THE MODIFICATION OF WIND TURBINE PERFORMANCE BY STATISTICALLY-DISTINCT ATMOSPHERIC REGIMES

Brian Vanderwende, Julie K. Lundquist
Atmospheric and Oceanic Sciences
University of Colorado at Boulder

We would like to thank the utility that provided the turbine data, Vaisala for providing the meteorological data, the National Center for Atmospheric Research (NCAR) for financial support, and our reviewers for their insightful comments.

Brian Vanderwende **brian.vanderwende@colorado.edu**
Julie K. Lundquist **julie.lundquist@colorado.edu**

1. How does the Atmosphere Impact Wind Power?

Traditionally, the wind energy industry represents the relationship between wind speed and turbine power output using the power curve. Prior studies prove this approach to be inadequate:

- Point observations, which cannot measure the wind shear profile, misrepresent the actual amount of power available to the turbine.[1]
- Using atmospheric stability data to derive stability-dependent power curves improves the correlation between wind speed and power output.[2]

We defined atmospheric states based on nacelle winds and measurements of boundary layer stability. These classes were used to generate condition-dependent power curves.

2. Wind Farm Terrain and Instrumentation Platforms

The wind farm was located in the High Plains of Central North America.

- Max elevation difference across farm was ~60m (**Figure 1**)
- Strong diurnal cycle (day to night difference: 3m/s and 10°C)
- 134 turbines with 80m hub height and rotor diameter
- 60m tower located 15km from wind farm measured 10 and 60m winds, temperature, and relative humidity

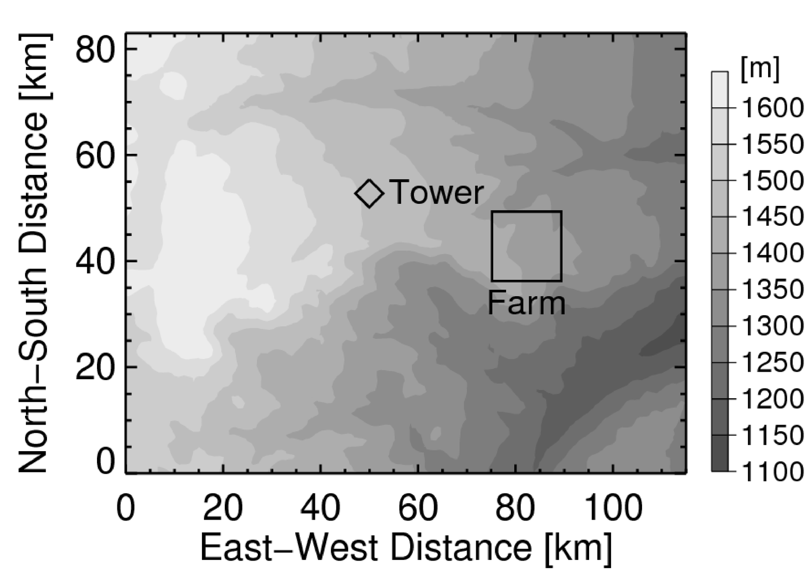

Figure 1: *Wind farm terrain and meteorological tower relative location.*

3. Data Processing and Removing Wakes from the Analysis

- 15-minute averages were computed spanning April-May 2010
- Periods with precipitation were filtered

Wake effects, shown in **Figure 2**, were removed using IEC61400 standard (use of flagged directional cones).

- Wind sectors were removed based on distance to upwind obstruction
- Accounted for any obstruction closer than 20D ≈ 1600m

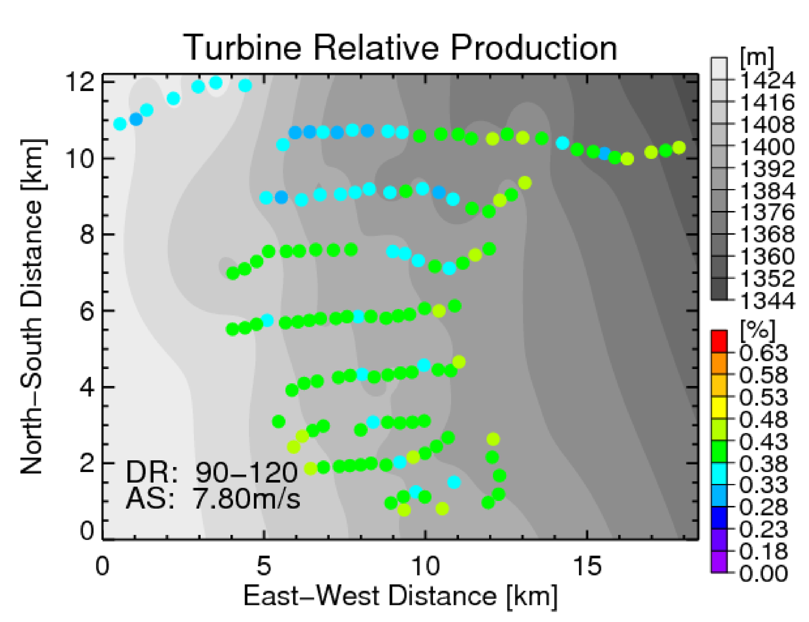

Figure 2: *Power (% of rated) for all turbines when wind was from ESE (7.8m/s avg. spd.)*

4. Binning Strategy: Bulk Layer and Stability Classes

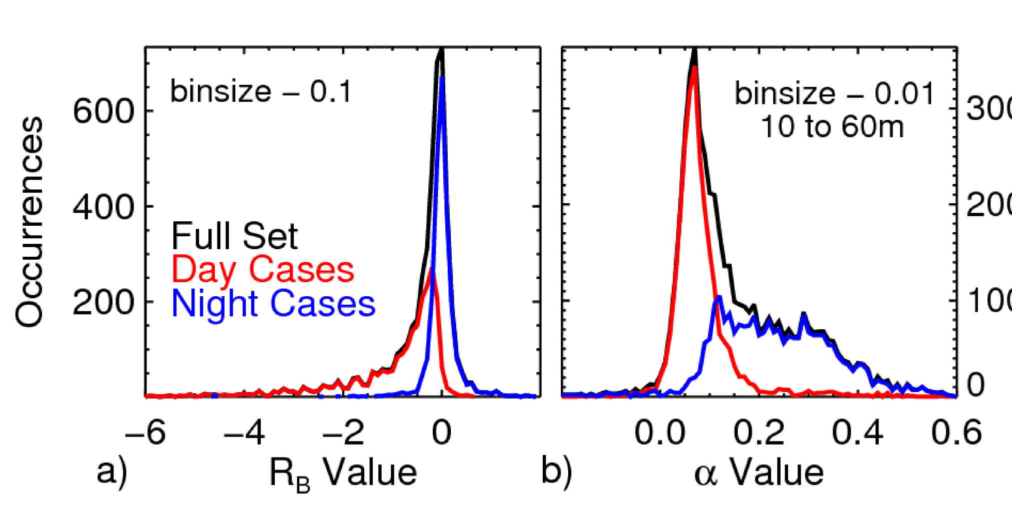

Figure 3: *Histograms of 10-60m a) bulk Richardson number, b) wind power law coefficient. Data is separated by time of day.*

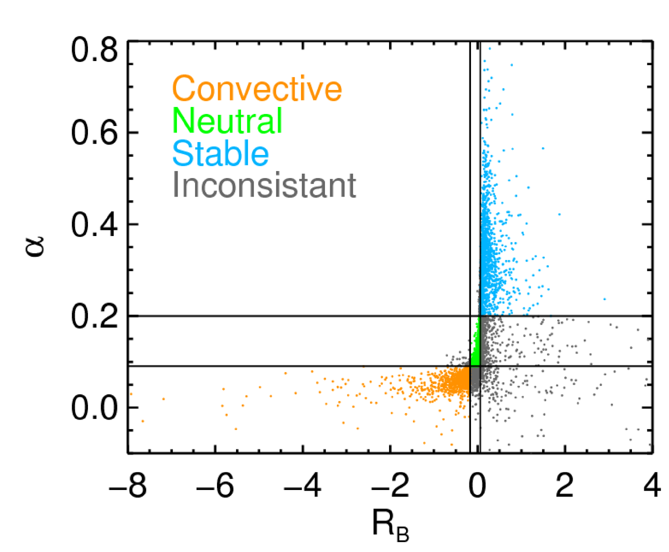

Figure 4: *Comparison of R_B and α. Stability bins are demarcated.*

Day/night distributions of the wind profile power law coefficient (*α*), and bulk Richardson number (*R_B*) were calculated using data from all turbines at all non-flagged times (**Figure 3**). *R_B* and *α* were compared in **Figure 4** to define bounds for convective, neutral, and stable stability classes (**Table 2**). The equations for *α* and R_B are provided for reference.

$$U_2 = U_1 \left(\frac{z_2}{z_1}\right)^{\alpha}$$

$$R_B = \frac{g \cdot \Delta\theta \cdot \Delta z}{\bar{\theta} \cdot (\Delta u^2 + \Delta v^2)}$$

Table 1: α-R_B Stability Classifications

Stable	$0.22 \le \alpha$	$0.01 \le R_B$
Neutral	$0.09 \le \alpha < 0.22$	$-0.4 \le R_B < 0.01$
Convective	$\alpha < 0.09$	$R_B < -0.4$

Conclusions

- Stability classes, created through the successful use of nacelle wind observations, were effective in exposing relative overperformance at this wind farm during periods of high mixing
- Improved power prediction is enabled though the use of condition-based power curves assuming skillful boundary layer forecasts and accurate wind-power relationships

Vanderwende, BJ, and JK Lundquist. 2012. *Environ. Res. Lett.* 7 034035

5. Power by Combined α-R_B Stability Metric

Observed variations in farm-averaged turbine power output, binned by α-R_B based stability classes, are shown (in kilowatts) in **Figure 5**.

Higher performance was observed in convective (day) conditions than in stable (night) for mod. wind speeds of 3.75m/s to 11.75m/s. Max power difference ~98kW.

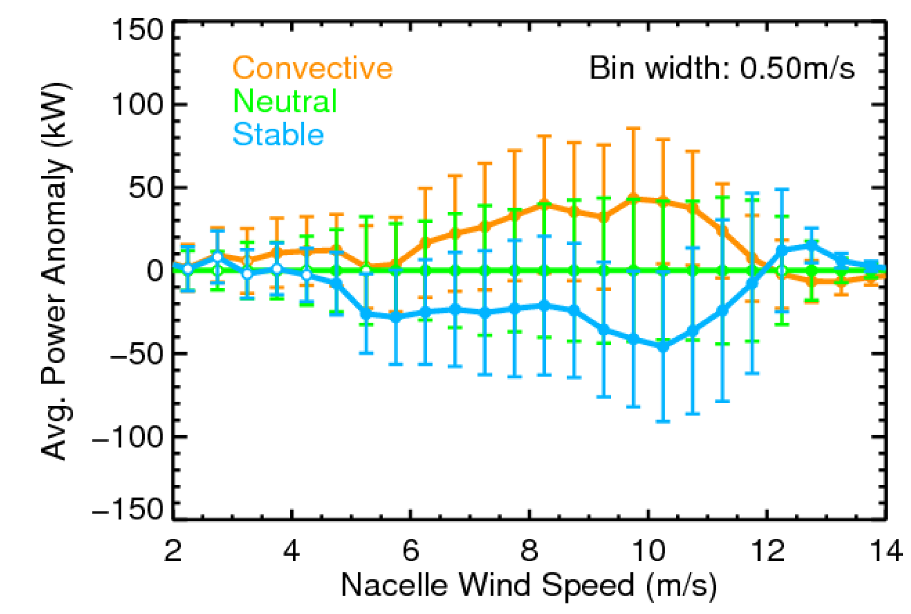

Figure 5: *Power curves segregated by the α-R_B stability classes defined in Table 2. Values are given in terms of anomaly from neutral conditions.*

6. Monte Carlo Testing of Nacelle Wind Significance

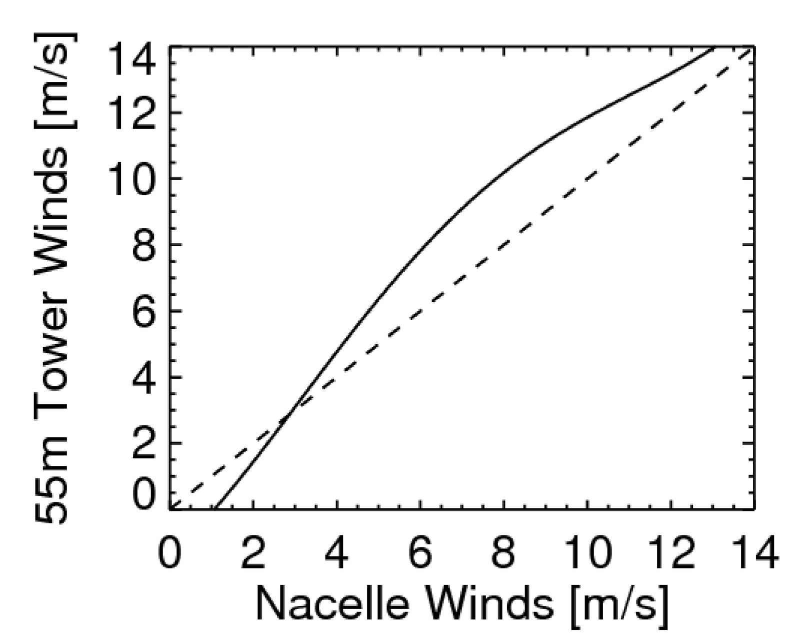

Figure 6: *Assumed systematic bias of nacelle winds vs. free-stream winds observed by a met tower.*

To address uncertainty in using nacelle wind measurements, a 1000-iteration Monte Carlo test was run for 10.25m/s bin using rank-sum test with assumed systematic error (**Figure 6**, adapted from Antoniou and Pederson 1997[3]) and 1m/s random error.

- 100% of tests significant at 0.01 level
- Average maximum power difference was 58kW
  - Smaller than original maximum difference, but still significant

7. Are Nacelle Winds Stability Dependent?

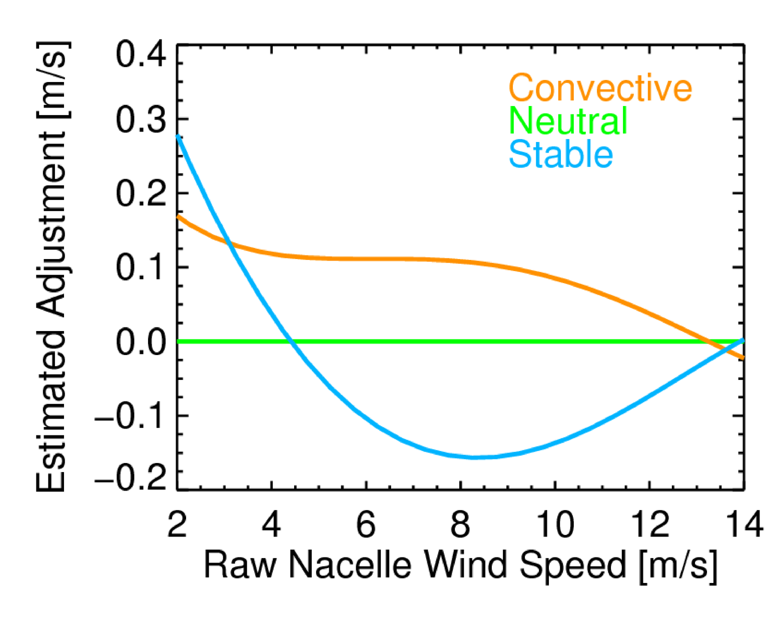

Figure 7: *Possible stability dependencies in nacelle wind to free-stream wind relationship estimated from calculated stability-based power curves.*

An outstanding issue remains: are the nacelle measurements themselves stability dependent? No studies have yet analyzed this question. We calculated stability corrections to nacelle winds that would be necessary to reconcile stability differences in power output (**Figure 7**).

- Stability dependence of nacelle wind to free-stream wind is likely smaller than stability dependence of power output
- We expect that future studies will examine these possible relationships

References

1. Wagner R, Antoniou I, Pedersen SM, Courtney MS, Jorgensen HE. The Influence of the Wind Speed Profile on Wind Turbine Performance Measurements. *Wind Energy* 2009; **12**: 348-362. DOI: 10.1002/we.297
2. Wharton S, Lundquist JK. Atmospheric Stability Impacts on Power Curves of Tall Wind Turbines – An Analysis of a West Coast North American Wind Farm. LLNL Technical Report LLNL-TR-424435, 2010.
3. Antoniou I, Pedersen TF. Nacelle Anemometry on a 1MW Wind Turbine: Comparing the power performance results by use of the nacelle or mast anemometer. Risø-R-941(EN), Roskilde: Risø National Laboratory, 1997.