in wind speed. Furthermore, the wind direction dependence of the NRCS of Cmod5 becomes much weaker than that of Cmod4 in the high wind regime.

3. High Wind Speed Dependence of the NRCS

Figure 1 shows a RADARSAT-1 SAR image of Hurricane Ivan, acquired on September 10, 2004 at 2307 UTC showing the surface signature of Hurricane Ivan. The plot beneath the image shows the change of incident angle over range. This image was received and processed at CSTARS.

![SAR image acquired by the Canadian RADARSAT-1 satellite on September 10, 2004 at 2307 UTC showing the surface signature of Hurricane Ivan. The plot beneath the image shows the change of incident angle over range. This image was received and processed at CSTARS.](image1)

![NRCS versus direction around the concentric circles in the SAR image of Figure 1.](image2)
This asymmetric dependence on wind direction is seen in the Cmod4. The 63 km plot shows an direction dependence more similar to the second harmonic becomes apparent. In particular, this curve shows a wind dependence of the NRCS plot begins to entire range is less than 1 dB. For the circle of 43 km radius, the NRCS is fairly constant around the entire circle. At these radii, the maximum change in NRCS over the 23 km, the NRCS is fairly constant around the entire circle. The variation of the NRCS with distance from the eye can be seen using the radii of the concentric circles shown in the figure. The NRCS increases dramatically at a distance of about 12 km from the eye, and remains roughly independent of the angular location around the eye for distances out to about 18 km. On a larger scale, one can also see in Figure 1, evidence of counter-clockwise circulation from the wind streaks and rain bands.

[13] To quantitatively investigate the wind direction dependence of the NRCS at various distances from the hurricane eye, we show in Figure 2 the NRCS plotted as a function of azimuth angle around each of the concentric circles in Figure 1 starting clockwise from 0°. Because of the cyclonic nature of the hurricane, these “circular transects” span all wind directions with respect to the antenna look direction. To reduce the effect of speckle noise in the transects, the NRCS was averaged over an area of ≈1 km². Note that the directions in the abscissa of the plot in Figure 2 correspond roughly to the wind directions expected in a (northern-hemisphere) hurricane. The different radii of the plots in Figure 1 were selected carefully in order to avoid areas in the SAR image which are significantly affected by non-wind induced artifacts, e.g., rain bands.

[14] Figure 2 shows that for the plots with radii of 13 and 23 km, the NRCS is fairly constant around the entire circle. At these radii, the maximum change in NRCS over the entire range is less than 1 dB. For the circle of 43 km radius, the wind direction dependence of the NRCS plot begins to become apparent. In particular, this curve shows a wind direction dependence more similar to the second harmonic behavior seen in the Cmod4. The 63 km plot shows an asymmetric dependence on wind direction. This asymmetry is partially due to the fact that the difference in incident angle between the near- and far-range (∼7°) is becoming significant for this case.

[15] It is important to note that the NRCS in the high wind regime near the hurricane eye wall appears to be independent of wind direction. We show in the following section that this apparent loss of direction sensitivity, which is not well represented by the Cmod4 model function, can have a large impact on the retrieved wind speeds in this regime.

4. Retrieved Wind Fields From Hurricane Ivan

[16] As discussed in section 2.2, differences between the Cmod4 and Cmod5 GMFs can be significant for hurricane force winds. To further investigate this issue, we have inverted the Ivan SAR image into two wind maps based on the Cmod5 and Cmod4 GMF (Figure 3, left and center Panel). For both inversions, we have used the LG-Method to determine the wind directions and the Thompson et al. [1998] PR. Perhaps most obvious is the fact that Cmod5 yields significantly higher winds than does Cmod4; 50 to 55 m s⁻¹ versus 25 to 30 m s⁻¹, respectively. As mentioned earlier, the maximum wind speed reported at the overpass time was about 65 m s⁻¹. We see that the predicted winds from Cmod5 are fairly close to this value, while those from Cmod4 are significantly lower. The right-hand panel of Figure 3 shows the difference image (Cmod5 − Cmod4). Notice the large differences especially near the north-east hurricane eye wall where the maximum winds are expected.

[17] The small circular dots shown at the wind vectors on the Cmod5 and Cmod4 wind maps represent wind speeds predicted by an interactive objective kinematic analysis (IOKA) model for tropical cyclones [Cox et al., 1992]. These dots are color coded using the same wind speed scale as the SAR wind map. The agreement is generally good for the Cmod5 map; especially in the higher wind region near the eye wall, while for the Cmod4 wind map, it is significantly worse.

[18] Figure 3 also shows that the angular dependence of the predicted wind speeds associated with Hurricane Ivan is closer to the expected behavior. In particular, the Cmod5 wind speeds near the hurricane eye are not only larger than those from Cmod4, but they are much more.
uniform around the full angular extent of the eye. To see this effect more clearly, we show in Figures 4a and 4b plots of the predicted NRCS versus wind direction for Cmod5 and Cmod4, respectively, that would occur around the concentric circles in Figure 1. These curves should be compared with the corresponding curves in Figure 2 extracted directly from the NRCS data from Hurricane Ivan shown in Figure 1. Note that the curves computed from Cmod5 compare reasonably well with the corresponding curves in Figure 2. The Cmod4 curves in Figure 4b show more sensitivity to wind direction at the higher wind speeds, and are generally rather different from those computed using Cmod5. The asymmetry about 180° apparent in the NRCS predictions of both GMFs in Figure 4 is due to the fact that the incident angle varies around the concentric circles in Figure 1. This variation of the incident angle (as well as the fact that wind may not be constant) also affects the angular dependence of the “circular transects” in Figure 2. The results shown in Figure 4 further confirm our conclusions based on the wind maps in Figure 3 that the Cmod5 GMF provides a better representation of the hurricane Ivan wind field.

5. Conclusion and Outlook

To the best of our knowledge, this letter describes the first attempt to extract quantitative wind speed estimates under hurricane conditions using the recently developed Cmod5 GMF. At least for this single case, we conclude that Cmod5 provides better wind speed estimates for hurricane force winds than the more commonly used Cmod4. The major difference between these two GMFs is that for Cmod5, the NRCS (at a particular incident angle) becomes rather insensitive to the local wind vector (speed and direction) for winds >25 m s⁻¹. This high-wind dependence is quite different from that of Cmod4, and as we have demonstrated, can have a major impact on the extracted wind field for the extreme conditions such as those of Hurricane Ivan. Although the Cmod5 GMF was developed empirically, its loss of wind sensitivity at high wind speeds has a more fundamental basis. In a recent letter, Donelan et al. [2004] showed that the drag coefficient over the ocean approaches a limiting value in high wind conditions. This behavior is significantly different from its behavior at intermediate wind speeds where the drag coefficient increases with wind speed. Qualitatively, the wind speed dependence of the NRCS predicted by Cmod5 mirrors that observed for the drag coefficient.

Much work remains to further refine wind estimation of hurricane force winds. It is clear that more cases are needed to substantiate the findings for Hurricane Ivan discussed here. Also, the issue of the proper C-band GMF for HH-polarization must be resolved. To begin to address this issue, we have ordered a VV-polarization EnviSat SAR image collected over Hurricane Isabel to compare with the HH-polarization image discussed here. We will examine this image to see if the same general conclusions found for the HH-polarization image still apply. The use of high-resolution SAR wind mapping under extreme wind conditions is just beginning to be recognized as a viable tool for hurricane tracking and prediction. Although much work remains to be done, we believe that the potential payoff is well worth continued effort.

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