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Extrapolation of Wind Profiles Using Indirect Measures of Stability

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ABSTRACT:
The dependence of wind shear on boundary layer stability can be described using Monin-Obukhov similarity theory and modified logarithmic wind profiles. Typical measurements for wind resource assessment, however, are insufficient to assess stability.
We show that useful, indirect inferences of stability are possible using measurements from typical instrumentation found on a meteorological tower installed for the purpose of wind resource assessment. Traditional power-law parameterizations, stratified by time of day and season, are often sufficient despite inter-day variations in stability. The effect of various wind speed extrapolation methods on wind energy estimates are demonstrated using measurements made during fall 2007 from a 50 m wind monitoring tower.

INTRODUCTION

The change of wind speed with height, wind shear, plays an important role in wind resource assessment, since wind monitoring often occurs at levels well below the eventual turbine hub height. Various factors may affect vertical wind shear, either directly or indirectly, including roughness, topography, time of day, season and wind direction. Investigation of the relationship between atmospheric stability and wind shear, and how to apply this knowledge with typical measurements holds the potential of improved wind resource assessment.

Wind monitoring often occurs at meteorological tower levels (commonly 50 m or 60 m) well below the eventual turbine hub height (typically 80 m). Wind speeds at multiple meteorological tower levels are used to estimate wind shear and extrapolate wind estimates from the upper tower level to the planned hub height. Common functional forms for the relationship of wind speed with height include the power-law profile:

$$U(z_2) / U(z_1) = [z_2 / z_1]^{\alpha} \tag{1}$$

and the logarithmic wind profile:

$$U(z) = (u^* / k) \log(z / z_o) \tag{2}$$

Both equations are approximations for the atmospheric boundary layer (roughly the lowest 100 m, with a depth that changes during the day), requiring adjustments for atmospheric stability. The corrections to the logarithmic equation with stability have been determined by Monin-Obukhov theory (Monin and Obukhov, 1954) and the results of several decades of scientific field experiments (see Arya, 2001). Example vertical wind profiles derived from the Monin-Obukhov equations are shown in Figure 1.

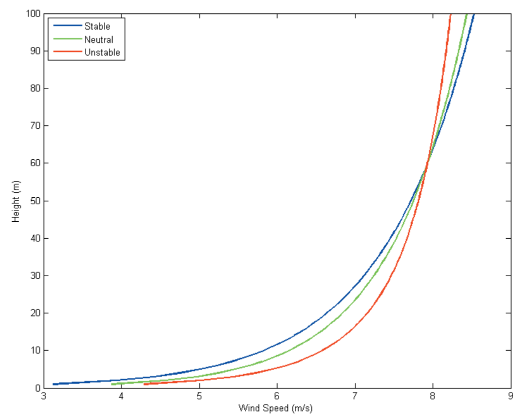

Figure 1: Changes in average wind speed (horizontal axis) with height above the ground (vertical axis) according to Monin-Obhukov stability corrections to a logarithmic wind profile. Examples are shown for a stable case (blue), an unstable case (red) and neutral conditions (green) with the same wind speed at a height of 60 m.

Atmospheric stability can be understood as a consequence of cold air being heavier than warm air, where other factors such as pressure are constant. Where there is warmer, lighter air above colder, denser air the situation is more stable. In this situation there is less vertical mixing, and air moving at greater wind speeds at higher heights mixes less with air moving at lower wind speeds below (as shown by the blue curve in Figure 1). Where there is colder, denser air above warmer, lighter air the situation is unstable; vertical mixing increases, with greater mixing of higher wind speeds above with lower wind speeds below (as shown by the red curve in Figure 1).

This description must be somewhat modified to account for the decrease of pressure and temperature with height. The meaning of 'warmer' and 'colder' with height must be determined with respect to a standard temperature lapse rate.

Typical measurements for wind resource assessment are insufficient to assess stability and determine all parameters for the modified logarithmic equation. As a result, a power-law parameterization, stratified by time of day and season, is often used despite the fact that stability may vary widely from day to day. The next section examines the ability of such a time-of-day (TOD) power-law to capture the effects of changes in stability and considers a possible method for further improvements.

METHOD

Measurements from a 50 m meteorological tower near Calgary, Alberta, for the period September 1, 2007 to October 24, 2007, were used for the analysis. A diagram of the tower measurement levels is shown in Figure 2. Wind speed measurements were available every 10 minutes for heights of 50 m, 36 m and 20 m. Two anemometers were initially operating at each level (RM Young 5103 Wind Monitor and an NRG #40C Anemometer) although the RM Young device at 20 m failed on September 7 and was unusable after that date.

It was hoped to use temperature sensors at 49 m and 19 m to assess stability more directly. The accuracy of the instruments limits the ability to assess stability directly since the temperature differences between the heights are not large.

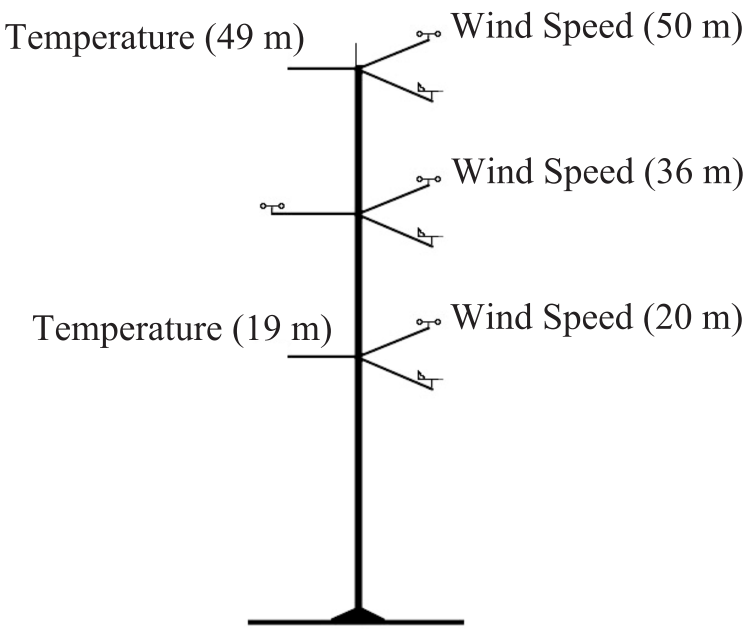

Figure 2: Measurement levels for meteorological tower used in the analysis.

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The variability of wind shear can be studied empirically by solving Equation 1 for the shear exponent, α using the 10-minute wind speed averages. This can be done using wind measurements from any two heights. In our case, we determined time series of observed α values for an 'upper level' between the 50 m and 36 m measurement heights and a 'lower level' between the 36 m and 20 m heights.

For the vertical extrapolation of winds, it is often assumed that wind shear (as characterized by α) is relatively consistent between levels. To test this with the available measurements, an objective is set to use wind speed measurements at 36 m to predict wind power density at 50 m. Wind speed measurements at 50 m on the tower are then available for verification of different wind extrapolation methods.

Several methods are tested based on the availability of different information:

- Method 1: Constant $\alpha = 0.2$, a typical value for this site, but with no time-of-day (TOD) adjustment.
- Method 2: Median TOD values of α from the lower level (20 m to 36 m), using assumption that upper level shear (36 m to 50 m) will be similar.
- Method 3: Median TOD values of α from the upper level (36 m to 50 m), representing the best possible TOD values of α. Results provide an upper limit of the accuracy of such methods.
- Method 4: Best TOD values of α (from Method 3) with an additional correction based on temperature differences between 49 m and 19 m. For each measurement time, the deviation of the vertical temperature difference from its average for that time of day is calculated. The best possible linear temperature difference correction for each time of day is applied. The result, when compared with the results of Method 3, indicates an upper limit for improvements in accuracy using linear temperature difference corrections.

The comparison of results indicates the relative accuracy of each method for the test measurements and suggests the level of added complexity that is justified to incorporate stability effects in the operational extrapolation of wind speeds for wind resource assessment.

RESULTS

The 24-hour cycle of solar heating of the ground and heating of the atmospheric boundary layer by the surface below produces a diurnal wind shear pattern. This is seen in the pattern of observed upper-level α values (36 m to 50 m, with 10-minute averaging) as shown in Figure 3. Lower values of α during the day are associated with enhanced mixing of wind speeds in the generally unstable conditions. During the night, generally stable conditions reduce mixing leading to higher values of α.

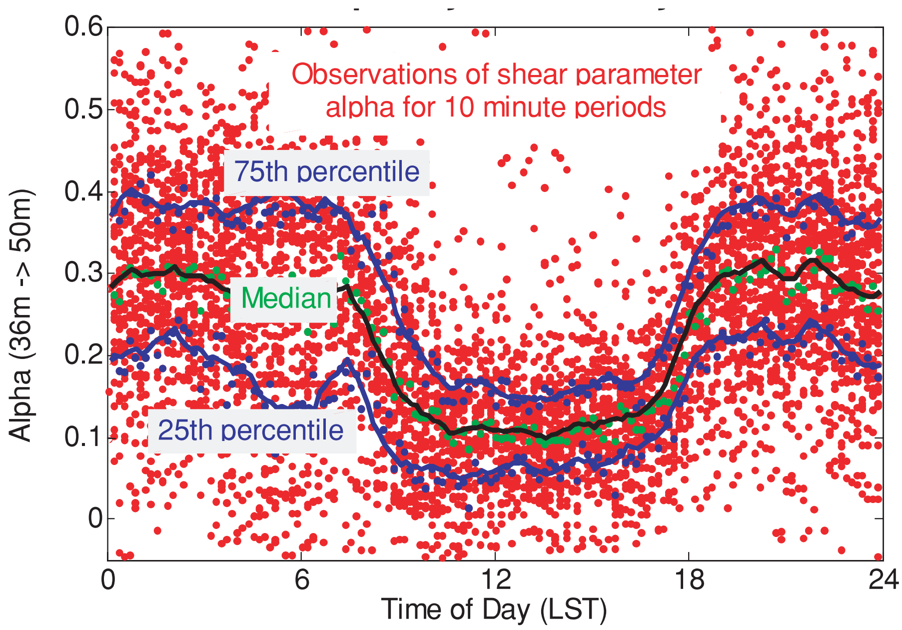

Figure 3: Values of shear parameter α calculated for the upper level (36 m to 50 m) from individual 10-minute averaged measurements.

A substantial scatter in values of α at each time of day is also evident in Figure 3. This is not surprising given that the data is based on 10-minute averaging. Sources of variability include:

- Measurement errors, either from instrument error, discretization of values or tower effects. These sources of error are especially significant for low wind speeds, and can be reduced by avoiding low wind speed cases from wind shear calculations.
- Wind speeds out of equilibrium, or with obstacles to the flow in certain directions.
- Differences in stability conditions compared to the average for the time-of-day.

The daily evolution of the boundary layer affects the value of α for both the upper level (36 m to 50 m) and lower level (20 m to 36 m). The combined pattern is shown in Figure 4. Average values of α by time-of-day are seldom exactly equal for the two levels, and differences change with the time-of-day, although differences are not large when compared with the general scatter in Figure 3.

In Figure 5 the effect of using Method 1, with a single value of α at all times, is shown in terms of the estimation of wind power density at 50 m using the measurements at 36 m and 20 m. On average, this method underestimates wind power density during the night but gives overestimates during the day. With an appropriate single value of α such systematic errors would balance out on average; however, electricity demand also experiences systematic changes with time-of-day, changes that may affect prices and issues of network load balancing. Correlations of errors, wind resource estimates and electricity demand and prices require greater accuracy.

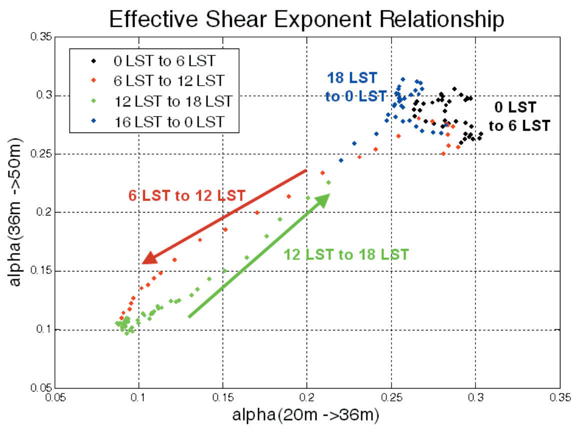

Figure 4: Median calculated values of shear parameter α by time-of-day, for the upper level (36 m to 50 m, vertical axis) versus the shear parameter α for the lower level (20 m to 36 m, horizontal axis). Times are shown in Local Standard Time (LST).

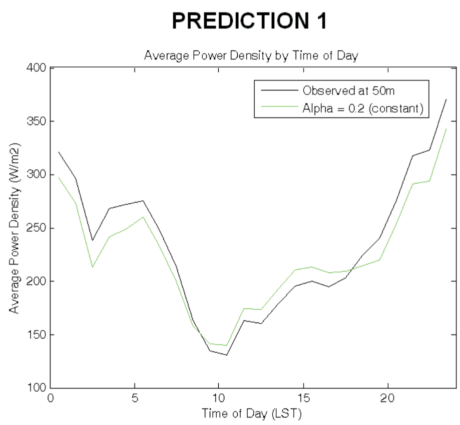

Figure 5: Comparison of wind power density at 50 m calculated from measurements averaged by time of day (black) and estimates using Method 1, with a single value of α at all times (green). Method 1 estimated the wind power density at 50 m using measurements at 36 m and 20 m.

Figure 6 shows the average percent error in estimates of atmospheric power density at 50 m (using the measurements at 20 m and 36 m) for Methods 1 to 4, as described in the previous section. Rather than the constant value of the wind shear parameter α in Method 1, the median low-level α for each time-of-day is applied in Method 2. The transition from Method 1 to Method 2 eliminated much of the error in averages at each time of day. Although more sophisticated averaging and exclusion of low wind-speeds would be applied in practice, Method 2 best resembles current methods for wind speed extrapolation at GENIVAR.

With the verification measurement of wind speeds at 50 m, it was possible to calculate the shear parameter α for the upper level (36 m to 50 m) as well as the lower level (20 m to 36 m). Operationally, α would not be available from the upper measurement height to the extrapolation height. Although Method 3, using the median TOD values from the upper level, is not operationally feasible, it provides an upper limit of the accuracy for methods that use a single value of α for each time-of-day. In Figure 6, the errors for Method 3 (in blue) are not much smaller than those for Method 2. For the time period and location examined there was minimal potential for improvement of Method 2.

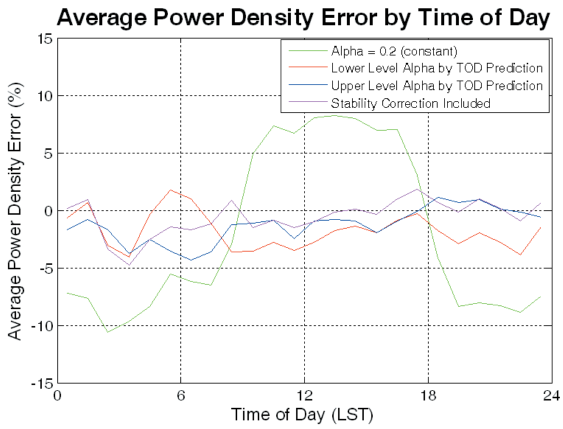

Figure 6: Average error in estimates of atmospheric power density at 50m using measurements at 20 m and 36 m with various methods: Method 1 (in green) with constant $\alpha = 0.2$, Method 2 (in red) using the best lower-level TOD values of α for the wind speed extrapolation, Method 3 (in blue) using the best upper-level TOD values of α for the wind speed extrapolation, Method 4 (in pink) using the best upper level TOD values of α with an additional linear correction for vertical temperature difference.

An initial attempt was made to adjust values of α for conditions at each time and day. In Method 4 the deviation of the vertical temperature difference from its average for that time of day is calculated, and the best-fitted linear correction for α as a function of vertical temperature difference (for each time-of-day) was calculated. These stability corrections were applied to the best TOD values already determined for Method 3. As shown in Figure 6 (in pink) there was no significant improvement of Method 4 over Method 3.

CONCLUSION

Much of the stability-related variations in wind speed extrapolation are captured by values of the shear parameter α adjusted by time-of-day (TOD method). In fact, most of the possible improvement could be achieved using measurements from below the extrapolation range, at heights where measurements are available in practice. An initial attempt to further improve the extrapolation beyond the TOD method using a linear correction for vertical temperature differences resulted in a negligible improvement; however, other possible approaches exist and will be investigated as part of future work.

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