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Wind Shear Characteristics at Central Plains Tall Towers

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Wind Shear Characteristics at Central Plains Tall Towers

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Background

The object of this study is to analyze wind shear characteristics at tall tower sites in the Central Plains of the United States. The hub heights of modern turbines used for wind farm projects are now 70 meters (m) to 100 m above ground and some advanced turbines under development for deployment during the second half of this decade are rated at 2–5 megawatts of energy generation with rotor diameters near 100 m and hub heights of 100–120 m. These advanced turbines will take advantage of the higher wind speeds aloft to generate more wind energy. Specific knowledge of important wind shear characteristics near and at turbine hub height is needed to optimize turbine design and wind farm layout. Unfortunately, wind speed shear measurements at heights of 80–120 m were virtually nonexistent a few years ago and are still quite uncommon today. The Central Plains is a prime wind energy development region and knowledge about the wind shear characteristics will reduce uncertainty about the resource and enhance wind farm design. Previous analyses of tall tower data (Schwartz and Elliott, 2005) concentrated on data from specific states.

The wind energy community has recognized the need to fill the gap of direct wind speed measurements at levels 70 m and higher above the ground. Programs instituted during the last 5 years at the state level and supported by the U.S. Department of Energy's (DOE) State Energy Program initiative have placed anemometers and vanes at several levels on existing tall (70 m+) communication towers. The Central Plains has a fairly high concentration of tall tower sites. The distribution of tall tower sites varies among the states in the Central Plains, because the tall tower program is new and the available state and federal funding to establish tall towers is variable. Our wind resource assessment group at DOE's National Renewable Energy Laboratory (NREL) has obtained much of these necessary measurement data from both individual state sources and regional organizations. Most of the data are available to the public, though data from one tower in Colorado are proprietary. We have begun to analyze important wind climate parameters, including wind shear from the tall towers. A total of 13 tall towers were used for this study. Eleven of the towers had the highest anemometer level between 100 m and 113 m. Two towers had the highest measurement level between 70 m and 85 m above ground. The distribution of the towers among the states is: two sites in Texas and Oklahoma; six sites in Kansas; and one site each in Colorado, South Dakota, and North Dakota. Figure 1 shows the locations and names of the thirteen towers. The wind resource at these sites can be classified as ranging from good - to - excellent. Eight tall tower sites have Class 3 resource, four sites have Class 4 resource, and one has Class 5 resource at 50 m.

Technical Approach

The first step for the study was to create "clean" data sets from each tall tower location. This step proved to be more problematic than was anticipated. as described later in this paper. The study uses the shear exponent α (alpha) from the power law equation $(v/v_o) = (z/z_o)^{\alpha}$ as defined in the *Wind Energy Resource Atlas of the United States* (Elliott et al., 1987) to describe the wind shear characteristics at the tall towers. Alpha values can vary widely from location to location but typical values range from 0.10 to 0.30. Alpha doesn't provide a complete description of the shear characteristics (for example, turbulence intensity at different levels) but it does provide basic information about the shear and is easy to use in a comparative analysis.

Figure 1. Locations of tall tower study stations in the Central Plains

The analysis used wind speed data at each tower from levels at or near 50 m up to its highest anemometer for baseline shear information. Each tower had either two or three measurement levels for its baseline data. Wind shear characteristics were calculated by averaging all alpha values from individual measurements between levels with speeds of at least 3.0 meters per second (m/s) occurring at the same time. The criteria of using speeds of at least 3.0 m/s resulted in the analysis not using about 9% of the measured data from all of the towers combined. The amount of data not used at the individual towers ranged from 6% to 13%. The types of wind shear characteristics analyzed included annual average alpha values, the diurnal and seasonal variability of alpha, the shear variation by prevailing wind directions, and the variation of alpha by height. Unfortunately, because of the influence of the equipment on communication towers and perhaps the tower itself on wind measurements, we felt that the quality of data at many measurement levels was sufficiently compromised to preclude using alpha calculations for this study.

Tall Tower Data and Tower Effects

The original intent for creating "clean" tall tower data sets was to use data from a set of anemometers on the same side of an individual tower to ensure consistency of data quality. The appropriate set of anemometers per tower would be judged by overall data quality, data recovery rates, and minimal tower flow interference. It was the last condition that proved to be troublesome. Upon close examination of the tall tower data, we discovered that tower effects on the quality of the data at certain measurement levels posed a greater challenge than anticipated.

The analysis of wind speed and frequency by direction data from the tall towers provided the best method of identifying tower effects in this study. Standard deviation of wind speed by direction is another method of detecting tower effects, but we did not have this type of data for all towers. The most common pattern observed with possible tower effects was a "notch" in the average speed over a 10-or-20 degree segment of wind direction. Average wind speeds on either side of the notch are about the same, but the average speed in the notch can be lower by 0.5 m/s or greater. Sometimes the notch in speeds is matched by a notch in direction frequency. If a notch in wind speed at a particular 10-or-20 degree segment does not appear at all measurement levels, or the reduction of wind speed within the notch is different for the measurement levels, then tower effects caused by equipment on the tower and/or the tower itself could be compromising data quality. Alpha values are very sensitive to tower influence. For example, if the measured speed at 50 m is 7.0 m/s and the 80-m speed is 7.6 m/s, the alpha value is 0.175. But, if tower effects increase the speed uncertainty by just 0.1 m/s at either anemometer height, then the range of possible alpha values is 0.117 to 0.223. We judged the directly measured alpha values of the levels used for this study to be within a 0.05 range of accuracy. A measured 0.2 alpha value likely represents an envelope of values between 0.175 and 0.225.

We concluded that eight of the 13 tall towers had at least one level affected by tower flow interference. This forced us to make subjective decisions to determine the least biased measurement levels to use in the analysis. This was not always easy because some of the tower effects appeared to be subtle and the influence on the measured speed hard to define. Nevertheless, trends in seasonal, diurnal, and wind direction shear variability at the tall towers could still be discerned despite the tower effects. In summary, tower effects tend to lower wind speed, are quite sensitive to wind direction, and do not necessarily affect all levels equally. We believe that, despite tower effects, the analysis provided good insights into the wind shear characteristics in the Central Plains.

Analysis Results

Table 1 shows the 13 tall towers used in the study, the levels on each tower used for analysis (in bold), the periods-of-record, and the annual average alpha value for the study levels. We hoped that the highest anemometer level at each tower could be used in the analysis to calculate the shear statistics from 50 m to the top of the tower, but tower effects and other data quality issues limited the use of the highest measurement level on about half the towers. The periods-of-record at 12 of the 13 towers was approximately 2 years. While there is some uncertainty associated with the exact shear statistics based on these short periods-of-record, we are confident that the trends shown in the data would still be valid for longer measurement periods.

Table 1. Names, anemometer heights, periods-of record, and annual average alpha values for tall tower stations. Anemometer heights in bold were used to calculate shear statistics.

Site Name	**Anemometer Heights**	**From**	**To**	**Shear (α)**
Lamar, CO	(3) **52 113**	10-05-2001	09-16-2003	0.150
Ellsworth, KS	**50** (80) **110**	04-18-2003	09-02-2005	0.165
Kearny, KS	**50 80** (110)	04-29-2003	09-02-2005	0.138
Sumner, KS	**50 80** (110)	06-11-2003	09-02-2005	0.254
Jewell, KS	**50** (80) **110**	04-23-2003	09-04-2005	0.206
Ness, KS	**50** (80) **110**	06-04-2003	09-03-2005	0.223
Logan, KS	**50 80** (110)	05-01-2003	09-03-2005	0.179
Hobart, OK	**40 70** (100)	04-01-2002	12-31-2003	0.195
Elk City, OK	(10) **40 70** (100)	10-30-2003	08-31-2005	0.227
Sweetwater, TX	**50** (75) **100**	05-17-2003	03-02-2005	0.220
Washburn, TX	**50 75** (100)	09-05-2003	10-03-2005	0.170
Crow Lake, SD	**50 70**	12-26-2001	12-31-2005	0.209
W. Finley, ND	(10, 41) **56 85**	08-07-2003	04-30-2005	0.200

Annual Average

The annual alpha values for the levels used at the 13 towers range from 0.138 to 0.254. We have a suspicion that the 0.138 alpha at Kearny may be too low because of possible tower effects. Nonetheless, even accepting the 0.138 value at Kearny, 12 of the 13 stations had alpha values above 0.143 (1/7), a shear value often used to extrapolate measured data at 50 m to the hub heights of modern turbines. It appears that for the Central Plains, the 1/7 shear assumption is too conservative and that the wind speed can increase with an exponent as high as 0.2 or 0.25. The shear pattern was quite interesting at the six Kansas towers. The highest measured wind speeds at 50 m were associated with the lowest shears, and towers with the lowest wind speed had the highest shears. This indicates that the wind speed tends to become more uniform in Kansas as low as 110 m above the ground. Also, data from 50-m, 80 m, and 110-m levels in the state show there is relatively little change of shear between 50-80 m and 80-100 m. There was insufficient data to come to any conclusions about the variation of shear with height in other parts of the Central Plains.

Diurnal Variability

Figure 2 shows the annual diurnal pattern of alpha values for four of the tall tower stations. These stations, which cover the Plains from Texas to South Dakota, show the diurnal variability that is typical for all 13 towers. The alpha values are lowest (near or just below 0.10) during the middle of the day and highest at night. Sumner, Kansas, is noteworthy because its high annual average alpha value of 0.254 is produced primarily by the extremely strong annual nighttime shear that is close to 0.40 for several hours. The other stations exhibit less extreme nighttime shear values but are still between 0.25 and 0.30. There are some notable seasonal diurnal pattern differences among the stations. Figures 3 and 4 show the diurnal shear pattern at Lamar, Colorado, for the 52-113-m levels, and Washburn, Texas, for the 50-75-m levels for 4 individual months, as well as the annual diurnal pattern.

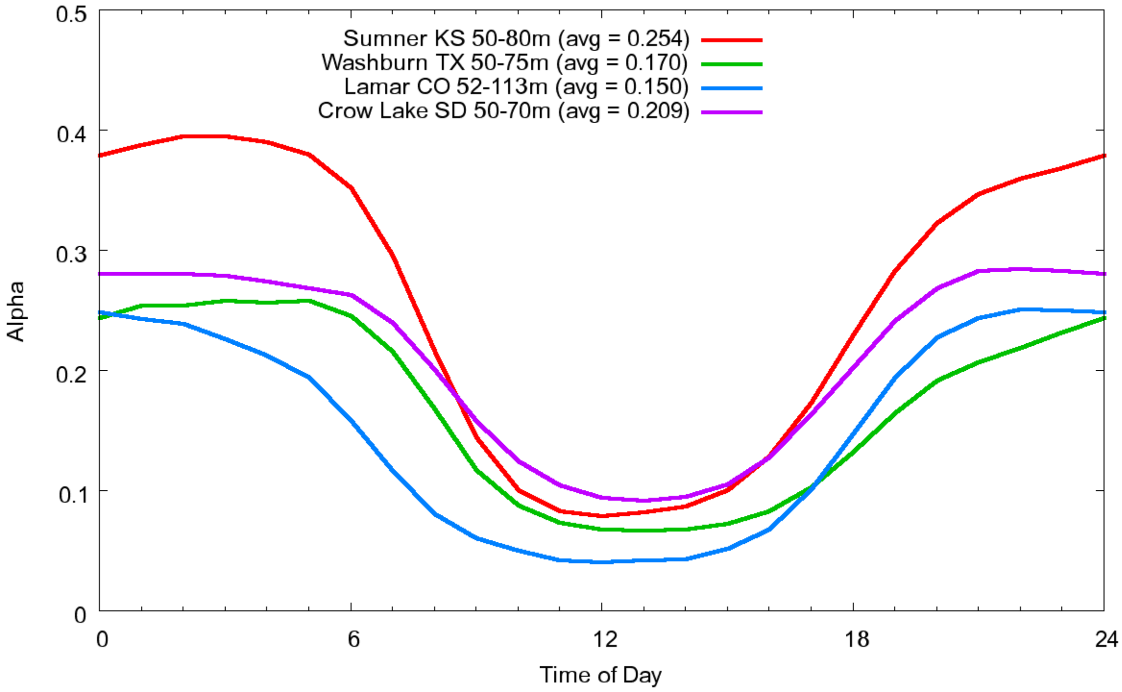

Figure 2. Annual diurnal wind shear exponent pattern for four tall tower stations. Annual average alpha values are in parentheses.

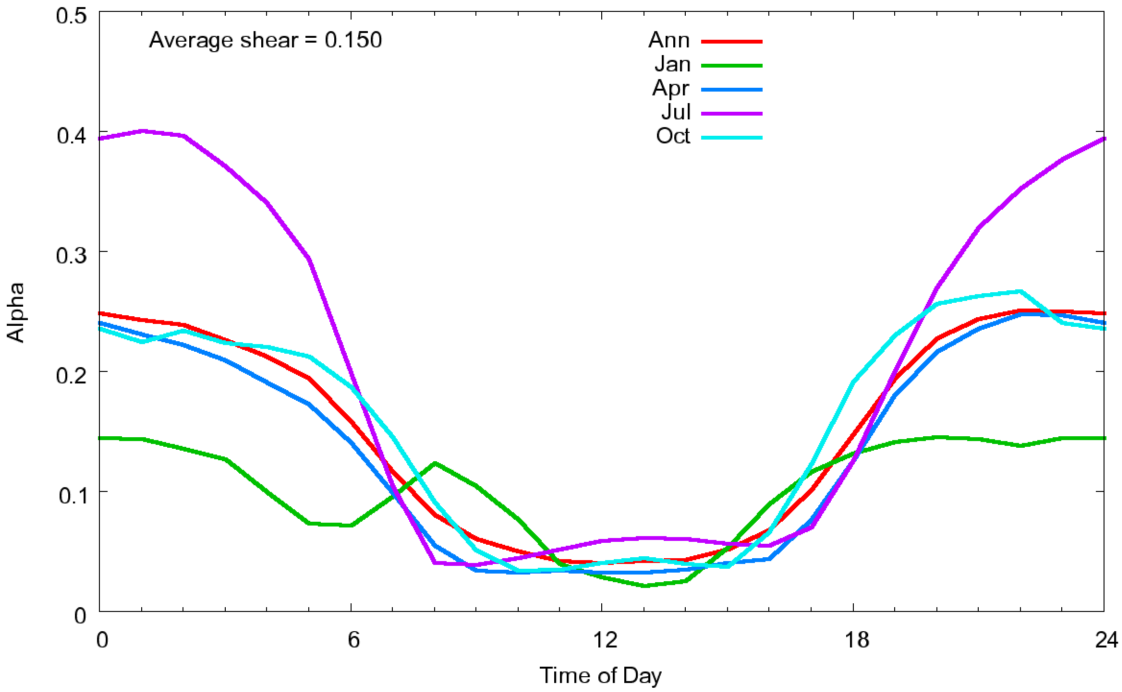

Figure 3. Diurnal wind shear exponent pattern at Lamar, CO, for 52-113-m levels.

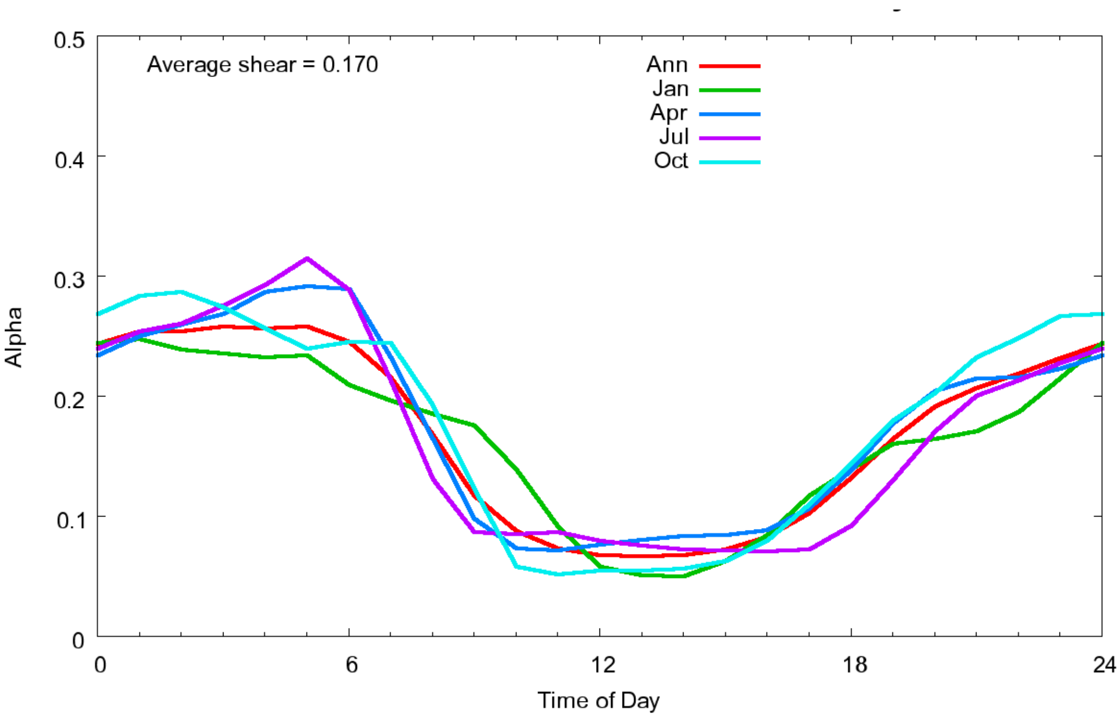

Figure 4. Diurnal wind shear exponent pattern at Washburn, TX, for 50-75-m levels.

The amplitude of the diurnal pattern in July at Lamar is quite large. The daytime alpha values are below 0.1, while the nighttime values peak at 0.4. In contrast, Washburn, Texas, has little seasonal variation of its nighttime alpha values between 0.25 and 0.30. Another station at Crow Lake, South Dakota (not shown), has a moderate spread of its nighttime shear. January values are about 0.2 while April and July values are 03.-0.35.

Seasonal Variability

The seasonal variability of alpha values at the 13 towers can be grouped into two patterns. Stations in northwest Texas, Oklahoma, and Kansas (nine stations) exhibited a flat seasonal pattern of alpha values. There was a slight tendency for maximum values to occur in early autumn and lowest values in late winter, but this tendency could have been due to the short periods-of-record at these sites. The other four towers in central Texas, Colorado, and the Dakotas showed a distinct maximum of alpha values from July to October and a minimum of shear from January through March or April. Figure 5 shows the pattern for three of the four tower locations. The pattern on the figure is based on an approximate 5-week running average of alpha values.

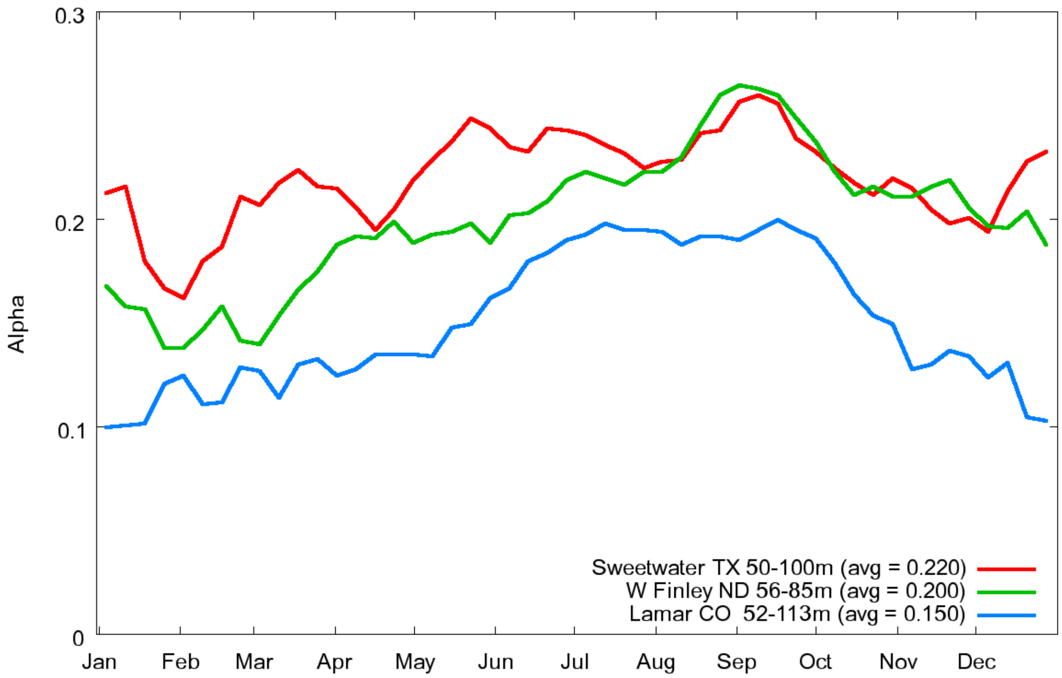

Figure 5. Season variability of alpha values for Sweetwater, W. Finley, and Lamar. The tick marks represent the first day of the month shown on the bottom of the figure. Annual average alpha values are in parentheses.

Shear Variability by Wind Direction

Figure 6 shows the prevailing wind directions in the Central Plains. The prevailing wind directions have a southerly and northerly component. The southerly winds prevail during the warm season and the north winds prevail in the cool season. In addition, westerly winds in the cool season play a significant role in the wind climate of eastern Colorado. The southerly winds predominate in the southern Central Plains. The northerly winds occur a bit more frequently than the southerly winds in the Dakotas.

The shear variability by wind direction was similar throughout the Central Plains from Texas to North Dakota. Figure 7 shows the wind shear variability by direction for five tall towers. The shaded areas represent the prevailing wind directions from the south and north. The curves on the graph are a 30 degree running average of alpha values. The southerly winds at all towers had alpha values between 0.2 and 0.3, with most values in the prevailing wind direction around 0.25. In contrast, the alpha values for the northerly winds were much lower, averaging between 0.1 and 0.2. The high alpha value at Crow Lake, South Dakota for north-northeast winds (20 degrees) reflects only a few observations, the prevailing direction there is from the northwest (320-330 degrees). The west winds at Lamar, Colorado, also had low alpha values between 0.1 and 0.15.

Summary and Conclusions

A study of alpha values at tall towers in the Central Plains revealed some distinct features of wind shear climatology. The annual average wind shear is generally between 0.15 and 0.25, greater than the 1/7 power law alpha value of 0.143. There was greater variation of shear between towers within a region (exemplified by Kansas) than there was between the southern and northern

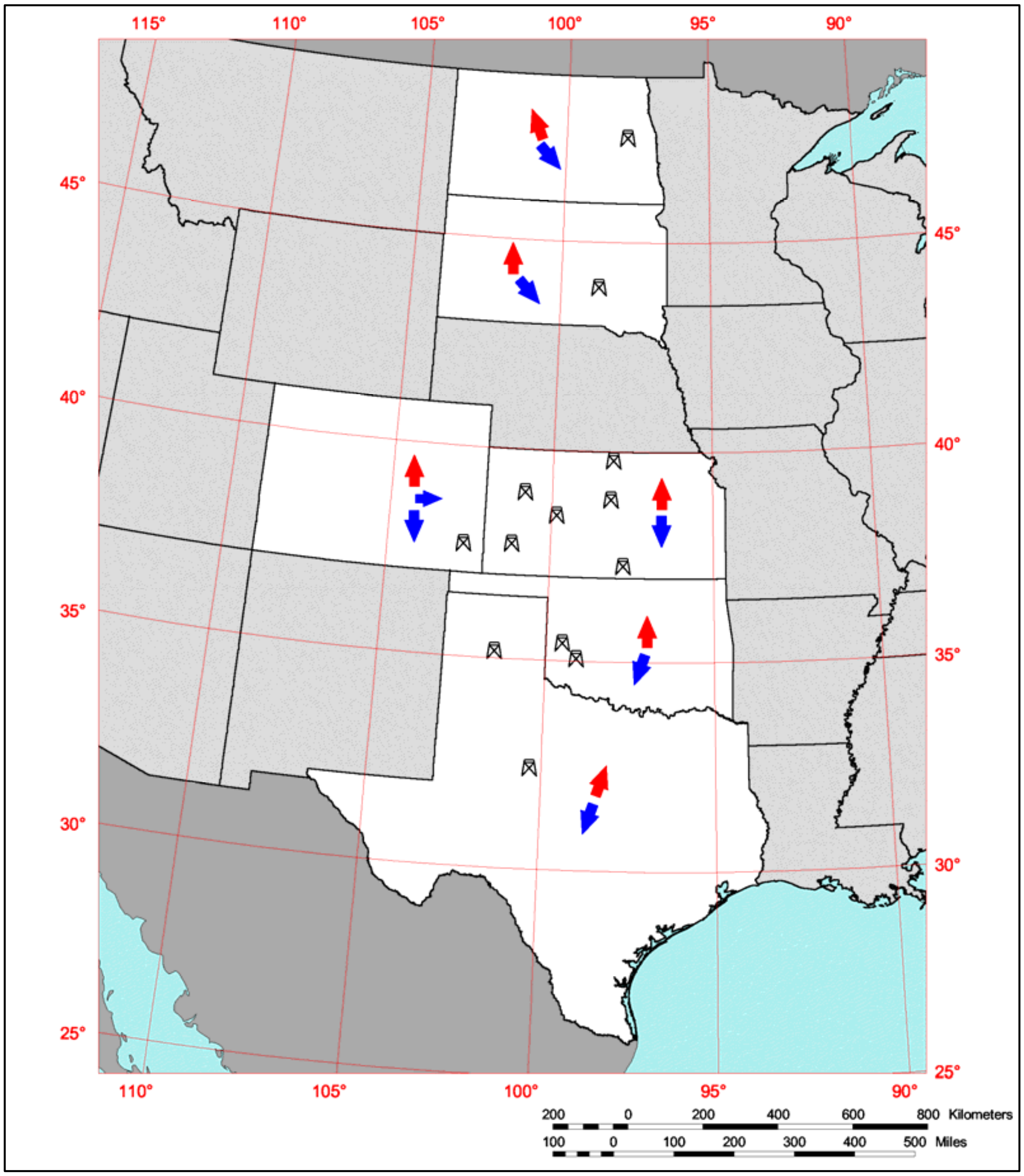

Figure 6. Prevailing wind directions in the Central Plains. Red arrows represent wind directions in the warm season. Blue arrows represent the wind directions in the cool season.

Central Plains. Limited data from Kansas also indicated that the alpha value did not change much with height.

The diurnal shear pattern was similar throughout the region. Daytime alpha values were generally near or slightly below 0.1, and nighttime values were between 0.25 and 0.4. There was some variation in the seasonal diurnal pattern among the towers with Lamar, Colorado, exhibiting tremendous variation in July, while Washburn, Texas, showed little seasonal variation in its pattern.

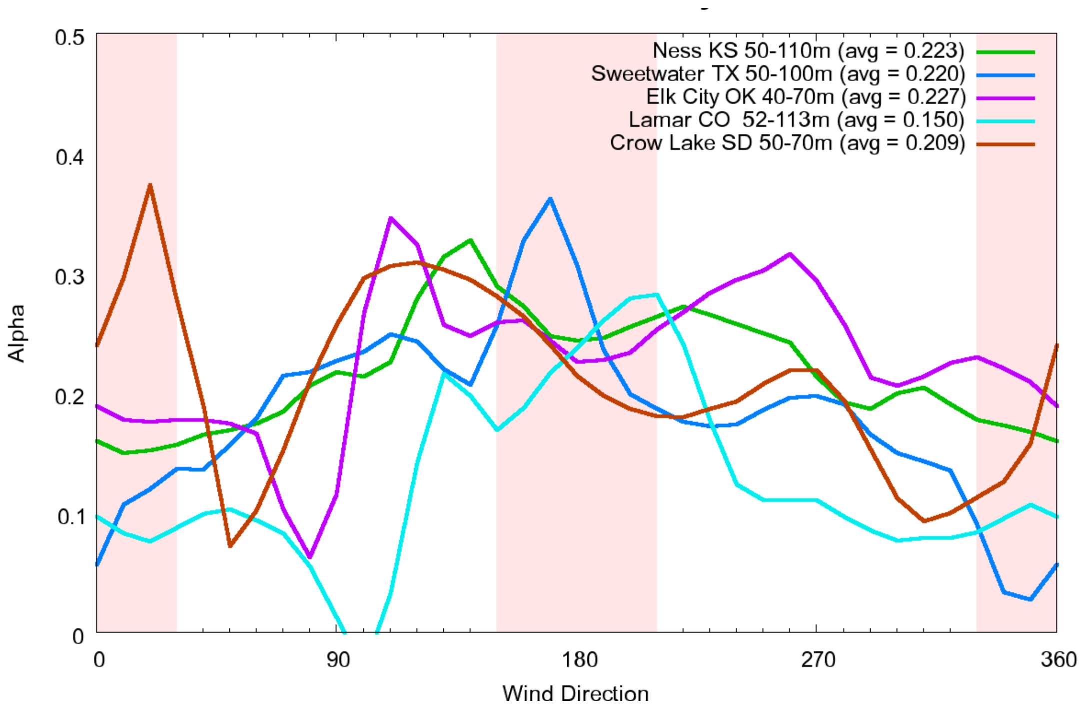

Figure 7. Alpha values by wind direction for five tall towers. The shaded areas represent the prevailing wind directions in the Central Plains. Annual average alpha values are in parentheses.

Winds from the south exhibited higher shear than winds from the north throughout the Central Plains. The alpha value for southerly winds was between 0.2 and 0.3, while northerly winds had values from 0.1 to 0.2.

The seasonal variability of alpha values was grouped into two distinct patterns. Towers in west Texas, Oklahoma, and Kansas had a flat seasonal pattern with no distinct change of alpha values. Stations in central Texas, Colorado, and the Dakotas had a distinct maximum of alpha from July to October and minimum values from January through March and April. One hypothesis for this difference in patterns is that the area of west Texas, Oklahoma, and Kansas is subject to more frequent high-shear southerly winds in winter than areas to their south and north because of the development of surface low pressure areas to the lee of the central Rocky Mountains.

A major problem to overcome when collecting and analyzing tall communication tower data is wind flow interference caused by equipment on the structure and the tower itself. Both elements can affect the wind flow and raise the uncertainty of the measurement data. Organizations that collect tall tower measurements on communication towers should attempt to minimize tower effects, but it is unlikely that all effects can be eliminated. Therefore, it is important not to take wind shear information at face value but to carefully analyze and identify tower effects. This is not always an easy task. We believe that accurate wind direction data are essential for identifying tower effects. In this study however, only about 60% of the measurement levels across the 13 towers had high-quality direction data. Nevertheless, we believe tall tower data will continue to be an important source of wind speed and shear data for levels near and above turbine hub-heights across the United States.

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