Three-Dimensional Structure of Wind Turbine Wakes as Measured by Scanning Lidar

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Abstract

Based on lidar wind measurements at the CWEX-13 field campaign in a wind farm in Iowa, we extend, present, and apply a quantitative algorithm to assess wake parameters such as the velocity deficits, the size of the wake boundaries, and the location of the wake centerlines. We focus on wakes from a row of four turbines to explore variations between wakes from the edge of the row (outer wakes) and those from turbines in the center of the row (inner wakes). Using multiple PPI scans at different elevations, a three-dimensional structure of wakes from the row of turbines can be created. Wakes erode very quickly during unstable conditions, and can in fact be detected primarily in stable conditions in the conditions measured here. During stable conditions, important differences emerge between the wakes of inner turbines and the wakes of outer turbines. Further, the strong wind veer associated with stable conditions results in a stretching of the wake structures, and this stretching manifests differently for inner and outer wakes.

Keywords: *Scanning lidar, Wakes, Wind veer.*

Introduction

The slower wind speeds and increased turbulence that are characteristic of turbine wakes have considerable consequences on large wind farms: turbines located downwind generate less power and experience increased turbulent loads [1],[2]. Therefore, wakes need to be studied and understood in order to maximize the efficiency of wind energy production; wake characterization from field data can validate and improve numerical models. Lidars [3] and radars [4] have been widely used recently to characterize wind turbine wakes. Herein, we analyze scanning lidar and profiling lidar measurements from the CWEX-13 field campaign in a large wind farm in Iowa, and we extend an individual wake detection algorithm [5] to characterize multiple wakes. The three-dimensional structure of wakes from a row of four turbines is assessed, in terms of velocity deficit, wake width, and wake centerlines.

Data and Methods

We analyze the scanning lidar and profiling lidar measurements from the CWEX-13 observational campaign which took place in a wind farm in central Iowa during summer 2013. Three profiling lidars were deployed at the site during the field campaign, and a LEOSPHERE WINDCUBE 200S scanning lidar was colocated with one profiling lidar. We analyze data from PPI scans performed at six different elevation angles, giving a range of different vertical positions. We use measurements from a sonic anemometer at a nearby surface flux station to assess atmospheric stability via the Obukhov length. We focus on two days (23 and 26 August 2013) with southerly wind conditions.

The line-of-sight velocity (LOSV) measured by the scanning lidar during the PPI scans can be analyzed to determine wake characteristics and how they evolve as the wakes propagate. Aitken et al. [5] proposed a wake detection algorithm and applied it to the wake from a single turbine. Here we expand the same algorithm to characterize wakes from a row of four turbines. Measurements of LOSV at each range gate in each PPI scan are fitted to two different models: the first is for ambient flow conditions without wakes, the second represents each of the four wakes as a Gaussian function subtracted from uniform ambient flow. An extra sum-of-squares F test is applied to determine if the second model, which is naturally suited to better fit data considering its higher number of parameters, is significantly better than first model in fitting the data. The wake characteristics database, resulting as output of the application of the wake detection algorithm, is then used to study how wake characteristics evolve in 3D space.

Results

Atmospheric stability has a major impact on wind turbine wake evolution: during unstable conditions, the algorithm does not detect wakes at least 40% of the time. Moreover, wakes in stable conditions persist for long distances downwind and are detected in most of the scans up to approximately ~12 D downwind. In unstable conditions, enhanced turbulent mixing erodes the wakes erode more quickly.

Velocity deficit decreases with downwind distance, as the speed reduction in the wake becomes smaller due to the entrainment of free-stream surrounding air. Moreover, we find that wakes from outer turbines have lower velocity deficits than the wakes from inner turbines, with a difference up to 15%.

The wake widths increase downwind from the turbine, exceeding 2D after a downwind distance of 8-10 D, with a systematic dependence of the detected wake widths on the relative position between the wake and the scanning lidar: the scanning lidar systematically identifies as the widest the wake which, at a given downwind distance, is the most perpendicular to the laser beam. This result is due to the relationship between the viewing angle and the aspect ratio of the lidar retrieval “pixels”, which are related to the relatively long range gate (50 m) and relatively narrow azimuthal resolution (0.5°).

A clear change in the position of the wake centers is detected between low and high vertical levels. This change of the wake centerline with height causes a stretching of the vertical structure of the wakes. Although the angular change in the wake centerline at different vertical levels is systematically detected, the angular difference between the wake centerlines at the different vertical levels is always much smaller than the inflow wind veer, perhaps due to the rotation of the wake itself. Moreover, wakes from outer turbines often present a larger angular difference in wake centerlines compared to wakes from inner turbines.

Conclusions

Wakes from a row of four turbines have been characterized using line-of-sight wind speed measurements from PPI scans performed by a scanning lidar. Data were collected in late summer 2013 during the CWEX-13 field campaign, in a wind farm in a flat region of central Iowa. The wake characterization algorithm proposed by Aitken et al. [5] has been extended to assess wakes from multiple turbines.
The 3D evolution of wake characteristics (velocity deficit, wake width, and wake centerline) has been studied. For the first time we have quantified the effect of ambient wind veer on the stretching of wakes. In fact, the angular change in the wake centerlines at different heights is systematically much lower than the wind veer registered at the same heights. These results can become critically important to assess and improve large-eddy simulations of wakes as well as to suggest improvements to mesoscale parametrizations to account for subgridscale wake interactions. Moreover, wind energy companies can also benefit from our results in trying to enhance the quality of low-order wake models currently used.

References

1. Barthelmie, R. J., Pryor, S., Frandsen, S. T., Hansen, K. S., Schepers, J., Rados, K., Schlez, W., Neubert, A., Jensen, L., and Neckelmann, S., 2010: Quantifying the impact of wind turbine wakes on power output at offshore wind farms, Journal of Atmospheric and Oceanic Technology, 27, 1302–1317.
2. Sathe, A., Mann, J., Barlas, T., Bierbooms, W., and van Bussel, G., 2013: Influence of atmospheric stability on wind turbine loads: Atmosphericstability and loads, Wind Energy, 16, 1013–1032.
3. Banta, R. M., Pichugina, Y. L., Brewer, W. A., Lundquist, J. K., Kelley, N. D., Sandberg, S. P., Alvarez II, R. J., Hardesty, R. M., and Weickmann, A. M., 2015: 3D volumetric analysis of wind turbine wake properties in the atmosphere using high-resolution Doppler lidar, Journal of Atmospheric and Oceanic Technology, 32, 904–914.
4. Hirth, B. D., Schroeder, J. L., Gunter, W. S., and Guynes, J. G., 2012: Measuring a utility-scale turbine wake using the TTUKa mobile research radars, Journal of Atmospheric and Oceanic Technology, 29, 765–771.
5. Aitken, M. L., Banta, R. M., Pichugina, Y. L., and Lundquist, J. K., 2014: Quantifying wind turbine wake characteristics from scanning remote sensor data, Journal of Atmospheric and Oceanic Technology, 31, 765–787.