Comparison of Ocean-Surface Winds Retrieved From QuikSCAT Scatterometer and Radarsat-1 SAR in Offshore Waters of the U.S. West Coast

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Abstract—In this letter, we generate a temporal/spatial matchup data set between QuikSCAT scatterometer and RADARSAT-1 synthetic aperture radar (SAR) wind products in offshore waters along the U.S. West Coast. Analysis of the resulting three-year database shows that, in general, the wind products from both sensors have characteristics similar to those reported in the literature. Then, we perform an error analysis in the space domain and find that there is significant discrepancy between the two wind products as the matchup points move closer to the coast. The root-mean-square error (rmse) and standard deviation (STD) between the two data sets increases markedly for points matched within about 100 km of the coastline. Beyond 100 km, the rmse, STD, and systematic bias become small and stable. In addition, an empirical relationship between QuikSCAT and SAR winds in coastal region is proposed. Thus, the bias and errors should be taken into account if the standard operational QuikSCAT wind products are used for forcing models in the coastal ocean.

Index Terms—Remote sensing, scatterometer, synthetic aperture radar (SAR), wind.

I. INTRODUCTION

AC CURATE ocean-surface wind data near the coastline are very important for wind-energy estimates [1], hurricane-evacuation decision making [2], and coastal ocean–atmosphere coupling research [3], among others. Spaceborne active microwave sensors, such as scatterometer and synthetic aperture radar (SAR), can provide a synoptic view of the ocean-surface wind field at different spatial and temporal resolutions. Both scatterometer and SAR measure the variation of normalized radar cross section (NRCS) from the wind-roughed sea surface, which is a function of both wind velocity and direction. Geophysical model functions (GMFs) have been developed to establish the relationship among calibrated NRCS, wind speed, wind direction, and sensor viewing angles for radars in different bands and polarizations.

QuikSCAT scatterometer wind products had been used operationally at the National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service within numerical weather prediction (NWP) models. Typical QuikSCAT wind products are produced at 12.5- and 25-km spatial resolution globally, and an experimental 2.5-km ultrahigh-resolution wind product is currently being created [4]. To ensure the quality of these wind products, QuikSCAT scatterometer wind retrievals have been validated against quality-controlled in situ buoy measurements [5]. It is found that the accuracy of these products has a root-mean-square error (rmse) value of 1.01 m/s in wind speed and 23° in wind direction in the open ocean. For the 12.5-km resolution QuikSCAT wind product validation, Tang et al. [6] found that the rmse are larger close to the coast due to land contamination of radar backscatter signal from the large scatterometer footprint and the complexity of air–sea interaction processes in the coastal ocean. All these studies are based on National Data Buoy Center (NDBC) moored buoy measurements at fixed locations, some tens of kilometers away from the coastline. In order to analyze the accuracy of wind-speed data for different NWP models, Kara et al. [7] performed a comprehensive comparison of three NWP model 10-m wind speeds and two satellite-based products (QuikSCAT and Special Sensor Microwave/Imager) near the land–sea boundaries over the global ocean. They suggested that special action needs to be taken to ensure that wind speed over land from NWP products does not contaminate wind speed over the sea near coastal boundaries, allowing these products to be used with more confidence for offshore applications. Unfortunately, after nearly ten years of operation, the QuikSCAT mission ended on November 23, 2009, caused by the antenna’s failure. Currently, global operational satellite scatterometer wind data is still available from European Space Agency’s advanced scatterometer (ASCAT) on board the meteorological operational (MetOp) satellite.

Similar to scatterometer wind retrieval, SAR wind retrieval is also dependent upon knowledge of the NRCS obtained from the calibrated SAR image [8], [9]. Unlike the QuikSCAT scatterometer, SAR instruments have only one azimuth viewing angle. Therefore, to derive the wind velocity, one must obtain the wind direction independently from another source, i.e., from operational weather model output [8], from finding the wind-aligned patterns in the SAR data itself [9], or from buoy measurements [10]. The advantage of SARs is their very high spatial resolution. Depending upon the radar-beam mode, SAR usually has a spatial resolution ranging from a few meters to...
100 m with a swath coverage ranging from tens of kilometers in standard mode to about 500 km in wide-swath or ScanSAR mode; e.g., RADARSAT and ENVISAT. The resolution is high enough to resolve very fine scale wind variations associated with marine atmospheric boundary layer phenomena, including katabatic winds [11], roll vortices [12], atmospheric gravity waves [13], [14], and vortex streets [15], [16], among others. Since 1999, NOAA has conducted a demonstration of the production and the use of SAR quantitative and qualitative products in a preoperational environment [17]. Subkilometer high-resolution SAR wind products have been generated for U.S. coastal waters, primarily from the Canadian RADARSAT-1 SAR (e.g., Fig. 1). Validation studies have been performed against NDBC buoys, and QuikSCAT scatterometer winds match close in time and space. Global statistics are fairly stable with a standard deviation (STD) of less than 2 m/s for wind speeds up to 20 m/s [8], [18].

Although validation studies of scatterometer and SAR wind retrieval were done in the past, none of these analyze the spatial distribution of scatterometer wind-retrieval errors or scatterometer–SAR wind differences with respect to distance from the coast. Since SAR has a smaller footprint and can provide wind measurements right up to the coastline, it is the purpose of this study to use RADARSAT-1 C-band SAR wind [19] as a “ground truth” to quantitatively analyze the accuracy of QuikSCAT scatterometer wind products with respect to distance off the coastline.

II. DATA PREPARATION

A. SAR Wind Data Preparation

The study region is off the U.S. West Coast in the region $46^\circ$ N to $50^\circ$ N latitude and $124^\circ$ W to $131^\circ$ W longitude. From
2006 to 2008, 234 Radarsat-1 SAR images were collected in this region. These SAR images were received at the Alaska Satellite Facility located at the University of Alaska, Fairbanks. After calibration, we process these NRCS images into wind images using the CMOD5 GMF [20] modified for HH polarization [21] for RADARSAT-1 SAR. The polarization ratio is set to be 0.6. Wind-direction input is from hourly Navy Operational Global Atmospheric Prediction System model output matched closest with the SAR imaging time. Both SAR standard mode (30-m resolution with 100-km swath) and ScanSAR mode (100-m resolution with 450-km swath) images are used in this study, and the SAR wind product is subsampled to 500-m spatial resolution.

B. QuikSCAT Wind-Data Preparation

QuikSCAT scatterometer wind data products are obtained from the National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center data distribution site: http://podaac.jpl.nasa.gov. The QuikSCAT wind data used in this study have a spatial resolution of 12.5 km. Since the QuikSCAT scatterometer operates in the Ku-band, a much shorter microwave wavelength compared with that of C-band RADARSAT-1 SAR, a noticeable shortcoming for Ku-band radar is that its radar signal is severely affected by rain contamination. Therefore, we eliminated all rain-contaminated retrievals using both the “rain-impact flag useable” and the “rain-impact flag” contained in the QuikSCAT Level 2 wind products. A pixel is considered to be rain-free when both flags indicate no rain.

III. Matchup Data and Statistics

This letter aims to compare coincident SAR and QuikSCAT wind products in the coastal ocean. Therefore, a matchup data set is generated with the following temporal and spatial criteria.

1) Temporal matchup: For each SAR image, we search through the QuikSCAT data file and locate all the wind products within 20 min of the SAR overpass time.

2) Spatial matchup: We find all the collocated SAR/QuikSCAT pixels. Since the SAR wind product has a resolution of 500 m and the QuikSCAT wind product has a spatial resolution of 12.5 km, one QuikSCAT pixel may contain multiple SAR wind pixels. To generate a one-to-one matchup, we first average the SAR winds within a QuikSCAT pixel and use the averaged value as the SAR wind speed at that location.

We have 5352 data points satisfying the aforementioned criteria. Fig. 2 shows the SAR and QuikSCAT wind comparison in the matchup database. The bias and STD of SAR minus QuikSCAT wind is $-1.03$ and 1.65 m/s, respectively. These results are close to published comparisons, bias $=-0.77$ m/s and STD $=1.78$ m/s [18]. The wind speed ranges from about 1 to 15 m/s. There are significant biases for wind speeds under 2 m/s. This phenomenon is well known to be due to damping of Bragg waves at very low wind speeds.

![Fig. 2.](image)

We also perform a SAR and QuikSCAT wind comparison as a function of distance to the coastline. We extract coastline data from the ArcGIS usstpln83.shp database at 0.05° latitude resolution and calculate the distance between a matchup point position and the nearest coastline. The map resolution is sufficient as the coastline in the study region is approximately in a north–south orientation and has little curvature. Fig. 3 shows a statistical plot of SAR/QuikSCAT comparisons at 25-km steps from the coastline. The numbers above the black bars are the number of matchup points within each 25-km step. The bias, STD, and rmse are calculated and shown in Fig. 3.

From Fig. 3, one can see that the SAR/QuikSCAT wind bias reduces as the matchup points are located further away from the coast. Within 75 km from the coast, the rmse is as high as 2.8 m/s, and the STD is about 2.3 m/s. The STD reduces to
about 1.4 m/s, a number comparable with that in the literature from the global SAR–QuikSCAT comparison [18], and becomes stable when the matchup is made 100 km or further from the coastline. The systematic bias between the two data sets is in a range from 1.5 to 1.8 m/s within 125 km of the coastline. It reduces to 0.6 to 0.8 m/s for matchup points located 175 km and further away from the coastline.

The SAR sensor footprint is small, and it has been shown in the literature that SAR wind retrievals have been stable against coastal NDBC buoy measurements. Therefore, we can use SAR wind as a ground truth. In general, the distance of 100 km from the coastline can be treated as a boundary. Within this distance, which we define as coastal waters, the scatterometer wind-retrieval errors are high and varying, while beyond this distance, which we define as the open ocean, the errors become small and stable. Thus, the statistical results shown in Fig. 3 suggests that if coastal-water wind users need high-accuracy winds, they should carefully deal with satellite scatterometer wind data. Revalidation or recorrection with local high-accuracy field data seems to be needed.

In addition to the statistics of errors versus the distance off the coastline that is shown in Fig. 3, we draw a 2-D distribution map of rmse between the SAR and QuikSCAT wind speeds in the coastal ocean off the U.S. West Coast (Fig. 4). RMSE data are calculated from the SAR/QuikSCAT wind matchup data set mentioned earlier. From Fig. 4, one can see that, in general, rmse reduces as the pixels are further away from the coastline. The high-rmse area (3 m/s contour) is mainly located within 100 km of the coastline, and the 2-m/s contour line is mostly within 200 km of the coastline. Beyond 200 km, rmss are below 1 m/s. The bias and STD maps show similar patterns (omitted for brevity).

IV. QUIKSCAT NEAR COAST WIND CORRECTION

From the previous analysis, one can find that the QuikSCAT winds are inconsistent with the SAR winds within 100 km from the coastline. We scatter plot the matchup data in this near-shore region (< 100 km) in Fig. 5. An empirical exponential relationship to corrected coastal QuikSCAT winds can be derived as

$$W_{SAR} = W_{QS_{Coast}} = 0.59 \times \exp(0.27 \times W_{QS})$$

where $W_{QS}$ and $W_{SAR}$ are the wind speed retrieved by QuikSCAT and SAR within 100 km from the coastline, respectively. $W_{QS_{Coast}}$ represents corrected QuikSCAT wind. $R^2$ is about 0.6.

V. SUMMARY AND DISCUSSION

In this study, three year’s worth of SAR imagery off the U.S. West Coast has been used to generate ocean-surface wind fields. The SAR-derived winds are compared with collocated and coincident QuikSCAT wind products. Statistically, the ocean-surface winds from both instruments agree very well, with a bias of $-1.03$ m/s (SAR wind is lower) and STD of 1.65 m/s. We further examine the difference in terms of the distance between a matchup point and the closest coastline. We find that the bias remains fairly stable in the open ocean but increases somewhat for matches within 125 km of the coast. The rmse and STD increase markedly for matchups within 100 km of the coastline. Beyond 100 km, rmse (< 2 m/s) and STD (< 1.5 m/s) become small and stable. Large operational QuikSCAT wind-retrieval bias and errors should be anticipated and taken into account when using scatterometer winds in coastal regions.

The 2-D distribution map of rmse between SAR and QuikSCAT wind speeds in the northwest coastal ocean of the U.S. shows that rmse reduces for matchups further away from the coastline, implying that land contamination within the large
QuikSCAT footprint near the coast may be a major error source. The QuikSCAT wind product has a large bias and STD within 100 km of the coastline. There is no scatterometer data in the white area (Fig. 4) near the coast. In addition, the rmse contour lines within 100 km of the coast seem to show a more complex pattern. We think that they are related to the mixing boundaries or fronts between different water masses, or coastal ocean processes. In the study area, coastal upwelling, offshore eddies, and river plumes are all possible. However, an interesting question is how do these processes “invade” into the satellite wind fields? Two possibilities are 1) local variations in the SAR-derived winds caused by backscatter changes from ocean processes or 2) highly variable winds near shore. This is a challenge for future studies.

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REFERENCES


