Characterizing Wind Speed and Direction Shear with SoDAR Data

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Summary

SoDAR data from three sites were analyzed to identify frequency of occurrence of atypical wind conditions sufficient to impact resource suitability or turbine performance. Wind speed and direction measurements were obtained for a set of heights spanning a typical wind turbine rotor. For each site, 10-minute wind averages were collected for a three-month period. A power-law shear coefficient was then fit to each 10-minute set of wind speed measurements, yielding an accurate short-term measure of wind speed shear. Similar analysis was performed for wind direction shear (also called veer) by fitting a straight line to each set of 10-minute wind direction measurements. The wind direction change from lower to upper blade tip was then used as a short-term measure of veer.

To highlight the effect of speed and direction shear on turbine operation, data samples with hub height wind speed below 6 m/s were removed from the data set. Histogram representation is used to show the frequency-of-occurrence of speed and direction shear values, and the heavy-tailed distributions suggest that extreme shear and veer, while somewhat rare, occur surprisingly often and usually at night, when atmospheric stability reduces coupling between upper and lower level air. A reverse cumulative distribution, or frequency of exceedance plot, is shown to be useful in comparing the frequency of occurrence of degrees of shear at the three example sites.

Objectives

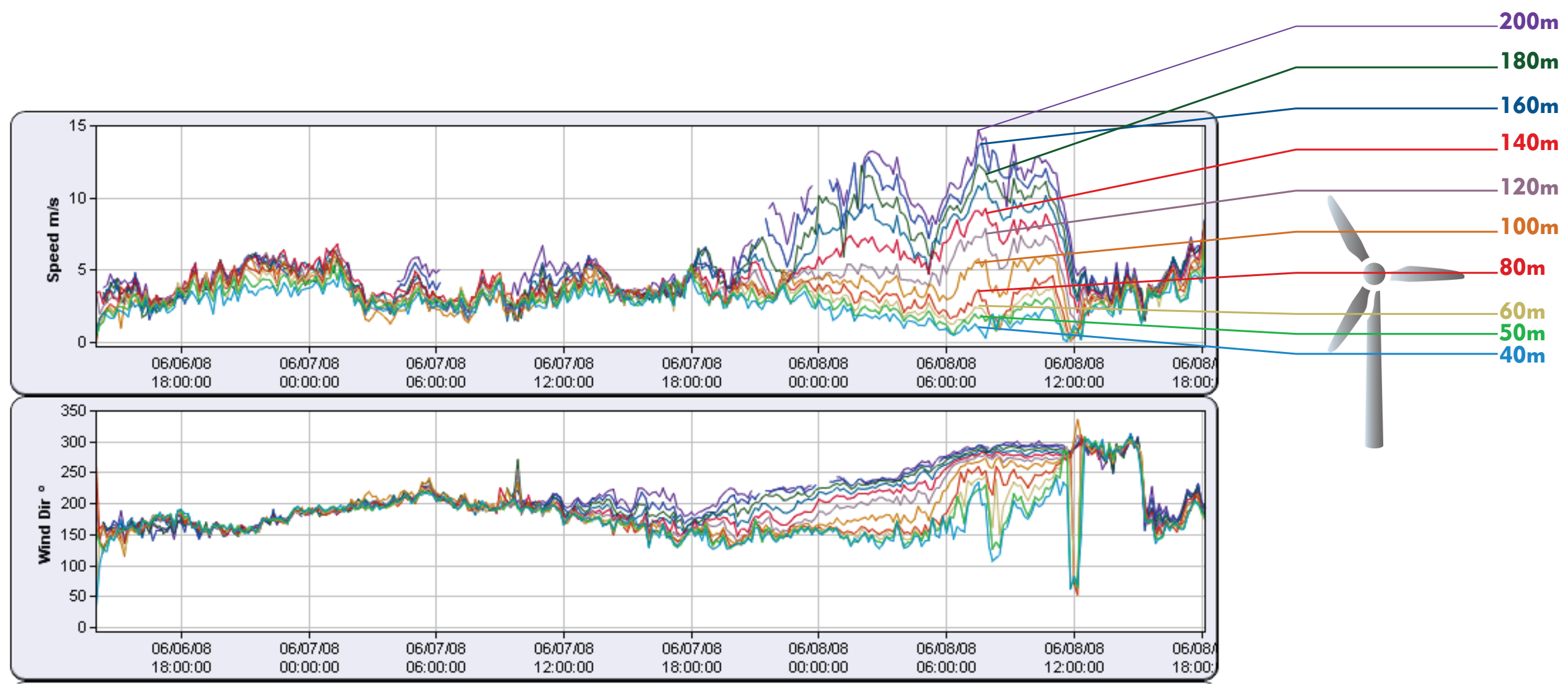

FIGURE 1. Example Triton Wind Speed (top) and Wind Direction (bottom) Measurements with Extreme Shear

The primary objective of wind resource assessment is to identify sites with sufficient winds for power generation. When a candidate site is identified, the wind data for the site is further analyzed to ensure suitability of the local wind conditions for wind turbine operation. One aspect of suitability that is often neglected is the occurrence of extreme wind shear. Often, only a single, seasonal, average shear coefficient is obtained for a site, even though such long averages mask the presence of wind shear extremes that occur infrequently.

A common reason for over-averaging wind shear is the lack of accurate data. When the only available data are from below-hub-height met masts, wind shear values must be extrapolated from a small set of readings. As tower shadow and anemometer over-speeding can cause small errors in those readings, the extrapolated shear values will have uncertainty when averaged over short time intervals. Also, it is common to ignore wind direction shear altogether, because many met towers are instrumented with wind direction vanes at only a single height.

The development of inexpensive remote sensing technology, such as Sonic Detection and Ranging, or SoDAR, has made it practical to obtain accurate measurements of wind speed and direction at several heights across the swept area of a typical wind turbine rotor. Because modern SoDAR equipment is robust, is easy to deploy, and can run continuously, it is an ideal choice for studying the variety of local shear conditions present at any potential windfarm site.

For this research, we used measurements from a Second Wind Triton Sonic Wind Profiler, which measures 10-minute average wind speed and direction at six different heights spanning a typical rotor swept area. The measurements were analyzed to compute accurate 10-minute values for both speed and direction shear over a three-month period. Without a standard practice for incorporating short-term shear measurements, it is not clear what to do with such a large quantity of shear data. This paper develops a simple technique for plotting shear frequency of occurrence in order to highlight site-to-site differences that would affect wind turbine performance and reliability.

Methods

Before examining the wind shear distribution, a correlation study was conducted for each three-month data set in order to ensure its validity. The wind speeds as measured by the Triton were compared to adjacent tower wind speed data and correlation coefficients were determined. Figure 2 shows scatterplots of Triton and anemometer wind speeds measured at 50, 100, and 150 m at the Boulder Atmospheric Observatory from September to November 2008. The correlation coefficients were found to be 0.985, 0.985, and 0.973 at 50, 100, and 150 m, respectively. Upon successful completion of each validation study, the wind shear and veer distributions were analyzed.

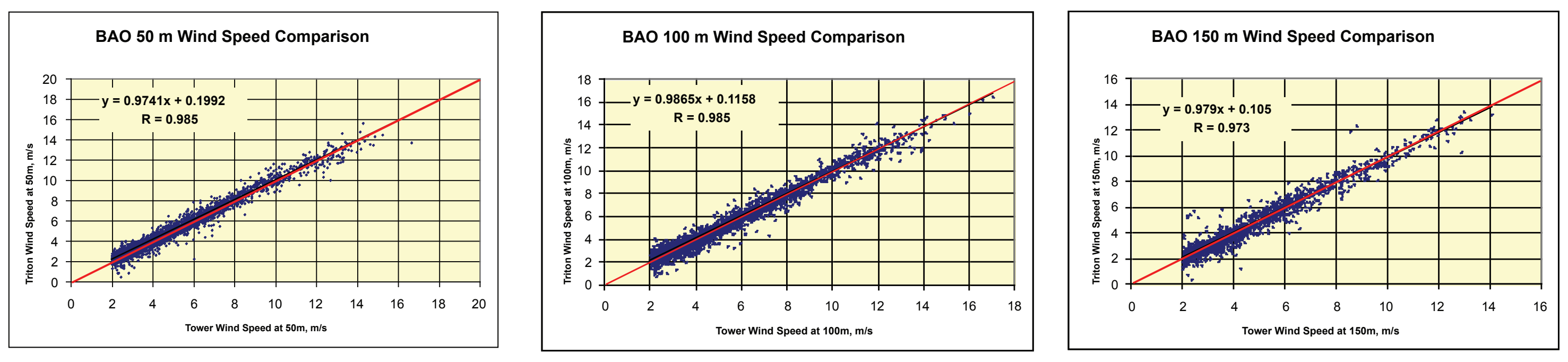

FIGURE 2. Scatterplots Showing Correlations Between Tower and Triton Measurements

The power law wind speed shear exponent, alpha, can be determined from the following formula:

$$\left(\frac{U_1}{U_2}\right) = \left(\frac{H_1}{H_2}\right)^{\alpha}$$

where $U_{1,2}$ are wind speed measurements at heights $H_{1,2}$.

Using the logarithm, the equation becomes:

$$\log\left(\frac{U_1}{U_2}\right) = \alpha \log\left(\frac{H_1}{H_2}\right)$$

To find an aggregate shear exponent from a whole set of measurement points, U_i at H_i, the equation can be reduced to the form of a straight line fit to the points $(\log(H_i), \log(U_i))$ as in:

$$\log(U_i) = \alpha \log(H_i) + c$$

The slope of the fit line is α, the power law wind shear profile exponent known here as the wind speed shear coefficient.

A representative wind turbine was assumed to have an 80 m hub height and an 80 m blade diameter, so measurements from heights ranging from 40 m to 120 m were included in the analysis. Figure 3 shows how a typical computed shear coefficient reflects the original 10-minute average wind speed data. The plot shows how the SoDAR data from heights spanning a turbine rotor nicely capture the 10-minute average shear characteristic without extrapolation.

Wind direction shear was calculated using a straight line fit to the wind direction measurements as a function of height. Using the same 40 m to 120 m height range, Figure 3 shows the line fit to a typical set of 10-minute wind direction measurements. To give a total measure of veer, the variation in wind direction with height was multiplied by the blade diameter, yielding the total change in wind direction over the rotor swept area.

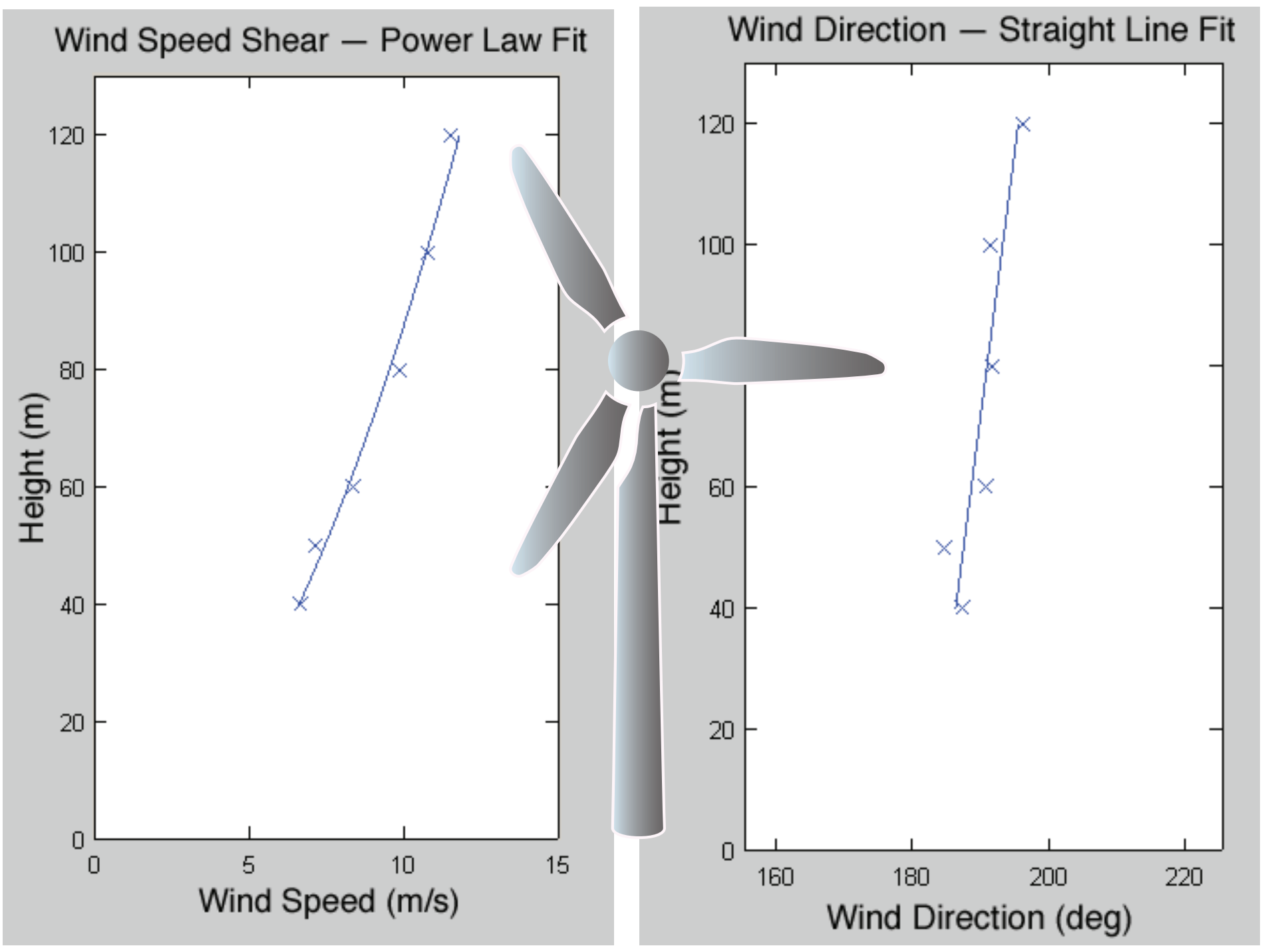

FIGURE 3. Sample Wind Measurements Showing Power Low Exponent Fit (left) and Change of Direction with Height (right)

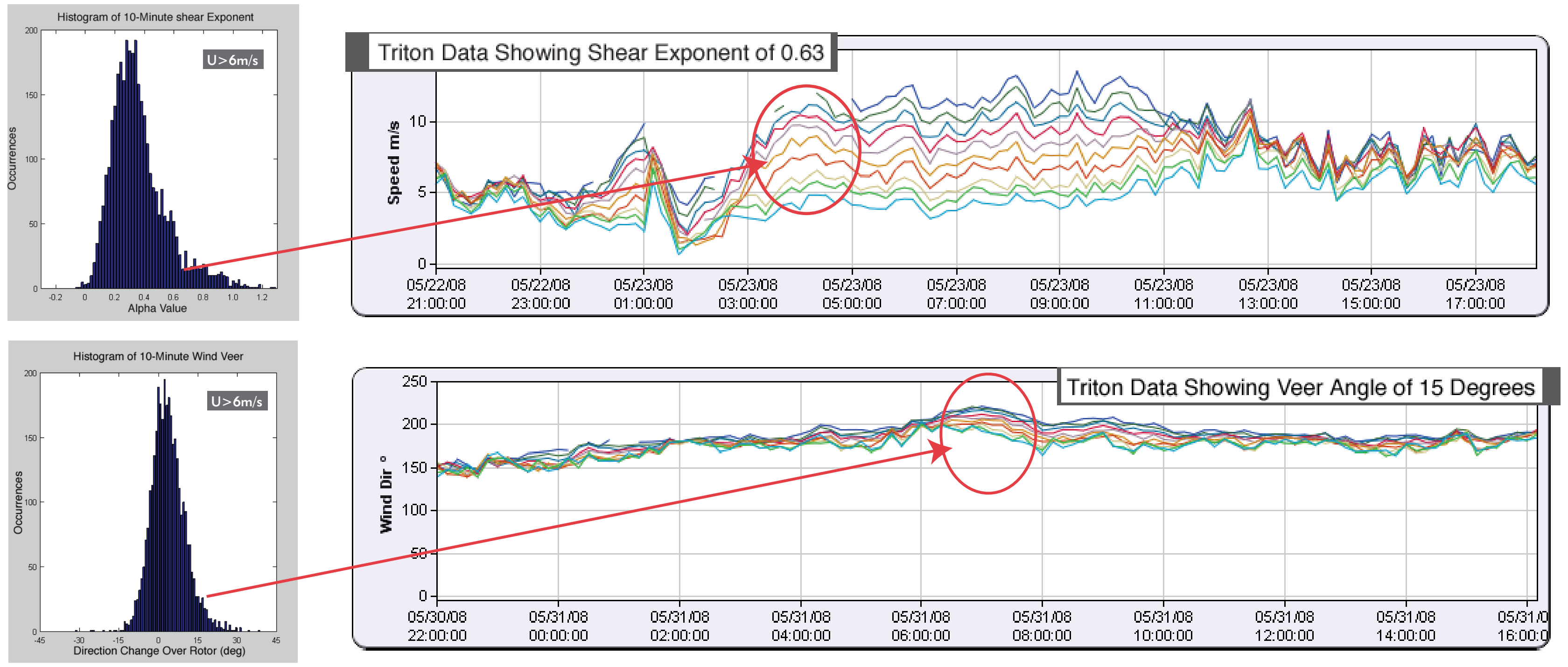

FIGURE 4. Histograms for Wind Speed Shear Exponent (top) and Directional Shear (bottom) with Matching Time Series Data.

As wind shear at low wind speeds has little or no consequence, all 10-minute data with hub height wind speed below 6 m/s were removed from the data set. In all likelihood, the remaining shear values occurred well within the operating range of most wind turbines. Histograms are shown for wind speed shear and wind direction shear in Figure 4. Also shown are the time-series SoDAR data from times of fairly extreme, yet frequently occurring shear and veer. The speed shear time-series example has a tip-to-tip wind speed ratio of 2:1 ($\alpha = 0.63$). The veer time-series example shows a tip-to-tip direction discrepancy of 15 degrees. The histograms show that, at least for short periods of time, far greater shear values occur. These shear extremes are most often masked in resource assessment, because shear coefficients are derived from long term data averages.

Results

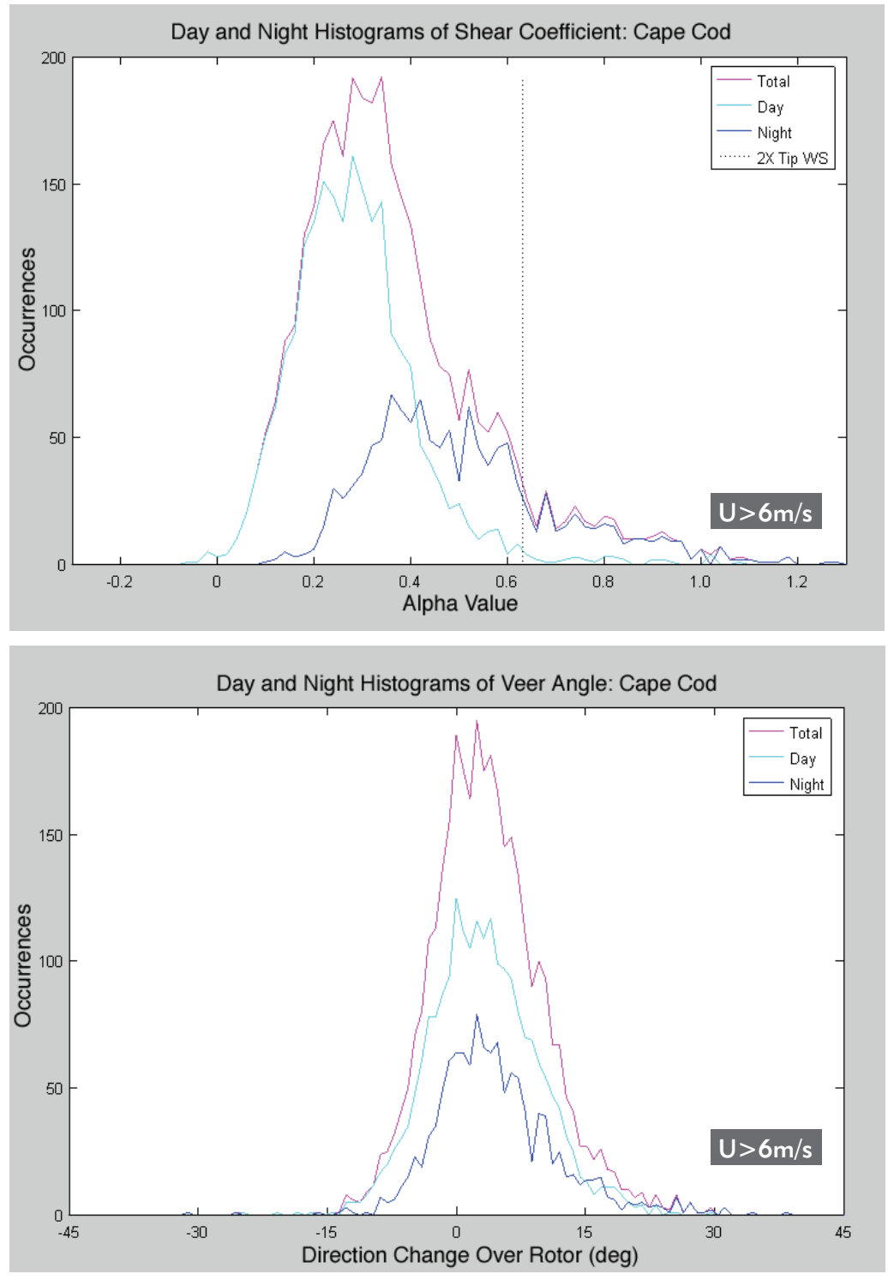

FIGURE 5. Day/Night Histogram for Cape Cod Site Shear Exponent (top) and Veer (bottom)

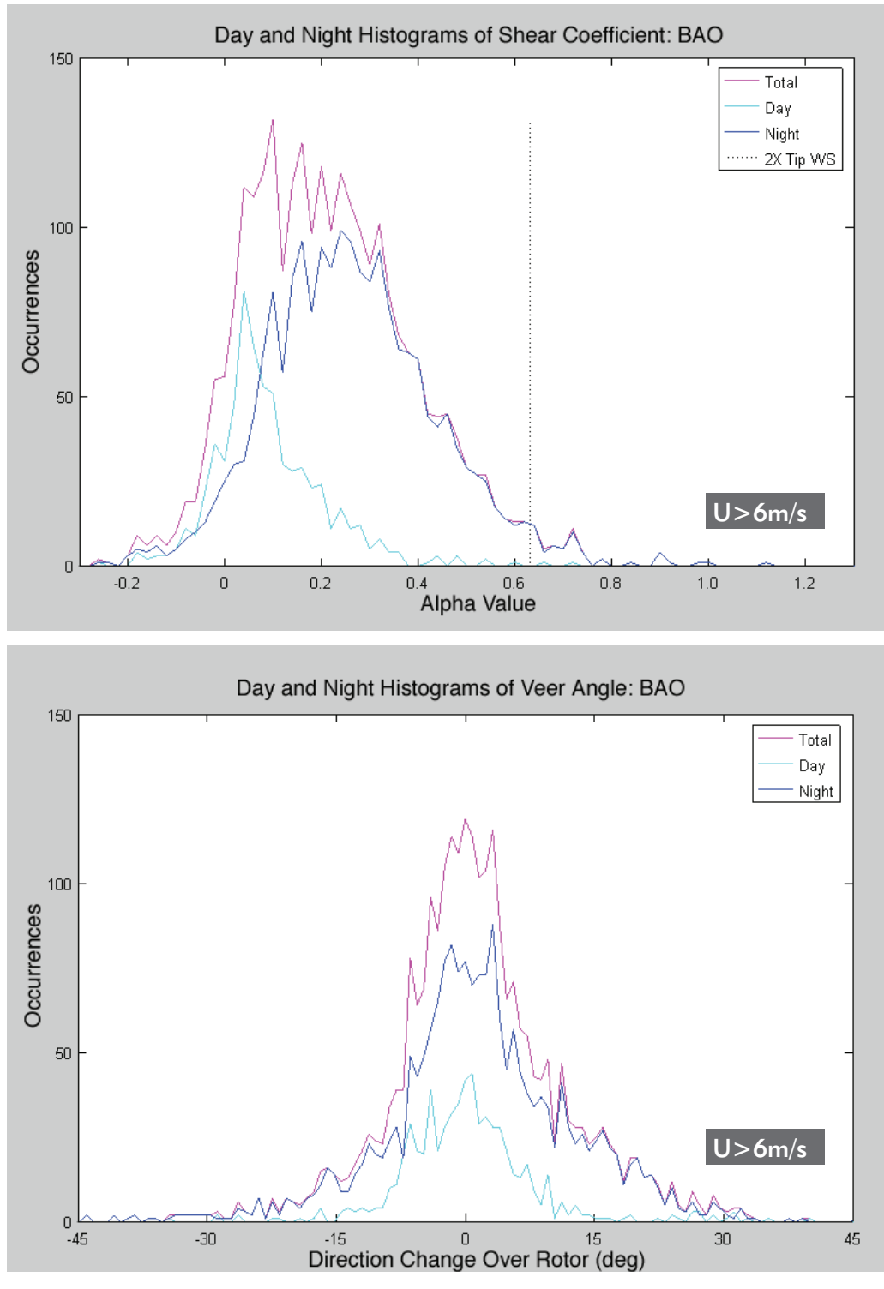

FIGURE 6. Day/Night Histogram for BAO Site Shear Exponent (top) and Veer (bottom)

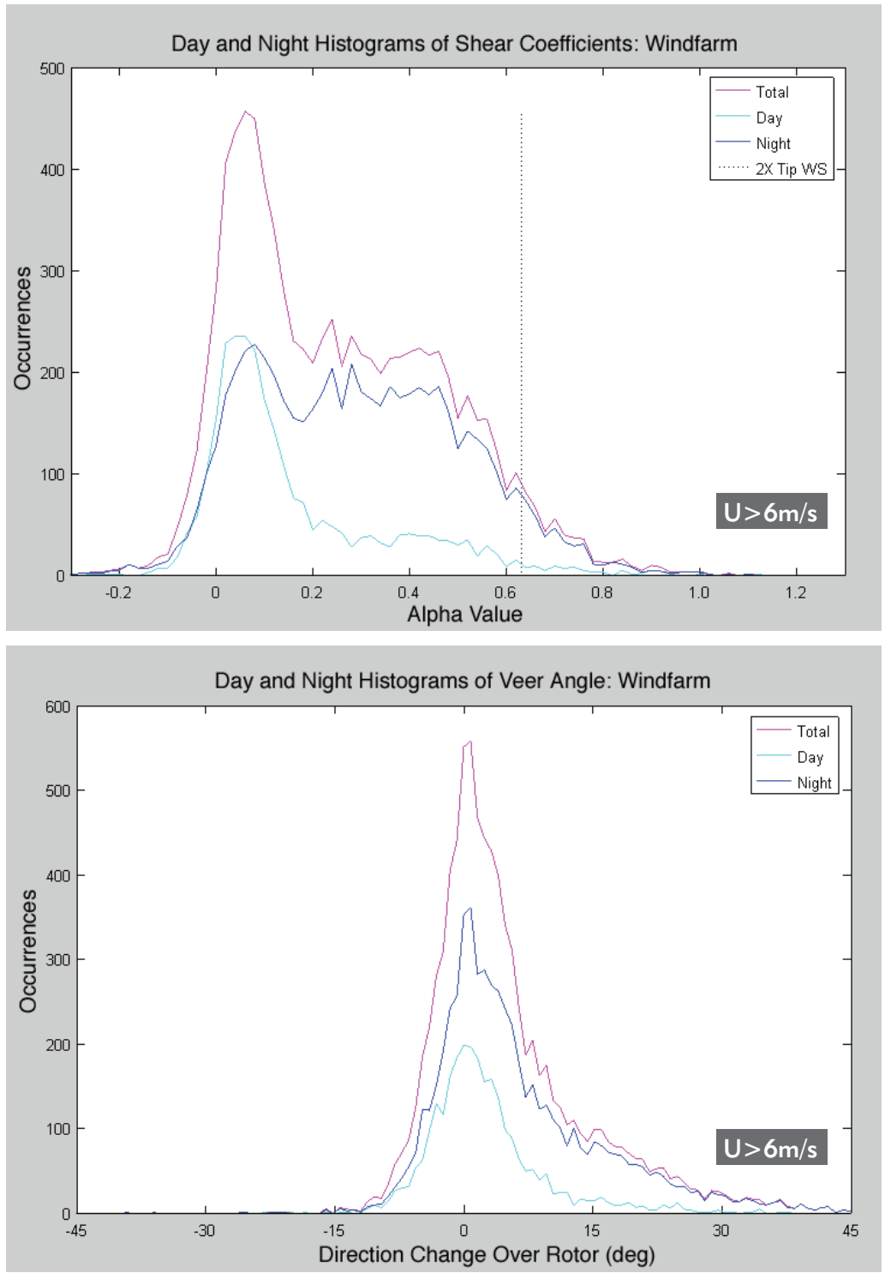

FIGURE 7. Day/Night Histogram for Windfarm Site Shear Exponent (top) and Veer (bottom)

Wind shear is reduced by coupling between layers of air during periods of atmospheric instability, such as when solar heating causes convective mixing of the air. For this reason, most extreme shear events occur during periods of high atmospheric stability, usually at night. Even on overcast days, atmospheric stability is usually somewhat reduced, providing a degree of protection against extreme shear. This diurnal trend is demonstrated by segregating the shear and veer histograms by time of day.

A three-month data set was obtained for each of three example sites:

Site	Period	Location	Description
BAO	Sept–Nov 2008	Boulder Atmospheric Observatory	Nearby 300 m Tower
Cape Cod	May–July 2008	Massachusetts	Coastal Cranberry Bog
Windfarm	Nov–Jan 2008/9	Texas	Operating Windfarm

Figures 5, 6, and 7 show the wind speed and direction shear histograms for the three test sites. At all sites, the extreme speed shear, visible in the tails of the distribution, is a nighttime phenomenon. The wind veer histogram shows a similar characteristic, and the noticeable right-sidedness of the veer histogram is the related to the Ekman spiral, where friction and the Coriolis force vector in the Northern Hemisphere cause a positive shift of wind direction with increasing height.

The diurnal histograms from the three different sites have similar character, but a more detailed site comparison can be achieved using a frequency of exceedance distribution. Like an inverse cumulative distribution, the frequency of exceedance indicates the percentage of time that the sheer was in excess of a value. Because the data were filtered to remove periods with low wind speed, the percentages indicated are with respect to turbine operational time. Figure 8 shows the frequency of exceedance of wind speed shear for the three example sites. From the chart, it is evident that swept area shear in excess of 2:1 ($\alpha = 0.63$) occurs almost 10% of turbine operational time at the Cape Cod site, while only 2% at the BAO site.

Figure 9 shows the frequency of exceedance of the absolute value of wind direction shear for the three example sites. From the chart, it is evident that swept area veer in excess of 20 degrees occurs almost 10% of turbine operational time at two of the sites, but only occurs 2% of the time at the Cape Cod site. Thus the site with the highest speed shear is seen to have the lowest directional shear.

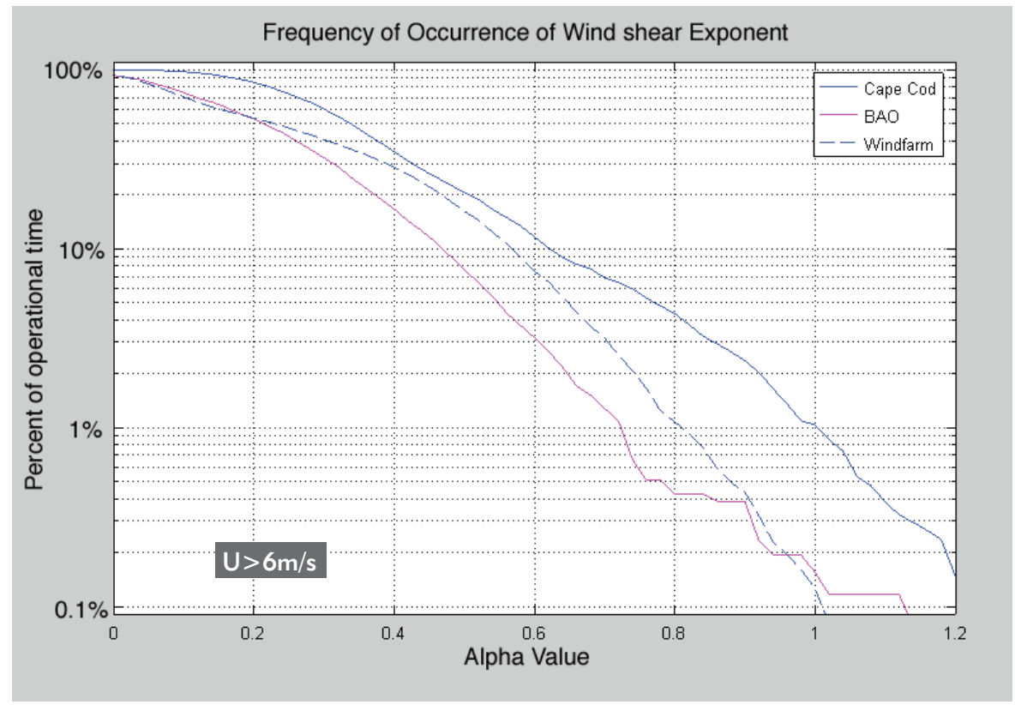

FIGURE 8. Frequency of Exceedance of Shear Exponent at Three Example Sites

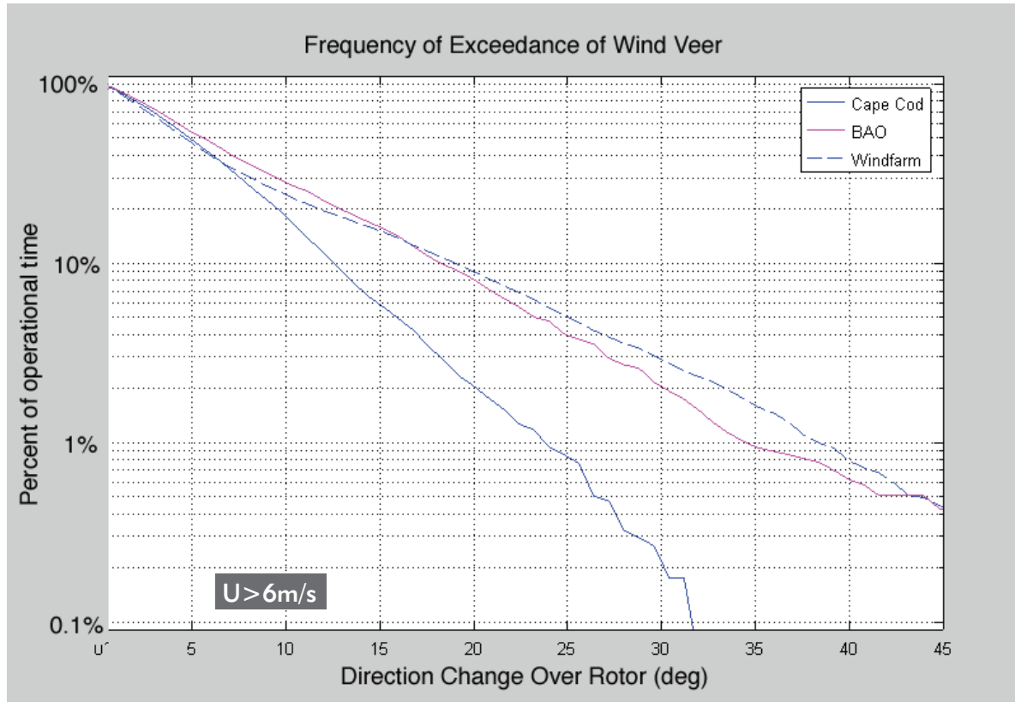

FIGURE 9. Frequency of Exceedance of Veer at Three Example Sites

Conclusions

Short-term wind speed and direction shear values were computed based on 10-minute average SoDAR measurements. The results indicate the presence of extreme shear at all example sites, even though the data were filtered to remove light wind periods, when the hub height wind speed was below a conservative, 6 m/s cut-in threshold. Extreme shear is shown to occur mostly at night, presumably because the more stable atmosphere overnight does little to relieve the atmospheric force gradients that cause shear. Lastly, the frequency of occurrence of shear extremes is shown using a log-scale frequency of exceedance plot, and the distributions are observed to differ substantially from site to site.

More work is needed to assess the importance of measuring short-term wind shear values. As wind turbine technology advances to include individual blade pitch control, the extent to which differing winds across the rotor cause performance and reliability problems may change. At the current time, however, extreme wind shear is thought to contribute to performance degradation and operational down time, so site statistics beyond simple, extrapolated, seasonal averages should be evaluated, and SoDAR measurement technology is well suited to provide the data.

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