Effect of wind turbine wakes on summer-time wind profiles in the US Great Plains

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Wind Energy & Agriculture

- Wind energy currently provides 3% of U.S. electricity and accounts for 35% of new generating capacity.
- Midwest US is one of the richest **wind** & **agriculture** resources (Figures 2 & 3)
- How do wind turbines affect local wind patterns?
- Do the changed wind patterns alter surface fluxes?
- Do changes in surface fluxes affect biological growth?
- What does this mean for the economic and technological futures of co-located wind energy & agriculture?

Figure 1: A multi-MW wind turbine operating in a corn field.

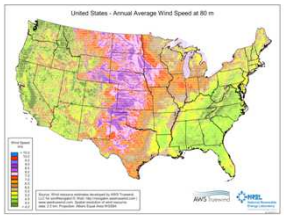

Figure 2: 80m above surface wind resources in the US
From: http://www.windpoweringamerica.gov/pdfs/wind_maps/us_windmap_80meters.pdf.

Figure 3: Corn production in the United States.
From: http://www.usda.gov/oce/weather/pubs/Other/MWCACP/Graphs/USA/corn.pdf

Experiment Description

- From 2 Jul to 16 Aug 2011, teams from CU-Boulder/ NREL, NCAR, & Iowa State University collected meteorological measurements from an operating wind farm in **central Iowa**.
- Surface station measurements and LIDAR wind and turbulence profiles were taken on opposite sides of a row of multi-MW wind turbines.
- Turbine **rotors span** from **40m to 120m** above the surface with a **hub height of 80m**.
- The table below details the available measurements made at each locations show in the map to the right.

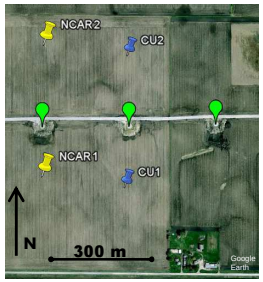

Figure 4: Map of the experiment location. = Wind Turbine = NCAR Surface Station = CU Wind LIDAR

Instrument	Measurement	Height AGL (m)	Output Frequency
Windcube LIDAR (CU-Boulder)	3 component wind speed and variance	40, 60, 80, 100, 120, 140, 160, 180, 200, 220 (adjustable)	2 min.
CSAT3 Sonic Anemometer (NCAR)	3-D wind speed, Temperature	4.5 m	20 Hz
Infrared Gas Analyzer (NCAR)	H_2O, CO2 Concentration	4.5 m	20 Hz
Pressure Transducer (NCAR)	Pressure	2 m	1 Hz

Convective Boundary Layer

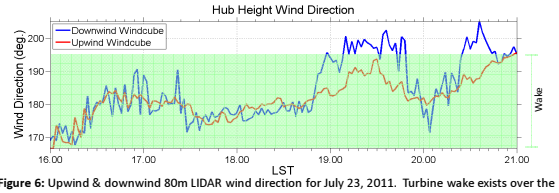

Figure 6: Upwind & downwind 80m LIDAR wind direction for July 23, 2011. Turbine wake exists over the downwind LIDAR for wind directions of 167° to 195° assuming a 5° wake expansion.

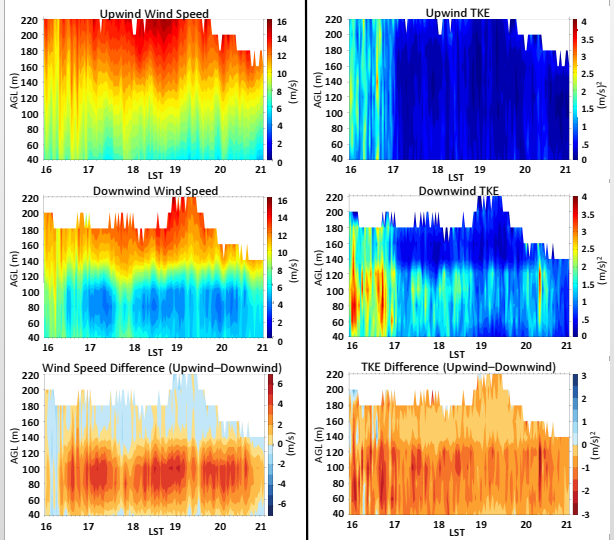

Figure 7: Upwind, downwind and difference of wind speed for July 23, 2011.

Figure 8: Upwind, downwind and difference of TKE for July 23, 2011.

- Wind Speed is calculated from the two horizontal wind components
- Maximum velocity deficit in wake is **above hub height**
- Wind speed above the rotor disc is slightly affected by wake

- Turbulent Kinetic Energy (TKE):

$$TKE = \frac{\sigma_u^2 + \sigma_v^2 + \sigma_w^2}{2}$$

- TKE increases by as much as $3 m^2/s^2$ in the wake
- Maximum TKE enhancement occurs in top half of rotor disk, coincident with maximum velocity deficit

Stable Boundary Layer

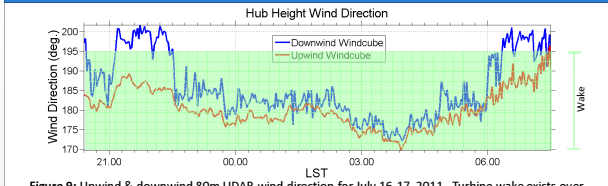

Figure 9: Upwind & downwind 80m LIDAR wind direction for July 16-17, 2011. Turbine wake exists over the downwind LIDAR for wind directions of 167° to 195° assuming a 5° wake expansion.

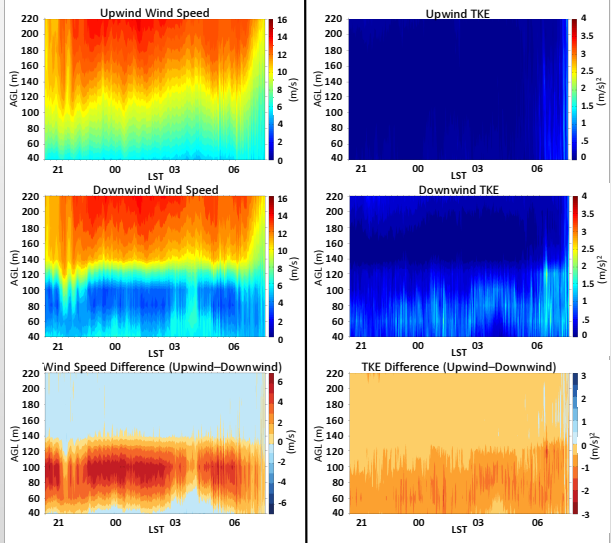

Figure 10: Upwind, downwind and difference of wind speed for July 16-17, 2011.

Figure 11: Upwind, downwind and difference of TKE for July 16-17, 2011.

- Wake velocity deficit is larger for stable conditions despite slower wind speeds
- Similar behavior aloft between stable and unstable conditions

- Enhanced TKE exists in shallow layers **closer to surface** for stable BL
- TKE maxima occur at several levels within turbine rotor disk

Comparison of two LIDARs

- LIDARs were deployed side-by-side for 2 days at the southern location to quantify measurement difference.
- Results (**Figure 5**) verify agreement between the LIDARs
- Following this short verification period, CU2 LIDAR was moved to the northern location

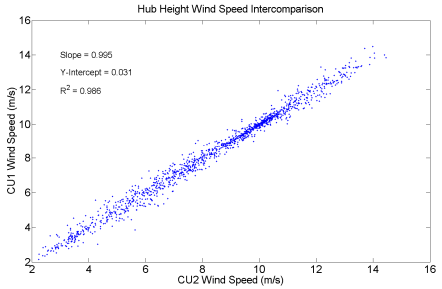

Figure 5: Horizontal wind speeds at 80m for the two Windcubes during the 2 day intercomparison period

Conclusion

- Upwind and downwind LIDAR profiles enable characterization of turbine wake effects
- A **momentum deficit exists in turbine wake** for both stability conditions.
  - Momentum deficit is larger in stable conditions although upwind wind speed is lower in stable conditions than in convective
  - The maximum deficit is found above hub height
- **Turbulence Kinetic Energy increases in the wake** for both stability conditions
  - Maximum TKE enhancement occurs during stable conditions
  - TKE differences are observed at the lowest altitude observable by LIDAR, suggesting wake enhancements of TKE may impact the surface
- Ongoing analysis in conjunction with surface station data will explore wake impacts on surface
- LIDAR profile dataset may be useful for testing large-eddy simulations of turbine wake dynamics

Acknowledgements

This work would not be complete without help and support from Dr. Gene Takle's group at Iowa State University, the National Renewable Energy Laboratory (NREL), the National Center for Atmospheric Research (NCAR), NRG Systems Inc., and the cooperation of the property owners and wind farm owner/operator.