Analysis of wind shear models and trends in different terrains

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ABSTRACT

The importance of characterizing the wind shear at a given site for a utility scale wind turbine cannot be overemphasized. Such characterization is needed for both the turbine design and an accurate prediction of its power output. Thus, the objective of this work based on the use of several US tall tower wind data sets was to determine the accuracies of different wind shear methods, especially when used at sites having hills and/or forests. In addition, average wind shear variations with respect to terrain, seasonal and annual effects, and data length are presented for the various data sets. The results showed that the most accurate predictions for hub height wind speed characterizations were obtained when only wind speed data greater than 4 m/s were considered. Also, at some of the sites the greatest average wind shear was found during the summer. For the site with the most complex terrain, the average annual wind shear varied up to 7% between different years. Based on a statistical analysis of the prediction errors, there is no significant difference between the performance of the log and power laws; using either may result in inaccurate predictions of hub height mean wind speeds.

1. INTRODUCTION

Wind shear is the variation of wind speed with elevation. It is important to understand because it directly impacts the power available at different wind turbine hub heights and strongly influences the cyclic loading on the turbine blades. For decades, academic and commercial researchers alike have worked on developing methods to obtain accurate wind shear profiles for a site. While kite anemometers were used more than 20 years ago, today people employ techniques ranging from remote sensing to computer modeling. Even still, wind shear characterization for wind turbine site assessment is a complex task, as it is dependent on numerous factors, including the speed of the wind, the height above the ground, the ground's surface roughness and its roughness variation, the atmospheric stability, and the nature of the terrain.

It is essential for wind power developers to accurately know the wind speeds at turbine hub heights (generally ranging from 60 to 100 m) because they determine the turbine's potential electricity production, and therefore the economic feasibility of a candidate wind turbine site. Wind speeds at these heights of interest can be measured by: 1) remote sensing, such as collecting SODAR or LIDAR data, or 2) installing tall (60 to 100 m) meteorological towers (met towers). On the other hand, if wind speed data at these heights are not available, measurements at lower heights, such as from 40 to 50 m standard met towers, can be used along with wind shear models to extrapolate wind speeds to the desired hub heights.

1.1 Objectives

This paper addresses several issues relating to wind shear assessment, especially regarding the effects of terrain such as forests and hills. The objectives of this research included:

- A determination of the performance of commonly used shear models and how performance varies with respect to different types of terrain.
- A comparison of published wind shear parameter values to the wind shear parameters calculated according to the type of terrain.
- Identification of data analysis procedures appropriate to the sites that most accurately predict the hub height mean wind speeds.
- A study of the seasonal and annual wind shear variations at selected sites.
- A study of the effects of terrain on wind shear, particularly for the mountainous site at Boulder, CO.

1.2 Use of Tall Tower Data Sets

To accomplish these objectives, thirteen tall tower wind data sets (summarized in Table 1) were analyzed. These data sets were obtained from the regional wind databases compiled by the Energy & Environment Research Center at the University of North Dakota [1]. Each site has wind speed data from at least 3 heights, where the highest height is at least 75 m. In order to identify terrain effects, the data were organized into the following three categories: 1) flat with no trees, 2) hills with no trees, and 3) forested (all of the forested sites have some hills). The data sets were placed in each category based on topographic maps of each site. In order to account for gaps of missing data, all the wind speed data recorded as a zero or blank were ignored. As a result of this, the overall mean wind speeds reported for the sites might be different if the missing data could have been considered, however the results of this wind shear model analysis will be unaffected.

Table 1: Summary of tall tower data sets.

Site Name	Site State	Wind Speed Heights [m]	Measurement Period	Time Step	Latitude & Longitude
FLAT WITH NO TREES					
Glenmore	WI	37, 60, 83, 103, 123	11/1999 – 9/2001	Hourly	44.3358°N 87.9858°W
Hatfield	MN	30, 60, 90	10/1998 – 7/2004	10-min	43.9881°N 96.2092°W
Hobart	OK	40, 70, 100	3/2002 – 8/2003	Hourly	35.0497°N 99.0971°W
Mohall	ND	20, 50, 80	12/2004 – 1/2005	10-min	48.7644°N 101.6947°W
HILLS WITH NO TREES					
Boulder	CO	10, 20, 50, 80	9/1996 – 12/2003	Hourly	39.9136°N 105.2469°W
Currie	MN	30, 60, 90	6/1995 – 7/2004	Hourly	44.0983°N 95.5636°W
Marshall	MN	30, 60, 90	8/2000 – 7/2004	Hourly	44.4456°N 96.0122°W
St. Killian	MN	30, 60, 90	9/1998 – 7/2004	10-min	43.7803°N 95.8742°W
FORESTED					
Detroit Lakes	MN	30, 50, 85	7/2002 – 8/2003	10-min	46.8275°N 95.8514°W
Fountain	MN	30, 60, 90	8/2003 – 7/2004	10-min	43.7497°N 92.0858°W
Hillman	MN	30, 60, 90	1/2001 – 7/2004	10-min	46.0069°N 93.8878°W
Isabella	MN	30, 50, 75	12/2000 – 6/2004	10-min	47.6186°N 91.3686°W
Red Lake	MN	30, 60, 90	8/2003 – 7/2004	10-min	47.8436°N 95.0386°W

2. DETERMINATION OF WIND SHEAR

A major objective of this paper is to identify shear models and procedures that decrease the uncertainty associated with wind shear estimations. While remote sensing and tall towers are the most accurate methods of measuring wind shear at a candidate wind turbine site, they are more expensive than installing a standard met tower and using wind shear models. The use of wind shear models, however, introduces additional uncertainty into the wind resource estimate.

The most commonly used methods of estimating wind shear are known as the log law and the power law. The log law is based on principles of boundary layer flow and is given below as Equation 1, where z and z_r are the target and reference heights, respectively. $U(z)$ and $U(z_r)$ are the target and reference height wind speeds and z_o is the surface roughness length [2].

$$\frac{U(z)}{U(z_r)} = \frac{\ln\left(\frac{z}{z_o}\right)}{\ln\left(\frac{z_r}{z_o}\right)} \tag{1}$$

The surface roughness length is a parameter used to characterize shear and is also the height above ground level where the wind speed is theoretically zero. The surface roughness length varies according to the terrain of the site and wind power developers and researchers typically use surface roughness lengths close to those provided in Table 2 [2]. If a stability correction is not used, the log law is theoretically only applicable for neutral atmospheric stability.

Table 2: Surface roughness values for various types of terrain [2].

Terrain Description	Surface Roughness Length, z_o (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.01
Fallow field	0.03
Crops	0.05
Few trees	0.1
Many trees, hedges, few buildings	0.25
Forest and woodlands	0.5
Suburbs	1.5
Centers of cities with tall buildings	3.0

A variation of the log law is the modified log law, which takes into account the effective ground level at a site. It is often used to account for the affect of tree canopies on wind shear. The modified log law is defined as Equation 2 [3],

$$\frac{U(z)}{U(z_r)} = \frac{\ln\left(\frac{z-d}{z_o}\right)}{\ln\left(\frac{z_r-d}{z_o}\right)} \tag{2}$$

where the parameters are defined the same as with the log law. The additional variable is the displacement height, *d*, and it is often approximated to be two-thirds of the tree height at the site of interest [4, 5]. In the modified log law, the height at which the wind speed is theoretically zero is $z_{U=0} = z_o + d$, whereas in the log law, $z_{U=0} = z_o$.

It is important to note that a weakness of the log law is that it cannot to be used to represent the wind shear for all conditions. That is, the log law is mathematically undefined for time periods where the wind speeds at two different heights are the same. Furthermore, if wind speeds decrease with height, then the calculated surface roughness length for that time period is unrealistically large. For these reasons, wind speed data matching these criteria were excluded from log law calculations.

Another widely used wind shear model is the power law, which is an empirically developed relationship given as Equation 3.

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{3}$$

The equation variables are defined as before, and the power law exponent is α. For fairly flat terrain, many investigators have used the one-seventh power law, where $\alpha = 1/7$. Researchers have also determined empirical relationships for the power law exponent as functions of parameters such as wind speed and surface roughness length [1, 6]. Table 3 provides power law exponent values for different types of terrain [7].

Table 3: Typical power law exponents for varying terrain [7].

Terrain Description	Power law exponent, α
Smooth, hard ground, lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22 – 0.24
Wooded country – small towns and suburbs	0.28 – 0.30
Urban areas with tall buildings	0.4

For each of these shear models, the values for z, z_r, $U(z)$, and $U(z_r)$ are available from standard met tower data measurements and one can determine such parameters as z_o and α. The widespread use of these wind shear models, however, does not necessarily mean they are accurate for all situations or that the typical shear parameter values (Tables 2 and 3) result in accurate hub height wind speed predictions.

For example, Bechrakis and Sparis [7] used wind data from heights of 2 and 10 m to obtained a power law exponent of $\alpha = 0.20$ for a flat site with foot-high grass, for which a power law exponent of $\alpha = 0.16$ would be assumed. For an area on the island of Malta, described as a mixture of farmland, low and dense trees, stone rubble walls, and storage buildings, Farrugia [8] used the mean wind speeds from 10 and 25 m to calculate an average power law exponent of α = 0.36. This is quite different than the power law exponent in Table 2, which gives α = 0.20 – 0.24 for terrain with a few or many trees and occasional buildings. Research by Maeda, et al. [9] found that at one site in Japan with complex terrain, using the power law with 20 and 30 m wind data over predicted the mean wind speed at 100 m by more than 20%. Thus, as shown by comparison with actual data, the accuracy of the power or log shear laws cannot be guaranteed.

3. WIND SHEAR ANALYSIS

In this paper, the wind speeds that were measured at heights between 10 and 60 m are referred to as the lower height wind speeds. The higher of these heights is called the highest of the lower heights. The highest height for which wind data are available is termed the hub height. For example, if wind data were measured at heights of 30, 60, and 90 m, then 30 and 60 m are the lower heights, 60 m is the highest of the lower heights, and 90 m is the hub height. For many of these analyses, only one year of the available data was used, except for the four data sets where annual variations in wind shear are reported (Hatfield, Boulder, Currie, and Marshall).

3.1 Data Analysis Procedures

In order to compare the accuracy of the shear models, the wind speeds from the two lower heights were used to calculate the shear parameter for the appropriate shear model. The log and power laws were applied to all the data sets, but the modified log law was only applied to the data from forested areas. The calculated shear parameter was then used along with the wind speed at the highest of the lower heights to predict the wind speed at the hub height. Finally, the predicted wind speeds at hub heights were then compared to the actual mean wind speeds at those heights.

The modified log law was used on the wind data from the forested sites and surface roughness lengths were calculated using the two lower height wind speeds. With no actual tree height information available for the forested sites, a displacement height of $d = 10$ m was assumed. It is important to note that, mathematically speaking, the modified log law can only improve an underestimated log law mean wind speed prediction.

Three approaches were used to average the wind data in order to extrapolate hub height mean wind speeds from the lower height wind data (note: wind data are usually averaged over 10 minutes or an hour; for the following list the word “hourly” can replace “10-minute” depending on the data set):

1. Overall mean: The overall mean wind speeds of the two lower heights were calculated from the 10-minute data. These mean wind speeds were used to calculate an overall mean shear parameter. With the highest of the lower height mean wind speed and the overall mean shear parameter, a mean wind speed was calculated at the hub height.
2. Parameter average: For each of the 10-minute data, the wind speeds measured at the two lower heights were used to calculate a 10-minute shear parameter. All of these 10-minute shear parameters were averaged, resulting in an average 10-minute shear parameter. This parameter was then used as in approach 1: the overall mean wind speed from the highest of the lower heights was used to estimate a wind speed at the hub height.

3. Extrapolated time series: Each 10-minute shear parameter was used with its wind shear model to extrapolate a wind speed time series to the hub height. The overall mean of this extrapolated time series was compared to the actual mean wind speed at that height.

In addition to these three analyses, the effect of wind speed on shear estimation was considered by repeating the log and power law analyses using only wind speed data greater than 4 m/s. Here, 4 m/s is taken as a typical cut-in speed of a wind turbine, and wind speeds that are less than this do not affect power production. Thus, this analysis gives a prediction of the mean at hub height of only the wind speeds greater than the cut-in speed instead of the mean wind speed over all wind speeds.

The tower at Boulder, Colorado, measured wind speeds at 4 different heights, three of which were lower heights (between 10 and 60 m). Therefore, for this site, the log and power law shear parameters were calculated using best-fit relationships based on the wind data from the three lower heights. This is a useful exercise because met towers often have anemometers at three lower heights. Using wind data from all three levels may give a better prediction of the hub height mean wind speed than using only two of the lower heights. Unfortunately, only one site had wind data suitable for a best-fit analysis.

3.2 Data Length & Terrain Considerations

Sometimes SODAR or LIDAR systems are deployed at a proposed wind turbine site and these systems can measure hub height wind speeds [10, 11]. Due to economic limitations however, these systems often only collect data over a short period of time, say a few weeks or a month. Therefore, in order to stream-line wind shear assessment and decrease assessment costs, it is important to understand how short-term wind shear data can improve wind shear estimates for a proposed site. It is also necessary to establish how much wind shear estimates improve as a function of data length. To these ends, seasonal and annual average wind shear values were determined for selected sites and a running average of the wind shear was calculated for each of the forested sites.

In all of these analyses, the wind shear is expressed simply as a ratio of the hub height wind speed to the wind speed from the highest of the lower heights. For example, if wind speed data were available for heights of 30, 60, and 90 m, then the wind shear ratio (S_R) was expressed as Equation 4:

$$S_R = \frac{U_{90}}{U_{60}} \tag{4}$$

It is generally accepted that as terrain complexities increase, the wind shear also increases [1]. To understand the relationship between wind shear and topography, the average wind shear ratio was also determined by compass direction at the Boulder site, which has significant topological features. Also, the wind shear ratios of the lower heights were compared to the ratios of the highest heights.

4. WIND SHEAR ESTIMATION RESULTS

The calculated results, including the performance of wind shear models, averaging methods, and the above cut-in wind speeds method are given in this section. In addition, the effects of data length, time of measurement, and terrain on wind shear are addressed.

4.1 Wind Shear Models & Averaging Methods

Table 4, 5, and 6 summarize the results of testing the accuracy of the three different averaging methods using the power law and log law. For each site, the parameter of the shear model that gave the smallest percent error is listed, along with the averaging method, predicted and actual mean wind speeds, and the percent error of the hub height mean wind speed prediction.

For the flat sites in Table 4, the power law, when used with the parameter averaged method, usually performed the best. Nearly all the predictions using either shear model or averaging method were within 5% error, with the exception of Mohall. The calculated power law exponents, however, were significantly higher than the one-seventh power law exponent (or α = 0.14), which is typically used for areas of flat terrain.

Table 4: Summary of results for flat terrain.

Site	Averaging method	Estimated shear parameter	Predicted mean wind speed [m/s]	Actual mean wind speed [m/s/]	% Error
Glenmore, WI	Parameter average	$\alpha = 0.32$	7.28	7.34	-0.8
Hatfield, MN	Parameter average	$\alpha = 0.28$	7.79	7.81	-0.3
Hobart, OK	Parameter average	$\alpha = 0.22$	8.08	8.09	-0.2
Mohall, ND	Time series	z_o varied	4.02	4.40	-8.7

In Table 5 for the sites with hills, the log law gave the best predictions most of time and the overall mean averaging method worked the best all the time. Only the predictions for Boulder and Marshall, however, have less than 5% error. In addition, the values of the power law exponent and surface roughness lengths vary widely and are not generally consistent with the shear parameters givens in Tables 1 and 2.

Table 5: Summary of results for sites with hills with no trees.

Site	Averaging method	Estimated shear parameter	Predicted mean wind speed [m/s]	Actual mean wind speed [m/s/]	% Error
Boulder, CO (10 & 50 m)	Overall	$\alpha = 0.10$	4.75	4.75	1.8
Boulder, CO (20 & 50 m)	Overall	$z_o = 0.15$	4.99	4.75	3.3
Boulder, CO (Best-fit)	Overall	$z_o = 0.0004$	4.80	4.75	1.2
Currie, MN	Overall	$z_o = 0.42$	8.38	7.57	10.7
Marshall, MN	Overall	$z_o = 0.79$	8.36	8.14	2.7
St. Killian, MN	Overall	$z_o = 2.96$	8.87	7.88	12.6

The mean wind speed predictions for the forested sites of Fountain, Hillman, and Isabella had less than 5% error (Table 6). The surface roughness lengths, however, were much larger than z_o = 0.5, which is the value typically used for forests and woodlands (see Table 2). Also, when the performance of the modified log law was compared to those of the log and power laws, no consistent improvements were found.

Table 6: Summary of results for forested sites.

Site	Averaging method	Estimated shear parameter	Predicted mean wind speed [m/s]	Actual mean wind speed [m/s/]	% Error
Detroit Lakes, MN	Overall	$z_o = 3.01$	6.31	5.87	7.4
Fountain, MN	Time series	α varied	6.68	6.69	-0.1
Hillman, MN	Time series	α varied	5.97	5.81	2.8
Isabella, MN	Parameter average	$z_o = 6.47$	5.98	6.02	-0.7
Red Lake, MN	Overall	$z_o = 3.04$	6.16	5.81	6.0

In order to summarize and quantify the performances of all the wind shear methods, a statistical analysis was performed. The mean and standard deviations of the errors in the log and power law estimates were calculated for each of the terrain categories and across all of the sites. These were then used, assuming a normal distribution, to determine the probability that a method would result in a hub height mean wind speed prediction within 5% of the actual hub height mean wind speed. It should be noted that since the errors in this analysis may represent different wind regimes or even predictions at different heights, the statistical measures only indicate the relative performance of wind shear models.

Figure 1 summarizes the probability that using the log or power law with any of the averaging methods at any given site (within the defined terrain categories) will have an error within 5% of the true hub height mean wind speed. The results indicate that in general, wind shear estimation errors are likely to be quite large. For example, even at a flat site, the highest probability that an error would be within 5% of the actual hub height mean wind speed is only 57%. Worse yet, for a site with hills the best method is the overall averaging method with the log law, but this has a probability of accuracy of only 33%.

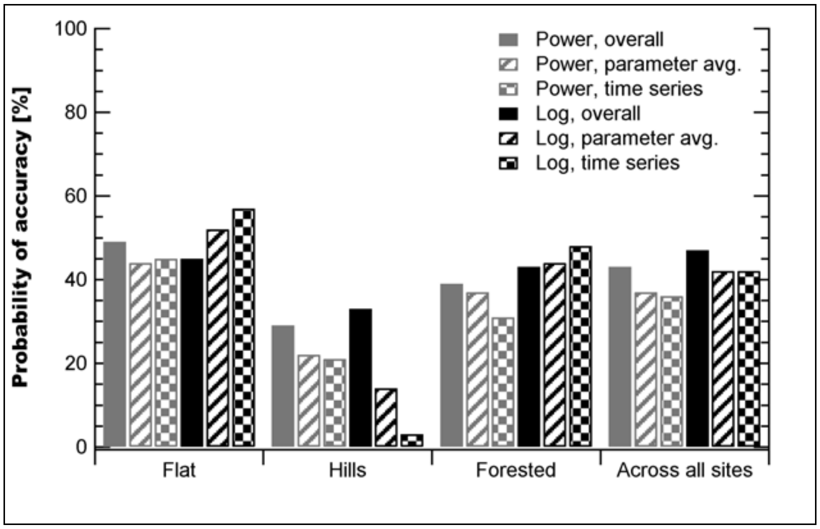

Figure 1: Percent likelihood that errors are within 5% of actual hub height mean wind speeds.

4.2 Above Cut-in Wind Speeds

In considering the benefit of using only higher wind speed data, the wind shear analysis was repeated using only wind speed data greater than 4 m/s, which represents the wind turbine cut-in speed. This analysis resulted in higher mean wind speeds at each height because they were the average of only those speeds greater than 4 m/s. The calculated wind shear was also lower, but this was expected because wind shear generally decreases with increasing wind speed [1]. While 4 m/s was chosen here, a different value for the cut-in speed might be chosen depending on the wind turbine of interest. In this analysis, only the overall averaging method was used.

Figures 2 and 3 detail the resulting error for each method. "All data" indicates the method used in the previous analysis, where all the data were used to calculate the wind shear and mean wind speeds. ">4 m/s data" refers to the method where both the wind shear and mean wind speeds were calculated based on wind speed data greater than 4 m/s.

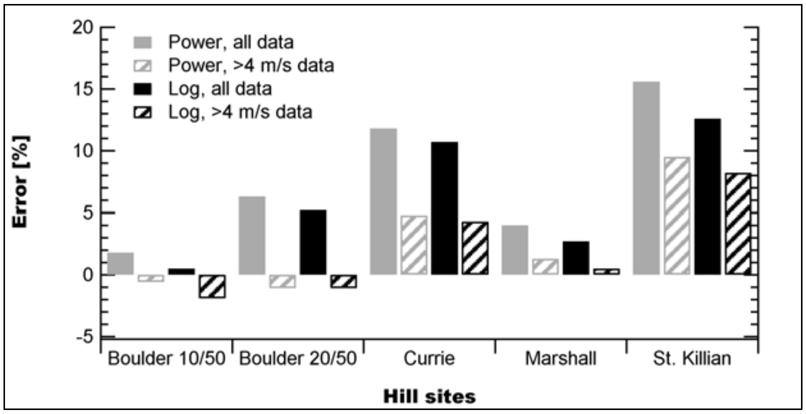

Figure 2: Comparison of results for sites with hills.

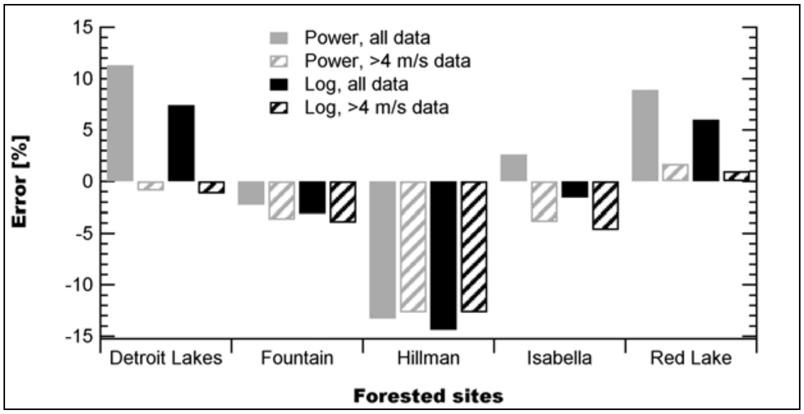

Figure 3: Comparison of results for forested sites.

For the sites with hills, the results show that using the >4 m/s wind shear to predict the >4 m/s mean wind speed at the hub height reduced the percent errors for nearly all of the sites and gave percent errors less than 5% for all the sites except St. Killian.

Using the >4 m/s wind shear and >4 m/s mean wind speeds gave errors less than 5% for nearly all of the forested sites, but it was not always the method with the lowest percent error. Recall that for these comparisons, the >4 m/s error compares the predicted mean wind speed of only wind data greater than 4 m/s with the actual hub height mean wind speed of the data greater than 4 m/s; the comparison is not with the actual hub height mean wind speeds over all speeds. Using the >4 m/s wind shear with the "all data" mean wind speeds was also considered in this analysis, but no consistent improvements were found.

4.3 Data Length and Seasonal Trends

The average annual wind shear for each forested site is listed in Table 7. The running average wind shear ratio is compared to the annual average wind shear ratio for all of the forested sites (Figure 4) and shows how the percent error of the running average wind shear changes with increasing data length, ending with 365 days of data. After 210 days of measurement length, the average wind shear ratios for all of the forested sites were within 1% of the annual average wind shear ratios. A 1% difference in the wind shear ratio translates into a 1% difference in the predicted hub height wind speed.

Table 7: Average annual wind shear ratio for forested sites.

Site	Wind Shear, S_R
Detroit Lakes	1.14
Fountain	1.15
Hillman	1.26
Isabella	1.22
Red Lake	1.08

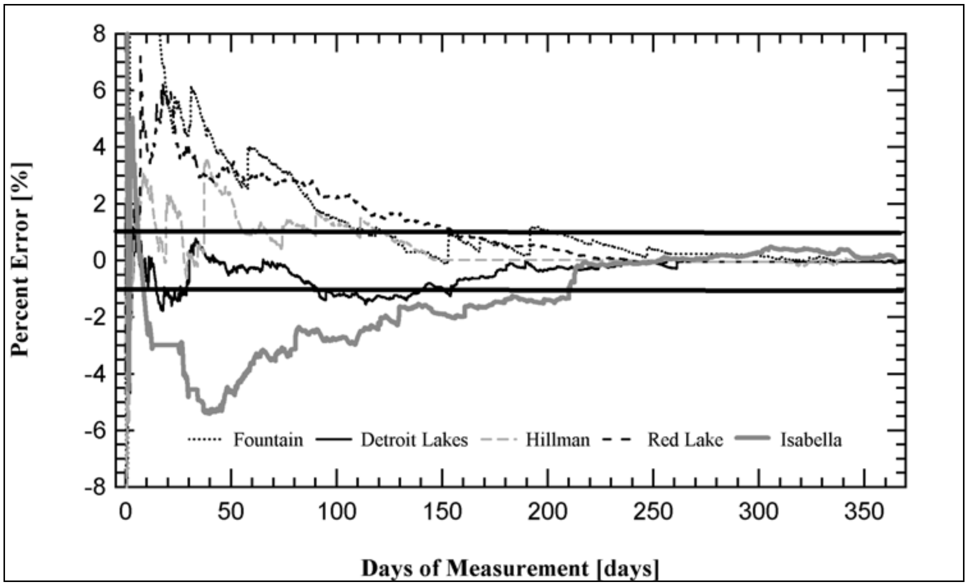

Figure 4: Change in percent error with increasing data length for forested sites.

For short-term wind shear measurement campaigns to be most effective, it is important to understand how wind shear varies seasonally and annually. Figure 5 presents a plot of how the average annual wind shear ratio varies year-to-year at four different sites. The greatest variation is at the Boulder site where the average annual wind shear varied from $S_R = 1.07$ in 1998 to $S_R = 1.00$ in 2001. Of the sites in Figure 2, Hatfield has the simplest terrain, but it also had the highest wind shear. The Hatfield wind shear was also varied the least between years.

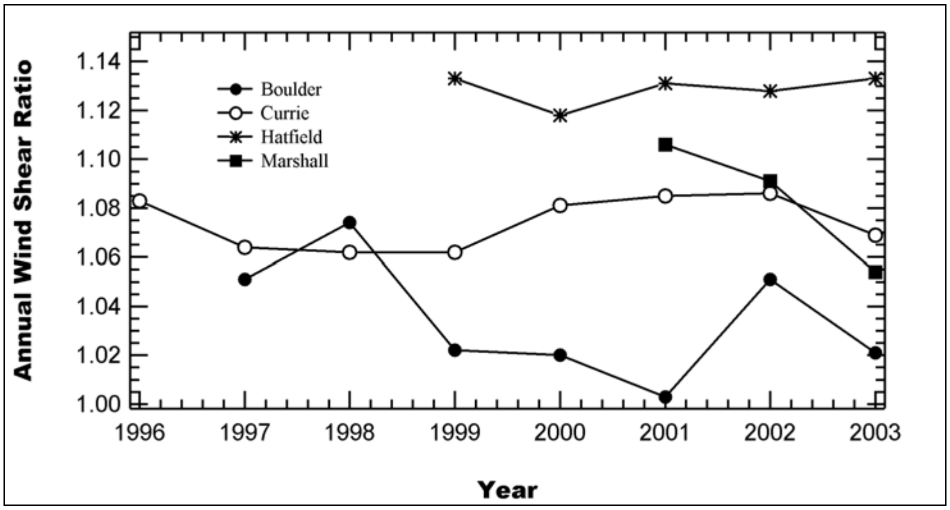

Figure 5: Annual variation of average wind shear ratio for Boulder (hills), Currie (hills), Hatfield (flat), and Marshall (hills).

The seasonal variations of wind shear for one year of data from the forested sites are plotted in Figure 6. At Isabella and Red Lake, the wind shear ratio is the highest during the summer and fall and slightly decreases in the winter and spring. At Detroit Lakes however, the winter and spring have the highest wind shear.

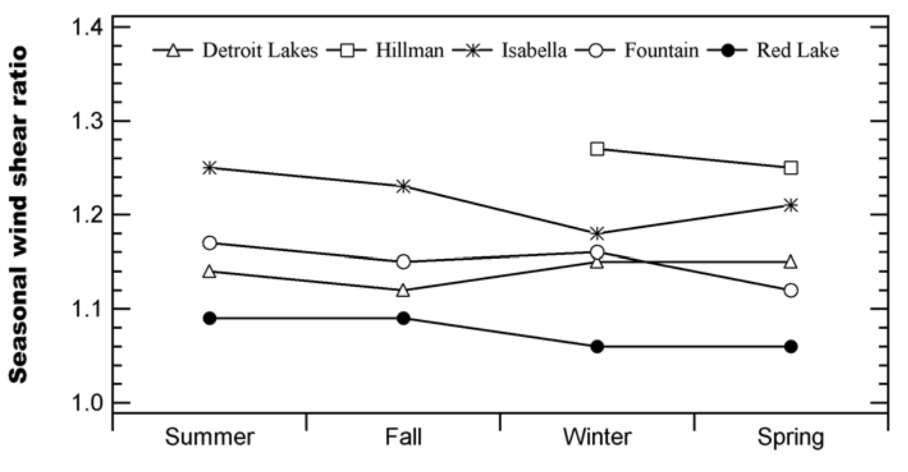

Figure 6: Seasonal average wind shear ratio at the forested sites.

4.4 Terrain Effects

Figure 7 gives a map of the Boulder site, where the met tower from which the data were collected was located in the center of the direction compass. The first number at each direction is the wind shear ratio calculated using the 20 and 50 m wind speed data such that $S_{R,L} = U_{50}/U_{20}$. The second number for each direction is the wind shear ratio between 50 and 80 m, $S_{R,H} = U_{80}/U_{50}$.

Both of the ratios ($S_{R,L}$ and $S_{R,H}$) indicate that the greatest wind shear comes from the north and northwest, where the terrain is the steepest. The $S_{R,L}$ wind shear indicates that the lowest shear is from the south and southwest, and this is somewhat affirmed by the shear ratios of $S_{R,H} = 1.00$ between 50 and 80 m. However, the lowest $S_{R,H}$ is from the east and southeast. In fact, for these directions and heights, the wind speeds slightly decrease with height, but the $S_{R,L}$ would imply that the wind shear is quite high from the east. Clearly, at the Boulder site, the lower height wind shear may not reflect the hub height wind shear.

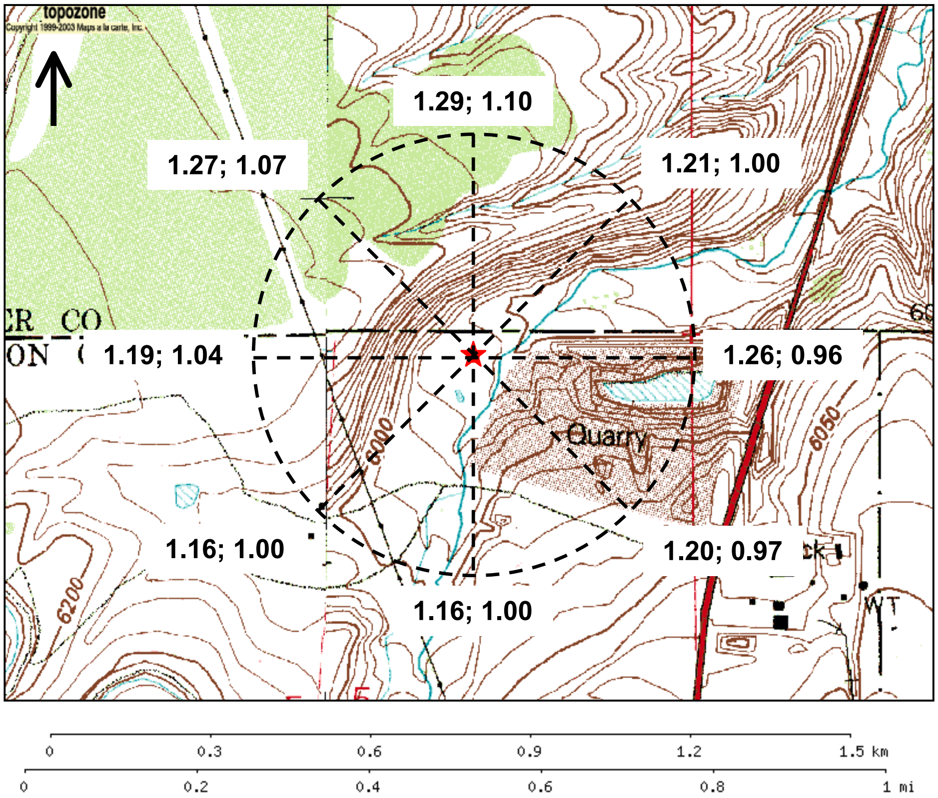

Figure 7: Average wind shear ratio by direction at the Boulder site.

5. CONCLUSIONS

The objective of this research was to determine the accuracy of commonly used wind shear models and methods, especially when used with wind data from sites having hills and/or forests. It was found that there is not a significant difference in performance between the log and power laws. The odds that either method gives an accurate prediction are low and using either of these shear models may result in significantly large hub height mean wind speed estimation errors.

Very few of the calculated shear parameters in this analysis at any of the sites were consistent with the typically assumed values for the power law exponents and surface roughness lengths (Tables 1 and 2). Even for the flat sites, it was found that the one-seventh power law could not represent the wind shear. Clearly, tabulated shear parameters and rules of thumb alone should not be relied upon to best represent the wind shear at a site; analyzing the wind data is an important aspect of accurately predicting the hub height wind speeds.

The analysis method found to yield the smallest prediction errors was based on the use of the above cut-in wind speed data (here, this is assumed to be 4 m/s) to calculate the hub height mean wind speed of those above cut-in wind speeds. In other words, hub height wind speed estimation errors were reduced when the hub height mean wind speeds for winds above 4 m/s were predicted instead of the hub height mean wind speed over all wind speeds. While most power production calculations use the mean wind speed over all wind speeds, future methods can be developed that use the better predicted above cut-in mean wind speed instead.

After 210 days of data collection, the average wind shear ratio was within 1% of that year's annual average. The importance of considering variation of wind shear between years is evident from the results of the Boulder site (complex terrain) as the annual average wind shear ratio varied by up to 7% between years. On the other hand, Hatfield, a flat site with no trees, had very little variation between annual average wind shear ratios.

It was also found that generally accepted wind shear trends are not necessarily true. For example, previous research has shown that wind shear decreases in the summer and increases in the winter [7, 12]. However, for two of the forested sites, the wind shear was highest in the summer. Wind shear is also usually assumed to be greater at sites with the complex terrain [1], but interestingly, the flat site of Hatfield had significantly greater wind shear than Boulder, a site with fairly complex terrain. Furthermore, due to complex terrain at Boulder, the lower height wind data in some of the direction sectors did not accurately represent the hub height wind shear.

ACKNOWLEDGEMENTS

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