# OCEAN WIND SPEED CLIMATOLOGY FROM SPACEBORNE SAR IMAGERY

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The authors discuss the potential generation of a >10-yr archive of *Radarsat-1* synthetic aperture radar wind speed data and its use to compute wind speed climatologies.

**SAR WIND SPEED RETRIEVAL.** The capacity to retrieve high-resolution (<500 m) winds from spaceborne synthetic aperture radar (SAR) imagery has matured significantly over the past decade (Dagestad et al. 2012). The retrieved speeds have been shown to have standard deviations of less than 2 m s$^{-1}$ when compared to buoys and other independent measures (Horstmann et al. 1998; Monaldo et al. 2004; Yang et al. 2011; Thompson et al. 2012). Calibrated SAR radar cross section imagery is being converted to wind speed operationally at the National Oceanic and Atmospheric Administration (NOAA) to aid the National Weather Service (NWS). SAR wind data are also used to aid in offshore wind power siting (Christiansen and Hasager 2005; Christiansen et al. 2006) and applied to study the spatial variability of wind fields, particularly in coastal areas (Loescher et al. 2006).

Microwave measurement of winds from space is not new. The wind archives available from scatterometer satellites such as the Quick Scatterometer (QuikSCAT) and Advanced Scatterometer (ASCAT) provide important global data. However, scatterometer data have resolutions from 12 to 50 km (i.e., one to two orders of magnitude coarser that SAR winds). They are less valuable in coastal areas. SAR winds and conventional scatterometer winds are properly seen as complimentary.

The record of *Radarsat-1* and *Envisat* SAR imagery extends for over a decade and newer satellites [e.g., *Radarsat-2*, COSMO-SkyMed, and *TerraSAR-X*] are beginning to be used for wind speed retrieval. In early 2014, we expect the launch of Sentinel-1 by the European Space Agency, providing imagery on a free and open operational basis.

For over 12 years, NOAA conducted an application demonstration of near real-time SAR wind speed retrieval using *Radarsat-1* data. The software and protocols for this processing, known as the

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*The abstract for this article can be found in this issue, following the table of contents.*
DOI:10.1175/BAMS-D-12-00165.1

In final form 27 June 2013

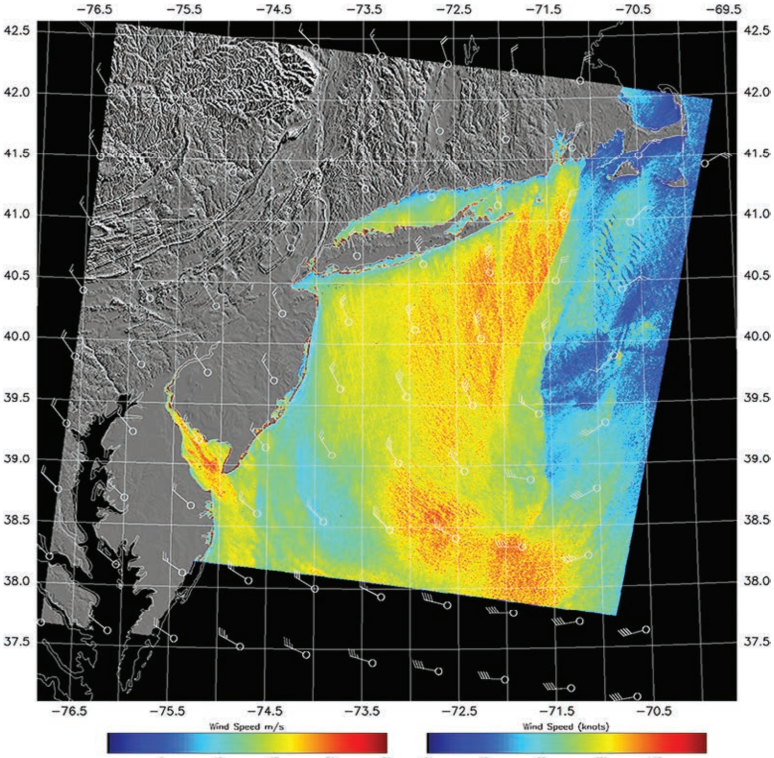


**Fig. 1. *Radarsat-1* SAR wind speed retrieval off the U.S. East Coast (including Maryland and Delaware) on 10:58:02 UTC 21 Jan 2001. This image shows winds blowing offshore toward the southeast. The wind barbs represent the National Centers for Environmental Prediction's Climate Forecast Reanalysis wind speed and direction for reference.**

Applied Physics Laboratory (APL)/NOAA SAR Wind Retrieval System (ANSWRS), became operational at NOAA on 1 May 2013. At present, the dominant source of data for this system is *Radarsat-2* SAR, but we anticipate that soon Sentinel-1 data will provide the bulk of the data for operational use. Figure 1 is an example of a *Radarsat-1* wind speed image off the coast of Maryland on 21 January 2001 produced by ANSWRS. Wind speed is represented by the color scale shown in the figure.

The multiyear archive of *Radarsat-1* data offers the prospect of generating a high-resolution wind data archive. Now that robust, operational, validated, and well-documented software is available, we intend to generate a SAR wind data archive—particularly useful for wind power assessment. This short paper announces the intention to generate a SAR wind speed database from the *Radarsat-1* record, illustrates the ability to generate a local high-resolution climatology, and introduces issues concerning local climatologies.

The normalized radar cross section (NRCS) for side-looking radars is a function of wind speed and direction, as well as the radar frequency, polarization, and incident angle. However, a single NRCS value can correspond to many wind speed and direction pairs. Given a wind direction, wind speed can be inferred. The ANSWRS software uses wind directions provided by the NOAA NWS Global Forecast System (GFS) model plus the NRCS measurement to perform the inversion to wind speed.

There are a number of available, empirically-derived model functions relating wind speed and direction to NRCS. These functions not only reflect the actual NRCS and marine wind relationship, but also can subtly compensate for small NRCS measurement differences between different satellite SAR instruments. *Radarsat-1* operates at C-band (5-cm wavelength) and HH-polarization. We have found that CMOD4 (for VV-polarization) (Stoffelen and Anderson 1997) and the Thompson et al. (1999) polarization ratio to convert to HH-polarization produce wind speed retrievals most consistent with independent wind speed estimates of 10-m neutral stability winds (Monaldo et al. 2001, 2004). The Thompson polarization ratio function uses a parameter $\alpha$, which we set to 0.6 to achieve this agreement.

Figure 2 is a comparison of SAR wind speeds retrieved using CMOD4 and the Thompson et al. (1999) polarization ratio with wind speeds estimated by NOAA's Climate Forecast System Reanalysis (CFSR). The area considered is off the coast of Maryland and Delaware (37.75°–39.00°N, 75.30°–74.75°W) covering the years 1996 to 2008 (Monaldo 2010). The data come from 1428 *Radarsat-1* images. There is almost no mean difference between the SAR and CFSR winds, and the probability density functions are similar. Hence, we chose this model function for this work.

## SAMPLE WIND POWER CLIMATOLOGY.

The *Radarsat-1* SAR images off the east coast of Maryland and Delaware were processed to wind speed at 500-m averaging to average out any NRCS variations associated with ocean surface waves and alleviate the effects of image speckle noise. These swath data are then resampled onto a regular 500-m sampling grid to generate a mean wind speed field. As an initial effort, we averaged SAR wind retrievals

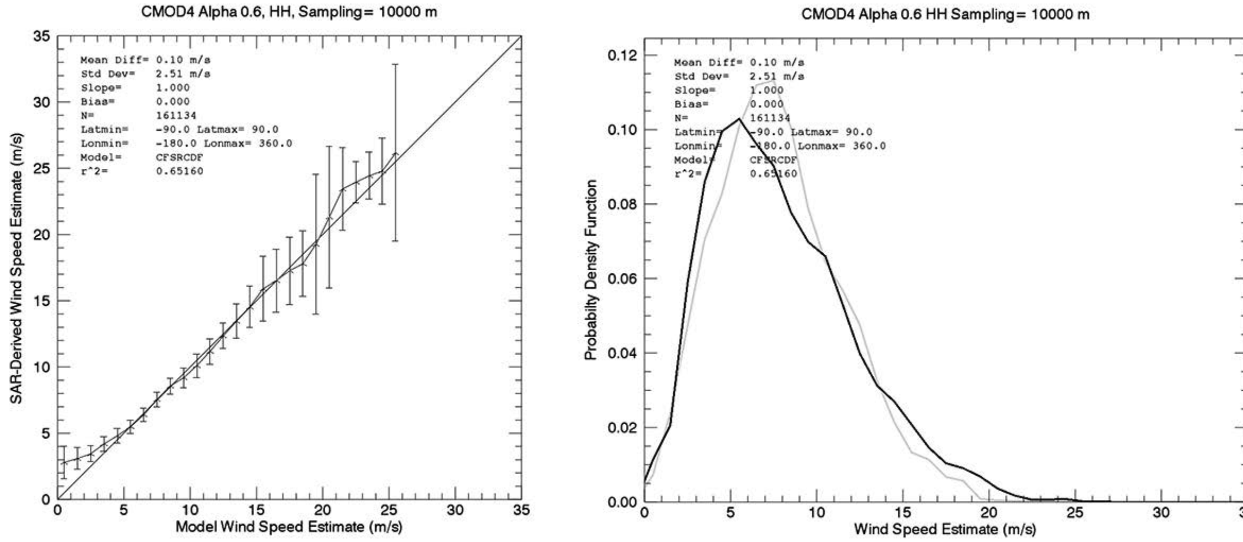


**Fig. 2. Comparison of SAR-derived wind speeds with CFSR reanalysis winds normalized to 10 m for a neutral stability atmosphere. The left graph is SAR vs model winds, with 95% limit error bars. The right graph compares the two probability density functions. The thick line represents SAR data and the light-gray line is from the model wind speeds.**

into 500 m × 500 m bins, and the mean wind at each sample in the grid was computed by averaging all the data available at any particular grid point from the entire multiyear *Radarsat-1* dataset.

We can relate the SAR-estimated wind speed at 10-m height to wind power at a hub height of 80 m with a standard logarithmic profile (Stull 1988). The potential wind power obtainable—the power flux—is related to wind speed by $P = \rho\, u^3/2$, where $\rho$ is the air density and $u$ is wind speed. Figure 3 shows the mean wind power density zooming in on a region bounded by 38.35°–39.00°N, 75.30°–74.75°W. Potential wind power clearly increases with distance from shore. The color green at 300 W m$^{-2}$ represents a nominal threshold where harvesting wind power becomes economically feasible. It is interesting to note that wind power estimates are possible even in inland waters such as Rehoboth Bay.

Several factors complicate the use and interpretation of SAR measurement for wind speed climatology. For example, surface roughness can be influenced by factors in addition to wind speed. In Fig. 3 there is an area in the Delaware Bay with apparently high wind power potential. However, we believe the surface roughness in this region is associated with local currents induced by local gradients in bathymetry and not wind speed.

Second, any particular satellite samples the wind field at a place on Earth perhaps twice daily. Given diurnal variability, such sampling could bias the wind speed distribution. Third, wind speed retrievals have been best validated in the regime of 2 to 25 m s$^{-1}$. Eliminating retrievals beyond these limits

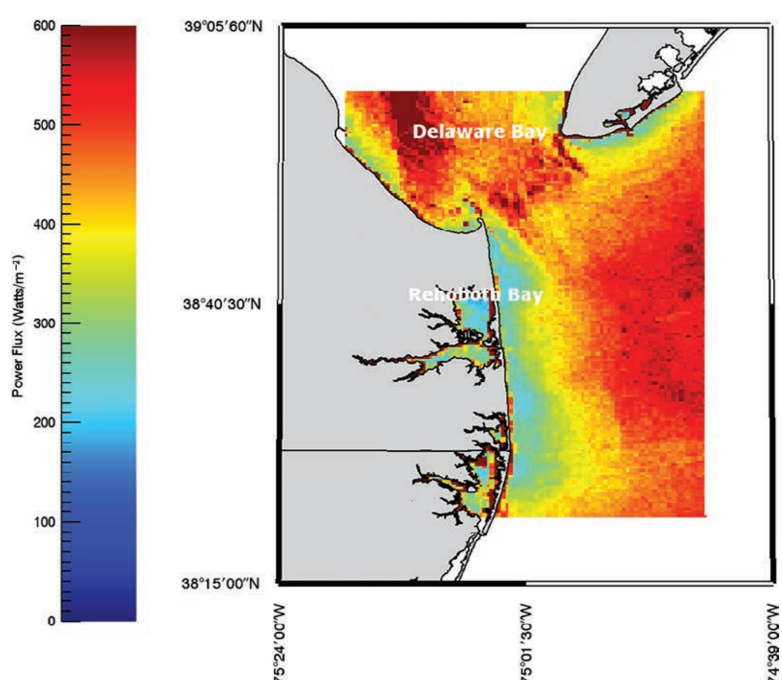


**Fig. 3. The mean wind power flux density (W m$^{-2}$) off the coast of Maryland. Gray represents a land mask and power density is encoded as color. The color red represents 600 W m$^{-2}$.**

could also bias the distribution. Finally, the number of wind speed measurements at a particular point—unlike buoy measurements, which are more continuous—limits the number of independent wind speed measurements.

Barthelmie and Pryor (2003), Pryor et al. (2004), and Barthelmie and Pryor (2006) have addressed these final three issues by analytic means and filtering research-quality buoy anemometer measurements from four different climatic regimes off the coast of North America to match the time and valid range limitations of SAR wind imagery. Within these constraints, they determined how well the moments of the filtered wind speed distribution compared with the moments computed from the entire anemometer database. The data from the filtered and unfiltered anemometer were fit with a Weibull distribution. They found that about 250 independent measurements (or SAR images) are required to fit the parameters of the Weibull wind distribution to the 90% confidence level.

The power flux density associated with wind speed (power/area) increases with the cube of wind speed. Hence, small errors in wind speed grow to fractionally greater errors in wind power. Pryor et al. (2004) performed a similar analysis with power density as with wind speed and found that, given limitations of sampling and limited wind speed range with remote sensors, approximately 1000 measurements (or SAR images) are required to estimate mean wind power flux density at the 90% confidence level.

An additional issue has also been considered. SAR wind retrievals have been tuned to produce wind speed estimates for 10 m above the surface for neutral atmospheric stability. While this is very useful for validation against buoy measurements, applying the results for wind power assessments requires estimating the wind speed at hub height. Badger et al. (2012) has found that combining SAR wind speed retrievals with model-derived wind profiles can, on average, produce accurate hub-height estimates. Even when a particular extrapolation is off, the mean height wind speed adjustment can successfully be made.

**FUTURE.** On 1 May 2013, NOAA near-real-time wind estimation with SAR became operational, with primary initial reliance on *Radarsat-2* data. Now that the wind speed product is operational, we plan to pursue a wind speed archive with retrospective data. The Alaska Satellite Facility at the University of Alaska, Fairbanks, has an extensive archive of *Radarsat-1* data from 1996 to 2008 (0.5 petabytes). These data were recently reprocessed into SAR imagery, using improved calibration, geolocation, and quality control techniques developed over a decade of processing experience.

The archive of *Radarsat-1* SAR imagery at the Alaska Satellite Facility is available to U.S. investigators. Now that SAR wind products are operational at NOAA, we anticipate the processing of this archive into wind speed data and determining which facility should host these data.

Using the previous research and lessons learned from computing the wind climatology for Maryland and Delaware, we intend to create a *Radarsat-1* wind speed dataset with the following characteristics:

Wind speed data will be stored in the common netCDF format with sufficient information to recompute wind speed as even better wind retrieval algorithms are developed.

High-resolution wind vector data from post-analysis NOAA GFS models will be stored as well, both as part of ongoing calibration/validation and to aid in the interpretation of SAR and model data.

Data from NOAA offshore moored buoys will be collocated and stored in the database.

Data will be posted online so that others may generate climatologies using different atmospheric vertical profile models and different averaging schemes.

**ACKNOWLEDGMENTS.** The views, opinions, and findings contained here are those of the authors and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

## REFERENCES

Badger, M., and Coauthors, 2012: Bringing satellite winds to hub-height. *Proc. EWEA 2012 European Wind Energy Conf.*, Copenhagen, Denmark, European Wind Energy Association. [Available online at http://proceedings.ewea.org/annual2012/allfiles2/979_EWEA2012presentation.pdf.]

Barthelmie, R. J., and S. C. Pryor, 2003: Can satellite sampling of offshore wind speeds realistically represent wind speed distributions? *J. Appl. Meteor.*, **42,** 83–94.

——, and ——, 2006: Challenges in predicting power output from offshore wind farms. *J. Energy Eng.*, **132,** 91–103.

Christiansen, M. B., and C. B. Hasager, 2005: Wake effects of large offshore wind farms identified from satellite SAR. *Remote Sens. Environ.*, **98,** 251–268.

——, ——, and F. M. Monaldo, 2006: Offshore winds observed from space: Issues for planning of offshore wind farms. *Windtech Int.*, **2** (5), 6–9.

Dagestad, K.-F., and Coauthors, 2012: Wind retrieval from synthetic aperture radar: An overview. *Proc. SEASAR 2012 Advances in SAR Oceanography,* Tromsø, Norway, European Space Agency, ESA SP-709.

Horstmann, J., W. Koch, S. Lehner, and W. Rosenthal, 1998: Ocean wind fields and their variability derived from SAR. *Earth Obs. Quart.,* **59,** 8–12.

Loescher, K. A., G. S. Young, B. A. Colle, and N. W. Winstead, 2006: Climatology of barrier jets along the Alaska Coast. Part I: Spatial and temporal distributions. *Mon. Wea. Rev.,* **134,** 437–452.

Monaldo, F. M., 2010: Maryland offshore wind climatology with application to wind power generation. Tech. Rep. SRO-10-10, Johns Hopkins Applied Physics Laboratory, 33 pp.

——, D. R. Thompson, R. C. Beal, W. G. Pichel, and P. Clemente-Colón, 2001: Comparison of SAR-derived wind speed with model predictions and buoy comparisons. *IEEE Trans. Geosci. Remote Sens.,* **39,** 2587–2600.

——, ——, W. G. Pichel, and P. Clemente-Colón, 2004: A systematic comparison of QuikSCAT and SAR ocean surface wind speeds. *IEEE Trans. Geosci. Remote Sens.,* **42,** 283–291.

Pryor, S. C., M. Nielsen, R. J. Barthelmie, and J. Mann, 2004: Can satellite sampling of offshore wind speeds realistically represent wind speed distributions? Part II: Quantifying uncertainties associated with distribution fitting methods. *J. Appl. Meteor.,* **43,** 739–750.

Stoffelen, A. C. M., and D. L. T. Anderson, 1997: Scatterometer data interpretation: Estimation and validation of the transfer function CMOD4. *J. Geophys. Res.,* **102** (C3), 5767–5780.

Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology.* 1st ed. Kluwer Academic, 666 pp.

Thompson, D. R., T. M. Elfouhaily, and B. Chapron, 1999: Polarization ratio for microwave backscattering from the ocean surface at low to moderate incidence angles. *Proc. 1999 Int. Geoscience and Remote Sensing Symp.,* Seattle, WA, IEEE, 1671–1673.

——, J. Horstmann, A. Mouche, N. S. Winstead, R. Sterner, and F. M. Monaldo, 2012: Comparison of high-resolution wind fields extracted from TerraSAR-X SAR imagery with predictions from the WRF mesoscale model. *J. Geophys. Res.,* **117,** C02035, doi:10.1029/2011JC007526.

Yang, X., X. Li, W. G. Pichel, and Z. Li, 2011: Comparison of ocean surface winds from Envisat ASAR, Metop ASCAT scatterometer, buoy measurements and NOGAPS model. *IEEE Trans. Geosci. Remote Sens.,* **49,** 4743–4750, doi:10.1109/TGRS.2011.2159802.