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Characterizing Inflow Conditions Across the Rotor Disk of a Utility-Scale Wind Turbine

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1. Introduction

Multi-megawatt utility-scale wind turbines operate in a turbulent, thermally-driven atmosphere where wind speed and air temperature vary with height. Changes in the wind profile across the rotor disk influence the power produced by the turbine, while turbulence can produce harmful transient loads.

To characterize the inflow into utility -scale turbines at the National Wind Technology Center (NWTC) near Boulder, Colorado, NREL built two 135-meter inflow monitoring towers (***Figures 1 and 2***). Measurements are synchronized with turbine data systems by GPS time stamps, allowing us to investigate inflow conditions that cause high loads, alarms, or other unusual events.

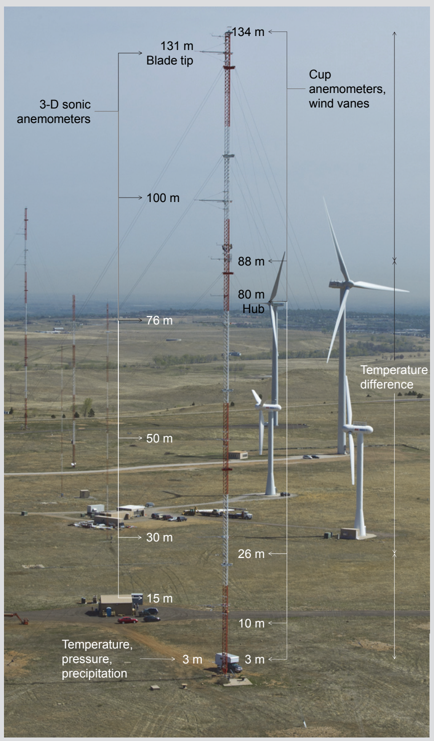

Figure 2. Instrumentation on the 135-m tower measures mean and turbulent properties of flow into a utility-scale turbine. *Photo by Dennis Schroeder NREL/PIX 19023.*

Figure 1. A wind turbine at the National Wind Technology Center near Boulder, Colorado. The hub is 80 m above ground. The inflow monitoring tower (left, WNW from the turbine) is 135 m tall. *Photo by Dennis Schroeder NREL/PIX 19013.*

2. Data Processing

We acquire data at 20 Hz from 73 instrument channels on the 135-m tower (***Figure 2***). That data is cleaned and converted into 10-minute summaries of the inflow conditions (***Figure 3***). These summaries include:

- Quality measures
- Average data from each instrument
- Profiles of wind speed, direction, and temperature
- Turbulence, including turbulent kinetic energy (TKE), turbulence intensity, and dissipation rates
- Stability measures, including sensible heat fluxes, Richardson Numbers, and Monin-Obukhov length.

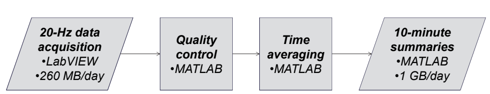

Figure 3. Processing 10-minute data from raw 20-Hz files to human- and machine-readable summaries.

3. Results

Winds at the NWTC are strongly seasonal, with frequent strong NW winds during the winter, and less common, weak southerly and northerly winds (***Figure 4***).

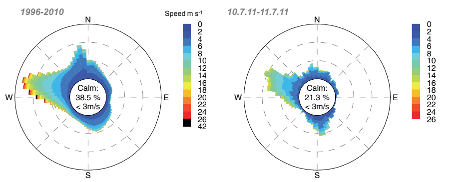

Figure 4. Wind roses at hub height. Left, 1996-2010 at the west end of the site. Right, October 2011 at a turbine test stand.

Stability has a clear diurnal cycle, changing from unstable during the day to stable at night (***Figure 5***).

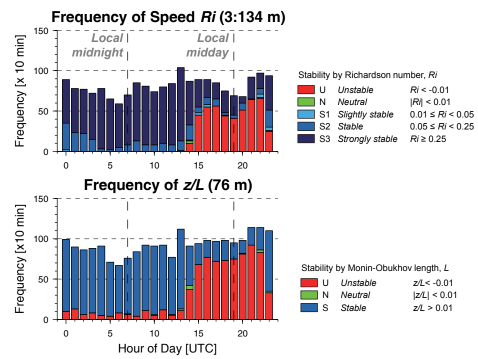

Figure 5. The diurnal stability cycle for winds greater than 3 m/s in October 2011. Data are grouped into unstable ('U'), neutral ('N'), and stable (S1-3) conditions.

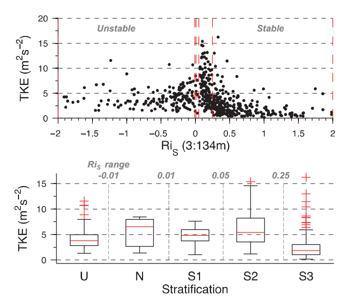

Figure 6. TKE as a function of stability in October 2011. Data are for wind speeds greater than 3 m/s from all directions.

Turbine inflow conditions during 1 month vary with wind direction and stability. Stability changes wind speed profiles and turbulence properties (***Figures 6 and 7***). Upwind terrain also impacts the turbine inflow, with flow over mountainous terrain adding turbulent kinetic energy.

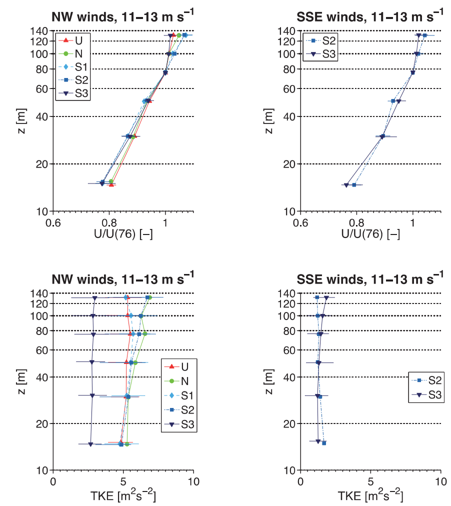

Figure 7. Changes in mean flow profiles and turbulent kinetic energy as a function of wind direction and stability. Data are from October 2011. Profiles are grouped into unstable (U), neutral (N), and increasingly stable (S1 – S3) conditions using the Richardson number from 3 to 134 meters above ground.

4. Conclusions

Inflow characterization at the NWTC by equipment on tall towers, and remote sensing, coupled with turbine monitoring, is helping us to understand the role that inflow turbulence, shear, and stability play in turbine performance and reliability.

Measurements taken during October 2011 show that mean flow and turbulence change with wind direction and stability, and that neutral conditions are rare. Profiles of wind speed and turbulence frequently change near turbine hub heights compared to what would be expected from measurements nearer the ground. These changes, together with high variation in stability, show a need for the use of direct measurement of inflow conditions rather than extrapolation from lower elevations.

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