2B.6 *Wind Flow Characteristics from Ship-borne Lidar Measurements in Support of Wind Energy Research*

Yelena L. Pichugina[1, 2,*], Robert M. Banta[2], W. Alan Brewer[2],
Scott P. Sandberg[2], and R. Mike Hardesty[2]

[1]*Cooperative Institute for Research in Environmental Sciences (CIRES), Boulder, CO, U.S.A.*
[2] *Earth System Research Laboratory (ESRL), NOAA, Boulder, CO, U.S.A.*

1. INTRODUCTION

It has been estimated that strong winds off the US coasts can be used in Wind Energy (WE) projects to provide up to 4% of the country's electric generating capacity by 2030 (DOE Report, 2008). Development of wind farms even in shallow waters (< 30 m) requires higher investments and maintenance costs in the tougher environmental conditions compared to inland wind farms. But offshore wind farms have a number of advantages to defray these expenses. Due to stronger and less turbulent winds at higher altitudes, wind turbine arrays installed offshore worldwide have greater capacity and produce more energy per unit compare to inland installations. Detailed analysis of the advantages and disadvantages of offshore wind-project developments are given in (Musial and Butterfield, 2004), where they listed positive factors such as considerable wind resources, reduced transmission costs due to closer location of wind farms to large load centers, minimal visual impact and land-use expenses. Besides, existing marine technologies can be used in WE practice to install larger, more cost-effective turbines (no competitive inland technologies exist).

Along with advanced technologies, an accurate assessment of wind resources at the height of turbine rotors is needed for success in wind-farm development and operations. As the capacity and size of modern wind turbines continue to grow, the uncertainty in extrapolation (both vertical and horizontal) of wind measurements from coastal automated network stations, Coast Guard stations, buoys, and occasional small meteorological towers instrumented by sonic/cup anemometers, increases significantly. Conventional measurements from tall (120-200 m) meteorological towers could provide reasonable estimates of wind field characteristics at least at a few points across the turbine rotor heights (Kelley et al., 2004), but the number of such towers is limited even on land and does not exist in US off-shore areas. In addition, tall towers are expensive; for example and these expenses can be 4-5 times higher for offshore installations, especially in deep (>30 m) waters.

Doppler lidars, which are able to provide high-quality measurements of wind and turbulence profiles from the surface up to several hundred meters above the water surface, can be a logical solution for offshore wind research needs. With the fast development of new technologies and more effective materials, these instruments are becoming less expensive and an affordable alternative to the traditional measurements in wind energy.

This paper provides examples of the kind of information that can be obtained from NOAA ship-borne lidar measurements off the New England coast and demonstrates usefulness of lidar data to better understand marine wind flow characteristics at turbine rotor heights. The data, from ESRL's High-Resolution Doppler Lidar (HRDL), were obtained during the New England Air Quality Study during summer of 2004 (NEAQS 2004).

2. EXPERIMENT DESCRIPTION

During NEAQS the HRDL, deployed on board the NOAA research vessel Ronald H. Brown (RB), operated in a continuous measurement mode from July 9 through August 12, 2004 with only occasional interruptions occurring during heavy rain and dense fog events. HRDL's operation from a ship-based platform provided many challenges, such as a constantly accelerating reference frame and

* *Corresponding author address*:
Yelena L. Pichugina, ESRL / NOAA,
325 Broadway, Boulder, CO 80305.
e-mail: Yelena.Pichugina@noaa.gov

vibration from ship engines. Development and implementation of a real-time motion compensation system allowed accurate wind velocity measurements to be obtained. As shown in Wolfe et al., 2006, the HRDL measurements were in good agreement with data obtained by rawinsondes that were launched 4-6 times daily, and with data from a radar wind profiler (permanently deployed on the ship providing hourly profiles at 60 and 100-m vertical resolutions) at levels above a few hundred meters. The lidar's scanning strategy included sweeps along both constant azimuth and elevation angles to provide a variety of high-resolution boundary-layer information. Azimuth scanning at constant elevation angle produces a cone of data that at the lowest elevation angles can provide near-surface wind data. Elevation scanning produces vertical slices of atmospheric flow features. This paper presents results obtained from conical- scan measurements only.

3. WIND-FLOW CHARACTERISTICS

The 360° azimuth scans, usually completed in 2 min or less, were processed to produce vertical profiles of the horizontal wind speed and direction using the velocity-azimuth display (VAD) technique (Browning and Wexler 1968). Employing the VAD method from low to high elevation angle sweeps, lidar-derived wind speed and direction profile information were obtained with vertical resolution ~ 15 m or better in the boundary layer.

3.1 *Case study*.

An example of a time-height cross section of wind speed and wind direction measured during July 21 is shown in Figure 1, where arrows indicate wind direction, and the color indicates wind speed magnitude from 0 (green) to 12 m s^{-1} (red).

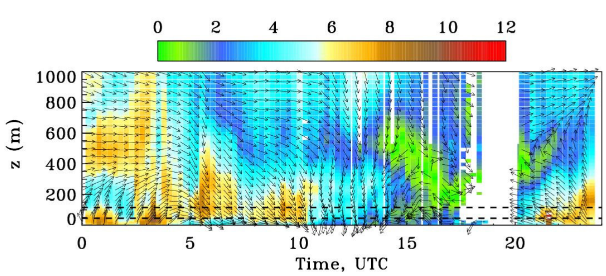

Figure 1. Mean wind speed (color) and direction (arrows), computed from HRDL conical scans during July 21, 2004. Two horizontal dotted lines indicate the hypothetical turbine rotor height of 55-155 m. Midnight local time is at 0500 UTC, and local noon, at 1700 UTC.

Figure 1 shows considerable difference between nighttime (~ 0 to 12 UTC) and daytime (~12 to 24 UTC) winds. At heights of 55-155 m, winds were about 6-8 m s^{-1} during most of the nighttime hours, with a several episodes of low-level jet (LLJ) occurrence, then winds calmed down to 3-4 m s^{-1} during the morning transitional period. About four hours of southwesterly winds (0-4 UTC) shifted to northwesterly (5-10 UTC) and then to northerly winds. By the late-morning hours, the wind direction frequently changed and wind speeds decreased to almost 0 m s^{-1} during an interesting apparent boundary-layer (BL) wave event.

Each vertical stripe of data3 in Fig.1 represents a 15-min averaged profile of wind speed and wind direction from 10 m to 1000 m above the surface. Examples of these profiles are shown in Figure 2 up to 500 m, to demonstrate details of the most observed situations happening during the 24-hour period of July 21: 1) Blue profiles on the left plot demonstrate almost constant wind speed across the turbine rotor layer, as the wind direction increased slightly (solid) or decreased linearly (dashed); 2) Red lines show LLJ-shape wind profiles with wind speed maxima at the bottom (solid) or at the top (dashed) of the rotor layer, and the wind direction is constant or slightly increasing in this layer; 3) Magenta solid profiles show a decrease in wind speed with height to almost 0 m s^{-1} at 180 m and about a 200 degree shift in wind direction at this height. Magenta dashed profiles illustrate almost constant wind speed and strong decrease in wind direction. Thus, the magnitude and shape of the winds profiles varied significantly within this 24-hr period.

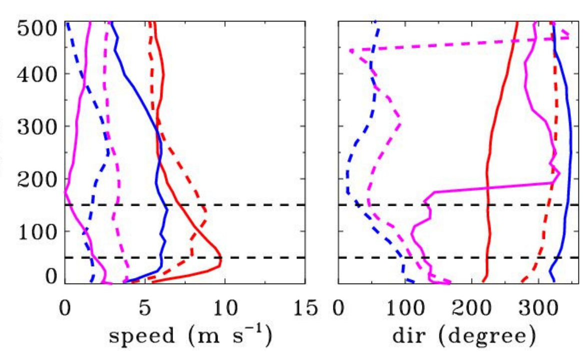

Figure 2. Examples of wind speed and direction profiles during most observed wind flow situations as described in the text. As in Fig. 1, two horizontal dotted lines indicate the hypothetical turbine rotor height of 55-155 m. 1) Blue lines: solid-, 1015 UTC, dashed-1430 UTC; 2) Red lines: solid- 0315 UTC, dashed- 0515 UTC; 3) Magenta lines: solid -1630 UTC, dashed - 1530 UTC.

Various wind-flow situations, as in Fig. 1 and Fig. 2, demonstrate the important ability of HRDL to provide high-resolution profiles of wind flow and estimates of speed and directional shear across the entire layer where offshore turbine rotors would operate. Knowledge of these quantities is very important for turbine operation, since modern turbine rotors are so large that wind conditions can differ significantly above and below the turbine hub.

Diurnal variation of wind-flow within the turbine rotor layer, as a function of time, is shown in Figure 3 for July 21, where time series of wind speeds (left panels) and wind directions (right panels) at several heights are shown by different colors.

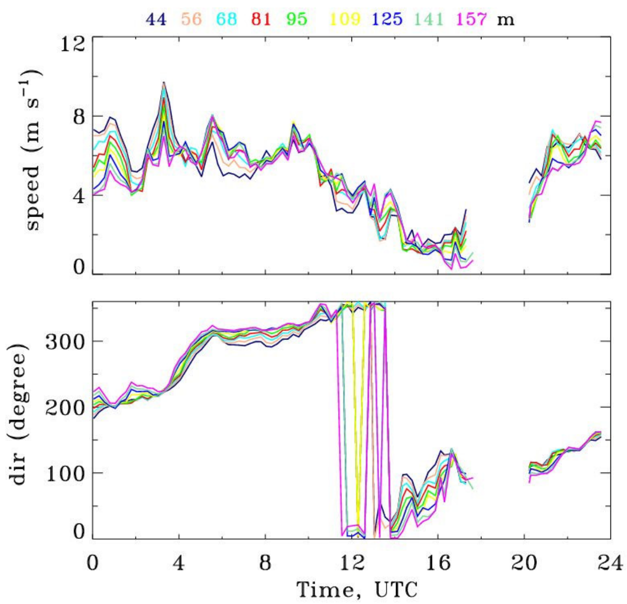

Figure 3. Time series of wind speed (top) and wind direction (bottom) at several heights across the turbine rotor swept area in July 21, 2004.

Figure 3 illustrates a typical diurnal pattern in offshore winds for a summer period, the stronger wind speeds in nighttime hours and the lower winds during early morning to midday hours. Strongest (~4 s^{-1}) wind shear occurred in the evening-transition (~0100 UTC) and early-night (~0400 UTC) periods, along with several ramp events during both nighttime and daytime hours. The bottom panel illustrates wind direction that gradually shifted from southerly (200^{o}) to northwesterly (~300^{o}) during nighttime hours and shifted to an almost opposite direction in early morning hours (~1200 UTC), followed by several hours of smaller directional fluctuation all morning long. Strong speed and directional shear and even small ramp events, if they are frequent enough, can increase wear and tear on hardware components and decrease periods between turbine-hardware outages and maintenance, and, overall, turbine life-time.

3.2 ***Monthly statistics***

Examples of monthly mean wind data for the diurnal cycle are presented in Fig. 4, where red lines show averages over 15-min intervals and black lines show 1-hour averages. Summer is the lowest wind resource season, although the average wind speeds are still greater than 5 m s^{-1}. The strongest winds of ~ 10 m s^{-1} were observed at 04-05 UTC when wind blow from the southwest (240°), and the lowest winds just above 5 m s^{-1} were observed during morning hours (12-18 UTC) for south-southeasterly flow

Overall, nighttime southwesterly winds at 80 m above water surface were only ~1 m s^{-1} stronger than the southeasterly daytime winds (nighttime, 7 m s^{-1} at 194^{o} ; daytime: 5.9 m s^{-1} at 154^{o}).

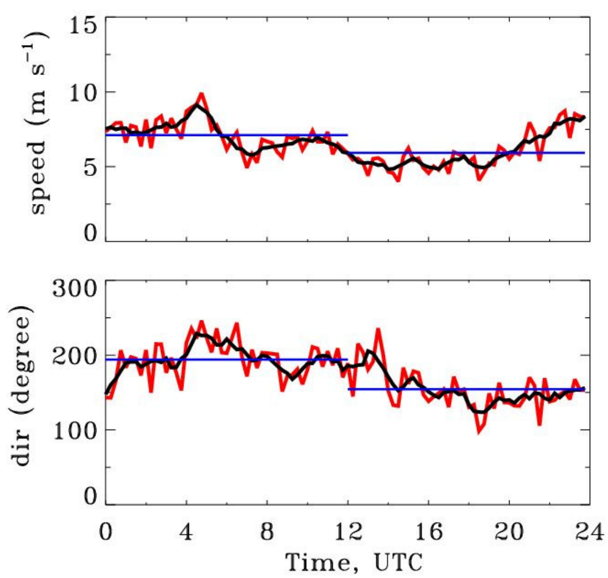

Figure 4. Time series of mean wind speed and wind direction at 80 m above water surface for July 2004. Red lines are 15-min averaged data, black lines are 1-hour averaged data, blue lines are nighttime (0-12 UTC) and daytime (12-24 UTC) means.

Profiles of high temporal and vertical resolution, provided by HRDL, are essential for estimating speed and directional shear of the wind at turbine rotor heights. Distributions of wind shear across 50-150 m layer of the atmosphere for the nighttime (0-12 UTC, left) and daytime (12-24 UTC, right) hours in July of 2004 are shown in Figure 5. Mean and median of distributions are shown in both panels by red and blue lines respectively.

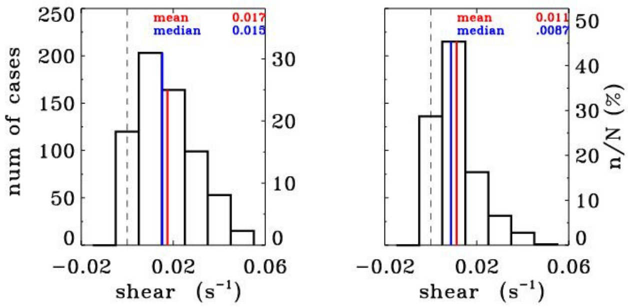

Figure 5. Distribution of mean wind-speed shear across the layer of 50-150 m for the nighttime (left) and daytime (right) hours in July, 2004. Mean value of the each distribution is shown by red lines, and median is shown by blue lines. Black dashed lines indicate zero.

Both histograms show similar means and range of the observed wind shear for nighttime and daytime. It was shown in (Pichugina et al., 2010) that steadier offshore winds resulted in wind shear across the rotor heights of 45-115 m half as large (0.021 s^{-1}), compare to nighttime observations over flat terrain near Lamar (0.048 s^{-1}), or in Kansas (0.039 s^{-1}). Note that larger shears have been measured in the layer below the LLJ nose, but here the layer considered often contains the LLJ nose, leading to smaller calculated values.

CONCLUSIONS

Sample results presented in this paper demonstrate the ability of HRDL to describe atmospheric characteristics that are difficult to capture with other instruments. They show the high potential of lidar measurements for offshore wind farm siting and operation, especially considering that to build offshore tall towers may be 10 times more expensive than on-land, and fast decrease of lidar prices due to development of new technologies.

The existing data sets of HRDL offshore measurements represent a resource that can be used to better understand the range of atmospheric conditions encountered by wind turbines above the surface at the level of the rotor blades, to validate numerical models, to support satellite estimates of wind resources, and to supplement developing offshore wind-resource maps.

ACKNOWLEDGMENTS

We thank our colleagues S. Tucker, R. Marchbanks, J. Machol, and B. McCarty for tremendous work on ship, collecting HRDL data.

REFERENCES

Banta, R.M. and Y.L. Pichugina, 2010: Reducing wind energy forecast uncertainty through improved measurements and modeling. *AMS 90th Annual Meeting,*17-21 January, Atlanta, GA

Browning, K. A. and Wexler, R.: 1968, The Determination of Kinematic Properties of a Wind Field Using Doppler Radar', *J. Appl. Meteor.* **7**, 105-113

Grund, C. J., R. M. Banta, J. L. George, J. N. Howell, M. J. Post, R. A. Richter, A. M. Weickmann, 2001: High-resolution Doppler lidar for boundary layer and cloud research. *J. Atmos. Oceanic Tech.,* **18**, 376-393

Department of Energy Report, 2008. 20% Wind Energy by 2030. Increasing Wind Energy's Contribution to U.S. Electricity Supply. *DOE/GO-102008-2567* • July 2008

Kelley, N.D., B.J. Jonkman, G.N. Scott, and Y.L. Pichugina, 2007: Comparing Pulsed Doppler LIDAR with SODAR and Direct Measurements for Wind Assessment. *Awea Windpower conference, Los Angeles, California.* NREL/CP-500-417

Musial, W., and S. Butterfield, 2004, "Future for Offshore Wind Energy in the United States," *Preprint for Energy Ocean 2004, Palm Beach, Florida*, June 28.29, 2004

Pichugina Y. L., R. M. Banta, W. A. Brewer, S. P. Sandberg, and N. D. Kelley, 2010-a: Lidar measurements as an alternative to traditional anemometry in wind energy research. *AMS 90th Annual Meeting*, 17-21 January, Atlanta, GA

Pichugina Y. L., R. M. Banta, W. A. Brewer, R. M. Hardesty, and C. J. Senff, 2010: Doppler lidar measurements of wind flow characteristics over flat terrain and over ocean. *International Symposium for the Advancement of Boundary Layer Remote Sensing* - 28-30 June 2010 - Paris, France

Wolfe D.E. , W. A. Brewer, S.C. Tucker, A.B. White, D.E. White, D.C. Welsh, D. Ruffieux, C.W. Fairall, M. Ratterree, J.M. Intrieri, B.J. McCarty, and D.C. Law: 2007. Shipboard multi-sensor merged wind profiles from NEAQS 2004. J. *Geophys. Res.*, **112,** D10S15