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THE WIND SHEAR EXPONENT: COMPARING MEASURED AGAINST SIMULATED VALUES AND ANALYZING THE PHENOMENA THAT AFFECT THE WIND SHEAR

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ABSTRACT

When assessing a region for wind energy the wind shear is a key factor to consider because of its profound effect on power density as a function of height. Traditionally, wind shear parameters are derived either from local velocity measurements at two or more heights or from surface roughness characteristics to predict the wind speed at hub height for a particular site. However, recent measurements in a complex terrain (non-mountainous) region indicate that the measured wind shear exponent is significantly higher than the value predicted by land use characteristics and modeled results. Virtual wind shear parameters: alpha and z_0 , created by the modeled flow fields of the complex terrain of southeastern Ohio's Appalachian foothills are determined with computational fluid dynamics simulations designed for complex terrain. Then the first year's measurements from the extra-tall tower in the region provide a direct evaluation of the wind shear parameters: alpha and z_0 . These values, characteristic of the measurements, are compared against values determined from the local land use characteristics as well as those found by modeling with a computational fluid dynamics wind simulator. It has been found that the measured value of the wind shear exponent is larger, by a factor of 2, than the values currently used in published state wind maps.

Phenomena affecting wind shear are also analyzed. Diurnal and changes in reference heights have large effects on the measured wind shear. It is demonstrated that for this site an overall annual average value of the wind shear coefficient is an inaccurate representation of the wind shear because of the range of variability that occurs seasonally. It is also shown that extrapolating from near-surface measurements to hub heights can yield inaccurate predictions of wind speed and, more importantly, wind power.

INTRODUCTION

When assessing a region for harvestable wind energy knowledge of how the wind speed changes with height, or the wind shear, is essential. The wind shear is commonly predicted using a power law relationship between two values of the wind speed velocity, V_2 and V_1 and the heights at which the velocities occur, H_2 and H_1 with the wind shear exponent, α [1].

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1} \right)^\alpha \quad (1)$$

This empirically derived power law is a commonly used model to predict the wind speeds at hub heights, because of its simplicity. This power law is based on Blasius' (1908) velocity profile in the laminar boundary layer of fluid flowing across a flat plate.[2] From this study the "1/7 power law" was presented because the velocity profiles across a flat plate fit well when α was 1/7.[1] At the same time, wind measurements across grassy, flat terrain also agree with this value.[3] Since then, the power law with variations in α , relating to terrain roughness, has been used to estimate the wind shear in applications from estimating wind forces on buildings to wind resource assessment.

Though easy to use, many studies have discussed the limitations of the 1/7 power law.[1,4,5,6,7] This "typical" profile only fits under the most ideal conditions: well mixed atmosphere (neutral stability), above flat terrain with a small roughness length, z_0 , with small pressure gradients [4,5,6]. Complicated dynamics such as the surface roughness and the turbulent fluxes of momentum and heat that occur in the atmosphere [4] are essentially not considered when this empirical relationship is employed. Sisterson and Frenzen

suggest that because of the complexities found in the atmosphere the only accurate way to determine the wind shear in a region is by measurements.

The formation of nocturnal jets and other low level wind maxima are the main cause of the discrepancies between the 1/7 power law and wind speed measurements across flat terrain.[4,5,7] These low level wind maxima occur commonly during summer nights (thus coined “nocturnal boundary-layer wind maxima” or “the nocturnal jet”) in the Midwest and Great Plains regions [7].

Another commonly used wind shear profile is the log law which incorporates the surface roughness length, z_0 , in the extrapolation of wind speeds to hub height rather than the wind shear exponent, α .[1,8]

$$\frac{V_2}{V_1} = \frac{\ln\left(\frac{H_2}{z_0}\right)}{\ln\left(\frac{H_1}{z_0}\right)} \quad (2)$$

Numerous studies have been performed to define seasonal values for the surface roughness length for different terrain types, most notably the 1992 National Land Cover Dataset (NLCD) by the Environmental Protection Agency.[9] Table 1 below displays a range of the surface roughness length values specified for different terrain types and season.

TABLE 1: Wind Shear Parameter Values

Terrain Description	α, Wind Shear Exponent [3]	z_0 (m), Winter / Summer [9]
Open Water	0.10	0.001 / 0.001
Pasture/Hay	0.19	0.01 / 0.15
Deciduous Forest	0.43	0.5 / 1.3
Mixed Forest	0.43	0.9 / 1.3
Evergreen Forest	0.43	1.3 / 1.3

It is obvious from Table 1 that obstacles that are taller such as forests have a larger value of surface roughness length than objects that are smooth such as open water. However, the value of z_0 does not represent the actual height of the obstacle but the height at which the wind speed in the vertical wind profile would be equal to zero when a log law (equation 2) is applied.[9]

Typical wind resource assessments measure the wind speeds well below hub heights and then extrapolate the wind speed using a wind shear exponent that was determined using wind measurements near the surface. Typically it is evaluated simply between two known heights, rather than using an optimized curve fitting approach even when three or more measurement heights are available, due to the added complexity. Values for the same site often change significantly when evaluated between different measurements heights, ΔH . The difference in the value of the wind shear exponent and the log law fit z_0 for different measurement height pairs will be evaluated.

Extra-Tall Tower Study In Appalachia Ohio

This study considers the measurements taken from sensors mounted on booms on a communications tower

(262 meters) with six wind measurement levels (43, 58, 85, 113, 174, and 241 meters) and three temperature measurement levels (10, 113, and 241 meters). There are also measurements of the relative humidity and barometric pressure at 113 meters. Because of the amount of detail that is available from these measurements, the wind shear exponent can be calculated for a range of measurement height pairs and at hub height.

The measurement site is located among the western foothills of the Appalachian Mountains in southeastern Ohio. Due to the forest coverage of the surrounding terrain, the surface roughness length is a significant factor when considering the parameters that affect wind shear. The terrain is relatively complex with rolling ridges and valleys that commonly have elevation changes in excess of 100 meters over 4 to 5 kilometers.

As of December 2010 one year’s worth of data has been acquired. In this study, virtual wind profiles and the measurements are analyzed and the wind shear is closely examined. Measured wind shear exponents, α , are compared to the reference value of 1/7 for the wind shear exponent in the power law, the effect of local surface roughness in the power law, results of computational fluid dynamics (CFD) software designed for complex terrain, and estimated values derived from wind maps for this area.[10] Additionally, measured changes in wind shear that occur seasonally and diurnally are presented.

METHODOLOGY

The CFD Numerical Model

A commercial wind energy simulation software is used to evaluate the effect of the terrain friction on the wind shear parameters at the extra-tall tower measurement site, located at the center of the 80 km by 80 km (50 miles by 50 miles) modeled domain.[11] This software numerically solves the Reynolds Averaged Navier-Stokes (RANS) equations using the elevation from U.S.G.S. 30 meter digital elevation model,[12] surface roughness lengths (winter season) from [9], and local prevailing winds from published reference. [10]

Because the size of this domain is much larger than the size of typical domains used in CFD wind farm simulations, a nesting procedure was used to achieve a final resolution of 120 m. An initial model was established at a coarse resolution. Four fine resolution models were then initiated from the results of this coarse model. The coarse model encompasses the entire domain, with a resolution of 300 meters (about 1,000 feet). This full domain is then separated into four equally sized quadrants, each 45 km by 45 km (28 miles by 28 miles) allowing a 10 km overlap region of each of the quadrants. This overlap minimizes boundary effects in the interior that are common with CFD simulations. At the center of the full domain is the extra-tall tower site. Figure 1 displays the quadrants and their overlap region. Each quadrant overlays the measurement location. These four quadrants have the resolution of 120 meters (about 400 feet).

With the terrain and surface roughness input, the wind simulator develops a database of flow fields by solving for the terrain effect on a wind profile initiated at the horizontal edge boundary with the given inlet shear and a 10 m/s value at the

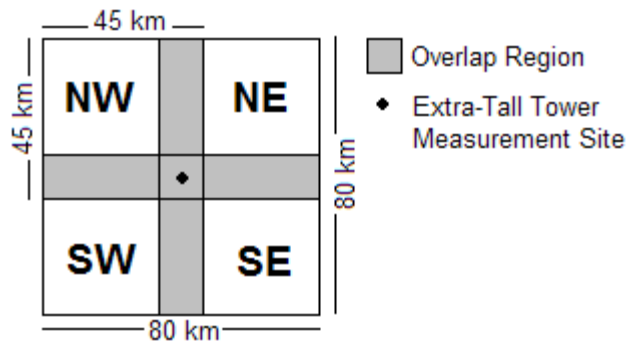


FIGURE 1: The modeled domain with the four quadrants and their overlap regions.

top of the upper modeled layer at 500 m. This initiation is repeated for each of twelve directional sectors, every 30°. Numerically, these profiles “blow” across the terrain and establish a profile defined by the friction effects of terrain and surface roughness. Reference meteorological data is used to scale the contribution from each sector, specifically the annual average wind rose published by the Ohio Power Siting Board (OPSB),[10] that is centered 0.5 miles west of the extra-tall tower measurement site. For this study of wind shear effects, wind profiles presented are normalized by the upper boundary layer velocity. The focus is on how the model develops wind shear, based on surface roughness, terrain elevation, and prevailing wind direction.

RESULTS

Numerically Determined Values

Because the extra-tall tower measurement site is located in each of the four numerically simulated quadrants, and the coarse initial run drives the perimeter conditions of each, it is expected that the measurement site wind profiles created by each quadrant will be very similar, as shown in Figure 2. The largest difference, only 3.2%, is found between the maximum heights of the SE and the SW sector.

The resulting values of the wind shear coefficient (α) and the surface roughness length (z_0) for each of these profiles are shown in Table 2. These values are calculated based on the velocity at nominally 23 ± 3 meters, near the bottom, and at 145 ± 10 m near blade-tip height, according to equations 1 and 2. The value of α is consistent between the four nested quadrants however there is a slight discrepancy in the values of z_0 , or more specifically, the value of z_0 in the NE quadrant. This difference may be an artifact of marginal vertical resolution seen near the bottom of the curves in Figure 2. A larger surface roughness length corresponds to more friction at the surface which creates more resistance to the flow of air through the atmosphere.

TABLE 2: Wind Shear Coefficient (α) and the Surface Roughness Length (z_0) for the Winter Season

Quadrant	α	z_0 (m)
NE	0.163	0.135
NW	0.165	0.120
SE	0.164	0.116
SW	0.161	0.110
Average:	0.163	0.120

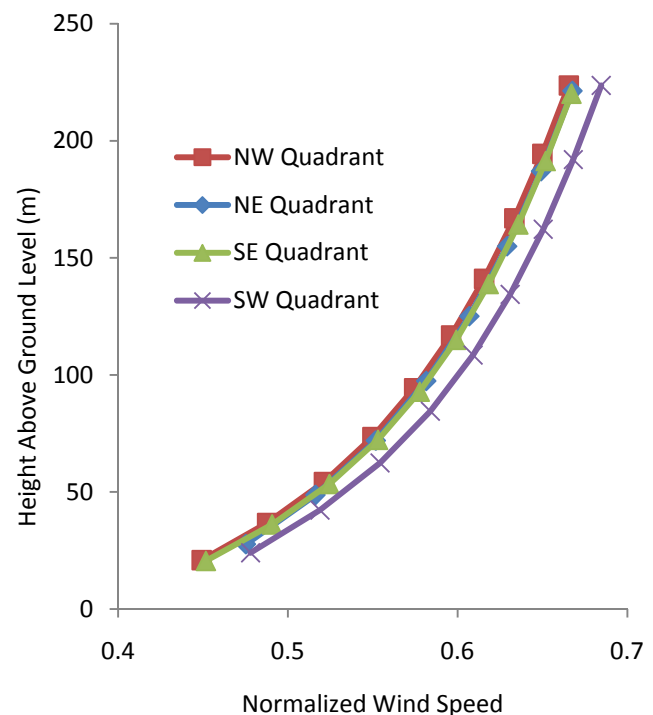


FIGURE 2: Wind profiles at the extra-tall tower measurement site for each of the four quadrants shown in Figure 1.

The values of α and z_0 for each quadrant were averaged to provide vertical wind profile parameters that represent the CFD vertical wind profile and the simulated values of α and z_0 : 0.164 and 0.123 meters respectively. It is important to note that the roughness values used to construct the numerical model are for the winter season only.

The vertical wind profiles using these values are shown in Figure 3. The largest difference between these two profiles is seen at heights between 30 and 50 meters which have differences of 2.1% over for the power law and 3.2% over for the log law fit (or about 0.1 m/s difference). The vertical wind profile developed using the 1/7 power law is also shown and it can be observed that this model does not match the representative NW Quadrant profile except below 70 m. When extrapolated from the bottom height value at 23 meters, the 1/7 power law under predicts the wind speeds and wind power density at and above hub heights by up to 3 to 7%.

Wind Shear Fits of Measured Values

The measured value of α and z_0 can be determined using the power law and log law, respectively. Figure 4 displays the annual average vertical wind profile that was observed during the period ranging from December 2009 through November 2010 (12 months) at the measurement location. Using Equation 1, the measured value of α is 0.429 and using Equation 2 the measured value of z_0 is 8.90 meters. These values were obtained using the wind speeds at heights of 43 and 241 meters.

The power law matches the end points, as expected, however differences of 3.5% and 5.0% are seen at heights of 85 and 113 meters, respectively. Although this difference is a

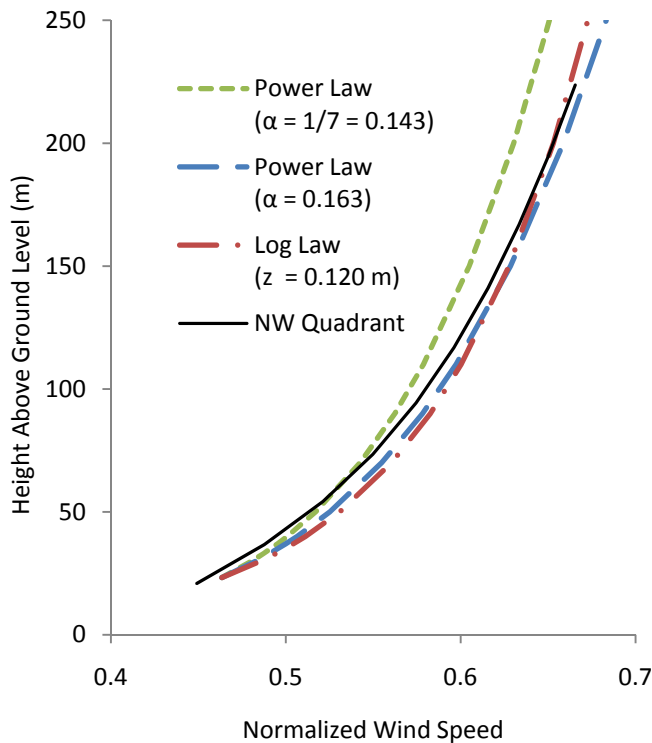


FIGURE 3: Power law profile, for $\alpha = 1/7$ and 0.163, and log law with $z_0 = 0.120$ m, each based on two nominal heights of about (23 m, 142 m) from the numerical simulation. NW Quadrant profile is plotted for reference.

small magnitude of wind speed, 0.16 m/s at 85 meters and 0.26 m/s at 113 meters, the resulting power difference is much larger due to the cubic relationship: 10% at 85 meters and 15% at 113 meters.

Visual inspection of Figure 4 suggests that the log law fit is much better, but the over prediction of 0.14 m/s at 85 m results in a 9.2% when analyzing the effect on power. At 113 m, the difference is less than one-tenth of a meter per second: 0.06 m/s which still over predicts the power by 3.5%.

Many studies have observed the effects that the time of day, season, and atmospheric stability has on the value of α [3,5]. These studies revealed significant changes in the value of α at different times of the day and during different months of the year. Also of interest is how the value of α changes when the atmosphere is unstable, neutral, or stable. Bailey's study considered the values of α at different stabilities of the atmosphere by classifying the stability based on the lapse rate, or how the temperature changes with height [9]. The stability of the atmosphere will be considered as it has been shown to have a profound effect on the value of α , however a more detailed assessment of the stability can be performed because the measurement site also records the pressure and the relative humidity at a height at the center of the tower. Using this data, the buoyant effects due to the temperature gradient throughout the atmosphere can be analyzed in addition to the buoyancy effects due to the moisture gradient as well.

Seasonal/Monthly Variation

Seasonal effects on the value of wind shear parameters are important to consider. It is an indication of how much the

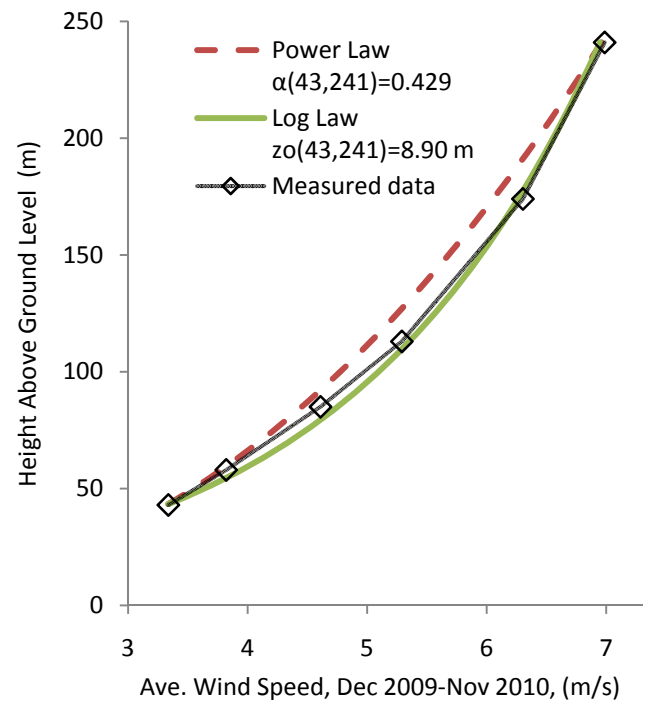


FIGURE 4: The annual vertical wind profile in 2010 at the measurement site, together with power law and log law profile fits made at 43 m and 241 m heights.

surrounding surface roughness elements change seasonally, as well as the dependence on average velocity.[6] The wind shear during different seasons is also important when predicting the power output of wind turbines corresponding to seasonal energy usage. Figure 5 displays how the value of α and z_0 changes from month to month during the measurement period between the heights of 43 and 241 meters. As expected, during the summer months (June-August 2009) there is an increase in both wind shear parameters due to the surrounding deciduous forest's increased foliage. The

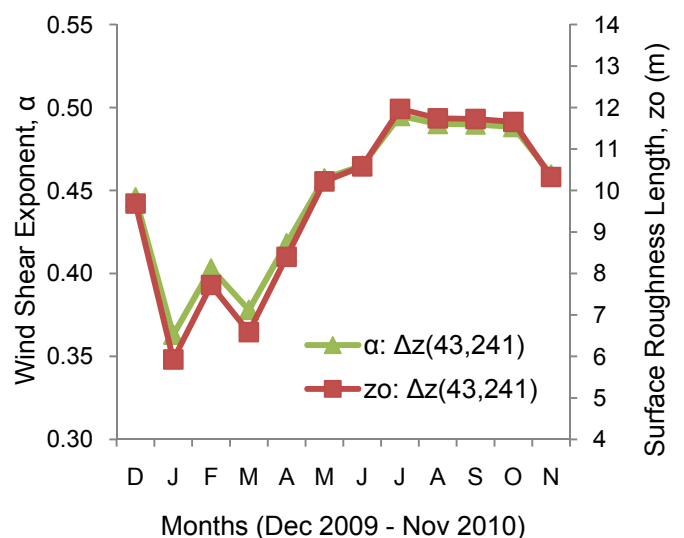


FIGURE 5: The monthly variation of α and z_0 during the measurement period.

increase in foliage decreases the porosity of the forest and increases the surface roughness length. January had the lowest value of both parameters while July had the highest. Table 3 displays tabulated values for α and z_0 for the measurement period. The bimodal seasonal variation suggests that an overall annual average value of α or z_0 is not sufficient as it essentially is averaging the two extreme cases of the wind shear.

TABLE 3: Monthly Values of Wind Shear Parameters

Month	α	z_0 (m)
December 2009	0.45	9.7
January 2010	0.36	5.9
February 2010	0.40	7.7
March 2010	0.38	6.6
April 2010	0.42	8.4
May 2010	0.46	10.2
June 2010	0.47	10.6
July 2010	0.49	12.0
August 2010	0.49	11.7
September 2010	0.49	11.7
October 2010	0.49	11.7
November 2010	0.46	10.3

Diurnal Variation

Time of day also has a profound effect on the wind shear parameters. Other studies have found a significant change in the wind shear during the daytime hours and nocturnal hours [5,6,7,13], caused primarily by the establishment of stable or neutral atmospheric conditions during the nocturnal hours up until sunrise due to surface cooling. Large values of α during the nocturnal hours have been credited towards the formation of nocturnal low-level wind maxima, or low-level nocturnal jets.[7] Figure 6 displays the annual average wind speeds measured throughout the day for the entire measurement period. A significant nocturnal low-level wind maxima is evident at heights of 113 meters and above. A wind speed increase between midnight and noon as much as 2.8 m/s (44% increase) at a height of 241 meters. However, at levels below 85 meters the opposite occurs. There is a significant wind speed increase during the day; as much as 0.65 m/s at 43 meters (21% decrease). These changes in wind speed during the day occur primarily due to mixing of the atmosphere due to daytime heating.

Notice that during the nocturnal hours (such as midnight or 0:00), there is a significant difference in the wind speed at each measurement height, thus more wind shear. During the daytime hours (such as noon or 12:00) the wind speeds are much closer together, thus there is less wind shear due to this atmospheric mixing that is driven by the daytime heating. This phenomenon is clearly evident in Figure 7, which displays the annual average variation of the value of α throughout the day between the heights of 43 and 241 meters. There is a sharp decrease in the value of α shortly following sunrise until noon when the value slowly increases to its nocturnal value. This change is significant: an increase in the value of α of 0.40, from 0.19 at 12:30 hours to 0.59 at 23:40, at nearly midnight.

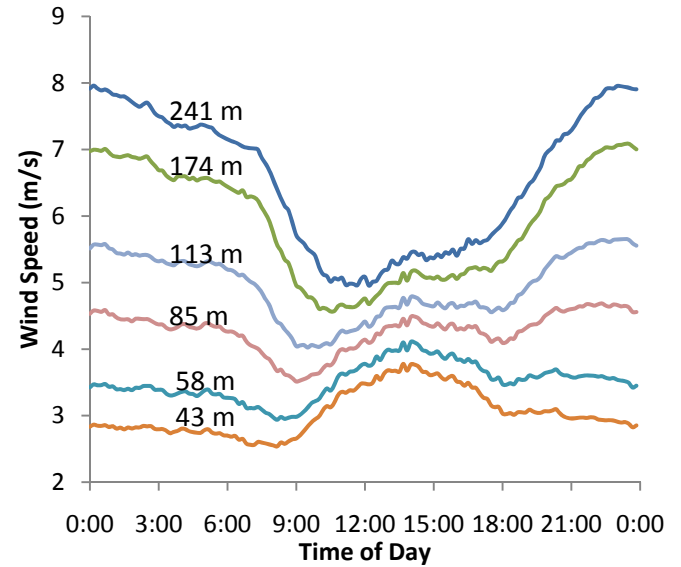


FIGURE 6: Diurnal variation of the wind speed at each measured level during Dec 2009 – Nov 2010.

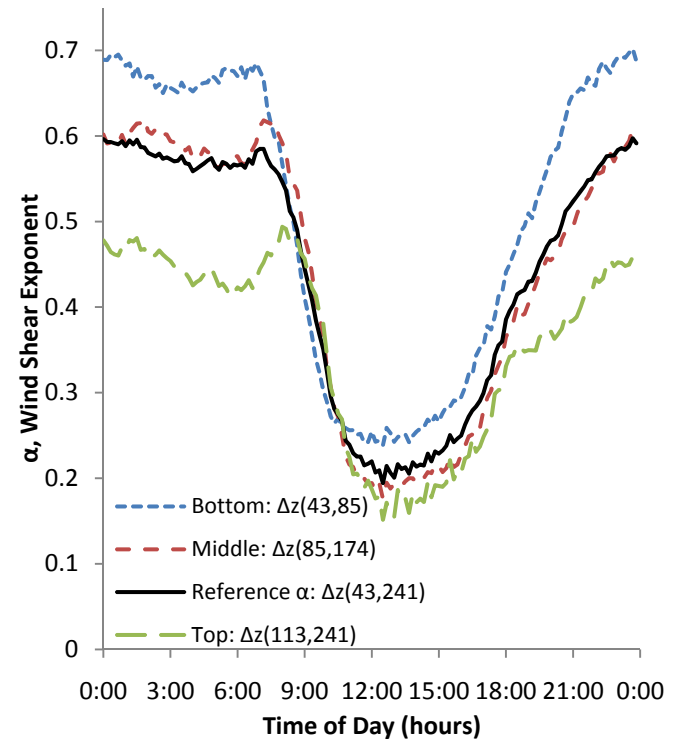


FIGURE 7: Measured annual diurnal variation of the wind shear exponent from Dec 2009 to Nov 2010. Black line represents reference α , evaluated between the heights of 43 m and 241 m. Dashed lines represent three selected height intervals described in Table 4.

Values of α From a Prevailing Wind Direction

The changes in the value of α that occur when the wind direction is changing are important to consider especially for the prevailing wind directions. Large changes in the values of α and z_0 that occur when the wind is coming from different directions is an indication of significant downstream effects of roughness or turbulence. Because the prevailing wind direction for this measurement site can be determined using

the measured data, the wind shear when the wind is coming from this direction is presented.

The frequency wind rose for the measurement site is displayed in Figure 8 below. This figure displays the frequency that wind blows from each direction at each of the measurement heights. The prevailing wind direction is clearly from the south-southwest. It is important to note that the directions where there appears to be a frequency of zero is due to the removal of data at that direction due to tower shading. A more in-depth analysis of the data screening process, including tower shading effects, is discussed in a separate study. Figure 9 displays the vertical wind profile when the wind is

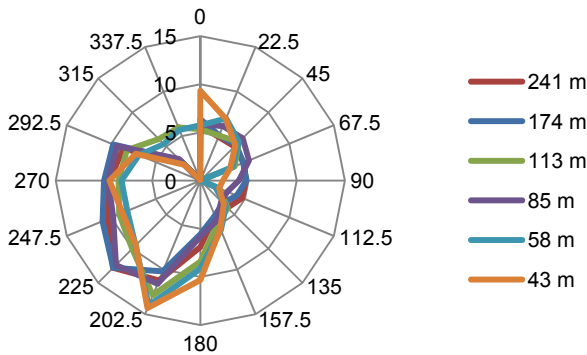


FIGURE 8: The measured annual frequency wind rose at the measurement site (Dec 2009 – Nov 2010).

blowing from this direction. More specifically, when the direction of the wind is between 200 and 250 degrees. When the direction of the wind is between this interval at all of the measurement heights, the average annual value of α is 0.407.

Values of α Using Different Height Intervals

It is common for wind resource assessments to record wind measurements near the surface and at an additional height well below hub height such as 60 meters. Using the measurements from these two heights, a value of α is calculated and then used to extrapolate to the hub height. Although this approach may be successful in simple terrain, when performed in complex terrain there are large changes in the value of α when evaluated between heights near the surface and between heights including the hub heights of wind turbines. The potential errors of extrapolating to hub heights rather than measuring at hub heights can cause drastic errors in the prediction of power generation. Table 4 displays the measured value of α when evaluated at three different height intervals termed lower, middle, and top. The lower height interval is between 43 and 85 meters and will represent the wind shear near the surface where the roughness of the terrain has its strongest effects. The middle height interval is between 85 and 174 meters and will represent the wind shear at typical hub heights. The top height interval is between 113 and 241 meters and will represent the wind shear above turbine heights where the surface friction has little effect. These intervals are chosen such that there are three measurement heights included in each.

Clearly there is a significant change in the value of α depending on which height interval is evaluated. It is expected that the wind speed does not change as significantly with

TABLE 4: Average Annual Measured Value of α at Selected Height Intervals (Dec 2009 to Nov 2010)

Layer	Height Interval	α
Top	113 to 241 meters	0.37
Middle	85 to 174 meters	0.45
Bottom	43 to 85 meters	0.50

height when evaluating height intervals that are higher into the atmosphere. This is because the surface friction has less of a drag effect on the wind speed profile. It has been well established that the wind speed profile will follow a logarithmic or power law trend. These trends account for this decreased drag effect. However, one overall power law defined from endpoints is unlikely to fully encompass how the wind speed shear changes as evidenced by Table 4.

It is also valuable to evaluate the value of α at these different height intervals by month and by time of day as was previously presented between the heights of 43 and 241 meters. The diurnal and monthly variation of α at each height interval is shown in Figures 7 and 9, respectively.

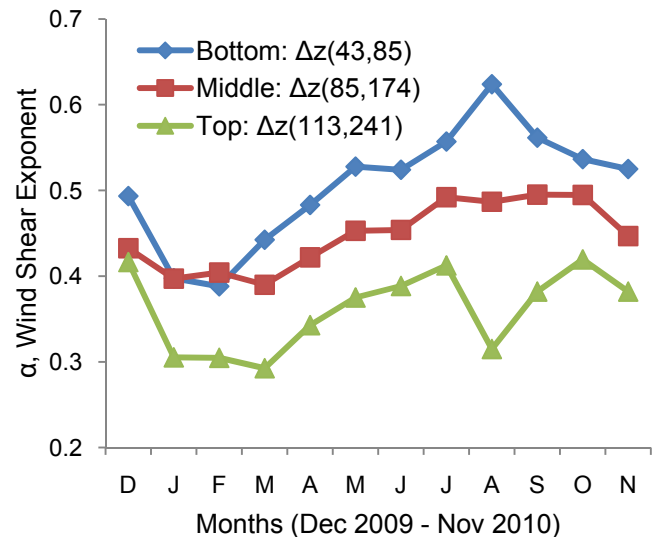


FIGURE 9: Monthly variation of the value of α at the three selected height intervals (Dec 2009 – Nov 2010).

The diurnal cycle of all three layers follow the same trend. All heights indicate significant mixing of the atmosphere during the day and a clear separation during the nocturnal hours; the same trend observed previously in Figures 6 and 7.

As expected, near the surface the value of α increases during the summer months where the ground friction near the surface is at its maximum, reaching a peak in August at 0.62. The middle layer is slightly affected by this change in surface roughness while the top layer follows a similar trend as the bottom layer except that it actually has a decrease in the value of α when the surface roughness is at its maximum in August. As also seen in Figure 5, this is evidence that surface roughness can lead to significant changes in the value of α as a function of season.

Conclusions

It has been demonstrated that the vertical wind profile, or the wind shear coefficient α , can change drastically depending on the time of day and the season. There are also changes in α depending on the direction of the wind speed. It has also been displayed that the value of α can change depending upon which two heights are used in the calculation. The simulated values of α for the winter seasons are largely different from the measured values during this season.

The changing of the seasons plays a large role in the value of α . Because of decreased foliage on the surrounding vegetation and the occurrence of persistent snow cover, the surface roughness length, z_0 , decreases. This decrease in roughness allows the value of α to decrease because leaf-less trees offer less resistance to the flow of air over the terrain.

There is also a large change in the value of α depending on the time of day. Because of the prevalence of surface heating and the mixing effects that it has on the atmosphere, the value of α decreases during the day and increases as the atmosphere begins to separate into layers during the nocturnal hours. This mixing effect is largely evident in the evaluation of the wind speeds at each measurement height throughout the day. The wind speeds are largely different during the nocturnal hours, but shortly following sunrise the surface heating causes the wind speeds at each height to become much more similar due to the mixing effects that surface heating has on the atmosphere.

Future work in this area of study will examine how annual average, monthly, and diurnal wind shear parameters change between measurement years. Closer analysis of the influence of atmospheric stability on the wind shear at the site using calibrated temperature sensors on the tower will also be an important follow up of the observed diurnal variations.

The most important concept that is portrayed in this study is that an overall average annual value of α is a representation of many phenomena all wrapped into a single value of α . Use of this average value to predict wind power resources at hub height can be uncertain because of the large variation in α for different seasons, and atmospheric conditions. When also considering the measurement heights that are used to calculate the value of α , there can be very large differences when using heights below the hub heights of turbines to extrapolate to turbine hub heights. Based on the measurements presented here, the value of α is larger near the surface than at hub heights. Near-surface measurements (greater than 30 m but less than 85 m) used to calculate α can lead to large errors in the estimation of the wind speed at hub heights, and even larger errors when estimating the power that is available at that height due to the cubic relationship between wind speed and power.

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