The Capability of Hurricane Wind Monitoring by SAR

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ABSTRACT

Synthetic Aperture Radar (SAR) images are more and more widely used in ocean wind monitoring. Their capability in accurate measurements for moderate ocean surface wind has been widely accepted. However, fewer studies have been done on the accuracy of SAR wind measurements in high hurricane wind conditions (>25m/s), except for some papers that focus on qualitative interpretations of the dynamical processes accompanying hurricane processes, such as rain bands, atmospheric boundary rolls etc. In this paper, the capability of hurricane wind retrieval from SAR is analyzed, based on our newly developed hurricane wind retrieval method, which can retrieve hurricane wind vectors directly from SAR images without any external information. The retrieved SAR wind is compared with in-situ measurements and QuikSCAT scatterometer winds. We show good potential for quantitative high wind monitoring by SAR. The challenge of more accurate wind retrievals of hurricane winds is discussed, which is the focus in our ongoing research.

Keywords: Hurricane winds, Synthetic Aperture Radar (SAR), retrieval

1 INTRODUCTION

Synthetic Aperture Radar (SAR) provides all day and all weather measurement over the earth, with high spatial resolution. Compared to scatterometer, which is a very useful proven instrument for open ocean wind monitoring, SAR has the potential to provide highly accurate, high spatial resolution wind fields, which can greatly improve our knowledge of mesoscale and microscale wind structures as well as coastal ocean dynamics. Furthermore, due to the capability of radar waves to penetrate through clouds, these measurements were less influenced by the weather than other remote sensing instruments which operate in different bands of the spectrum, such as visual band, infra-red band etc. Thus, SAR has the potential to monitor oceanic and atmospheric dynamics under severe weather conditions, like hurricanes. Due to the wide application of SAR data in oceanography and meteorology researches, SAR has been a regular sensor onboard several satellites, *e.g.* European Remote Sensing (ERS), Japanese Environment Resource Satellite (JERS), the Canadian Space Agency's Radarsat-1, the European Space Agency's Envisat, and it will also be included in future, as on the German Space Agency's TerraSAR-X and on Radarsat-2. The ScanSAR mode measurements of Radarsat-1 SAR and Envisat ASAR provide wide-swath measurements, which are suitable for the study of hurricanes.

There are two main kinds of applications of SAR data in hurricane studies, one is qualitative analysis of hurricane structures, which focuses on the accompanying processes of hurricanes, such as rain bands, atmospheric rolls, etc [*Katsaros et al.*, 2002]; the other application is the ocean surface wind retrieval, which has been widely studied in low-to-moderate wind conditions [*He et al.*, 2005; *Perrie et al.*, 2006].

Generally, two main methods are used for SAR near-surface (usually 10 m above sea level) wind speed retrievals [*Mondaldo et al.*, 2004; *Vachon and Dobson*, 2000; *Horstmann et al.*, 2000]. One method is the SAR wind direction algorithm (SWDA); the other is the SAR wind algorithm (SWA). In the SWDA method, wind direction must be known a priori, and is usually inferred from wind-aligned features visible in the SAR images, NWP winds, *in-situ* measurements (*e.g.* buoys), or remotely sensed measurements (*e.g.* scatterometers). Wind speed is retrieved from a geophysical model function (GMF), which relates the ocean wind speed, the normalized radar cross section (NRCS), the radar relative wind direction and the local incidence angle. In the SWA method, the near surface wind speed is estimated from the degree of azimuth cut-off of the SAR image spectrum [*Kerbaol and Chapron*, 1998]. This method requires models to describe the relationship between the spectral width of the azimuth spectrum, the ocean wave spectrum and the wind speed [*Vachon and Dobson*, 2000].

Besides SWDA and SWA methods, *He et al*. [2005] developed a new gradient method (GM) for SAR wind retrievals. This method is based on the assumption that the studied wind field is quasi-uniform, allowing retrieval of wind vectors from two neighboring sub-image blocks, having slightly different incidence angles. *Perrie et al.* [2006] extended the application of the GM formulation to the hurricane case. However, external wind direction information is still needed to find the best solution for the cost function. *Shen et al.* [2006] modified the GM formulation, making it possible to retrieve wind pairs (speed and direction) from SAR images without external information, in certain circumstances. However, an apparent bias still exists for hurricane directions in studies of both *Perrie et al*. [2006] and *Shen et al.* [2006]. Recently, we have established a hurricane wind retrieval algorithm, which can retrieval hurricane wind vectors (speed and direction) on the ocean surface from SAR images without any external wind information [*Shen et al*., 2006]. The method will be introduced in this paper in section 2. A Radarsat-1 SAR image of hurricane Erin is analyzed by the new method in section 3. To evaluate the accuracy of the retrieved hurricane wind from SAR, QuikSCAT scatterometer measurements and *in-situ* measurements are analyzed and results of comparisons are also presented. The conclusions are given in section 4.

2 METHODOLOGY

As we have discussed in *Shen et al*. (2006), mature hurricanes typically exhibit a quasi-axisymmetric vortex, which is in hydrostatic and rotational balance [*Emanuel*, 1991]. Inside the radius of maximum wind, the core is nearly in solid-body rotation. Wind speed near the hurricane eye is almost uniform [*Yueh et al*., 2001], and the hurricane structure is circular in shape. Therefore, wind speed values along any concentric circle centered on the hurricane eye, especially those near the eye, are quasi-constant and wind direction is approximately tangential and circularly varying. We thus assume wind speeds in three neighboring blocks of a given concentric circle are constant and wind directions are uniformly varying, which can be expressed as,

$$\begin{aligned} u_1 &= u_2 = u_3 \\ \theta_1 &= \theta_2 - \Delta\theta \\ \theta_2 &= \theta_3 - \Delta\theta \end{aligned} \tag{1}$$

where ($u_i, \theta_i \;\; i = 1,2,3$) are wind speed and wind direction of the i-th sub-image block along a specific radial circle, and $\Delta\theta$ is the wind direction difference of *i*th block relative to the (*i*-1)th sub-image block.

Wind speed and direction are related to NRCS by the GMF, whose general form is,

$$\sigma_0 = a(\phi)u^{\gamma(\phi)}\left(1 + b(u,\phi)\cos\theta + c(u,\theta)\cos 2\theta\right) \tag{2}$$

where σ_0 represents NRCS, u is wind speed, ϕ is the nadir incidence angle, θ represents the relative angle between radar look direction and the wind direction, and a, b, c, γ are empirical parameters. Here, we choose the CMOD5 GMF [*Hersbach*, 2003] for hurricane wind analysis because of its superior reliability in high winds compared to its counterparts such as CMOD4 [*Horstmann et al*., 2005; *Stoffelen and Anderson*, 1997], or CMOD-IFR2 [*Quilfen et al*., 1998], which have underestimation tendencies in high wind conditions.

For each sub-image block, wind speed and direction, NRCS and radar incidence angle are determined by CMOD5. From section 3.1, the equations for three neighboring blocks are,

$$\sigma_{0i} = \mathrm{cmod}\,5\left(u_i, \theta_i, \phi_i\right) \quad i = 1,2,3 \tag{3}$$

Replacing u_1, u_3 and θ_1, θ_3 in (3) by equation (1), the group equation (3) is reduced to three functions with three variables of u_2, θ_2 and $\Delta\theta$.

The final solution is the minimum of the following cost function,

$$J = \sum_{i=1}^{3} \left(\sigma_{oi} - \sigma_{ci}\right)^2 \tag{4}$$

where σ_{oi} is SAR observed and σ_{ci} is the calculated NRCS in the i-th block.

Since the method focuses on three neighboring sub-images blocks of any concentric circle relative to the hurricane center, the position of the hurricane eye needs to be located in advance. Thus, we use the automatic hurricane eye finding scheme introduced by *Du and Vachon* (2003). The SAR images are then divided into sub-image blocks based on the required spatial resolution within a polar coordination system. Since the CMOD5 GMF is a strong nonlinear equation, the solution of the cost function (4) may have more than one solution. Therefore, a reference wind speed method is needed [*Shen et al*., 2006]. Figure 1 shows the application of the procedure to hurricane wind retrieval from SAR images.

3 WIND RETRIEVAL AND EVALUATION FOR HURRICANE ERIN (SEP.1, 2001)

Based on the hurricane wind retrieval procedure introduced in Figure 1, a Radarsat-1 SAR image captured for hurricane Erin at 22:17UTC in September 01, 2001 was analyzed. Since Radarsat-1 operates at HH polarization, a hybrid model is needed for application of CMOD5, and it has the form [*Thompson et al.* 1998]

$$\sigma_0^H = \sigma_0^V \frac{\left(1+\alpha \tan^2 \phi\right)^2}{\left(1+2\tan^2 \phi\right)^2} \tag{5}$$

where ϕ is the incidence angle, parameter α is zero for Bragg scattering theory, and α =1 for Kirchhoff scattering theory, In this paper, we take α =1, following *Vachon and Dobson* [2000].

The position of the hurricane eye was located at (37.8ºN, 64.57ºW). The radial spatial resolution and angular resolution were set at 10km and $\pi/(2i-1)/2$ respectively, where i is the serial number of the concentric cycles. Figure 2 shows the retrieved wind vectors that have been downgridded to 25km spatial resolution to facilitate the comparison with QuikSCAT winds. The principal structure of the hurricane is clearly presented in the retrieved wind result. Since the wind direction was directly retrieved from the SAR images based on the principal vortex structure of hurricane, the method is quite suitable for high spatial resolution wind vector retrieval for these wind fields. Comparisons with QuikSCAT scatterometer data were used to evaluate the accuracy of the retrieved hurricane wind. Figure 3 shows the scatter plot of our SAR winds *vs*. QuikSCAT scatterometer winds. Generally, our retrieved SAR wind is very close to the QuikSCAT scatterometer measurements. However, bias exists in the very high wind domain, which we suggest is caused by the rain effect. Comparisons with available in-situ measurements from NDBC buoy 44011 (41.11ºN, 66.58ºW) show that our SAR retrieved winds are closer to *in-situ* measurements than QuikSCAT wind measurements.

4 CONCLUSIONS

Our new hurricane wind retrieval algorithm was successfully applied to a Radarsat-1 SAR image of hurricane Erin. The retrieved hurricane winds show good consistency with scatterometer winds and also with *in-situ* measurements. However, SAR measurements tend to be biased low compared to QuikSCAT measurements, in the very high wind domain (see Figure 3). Comparisons with *in-situ* buoy measurements suggest that the difference between our retrieved SAR winds and QuikSCAT winds is probably caused by an overestimation in QuikSCAT winds, under hurricane conditions. Therefore, we suggest that the negative bias in our SAR retrieved wind speeds, relative to the QuikSCAT data, is due to this QuikSCAT bias for hurricane Erin. For the Ku band scatterometer, QuikSCAT is more likely to be influenced by precipitation than SAR. This can lead to high or low biases in wind speeds depending on the size of rain drops [*Portabella*, 2002]. The same phenomenon was found in *Shen et al*. (2006) in an analysis of images of hurricane Isabel on Sep 18, 2003.

In conclusion, we have presented a new algorithm for hurricane wind retrievals. It is based on the primary vortex structures of hurricane processes and we showed that it is able to retrieve hurricane wind vectors on the ocean surface. Clearly, our new method has advantages in high spatial resolution hurricane wind retrieval, compared to the standard SWDA wind retrieval algorithm, which requires *a priori* wind directions. Comparisons with QuikSCAT wind and available simultaneous *in-situ* measurements show that SAR images are capable of monitoring hurricane processes.

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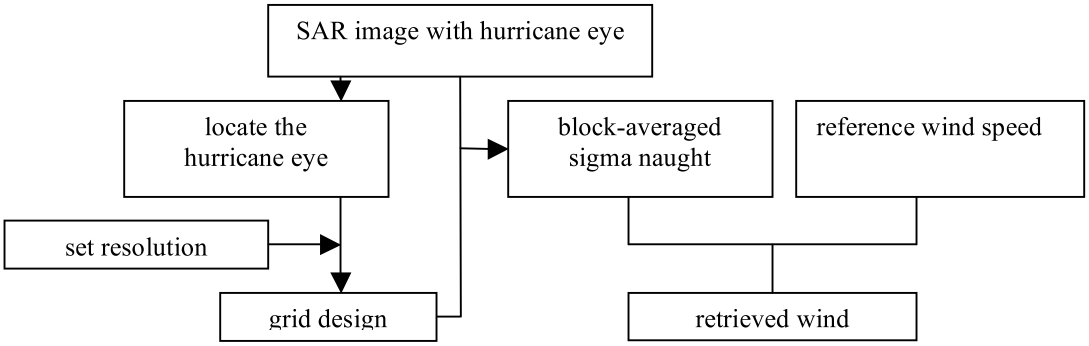

Figure 1. The procedure of hurricane wind retrieval from SAR

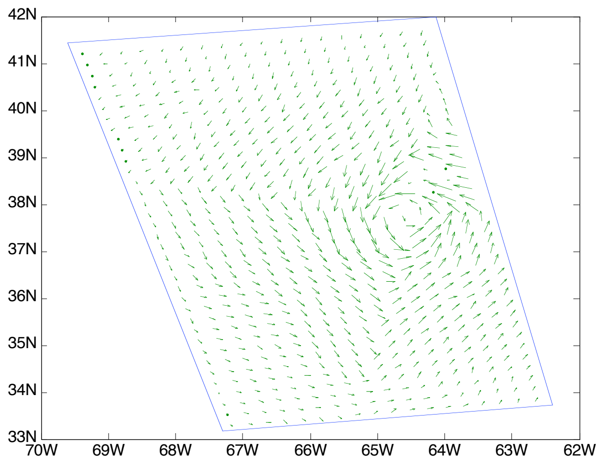

Figure 2. The retrieved SAR wind of hurricane Erin

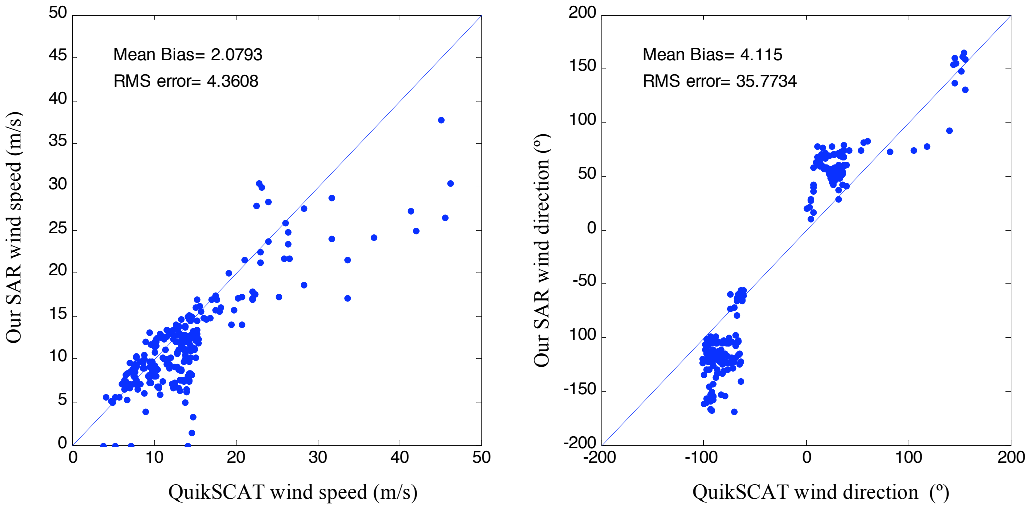

Figure 3. Scattered plot of our SAR wind and QuikSCAT wind