Accuracy of Vertically Extrapolating Meteorological Tower Wind Speed Measurements

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Introduction

Tower-based wind measurement systems typically become more expensive as the height of the tower increases. The tallest currently available tilt-up towers extend to 60 meters above ground, and 40 meter towers are much more common. The goal of this study was to quantify the level of uncertainty that would be expected if data from a short tower (40 meters tall or lower) was used to predict wind speeds at typical utility-scale wind turbine hub-heights of 70 meters and above. Data was collected from four tall towers at least 70 meters tall in the central United States. Anemometer data from levels below 40 meters was then used to predict wind speeds at higher levels. The predictions were compared to the measured wind speeds at the higher levels to assess the level of error in the predictions.

Typically, the profile of wind speed U as a function of height above ground z is modeled using the power- or logarithmic laws. The logarithmic law,

$$U(z) = \frac{U^*}{\kappa} \ln\left(\frac{z}{z_O}\right) \quad (1)$$

includes two constants, the friction velocity U^* and the surface roughness z_o, which vary depending on the site and climate. Typically, z_o is estimated based on the land use and vegetation of the surrounding terrain. A possible complication of using this relation in practice is that it becomes undefined if the wind speed is constant with height ($\partial U/\partial z = 0$).

The power law is typically written as

$$U(z) = U_{ref}(z_{ref})\left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (2)$$

The wind speed U at a height z is related to the wind speed U_{ref} at height z_{ref} by α, the power law exponent. By solving for α, the power law exponent can be determined if wind speed measured at two heights is available.

$$\alpha = \frac{\ln(U / U_{ref})}{\ln(z / z_{ref})} \tag{3}$$

With α characterized, the wind speed at any height can be predicted. Ray et al. (2006) studied wind profiles at several tall towers in the United States and concluded that the logarithmic and power laws were essentially equivalent in accuracy for predicting wind profiles. For this study, the power law was chosen as the model to evaluate.

In wind resource assessment, it is common to use the power law to predict wind speeds at the hub height of a potential turbine, based on wind speeds measured at an anemometer on a shorter tower. If a single anemometer is being used, α is typically estimated based on tables that relate α to the surrounding terrain (e.g., Ray et al., 2006) If no information is available, a value of $\alpha = 1/7$ may be used, resulting in the so-called "1/7 power law". (This should be done with caution since α can vary widely from 1/7.) However, if wind measurements are available at two or more levels, it is better practice to fit a curve to the data and calculate α directly.

The accuracy of wind speed profiles predicted using measurements at only one or a few heights near the surface has been of interest to researchers for quite awhile. There have been a number of prior studies that examined how power law exponents varied as a function of location, time and other factors. Mikhail (1985) examined the use of four different methods of predicting the wind profile at several tall towers in the American Midwest using anemometer data from a single level. He observed that the use of a modified power law expression was more accurate than application of the 1/7 power law or logarithmic laws. Schwartz and Elliott (2006) observed that annual average values of α were 0.15 to 0.25, well in excess of 1/7, at thirteen tall towers in the American plains states. Significant diurnal variations were observed, as well as some seasonal fluctuations. Ray et al. (2006) found significant variation with wind direction at Boulder, CO, a site in complex terrain. Other recent studies include those by Motta (2005), Perez et al. (2005) and Rogers et al. (2005).

While several researchers have investigated how power law exponents or logarithmic fits vary in wind speed profiles, there has been less investigation relating these findings to the practical question of how much uncertainty is introduced when these methods are applied to predicting turbine hub-height wind speeds from lower height anemometer data.

Data

Tall tower sites were chosen with wind speed measurements at two levels below 40 meters above ground, and at least one level at 70 meters or higher. This precluded many tall tower data sets, since many towers over 60 meters high do not have many anemometers at lower levels. For an observation to be useful, wind speed information was needed from many levels on the tower, as well as wind direction, which further reduced the number of observations available. A single malfunctioning or suspect anemometer or wind vane could invalidate an entire observation. In addition to these concerns specific to this study, tower effects on the anemometers, and icing and other events that impact instrument performance, had to be considered. Schwartz and Elliott (2006) provide a good overview of many of these issues. Some effects can be observed in the data, and the offending data removed from study. However, other factors such as anemometer bearing wear may simply result in consistent measurement errors, and not be readily apparent. It should be remembered that there is an inherent level of uncertainty in the use of tower-measured anemometer data.

Ultimately, hourly datasets from four tall towers were used in this study. Details are given in Table 1. Boulder, Breckenridge and Red Oak data was obtained from the database maintained by the Plains Organization for Wind Energy Research. This data included the bearing of anemometers on the tower. Oak Ridge data was from the Oak Ridge National Laboratory, and no anemometer location information besides height was available.

In instances where two anemometers were co-located at the same level, the interpolation scheme outlined in Appendix A was used to predict the "true" wind speed by performing a weighted average favoring the most upwind anemometer. This was done (instead of simply using the reading from the most-upwind anemometer) in order to smooth the resulting wind speed as a function of wind direction in the event the two anemometers slightly disagree.

In addition to checks for evidence of instrument icing or other failures, each observation was also checked to ensure the wind directions reported from multiple wind vanes were consistent. An observation was considered inconsistent if the lowest level wind speed was greater than or equal to 3.5 m/s and any two observed wind directions were more than 60° different.

Average Wind Speeds

The average wind speed at each anemometer level was calculated, and is given in Fig. 1. It is apparent that the four towers have markedly different wind speed and shear characteristics. Oak Ridge, installed at the national laboratory of the same name in Tennessee, experiences significantly lower wind speeds at all levels than any of the other towers. It is the only one that was not installed for wind energy purposes, and is in a region of complex terrain and low wind energy development potential.

The average wind speed profiles for both Breckenridge and Red Oak have shears that vary considerably between levels. Of specific concern is the 60 meter level at Breckenridge, and the "dog leg" around the 50 meter level at Red Oak. If one or more anemometers were off by, say, half a meter per second, these artifacts could disappear. Since it cannot be determined whether the data is in error or not (since the observations used in the averaging already passed quality control), no corrections or modifications were performed to adjust for these anomalies.

Power Law Exponent

For each observation, equation 3 was used to calculate the power law exponent α based on the wind speed at the two lowest measurement levels on the tower. These levels were at 10 m and, depending on the tower, 20 – 33 m above ground. The calculated value of α was then used with equation 2 to predict wind speeds at all of the higher levels on the tower. The mean value of α for each tower is given in Table 1.

Seasonal variations in α (Fig. 2) are less pronounced than diurnal variations (Fig. 3). Prior researchers have noted that α tends to be lower during the day, and higher at night, in many continental locations: this occurred consistently for these four towers. Oak Ridge has a phase lag of about two hours relative to the other towers, probably due to its more eastern location experiencing reduced day-time heating relative to the other towers.

When average α is calculated as a function of wind speed, it is readily apparent that the variation in α between the towers decreases as the wind speed increases (Fig. 4). This is consistent with Mikhail's (!985) observation that as wind speed increases, values of α trend toward a value near 1/7, while greater variance in α occurs at low wind speeds.

Average values of α were also calculated as a function of wind direction measured at the lowest level (Fig. 5). For all towers, at least 100 observations were available for each of the 16 directions. The Boulder tower is in hilly terrain, with the steepest terrain to the northwest. Ray et al. (2006) calculated the wind shear at this tower as a function of wind direction including data from 50 and 80 meters, and observed the similar trends to those in Fig. 5. Ray et al. chose the Boulder tower for this analysis because it is within an area of complex terrain. The Oak Ridge tower is also situated in complex terrain and shows considerable variation in α as a function of wind direction. However, the Breckenridge and Red Oak towers, which are in much less complex terrain than Boulder, showed greater α variations as a function of wind direction. It is believed this is partly due to higher average winds being experienced from some wind directions.

Table 1. Tall tower data. Bold print indicates anemometer levels used to calculate α. Levels marked with * indicate wind direction data at that level.

Location	Levels [m]	Mean Wind Speed (Highest Level)	Time Range	Data Availability (%), Number of Good Observations
Boulder, CO	**10***, **20***, 50*, 80*	4.81 m/s	1/1/1997 – 12/31/2003	83.7% (51360)
Breckenridge, MN	**10**, **30**, 40, 50, 60, 70	6.25 m/s	5/1/1996 – 7/3/2005	46.4% (37325)
Oak Ridge, TN	**10***, **30***, 100*	3.04 m/s	1/1/2003 – 12/31/2004	100% (17544)
Red Oak, IA	**10**, **33**, 50, 100	6.92 m/s	1/31/1995 – 5/29/1997	43.5% (8862)

Predicted Wind Speeds

The wind speed at each of the higher levels was predicted by calculating α based on the lowest two wind speed levels, and then extrapolating to the higher level using equation 2. For observation i, the prediction error is the predicted wind speed P_i minus the actual wind speed A_i. For a series of n observations, the mean error ME is

$$ME = \sum_{i=1}^{n} P_i - A_i \qquad (4)$$

and the mean absolute error MAE is

$$MAE = \sum_{i=1}^{n} \left| P_i - A_i \right| \qquad (5)$$

The error bias is given by ME. A positive ME indicates that over-prediction is occurring on average, while negative ME indicates under-prediction. MAE indicates the magnitude of the average prediction error: the higher the MAE, the less accurate the set of wind speed predictions.

The overall ME and MAE for each tower and predicted level are given in Table 2. At the three towers with more than one prediction level, the average prediction error for any observation, indicated by MAE, increased with height. Trends in overall prediction bias can not be generalized as a function of height: in some cases, ME decreased with height, meaning that while any given observation was likely to have a relatively high error (as indicated by the MAE value), the average of these errors was closer to the true average wind speed.

Table 2. Overall mean error and mean absolute error of wind speed predictions for each tower and prediction level.

Location	Level [m]	Height of Level Above Second Level [m]	Actual Mean Wind Speed [m/s]	Mean Error [m/s]	Mean Absolute Error [m/s]
Boulder, CO	50	30	4.62	-0.07	0.26
	80	60	4.81	-0.03	0.42
Breckenridge, MN	40	10	5.22	0.01	0.40
	50	20	5.53	0.01	0.81
	60	30	5.66	0.23	1.08
	70	40	6.25	0.11	1.31
Oak Ridge, TN	100	70	3.04	-0.23	0.62
Red Oak, IA	50	17	6.61	0.00	0.57
	100	67	6.92	1.49	1.99

Monthly variation of both ME (Fig. 6) and MAE (Fig. 7) differed significantly by location, while overall trends were difficult to discern. High error values at Breckenridge in February and Red Oak during the summer are mostly due to lower wind speed periods. Trends in ME as a function of time-of-day (Fig. 8) varied significantly between towers, although MAE (Fig. 9) tended to be slightly lower during midday at all of the towers.

When the accuracy of the wind speed predictions as a function of wind speed are considered, it is apparent that errors are much greater in light winds of 3 m/s or less. Generally, ME and MAE decrease as wind speed increases (Figs. 10 and 11). This supports the conclusion of Ray et al. (2006) that wind speed prediction accuracy can be improved by excluding observations where the wind speed is less than or equal to 4 m/s.

The characteristics of wind speed prediction accuracy as a function of wind direction were strongly dependent on the tower. Strong winds and terrain effects are both associated with specific directions. The towers at Boulder and Oak Ridge are situated in mountainous valley regions, and show wind direction variation consistent with their locations. However, while Breckenridge is located in relatively flat agricultural terrain, but ME and MAE still show significant dependence on wind direction.

Power Predictions

Predictions of power production at the highest level of each tower were generated to illustrate the effect of errors in predicted wind speeds. For each observation, the predicted and actual wind speeds at the highest level of the tower were input in to the power curve of a Vestas V82 1.65 MW wind turbine to predict the power production of a representative turbine with a hub height at the highest level on each tower. The total power production over all observations was determined in each case, as well as the percent difference between the power production based on the actual and predicted wind speeds. Prediction accuracy was strongly dependent on location. The possibility of significant errors being introduced by power law extrapolation is readily apparent in the results shown in Table 3.

Table 3. Predicted power for Vestas V82 wind turbine with hub height at top tower level, based on actual and power law predicted wind speeds. Total power production is for all observations in tower dataset.

Site	Simulated Hub Height (Highest Tower Level) [m]	Wind Prediction Levels [m]	Total Power Production		
			Actual Wind Speeds [kWh]	Predicted Wind Speeds [kWh]	Percent Difference
Boulder, CO	80	10, 20	13998243	13995872	0.0%
Breckenridge, MN	70	10, 30	18236495	16132940	-11.5%
Red Oak, IA	100	10, 33	5829948	7424212	+27.3%

Conclusions

There were a few characteristics that were common at all four sites. Mean absolute error of wind speed predictions increased as the height of the prediction level increased above the measured levels, although this did not hold true for mean error. For all towers, the power law exponent α was consistently lower during the day and higher at night, although this did not extend to wind speed prediction accuracy, which did not show a consistent pattern with respect to time of day. In terms of wind speed prediction accuracy, there were no consistent predictable trends in ME or MAE. This suggests that methods of predicting variation of the wind shear exponent, such as those studied by Perez et al. (2005), may not necessarily result in more significantly more accurate predictions of mean wind speed, although improved accuracy for specific times and seasons would be expected. For the Breckenridge and Red Oak towers, wind speed prediction accuracy was very low at wind speeds less than 2 m/s, however, at Boulder MAE was roughly constant over all wind speeds.

These results highlight the importance of accurate and reliable anemometer measurements. Seemingly minor changes in average wind speeds at an anemometer can have an outsized affect on the prediction of wind speeds at higher levels. The level of error in power law extrapolation of wind speeds is difficult to predict *a priori* for a given site, and very large errors are possible. Power law extrapolation of wind speeds at modern hub heights, based on wind measurements taken near the surface, should be reserved for cases where no other options are available.

Figures

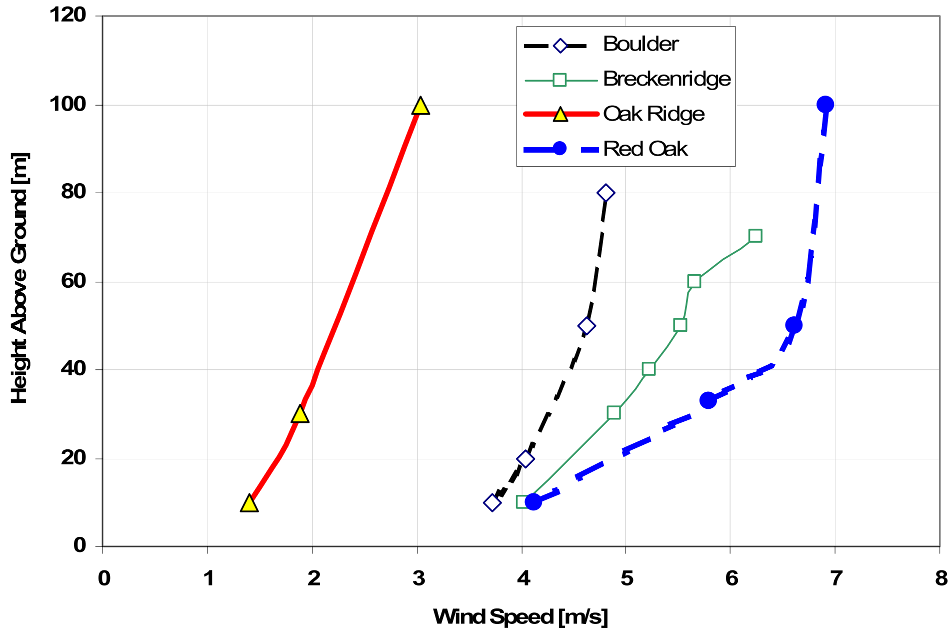

Figure 1. Average wind speeds at each tower.

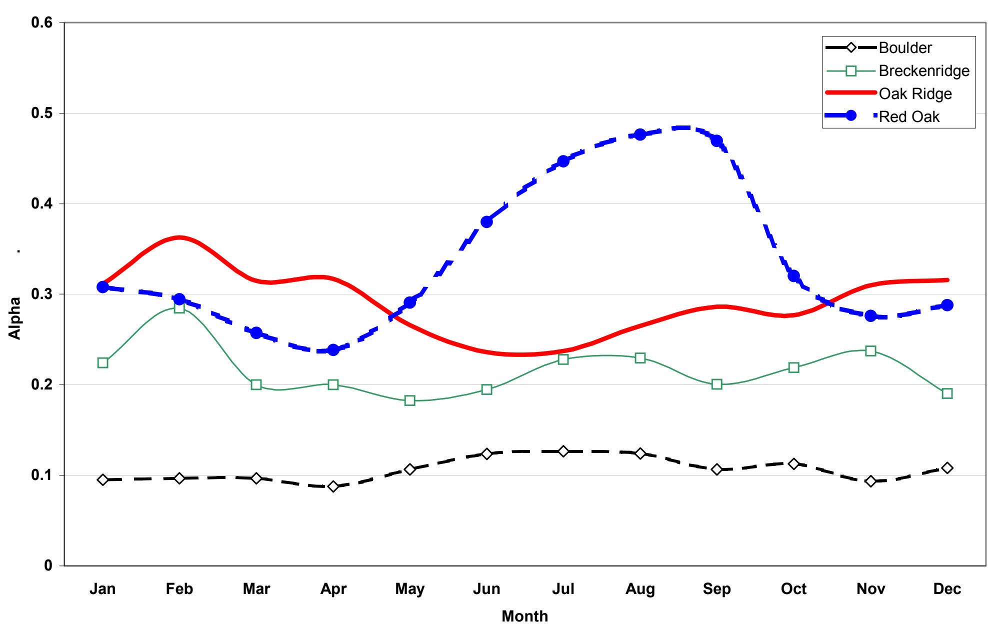

Figure 2. Monthly average power law exponent calculated from lowest two levels of wind speed data.

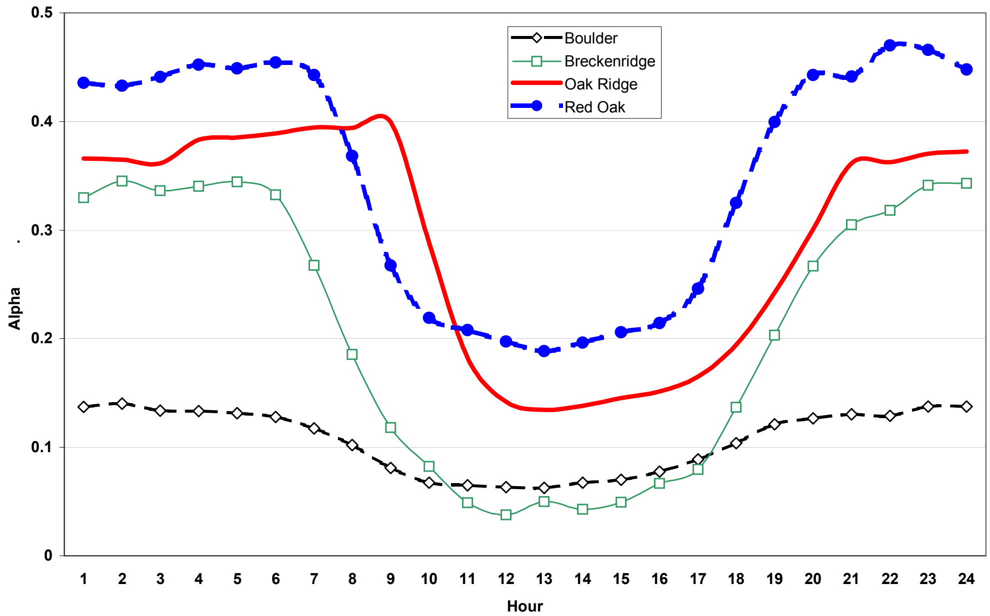

Figure 3. Average power law exponent by time of day. Calculated from lowest two levels of wind speed data.

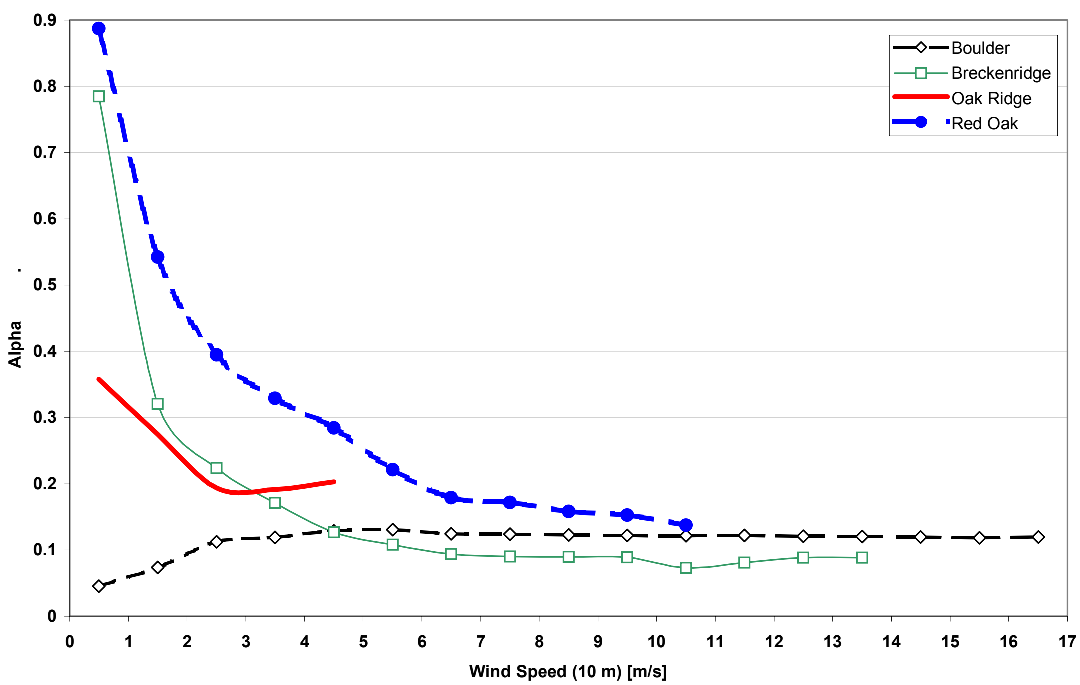

Figure 4. Average power law exponent as a function of wind speed.

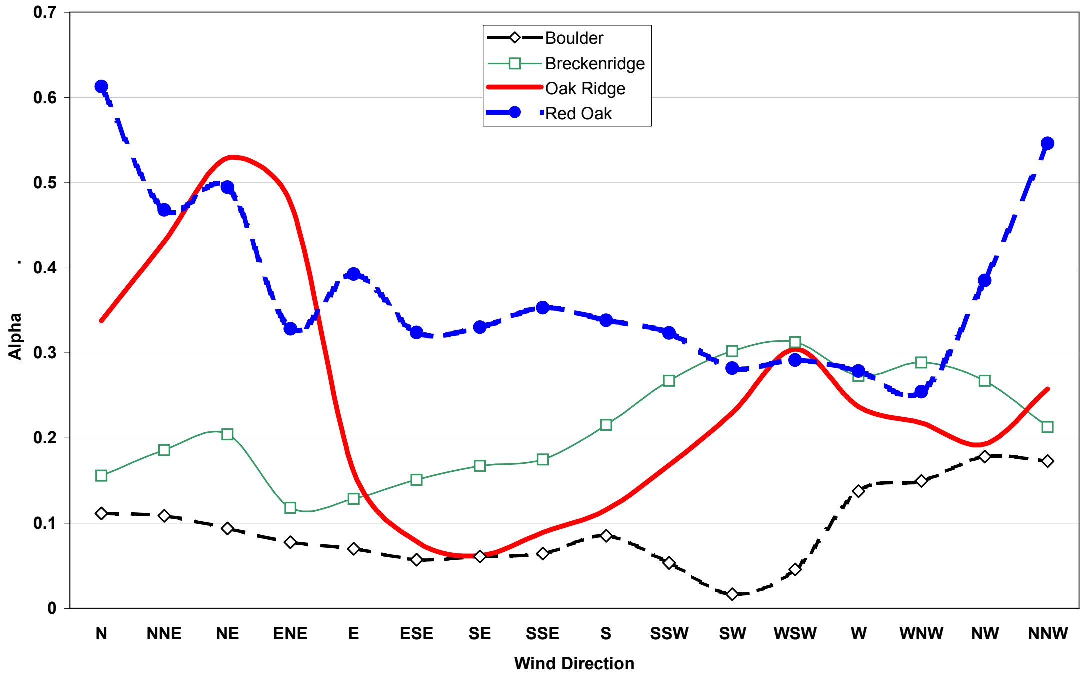

Figure 5. Power law exponent versus wind direction.

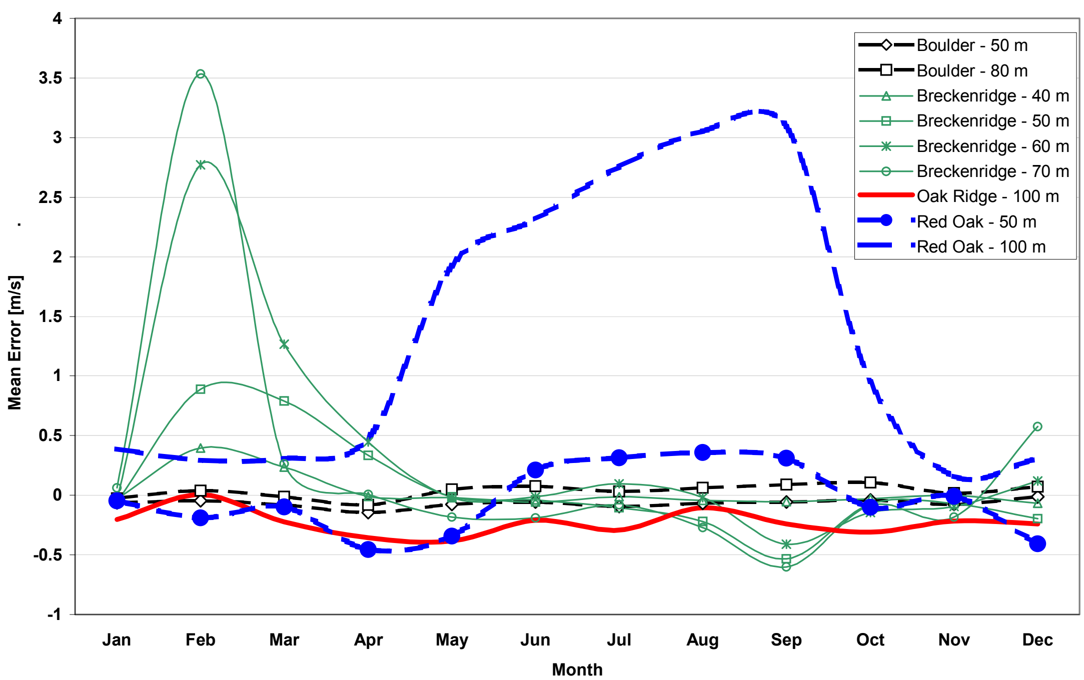

Figure 6. Monthly wind speed prediction mean error for each upper tower level.

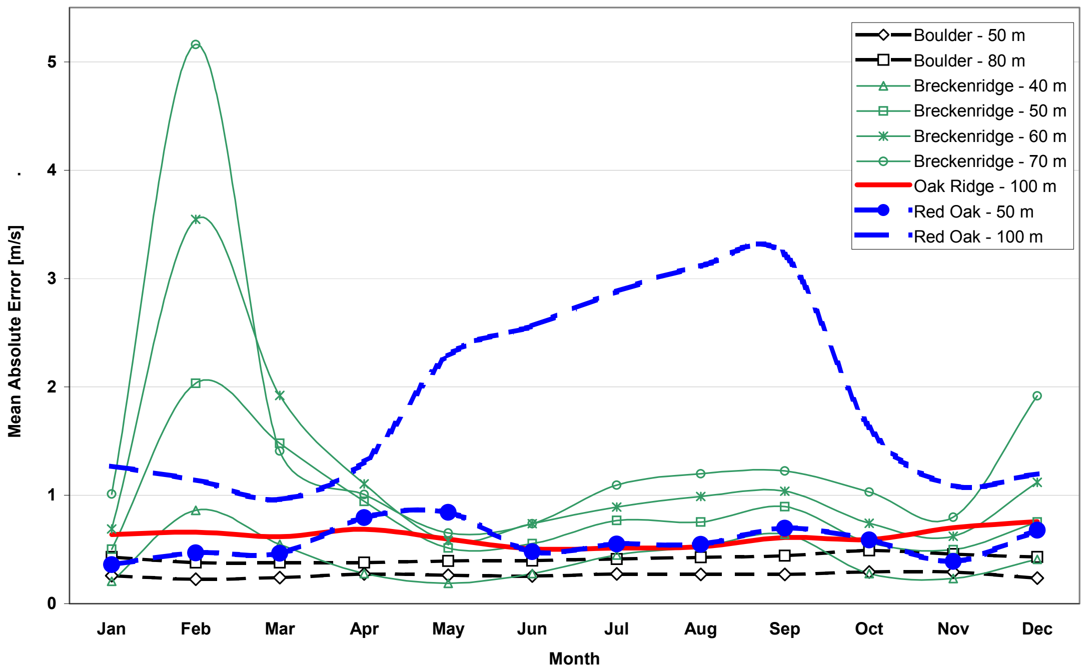

Figure 7. Mean absolute error of monthly wind speed predictions.

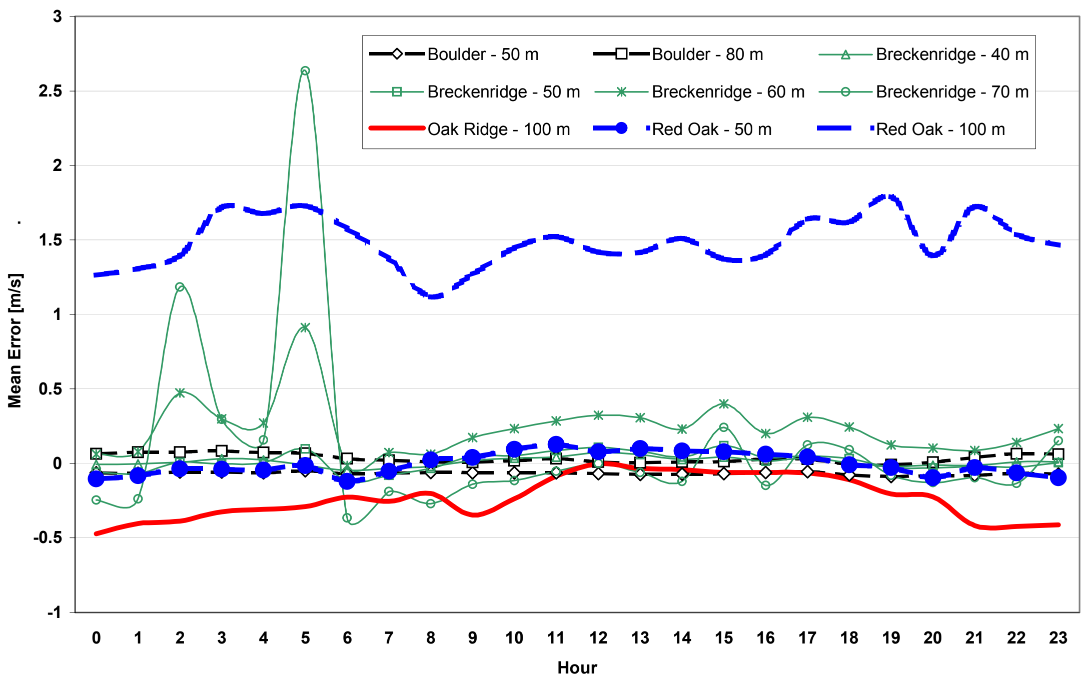

Figure 8. Mean error of wind speed predictions by hour of the day.

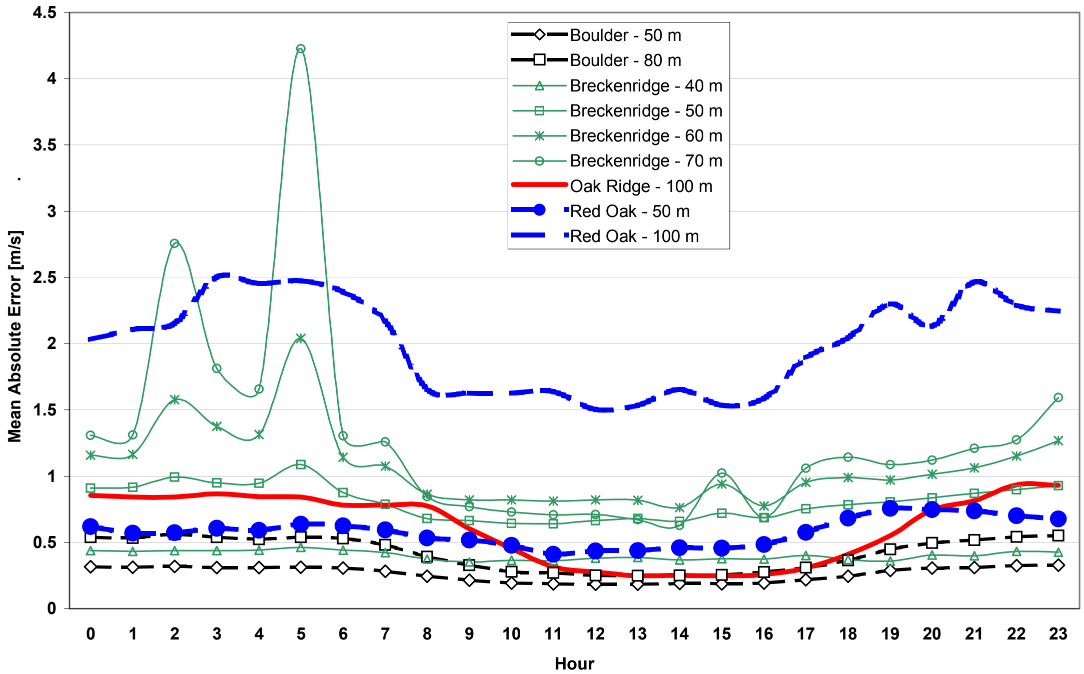

Figure 9. Mean absolute error of wind speed predictions by hour of the day.

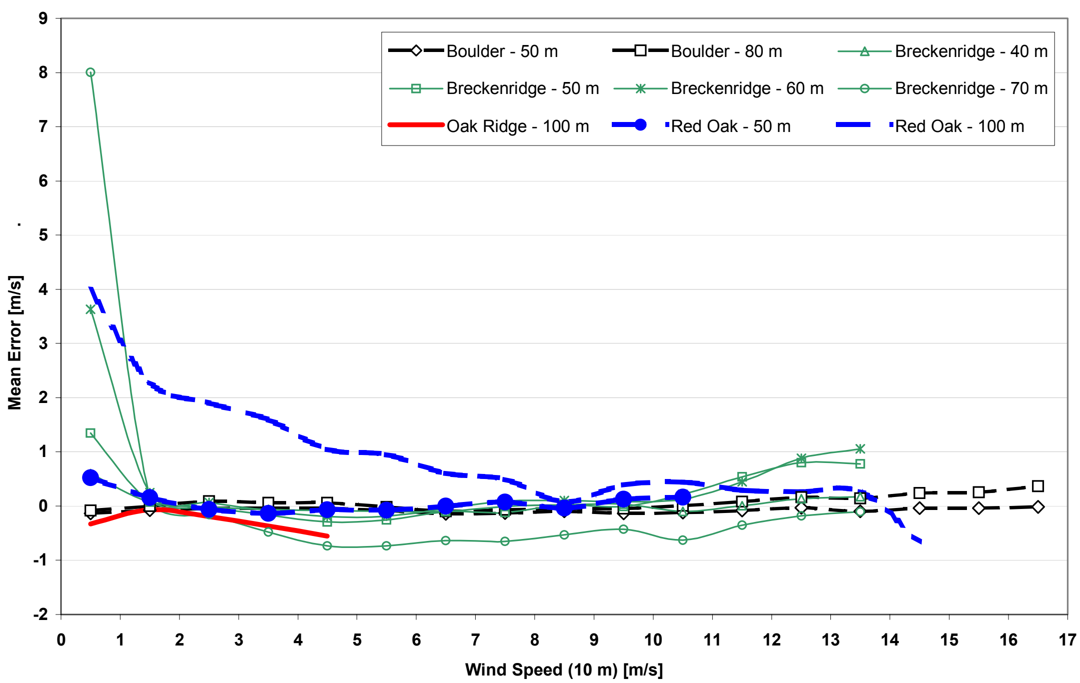

Figure 10. Mean error of wind speed predictions by wind speed at 10 m.

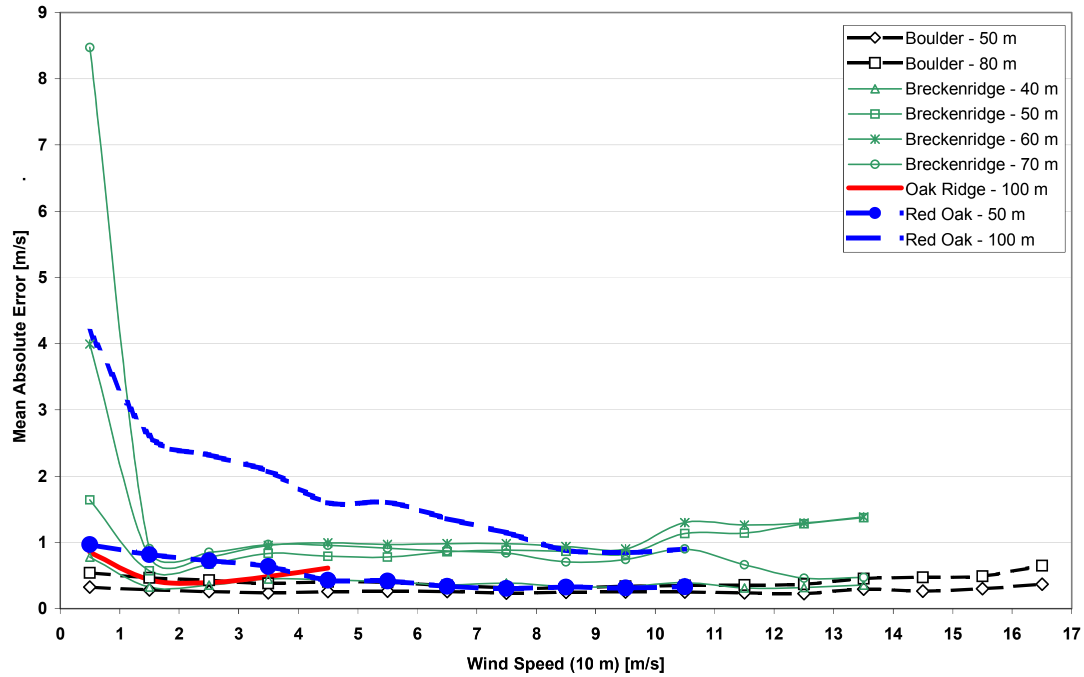

Figure 11. Mean absolute error of wind speed predictions versus wind speed at 10 m.

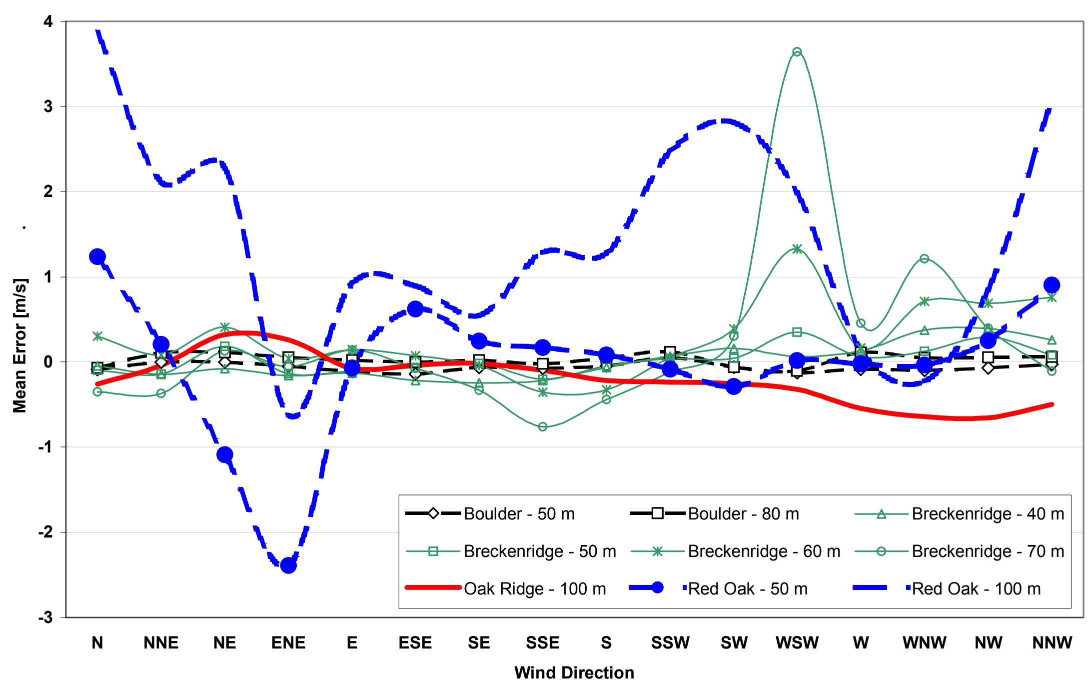

Figure 12. Mean error of wind speed predictions versus wind direction.

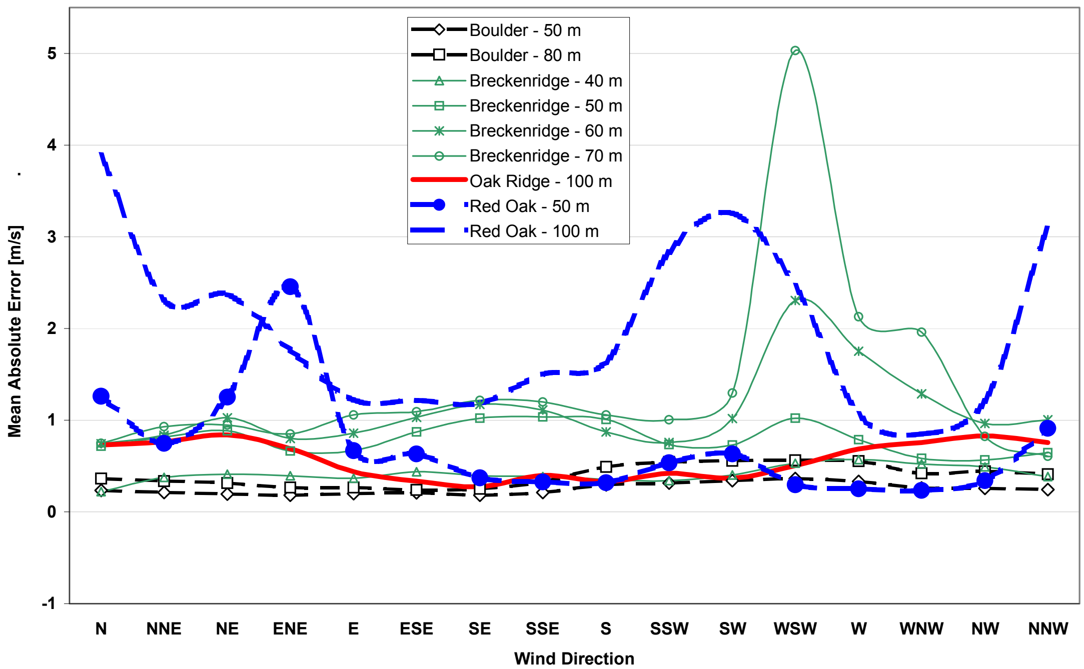

Figure 13. Mean absolute error of wind speed predictions versus wind direction.

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APPENDIX: Data Interpolation at Co-located Anemometers

Several of the tall towers in this study had pairs of anemometers at one or more levels above the ground, each attached to a different side of the tower. Data from these anemometers was interpolated by the following method to account for tower shadowing effects.

Assume two anemometers are at the same level on a tower. The anemometers are mounted on booms that project outward from the main tower at angles of B_1 and B_2, and have measured wind speeds of V_1 and V_2, respectively. A wind vane at this level, or a nearby level, measures a wind direction of θ. If $B_2 > B_1$, then the angular separation of the two anemometers is $D_A = B_2 - B_1$, while going around the other way, the angular separation is $D_B = 360 - D_A$ (assuming angular units of degrees). Then the interpolated velocity V is predicted using the following formulae:

If $\theta \geq B_1$ and $\theta \leq B_2$, then

$$D = \theta - B_1$$

$$V = V_1\left[\cos^2\left(\frac{\pi}{2}\frac{D}{D_A}\right)\right] + V_2\left[\sin^2\left(\frac{\pi}{2}\frac{D}{D_A}\right)\right]$$

otherwise,

$$D = \begin{cases} B_1 - \theta & \text{if } \theta \leq B_1 \\ D_B + B_2 - \theta & \text{if } \theta \geq B_2 \end{cases}$$

$$V = V_1\left[\cos^2\left(\frac{\pi}{2}\frac{D}{D_B}\right)\right] + V_2\left[\sin^2\left(\frac{\pi}{2}\frac{D}{D_B}\right)\right]$$