Offshore wind flow variability from ship-borne lidar measurements

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1. Introduction

Offshore wind power is an important source of renewable energy. It is crucial to have reliable data for wind resource assessment and understanding of wind-flow variability to locate, design and operate wind farms correctly. Currently, new technologies based on lidar measurements from different mooring/floating/fixed platforms are emerging on the wind energy market. These technologies are aimed at providing cost effective data through the layer swept by modern turbine rotor blades, if they succeed in overcoming measurement errors related to the ocean motion. Thus, developing motion compensation techniques and validating the accuracy of lidar measurements offshore is a big engineering challenge.

Given the critical importance of high-quality measurements of winds in the rotor layer to offshore WE development, any available data would certainly be a valuable resource to exploit. In this paper we show wind measurements obtained by the ship-borne High-Resolution Doppler lidar (HRDL) equipped with a motion-compensating scanning system during a 2004 experiment in the Gulf of Maine. Although conducted to address research objectives other than WE R&D, this data set contains high-quality measurements of wind-speed and wind-direction profiles from the water surface up to several kilometers.

2. Accuracy of HRDL measurements

HRDL is a scanning, coherent, pulsed Doppler lidar designed and operated by the Earth System Research Laboratory (ERSL) of the National Oceanic and Atmospheric Administration (NOAA) for atmospheric boundary-layer research, as described by Grund et al. (2001). Deployed on board the NOAA Research Vessel Ronald H. Brown, HRDL was operated over the Gulf of Main 24-h a day, during the NEAQS 2004 field campaign.

A major obstacle to obtaining accurate wind profiles from the high-precision lidar measurements using these techniques is compensating for the pointing error and along-beam platform velocity that are due to ship motions, including those induced by wave action. To accomplish this, the lidar is equipped with a system that 1) determines the orientation and motion of the platform and then actively stabilizes the pointing of the scanner and 2) corrects the lidar velocity measurement by estimating and removing the platform motion component along the lidar pointing direction. Several tests are used to determine the accuracy of the pointing-angle corrections (Pichugina et al. 2012) both in the laboratory using specially constructed platform to simulate pitch, roll and other ocean wave movements, and in the open ocean. These tests indicated that implementation of the real-time motion-compensation system allowed maintaining the chosen scan parameters in the world frame to within ~1^0 or so under conditions normally encountered. For more recent deployments, additional improvements have been implemented that allow compensation for the ship's motions to within 0.5^0.

The accuracy of lidar-measured wind profiles can be assessed by comparison with profiles measured by other instruments also operated from the ship. A strong correlation between rawinsondes and HDRL horizontal and lateral wind components with correlation coefficients of 0.97 and 0.98 respectively combined for all heights above 100 m was reported in Wolfe et al. (2007). We compared lidar and rawisondes at each height and the correlation-coefficient profile is shown in the left panel of Fig. 1. The right panel shows the number of reciprocal points used for the comparison at each height from the surface to 1500 m. Slightly reduced correlation with $R^2 < 0.96$ observed at 3 lowest heights of 30, 60, 90m is a result of the influence of the ship's atmospheric wake on the rawisonde measurements at these levels.

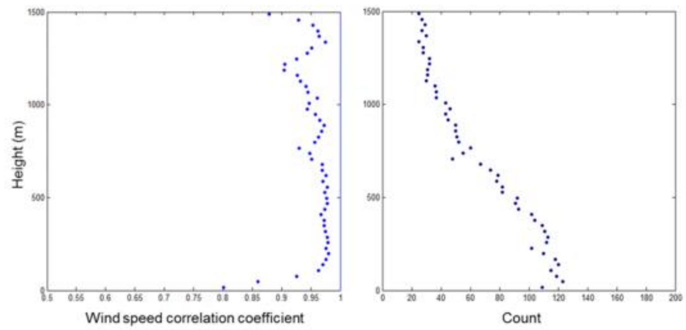

Fig.1. Correlation coefficients (left) between lidar and rawisonde wind speed at 30 heights above the water surface and (right) number of points at each height used in calculations.

Comparison of motion-compensated, sonic-anemometer ''flux-wind'' (Fairall et al. 2006) measurements at 17m and lidar measurements at the closest height of 12.9 m (Fig. 2), demonstrates high agreement between the two instruments with correlation coefficient of 0.92 for wind speed and 0.98 for wind direction.

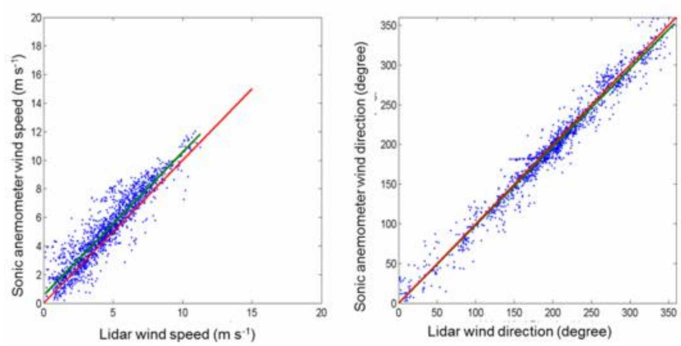

Fig. 2. Scatter diagrams show comparisons between (left) wind speed and (right) wind direction measured by lidar and sonic anemometer. The green solid line in both plots represents the best-fit linear regression.
The red line is the 1:1 line.

3. Spatial variability of winds from HRDL measurements

As a result of roughness and thermal contrasts between land and water, offshore flow generates transitional or "internal" boundary layer structures that can produce changes in wind speeds with distance from the coastline. The diurnal heating cycle produces sea-breeze circulations that change over periods of a few hours, and diurnally varying low-level jet (LLJ) structure has often been observed in available offshore wind profiles. The interaction of these processes with onshore topography or irregular coastlines adds further complexity to the horizontal and vertical structure of the flows offshore. All these factors can produce strong spatial and temporal variability to the offshore wind field (Pichugina et al., 2012). Some of this variability may result from spatial variability of the flow field, but some is due to the evolution of the wind field in time. Unequivocal identification of spatial changes is possible by retracing the ship path back and forth over an area. Although such patterns were not performed often during NEAQS, Fig.3 (top, left) shows one example where the RHB retraced the same course three times on 11 August.

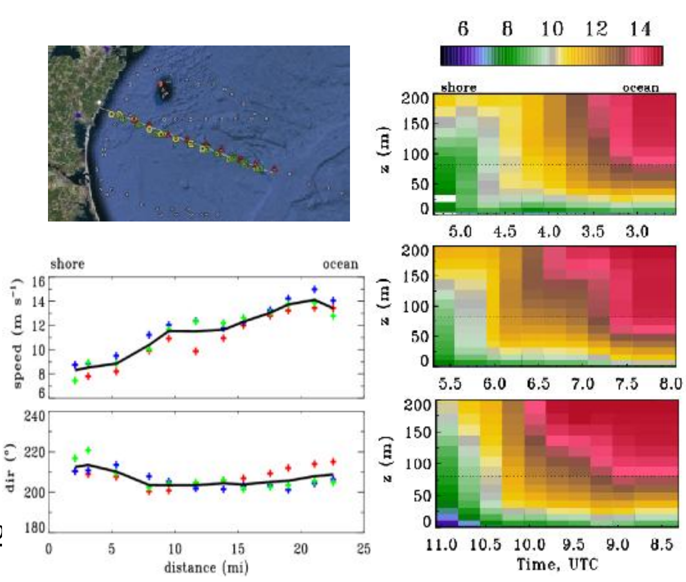

Fig. 4 (Left). The Google map of ship tracks on 11 August, when the RHB retraced the same course three times (color symbols). (Right). Time-height cross section of mean wind speed for each leg. (Left, bottom) wind speed and direction at 80 m shown as a function of distance from the shore. 15-min averaged data are shown in a different color for each trace (leg); solid black lines are mean values.

Replotted for each leg (Fig. 3, right), these cross sections show persistence of the spatial patterns in time. This repeatability indicates genuine spatial patterns in the wind features, such as the LLJ at 50-200 m in the open ocean. The bottom (left) plot of 80-m winds measured during each 3-3.5 h leg demonstrates stronger (14 ms^{-1}) winds further out to sea compared with the near-shore winds of ~8 ms^{-1}. Wind directions decreased slightly 6-7 miles out from the shore, and then became almost constant.

Another way to analyze the spatial distribution of winds is shown on Fig. 4 as a Google-embedded map of lidar-measured wind speed at 80 m above the water surface. For this map a weighted gridding was performed with a grid cell size of 0.100 x 0.083 degree using 15-min averaged data from the whole experiment. Similar plots could be obtained at any height from the water surface up to 300 m for any period of time, such as day- or night-hours, providing immediate information on vertical, spatial, and time variability of winds in the research area. Similar to Fig. 3, analysis of these gridded data allowed us to estimate mean wind speed/wind resource distribution along the coast line or as a function of a distance from the shore. As mentioned, such analysis could be applied at any given height or for any period of interesting atmospheric events such as cold front passages.

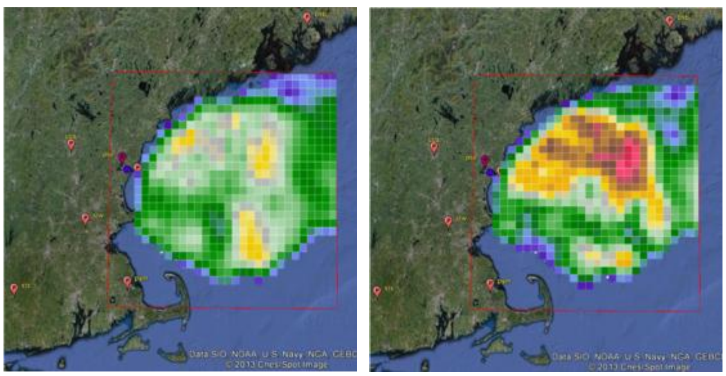

Fig. 4. Embedded grid of July 09-August 12 wind speed at (left) 10 m and (right) 80 m superimposed on Google Earth map of the region.

4. WRF model validation

A potentially important tool in providing offshore winds aloft is the numerical weather prediction (NWP) model, but without measurements at turbine blade levels for verification, the accuracy and fidelity of model output is unknown. In a recent study comparing annually averaged wind-speed forecast errors from a global model with data from two offshore wind towers on fixed platforms reaching 70 and 100 m above sea level, Drechsel et al. (2012) found model errors of 1-2 m s^{-1} and relative errors of 15-20%, depending on the model-derived variable used for comparison. Comparisons with turbine nacelle winds, which were available for this study, yielded poorer results, as expected. More such studies are needed.

To illustrate the usefulness of HRDL for model validation we used available WRF output derived along a ship track at the same points as the HRDL measurements. The model nested domain had a 4 km horizontal grid spacing (121×121 mesh) with a vertical grid composed of 41 full sigma (terrain-following) levels stretching from near surface (~12 m at the first half sigma level) to the model top (S.-H. Lee et al. 2011). An example of real lidar wind speed and direction is shown on Fig 5 (top), for the 24-h period of July 21, and modeled data are shown on the bottom panel of this figure.

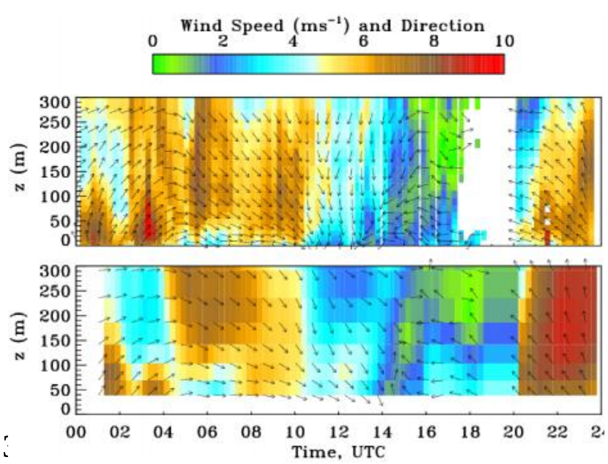

Fig. 5. Time-height cross section of lidar-measured and WRF modeled mean wind speed and direction. Vertical axis is height above sea level (m), and horizontal axis is time in UTC. Wind speed on both panels is color coded from 0 to 10 m s^{-1}, black arrows show wind direction. The gap in lidar data between 1800 and 2000 UTC was due to fog.

Both observational and modeled wind directions show overall good agreement, although noticeable discrepancies in wind speed could be seen for the period of 20-24 UTC. During this period the ship was moving slowly close to the shoreline and the model probably did not accurately represents atmospheric processes showing the stronger winds close to the shore.

We also compared 50 hours of data obtained during July 20-22 with modeled wind profiles derived along ship tracks for the same time. Overall, 3 different turbulent mixing (“PBL”) schemes were tried showing not much difference between schemes as demonstrated in Table 1 for the 80 m winds.

	BL1	BL2	BL3
R^2	0.68	0.69	0.71
bias	1.40±0.46	1.32±0.45	1.56±0.41
slope	0.70±0.07	0.65±0.06	0.57±0.05
RMS	2.70	2.70	2.70

Table 1. Comparison of lidar-measured and modeled wind speed at 80m above the water surface

In general, comparison results are not impressive as may be expected for this version of the model. Currently validation of the retrospective runs using more sophisticated models such as NOAA High Resolution Rapid Refresh (HRRR) is underway.

Summary

In the offshore region, where almost no information on hub-height winds exits, it makes sense to use what is already available. Past-year lidar measurements can provide valuable information on the spatial/temporal variability of marine winds, especially considering the great expense of doing new field programs.

The existing datasets of HRDL offshore measurements represent a resource that can be used 1) to better understand the range of atmospheric conditions, and their spatial and temporal variability, encountered by offshore wind turbines above the surface at the level of the rotor blades, 2) to validate numerical models using retrospective runs, 3) to support satellite estimates of wind resources, and 4) to supplement the development of offshore wind-resource maps. The large offshore area coverage of ship-borne lidar, and direct measurements at hub height can provide benchmark datasets that could be useful for U.S. offshore wind energy planning for years to come. This paper has presented a sampling of the kind of information available in these datasets.

Acknowledgments

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