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Ocean Surface Wind Speed of Hurricane Helene Observed by SAR

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Abstract

The hurricanes can be detected by many remote sensors, but synthetic aperture radar (SAR) can yield high-resolution (sub-kilometer) and low-level wind information that cannot be seen below the cloud by other sensors. In this paper, an assessment of SAR capability of monitoring high-resolution hurricane was conducted. A case study was carried out to retrieve ocean surface wind field from C-band RADARSAT-1 SAR image which captured the structure of hurricane Helene over the Atlantic Ocean on 20 September, 2006. With wind direction from the outputs of U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS) model, C-band geophysical model functions (GMFs) which describe the normalized radar cross section (NRCS) dependence on the wind speed and the geometry of radar observations (i.e., incidence angle and azimuth angle with respect to wind direction) such as CMOD5 and newly developed CIWRAP models have been tested to extract wind speed from SAR data. The SAR retrieved ocean surface winds were compared to the aircraft wind speed observations from stepped frequency microwave radiometer (SFMR). The results show the capability of hurricane wind monitoring by SAR.

Keywords: Synthetic aperture radar (SAR), hurricane, wind speed

Introduction

It has long been known that the sea surface wind field can be observed from space by satellite scatterometer measurements, with a relatively low spatial resolution of about 25 km. In contrast to the scatterometer, satellite-borne synthetic aperture radar (SAR) instruments can provide wind fields on a much finer scale because of their high spatial resolution (sub-kilometer). Thus, SAR instruments can be

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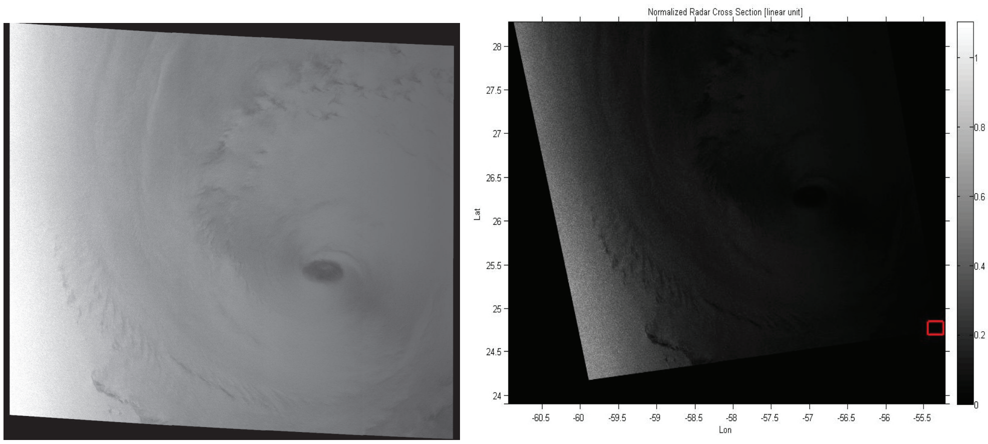
valuable tools for measuring high-resolution sea surface winds [1-3]. Using SAR images, we have also been able to image many types of storms, including polar lows and hurricanes. Although other existing sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS) can easily detect hurricanes and other mesoscale storms, SAR can contribute fine-resolution ocean surface information that cannot otherwise be obtained below the cloud deck [4].

RADARSAT-1's ScanSAR Wide (SCW) modes, with swath widths of 450 or 500 km and a spatial resolution of 100 m, can provide both synoptic scale and small-scale views of the imprint of hurricanes on the ocean surface's roughness [5]. In this study, the wind structure of hurricane Helene over Atlantic Ocean in 2006 was studied using a RADARSAT-1 SAR image. It was developed to tropical storm on September 14 and then changed into hurricane two days later. The *in situ* wind observations from aircraft stepped frequency microwave radiometer (SFMR) were also used to validate the accuracy of SAR estimation of hurricane wind speed.

Data sets and Methodology

Data sets. The data used in this study are C-band RADARSAT-1 SAR image acquired at horizontal (HH) polarization in transmission and reception and SFMR wind speed observations of hurricane Helene.

SAR data. Fig. 1a is a RADARSAT-1 SCW SAR image over Hurricane Helene taken at 21:52 UTC on September 20, 2006 when Helene was developed to a hurricane. The SAR image shows very fine hurricane structure. For example, the large waves around the hurricane eye, wave patterns around the eye wall and a series of convective cells in the rain bands.



(a) (b)

Fig. 1 (a) RADARSAT-1 SAR image over Hurricane Helene taken at 21:52 UTC on September 20, 2006 (© Canadian Space Agency/Agence spatiale canadienne). (b) The corresponding normalized radar cross section (NRCS) values in linear unit in geophysical coordinate. The red square shows the area where the aircraft flowed into on the same day. The enlarged image of the area is shown in Fig. 3.

SFMR data. The NOAA/Aircraft Operations Center (AOC) flew SFMRs on both WP-3D research aircraft for operational hurricane surface wind speed measurement since 1999 [6]. In this study, collocated wind speed observations from SFMR are collected within 1 hour and 20 minutes of SAR imaging time. There are totally 72 matchup points between SAR and SFMR data.

Methodology. Two newly developed C-band geophysical model function (GMF) CMOD5 [7] and CIWRAP [8] algorithms for measuring high wind speeds are used to derive hurricane wind speed from SAR. Sea surface wind retrieval from SAR is dependent upon knowledge of normalized radar cross section (NRCS) (Fig. 1b), which is a function of wind speed and direction and generally expressed in the form of [3]

$$\sigma_0 = A(U_{10},\theta)[1 + b_1(U_{10},\theta)\cos\varphi + b_2(U_{10},\theta)\cos 2\varphi]^B\,, \tag{1}$$

where σ_0 is the NRCS in linear units of SAR image acquired at vertical (VV) polarization in transmission and reception; φ is the relative wind direction which represents the angle between the radar look direction and the local wind direction; U_{10} is the statistically neutral wind speed normalized to 10 m height; θ is the incidence angle; A, B, b_1 and b_2 are coefficients depending on U_{10}, θ, radar frequency and polarization.

The C-band models were developed at VV polariztion. To retrieve wind speed from HH-polarized SAR data, a polarization ratio function is often used first to obtain NRCS at VV polariztion [9].

Since the SAR wind retrieval depends upon wind direction input, the Navy Operational Global Atmospheric Prediction System (NOGAPS) wind directions are used in this study.

Results and Discussion

Fig. 2 shows the wind speed of hurricane Helene derived from RADARSAT-1 SAR image using CMOD5 with NOGAPS wind direction. The spatial resolution is about 500m□500m. We can see that the wind map shows clearly the fine wind structure of hurricane Helene.

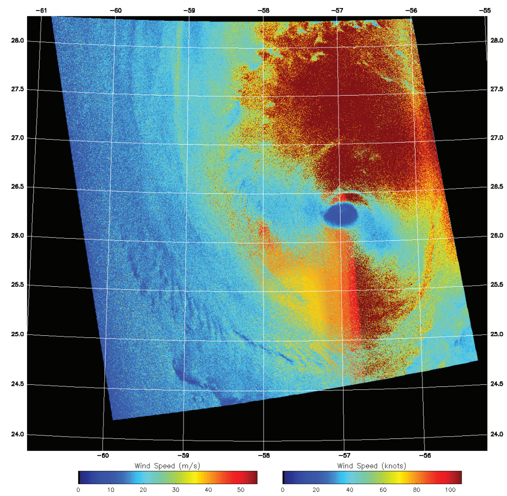
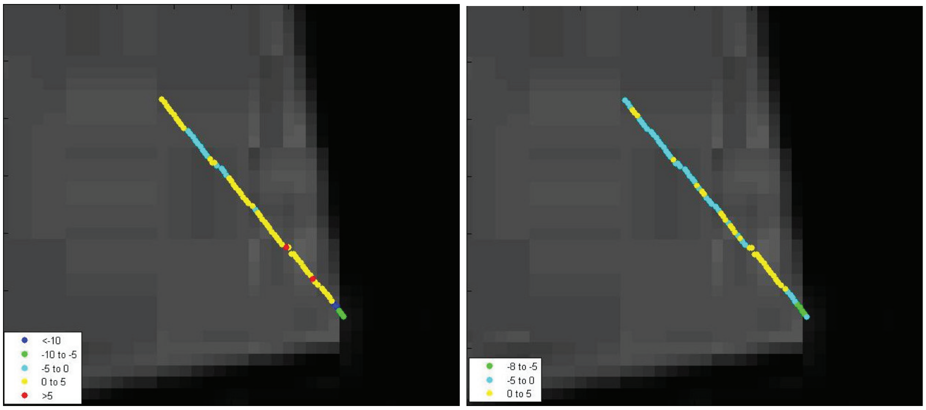


Fig. 2 Wind speeds of hurricane Helene derived from RADARSAT-1 SAR image using CMOD5 model, with wind direction from NOGAPS model output.

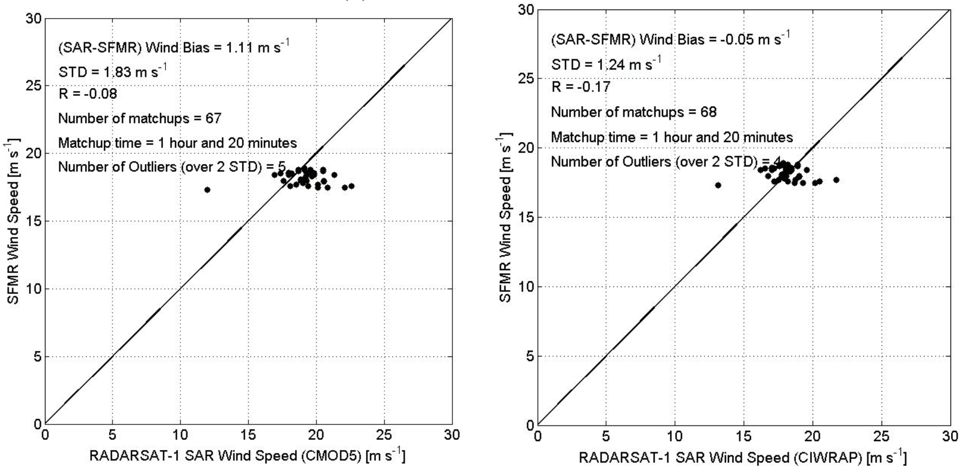
To investigate the accuracy of SAR wind, the differences between wind speeds retrieved from RADARSAT-1 SAR image using CMOD5 and CIWRAP and SFMR measurements are shown in Fig. 3a and Fig. 3b, respectively. In general, CMOD5 overestimates SFMR wind speed, while the positive and negative differences between CIWRAP wind and SFMR observations are quite similar.

To show the difference in more detail, we compare SFMR observations with SAR wind speeds derived from CMOD5 and CIWRAP using a scatter plot as shown in Fig. 4, where the comparison statistics are also given. STD denotes standard deviation. From the results we can see that there are good agreements between SAR and SFMR wind speeds. The standard deviations are smaller than 1.8 m s^{-1}. This indicates that the C-band GMF models are applicable for wind speed retrieval from SAR image at wind speed between 15-20 m s^{-1}. Compared with CMOD5, CIWRAP can generate a more accurate wind product.



(a) (b)

Fig. 3 The difference [m s^{-1}] between wind speeds retrieved from RADARSAT-1 SAR image using (a) CMOD5 and (b) CIWRAP and SFMR measurements.



(a) (b)

Fig. 4 Comparison of wind speeds retrieved from RADARSAT-1 SAR image using (a) CMOD5 and (b) CIWRAP, with SFMR measurements.

Summary

A case study for hurricane Helene was conducted to investigate the capability of SAR monitoring of high-resolution hurricanes. Two C-band GMF models, i.e., CMOD5 and CIWRAP for measuring high wind speeds are used to derive hurricane wind speed from RADARSAT-1 SAR image and compared with SFMR observations. The results show that the SAR wind speeds agree well with *in situ* observations. CIWRAP performs better than CMOD5. This indicates the capability of SAR monitoring of hurricanes. However, the SFMR observations in this study are between 15-20 m s^{-1}. For higher wind speed estimation from SAR, further study is needed.

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