Coastal Validation of Ultra-High Resolution Wind Vector Retrieval From QuikSCAT in the Gulf of Maine

A. M. Plagge, *Student Member, IEEE*, D. C. Vandemark, *Member, IEEE*, and D. G. Long, *Fellow, IEEE*

***Abstract*—An experimental 2.5-km ultrahigh-resolution (UHR) wind product provided by NASA's QuikSCAT scatterometer offers the potential for new access to coastal surface wind dynamics at the mesoscale level and below. To give future users the best indication of the value of these data, the UHR wind retrievals must be fully validated in nearshore areas. Comparison with meteorological buoys and standard QuikSCAT products allows detailed investigation of UHR winds. Speed and direction residuals are calculated between all scatterometer products and collocated buoys. An ambiguity selection routine improves wind direction agreement between the UHR winds and the other products. Magnitude residuals follow the patterns of the standard QuikSCAT winds, with a 1–2 m/s positive bias in light winds (below 4 m/s) and high winds (above 16 m/s) and standard deviations consistently below 3 m/s. After application of a land contamination removal algorithm, the UHR product provides extended coverage near the coast. An example of a specific wind event illustrates the potential benefits of improved resolution measurements for examining ocean–atmosphere dynamics.**

***Index Terms*—Meteorology, remote sensing, wind.**

I. Introduction

OCEAN vector winds from the SeaWinds instrument have been widely used since the sensor's launch on the QuikSCAT satellite in 1999. This Ku-band scatterometer was designed to retrieve wind speed and direction at a 25-km resolution, through normalized radar backscatter measurements and a geophysical model function. A newer product provides wind vectors at a resolution of 12.5 km [1]. QuikSCAT covers 90% of the globe in 24 h, and the spatial and temporal coverage provided makes scatterometer-derived wind data valuable for a variety of users.

In many coastal areas, weather forecasting abilities are complicated by land–ocean and atmosphere–ocean coupling [2], [3]. Coastal wind users need better tools to understand, model, and predict particular microscale meteorological features, such as the sea breeze and frontal and trough passages. Currently, satellite scatterometer wind data are used to improve oceanographic and weather models but it cannot resolve many nearshore dynamics occurring at length scales smaller than tens of kilometers. A higher resolution satellite wind product could provide an important tool to meet these needs. One known source is synthetic aperture radar (SAR). However, while SAR systems provide an extremely high-resolution (10–100 m) view of wind magnitude, coverage from even the two most accessible SAR instruments (Radarsat and Envisat) is infrequent at best, and data can be quite costly. Secondarily, although it is possible to retrieve wind direction from SAR, this is complicated. It is for these reasons that a high-resolution scatterometer wind product could benefit many users in the coastal ocean community. This type of product may resolve processes closer to shore and in greater detail than current scatterometer retrievals, and yet provide vector winds at a better temporal resolution than SAR.

Such an enhanced wind product is currently being created at Brigham Young University [4], [5]. This product is a novel attempt to go beyond the native resolution of the sensor to provide 2.5-km resolution winds. However, because of the methods used to create the product, there is an expected increase in noise, and additional questions about the reliability of a product that so thoroughly pushes the spatial resolution limits of the sensor. Therefore, before these new wind data can be used to investigate nearshore dynamics, they must be fully evaluated. This letter presents such a test using a year of data (2006) in the Gulf of Maine.

The first section discusses the data and validation analysis methods, as well as an additional postprocessing step to improve direction estimation. Comprehensive comparison with buoy winds provide the basis for the data evaluations. Results are provided in detail, including nearshore versus offshore comparisons, cross-swath trend analysis, directional accuracy, and spatial coverage. Finally, an example showing the scientific value of the enhanced wind retrievals is provided.

II. Methods

A. Data

The 2.5-km ultrahigh-resolution (UHR) wind product is, like the standard QuikSCAT products, available twice daily in all weather, with an extensive time series provided by the QuikSCAT data record from 1999 to present. The data were produced using the AVE algorithm [4].

The dense network of meteorological buoys in the Gulf of Maine provides an ideal testbed for this letter (see Fig. 1). Further information is obtained by comparing the UHR winds with standard QuikSCAT 25- and 12.5-km Level 2B (L2B) swath retrievals (produced by the NASA Scatterometer Project and distributed by the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory). Each

Manuscript received October 29, 2008; revised December 11, 2008 and December 23, 2008. First published March 21, 2009; current version published July 4, 2009.

A. M. Plagge and D. C. Vandemark are with the University of New Hampshire, Durham, NH 03824 USA.

D. G. Long is with Brigham Young University, Provo, UT 84602 USA.

Digital Object Identifier 10.1109/LGRS.2009.2014852

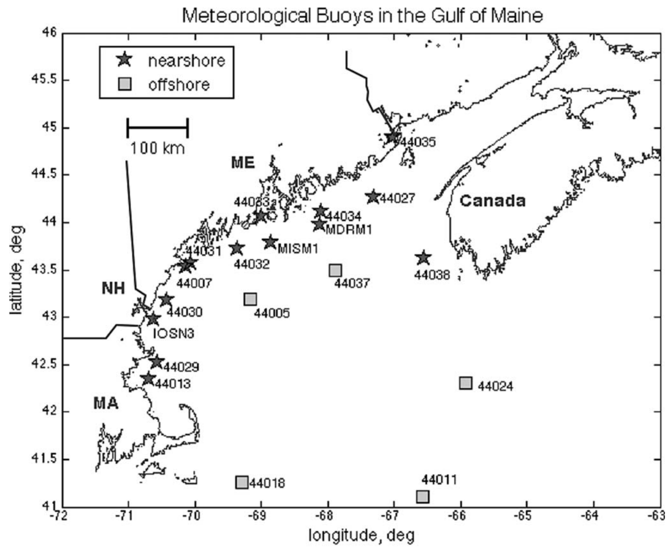

Fig. 1. Buoy network in the Gulf of Maine. Acknowledgments: NOAA's National Data Buoy Center and the Gulf of Maine Ocean Observing System.

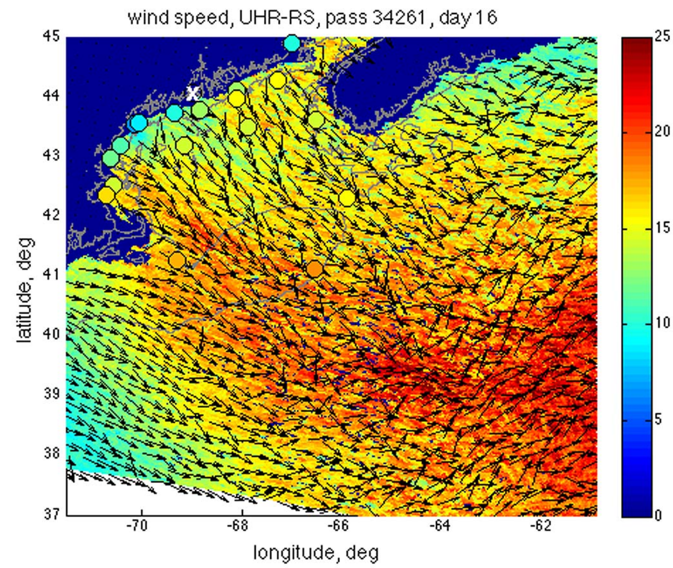

Fig. 2. UHR and buoy wind magnitude for January 16, 2006; subsampled (every fourth) unit wind vectors shown in black; buoy speeds in circles ("x" indicates no data).

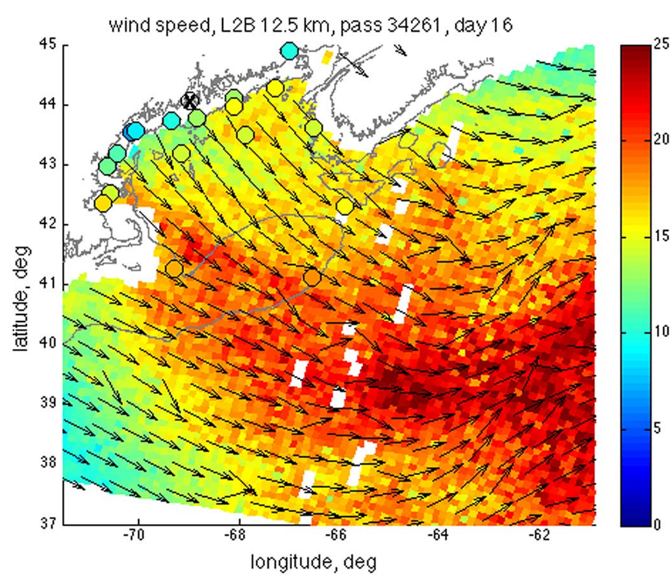

Fig. 3. L2B 12.5 km and buoy wind magnitude for January 16, 2006; subsampled (every tenth) unit wind vectors shown in black buoy speeds in circles ("x" indicates no data).

type of scatterometer data is collocated with each buoy by finding all pixels within a 10-km radius of the buoy location and taking the average for both speed and direction. Buoy and scatterometer measurements occur within ± 30 min of one another. The collocation for 2006 produces 8292 pairs for the UHR retrievals and 5806 and 1696 pairs for the L2B 12.5- and 25-km winds, respectively. Buoys closer than 100 km to shore are considered "nearshore;" farther are "offshore."

An initial comparison of UHR wind magnitude with that provided by the buoys, as well as with winds from a regional mesoscale meteorological model (run jointly by the University of New Hampshire and Atmospheric and Environmental Research, Inc.), indicated that high UHR retrieved wind speeds seen along the coast were an artifact of land contamination. The data were regenerated using a land contamination removal algorithm [6], [7], and the new masked wind retrievals avoid most of the nearshore bias.

Figs. 2 and 3 show a sample swath of UHR and L2B 12.5-km wind magnitude with unit wind vectors overlaid. Additionally, the color of the overlaid circular buoy symbols indicates buoy wind speed, according to the same scale as the UHR magnitude image. In this image from January 16, there is a strong northwest flow with wind speeds ranging from 8 m/s near the coast to 24 m/s farther offshore. As shown by the figures, the scatterometer wind retrievals for both products closely match the buoy wind data. Fine-scale structure seen in the UHR winds is not evident in the 12.5-km data: For instance, the locally high wind flow over Massachusetts Bay is more easily distinguished in Fig. 2 than in Fig. 3 (at 41.5°N, 70.5°W).

B. Statistical Analysis

This letter follows recent research that has focused on individual buoy-satellite pass analysis and direct comparison of buoy wind magnitude with that from the different scatterometer products [8]. Statistical methods are used to analyze a year of scatterometer–buoy pairs, including mean and standard deviation calculations. Speed and direction residuals (scatterometer minus buoy) are organized according to buoy wind speed, buoy station, and cross-swath position [1].

C. Ambiguity Reselection

Initial statistical analyses indicated instances where the UHR wind directions do not agree well with buoy winds or coincide with the direction from the other scatterometer products. Detailed examination of the original UHR data shows significant differences between the UHR and L2B wind directions in certain passes [9].

Because QuikSCAT obtains multiple "looks" at the ocean surface, wind direction can be determined as well as wind speed. There are several possible estimates of speed and

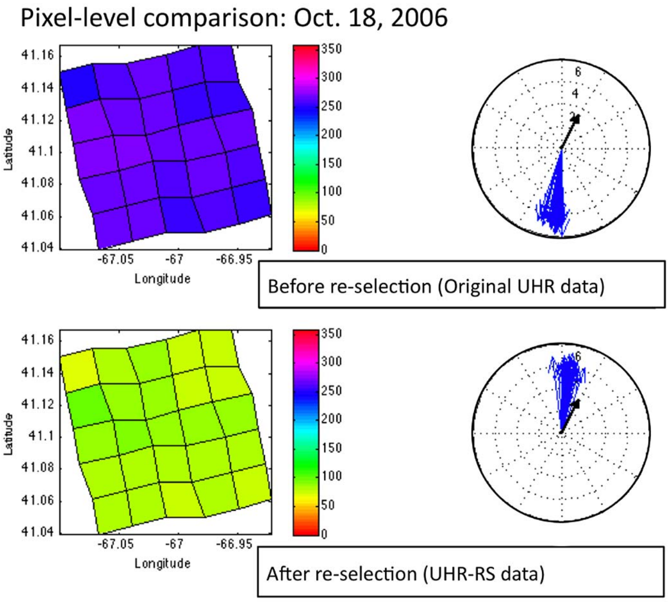

Fig. 4. Pixel-level comparison of UHR speed and direction before and after reselection routine. Pixel color indicates direction in degrees. Arrows on rose show wind vectors from (blue) the UHR pixels and (bold black) a nearby buoy.

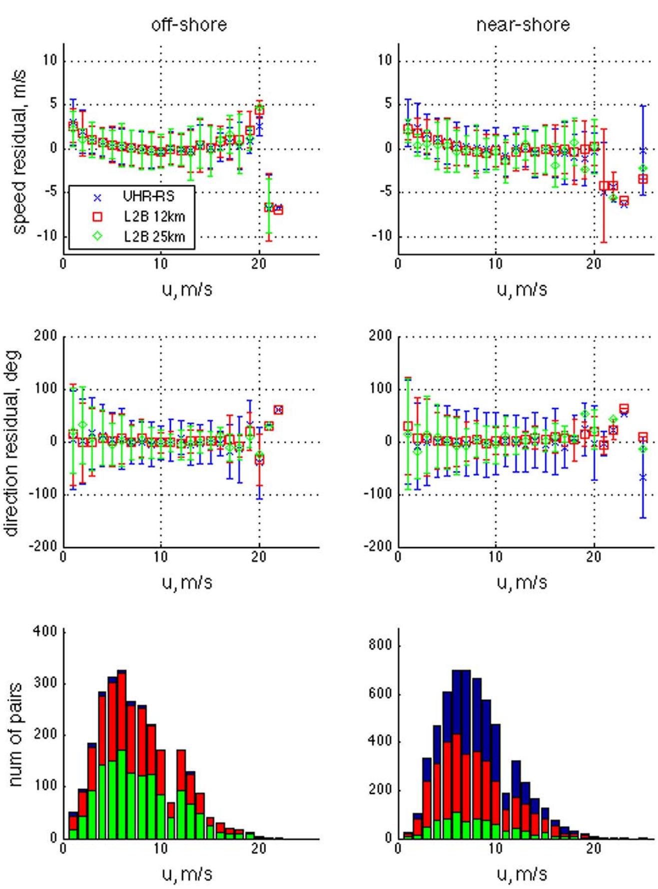

Fig. 5. Summary of scatterometer-minus-buoy residuals for 2006, plotted according to buoy wind speed.

direction for each measurement, referred to as "ambiguities." Occasional errors in the selection of ambiguities are expected [4]. It was hypothesized that in specific instances, the initial choice of ambiguity was flawed. A new algorithm selects one of the four UHR ambiguities with the minimum vector difference from the L2B 12.5-km product. This reselected speed and direction data is referred to as the UHR-RS product. Fig. 4 shows the improvement in direction for a subsection of a sample pass (October 18, 2006). Due to the fact that the new ambiguity choice is based on a minimum vector difference for each pixel, it sometimes occurs that an individual pixel's speed or direction appears to be farther from the "true" estimate. The residuals for the original UHR data throughout 2006 have a magnitude mean of -0.30 ± 2.26 m/s and a directional mean of $2.79^\circ \pm 50.77^\circ$. The reselected data (UHR-RS) have a magnitude mean of -0.29 ± 2.33 m/s and a directional mean of 1.67 ± 51.17. It should be stressed that 1) although the overall quality of the data has not changed a great deal, specific cases throughout the year were repaired using this postprocessing step and 2) the buoy comparison is not the only metric used to determine the value of the reselection. In a few cases, the algorithm misselects the ambiguity, but these instances are isolated and are often single pixels that could be repaired by filtering (not used here due to the desire to keep the highest possible resolution); the improvement in large (10 to 100 km) regions of direction retrievals outweighs the slight increase in noise.

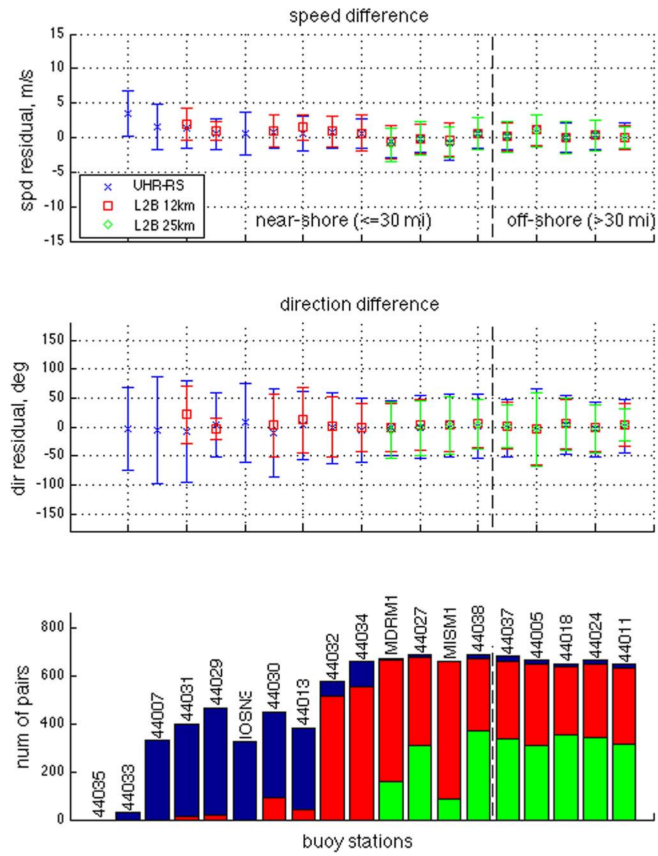

Fig. 6. Summary of scatterometer-minus-buoy residuals for 2006, plotted according to buoy station (arranged according to distance from shore).

III. Results

A. Speed and Direction

After implementation of the reselection process, the statistics for the full year are recomputed. Scatterometer-minus-buoy

TABLE I
DATA SUMMARY FOR 2006. $|U|$ INDICATES MAGNITUDE RESIDUALS. ϕ INDICATES DIRECTIONAL RESIDUALS. "NS" AND "OS" ARE NEARSHORE AND OFFSHORE, RESPECTIVELY

			nearshore	offshore	all	farswath	nearswath	nadir
$\|U\|$	UHR-RS	bias	-0.48	-0.09	-0.29	-0.22	0.09	0.32
		std	2.65	1.98	2.33	2.34	2.05	1.67
	12.5 km	bias	-0.62	0.07	-0.29	-0.17	0.09	0.23
		std	2.29	2.07	2.18	2.46	2.14	1.72
	25 km	bias	-0.54	0.33	-0.11	-0.11	0.12	0.19
		std	1.99	2.05	2.02	2.49	2.18	1.72
ϕ	UHR-RS	bias	0.17	3.29	1.67	-2.18	-1.59	-1.81
		std	55.82	46.09	51.17	52.37	47.09	55.05
	12.5 km	bias	8.45	4.31	6.47	-0.48	0.46	0.94
		std	33.56	35.21	34.35	51.96	39.41	41.60
	25 km	bias	6.52	2.26	4.44	-2.90	0.68	1.84
		std	33.30	32.30	32.81	52.24	40.88	35.78

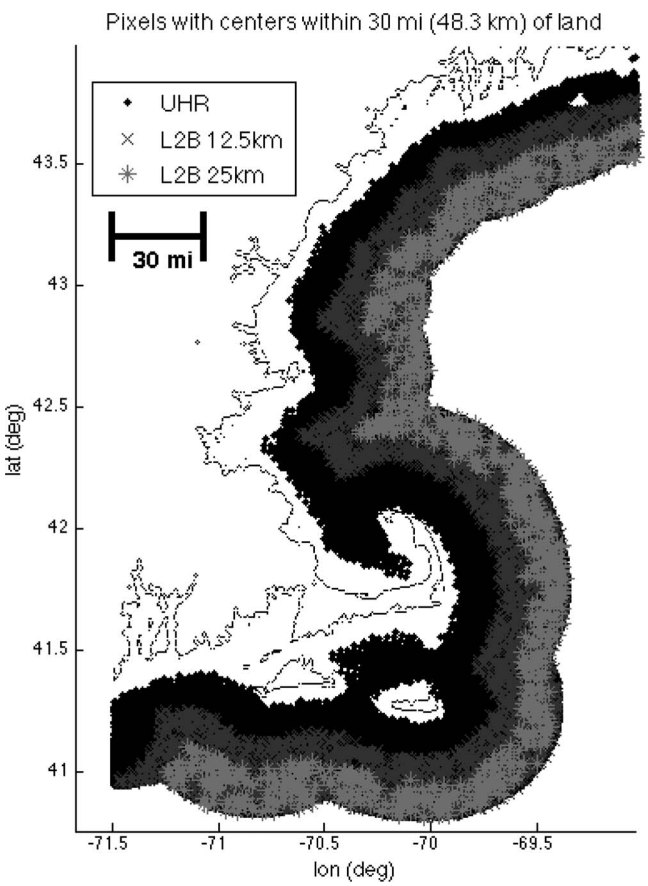

Fig. 7. Cummulative pixel center locations in January 2006: three types of QuikSCAT data.

residuals are organized according to buoy wind magnitude and buoy station (see Figs. 5 and 6); statistics are summarized in Table I.

Speed error increases slightly in both light wind and high wind conditions as expected [1], [10], but mean error and standard deviation for UHR-RS wind magnitude matches those for the standard QuikSCAT products [1], [10], [11]. In all products, standard deviations are slightly greater for nearshore buoys; additionally, wind speeds above 15 m/s show a mean UHR-RS speed 2–3 m/s below that measured by the buoys. Standard deviation of wind direction is higher than most published values

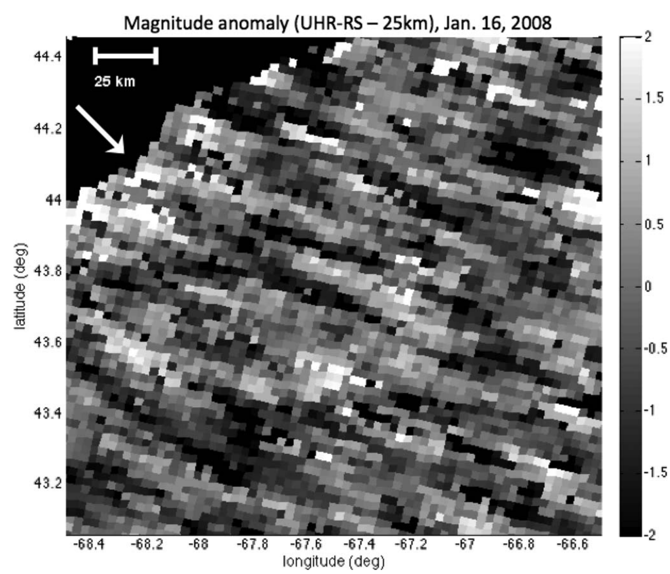

Fig. 8. Evidence of roll vortices during northwest flow event, January 16, 2006. White arrow shows prevailing wind direction.

for even the standard products (particularly at winds below 7 m/s) with the residuals showing an average standard deviation of 34° for the 12.5 km and 33° for the 25 km. The reasons for this are most likely related to: 1) the absolute accuracy of the buoy measurements themselves; 2) the time difference; and 3) the fact that the study takes place in the coastal ocean, where the wave field is not always full developed and other sources of surface roughness can complicate the backscatter signal. Standard deviation for the UHR residuals vary from 50° to 30° in the 5- to 15-m/s range; on average, they are 35% higher than the L2B residuals. Residuals for all three data types are worse in the nearshore region than in the offshore region, particularly in higher winds.

When compared across the satellite swath, residuals generally show greater bias and a higher standard deviation in the nadir and far swath regions (Table I). This is attributed to the viewing geometry of the satellite; QuikSCAT uses a conically scanning dual pencil beam antenna, with an inner and an outer beam. A single location on the ocean's surface will generally be observed four times with multiple viewing geometries: twice by both beams, once as they look forward, and once as they look aft. This variety of "looks" is what allows the determination of both speed and direction. The greatest diversity of azimuth and incidence angles, and therefore the best quality data, is found in the near swath, whereas retrievals from the far swath (which has only two flavors because it is only sampled by the outer beam) and the nadir region (having only two azimuth angles despite two beams) are less accurate [11]. However, in this letter, the effects are generally minimal, as shown in Table I.

B. Nearshore Coverage

Overall, the UHR-RS data in the Gulf of Maine represent the best spatial range of scatterometer wind retrievals in the coastal area. The nearshore coverage shows a marked improvement over even the L2B 12.5-km data. Fig. 7 shows every pixel center for January 2006 within the 30-mi limit in the Massachusetts Bay region for the UHR-RS data in black, the L2B 12.5-km data in dark gray, and the L2B 25 km in light gray. In many regions, the UHR-RS data come 10 km closer to the coast than the L2B 12.5-km data and 25 km closer than the L2B 25-km data. A proxy for this can also be seen in the number of buoy collocation pairs for each data type, again for one month in 2006; the UHR product reaches within 10 km of the nearshore buoys 46% of a possible 980 matches, whereas the 12.5-km data only found a pair 23% of the time. The fact that this 30-mi limit coincides with the local National Weather Service forecast office's region of responsibility for nearshore maritime forecasting makes this increase in available information particularly critical.

C. Illustration of One Potential UHR-RS Benefit

Besides the increase in nearshore coverage, another significant advantage to the UHR-RS data is the improved identification of the type of marine atmospheric boundary layer (MABL) processes that occur at length scales of 5 to 20 km. To this end, cold air offshore flow is an important wind regime that is being investigated in the Gulf of Maine using the UHR winds. For the purposes of this letter, offshore flow is defined as moderately high wind (above 10 m/s) from the northwest, and occurs generally in mid-January and late February to early March. In several instances of this type of flow, the existence of roll vortices is indicated in the UHR magnitude retrievals but not seen in the L2B 12.5-km data. An example is shown in Fig. 8, which shows the magnitude anomaly between the UHR-RS and 25-km L2B data for the wind event shown in Figs. 2 and 3. Horizontal streaking aligned with the prevailing wind direction suggests coherent structure in the MABL, in the form associated with roll vortices. The presence of these vortices is confirmed by MODIS True Color imagery. Additionally, the range of directions visible in the UHR wind vectors in Fig. 2 are potentially associated with boundary layer convection due to downdrafts at the surface. Identification of these dynamics can be important to scientists studying boundary layer processes [3] and ocean–atmosphere coupling [12]; this outcome is therefore quite encouraging and a focus of future studies.

IV. Conclusion

This letter indicates the potential of the UHR scatterometer winds in the coastal zone. UHR-RS wind retrievals are shown to be of similar quality to standard QuikSCAT products in the coastal region, although users should be aware that an ambiguity reselection process similar to the one described here is recommended for any project that incorporates wind direction. One clear benefit of the UHR-RS data appears to be in the improved distance to the shore, providing scientists, forecasters, and other users with information previously unavailable. Additionally, increased resolution does have the capacity to allow improved access to dynamics associated with air–sea interaction, providing further benefit to the scientific community.

References

[1] W. Q. Tang, W. T. Liu, and B. W. Stiles, "Evaluations of high-resolution ocean surface vector winds measured by QuikSCAT scatterometer in coastal regions," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 8, pp. 1762–1769, Aug. 2004.

[2] C. Accadia, S. Zecchetto, A. Lavagnini, and A. Speranza, "Comparison of 10-m wind forecasts from a regional area model and QuikSCAT scatterometer wind observations over the Mediterranean Sea," *Mon. Weather Rev.*, vol. 135, no. 5, pp. 1945–1960, May 2007.

[3] K. L. Davidson, P. J. Boyle, and P. S. Guest, "Atmospheric boundary-layer properties affecting wind forecasting in coastal regions," *J. Appl. Meteorol.*, vol. 31, no. 8, pp. 983–994, Aug. 1992.

[4] D. G. Long, J. B. Luke, and W. Plant, "Ultra high resolution wind retrieval for SeaWinds," in *Proc. Int. Geosci. Remote Sens. Symp.*, Toulouse, France, 2003, pp. 1264–1266.

[5] B. L. Williams and D. G. Long, "Hurricane wind field estimation from SeaWinds at ultra high resolution," in *Proc. Int. Geosci. Remote Sens. Symp.*, Barcelona, Spain, Jul. 2007, pp. 1075–1078.

[6] M. P. Owen, M. Stuart, and D. G. Long, "Ultra-high-resolution near-coastal wind retrieval for QuikSCAT," in *Coastal Ocean Remote Sensing*, vol. 6680, R. Foulin, Ed. Bellingham, WA: SPIE, Aug. 2003.

[7] M. P. Owen and D. G. Long, "Land contamination compensation for QuikSCAT near-coastal wind retrieval," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 3, pp. 839–850, 2009.

[8] A. M. Plagge, D. C. Vandemark, and D. G. Long, "Evaluation of QuikSCAT ultra-high resolution wind retrieval in the Gulf of Maine," in *Proc. Ocean Sci. Meeting*, Orlando, FL, 2008. OS1893.

[9] A. M. Plagge, D. C. Vandemark, and D. G. Long, "Validation and evaluation of QuikSCAT ultra-high resolution wind retrieval in the Gulf of Maine," in *Proc. Int. Geosci. Remote Sens. Symp.*, Boston, MA, Jul. 2008, pp. IV-204–IV-207.

[10] M. H. Pickett, W. Q. Tang, L. K. Rosenfeld, and C. H. Wash, "QuikSCAT satellite comparisons with nearshore buoy wind data off the U.S. West Coast," *J. Atmos. Ocean. Technol.*, vol. 20, no. 12, pp. 1869–1879, Dec. 2003.

[11] D. B. Chelton and M. H. Freilich, "Scatterometer-based assessment of 10-m wind analyses from the operational ECMWF and NCEP numerical weather prediction models," *Mon. Weather Rev.*, vol. 133, no. 2, pp. 409–429, Feb. 2005.

[12] J. Pullen, J. D. Doyle, and R. P. Signell, "Two-way air–sea coupling: A study of the Adriatic," *Mon. Weather Rev.*, vol. 134, no. 5, pp. 1465–1483, May 2006.