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# A wind turbine wake in changing atmospheric conditions: LES and lidar measurements

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Abstract. This work aims to reproduce the measured atmospheric conditions during one day of the CWEX-11 campaign, with a transient LES. The selected period includes several interesting atmospheric conditions for wind power generation such as a nocturnal low-level jet, a highly turbulent convective daytime boundary layer, as well as a distinct evening transition between daytime and nocturnal boundary layers. To include synoptic conditions, large-scale forcing profiles for the LES were derived from a mesoscale simulation with the WRF model. A comparison with lidar measurements shows that the trend of the wind conditions and the diurnal cycle is well replicated by the model chain. Selected periods of the day are simulated with the NREL 5MW turbine model, followed by a qualitative comparison of measured and simulated wakes. We find a strong dependency of the meandering and the shape of the wake on wind profile and turbulence, while a categorization by Obukhov length is less representative for the different conditions. As the veer in the wind profile increases, the deviation of the wind direction at hub height from the direction of the largest wake impact also increases.

#### 1. Introduction

The use of ground-based or nacelle-based lidars has rapidly increased knowledge about wind turbine wakes in recent years [1, 2, 3]. Lidars are mostly cheaper and are more mobile than meteorological masts, can be easier deployed in complex terrain and the remote technique allows measurements of the wake at a range of heights and distances. Still a single lidar cannot completely probe the three-dimensional structure of the wake as it evolves in time, leading to uncertainties in our understanding of wake evolution.

One method to complement lidar measurements of wind turbine wakes are numerical experiments [4, 5, 6]. Numerical experiments can deliver a temporally-resolved three-dimensional wind field to study the flow regions that were not observed. The possible benefit of the complementary simulations depends on the ability to reproduce, in the numerical environment, the aerodynamic behaviour of the turbine as well as the state of the atmospheric boundary laver.

Mesoscale models, with typical horizontal grid sizes in the order of 1-10 kilometers, can simulate the mesoscale and synoptic development of the atmospheric boundary layer. These models enable studies of the changing wind conditions at a wind farm site but are not highly resolved enough to model the aerodynamics of turbines and the interaction of turbines by means of their wakes. An approach for further downscaling towards smaller scales has been presented in Vollmer et al. [7, 8] using a Large-Eddy-Simulation model (LES), driven by the data of

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Figure 1. WRF model domain with the wind farm marked as cross in the innermost domain and topographic map showing the setup of the CWEX-11 campaign. Wind turbines (B1-B6), lidars (WC1-2) and surface flux stations (NCAR1-4).

a mesoscale model. The study showed that it is possible to replicate observed offshore wind conditions with a transient LES and that the simulated wakes show similar behaviour to the measured wakes.

In this paper we use the approach to simulate a case that is more interesting regarding the influence of atmospheric stability on wakes, as it represents an onshore day characterized by a strong diurnal cycle and a well-pronounced evening transition. The case study selected is one day (9 July) of the CWEX-11 measurement campaign in 2011 in Iowa, USA. From the selected day, lidar measurements from two vertical profiling lidars, placed upstream and downstream of a 1.5 MW turbine, and measurements from an upwind flux station are used. A part of the chosen day has been studied by means of quasi-stationary LES in Mirocha et al. [4]. Here we use the transient approach to simulate almost the whole day. During selected time periods, that represent different atmospheric stability conditions, wind turbine wake simulations with the NREL 5MW model turbine [9] are performed. Due to the different dimensions of the turbines in measurement and simulation, we performed a qualitative comparison in this study, and focused on the potential surplus of information that can be extracted from the accompanying simulations.

#### 2. Methods

#### 2.1. Observations

The Crop/Wind Energy EXperiment 2011 (CWEX-11) took observations along a row of wind turbines of a 200-turbine wind farm in Iowa, USA, from June to August 2011 [10, 2]. The turbines are 1.5 MW turbines from General Electric with a rotor diameter (D) of 77 m and a hub height of 80 m. The wind farm is situated in a flat region characterized by extensive agriculture (corn).

Two WindCube v1 lidars (WC1-2) measured the vertical wind profile at altitudes from 40

m to 220 m AGL. The lidars were placed 2.1 D south and 3.2 D north of one turbine of the southernmost row of the wind farm to capture free flow as well as wake flow for the prevailing southerly wind. Surface flux stations were also sampled upwind and downwind in similar fashion but for the next turbine to the west (Fig. 1). The original measured wind components from the lidars at 0.25 Hz were averaged every 2 minutes. In this paper we do not further analyse the uncertainty of the wind profile measurements that come from the velocity azimuth display (VAD) technique. For the effect of the individual beams and the volume averaging on the flow reconstruction by the lidar, especially inside wind turbine wakes, the reader is referred to Lundquist et al. [6].

Five-minute averages of the 20-Hz measurements from the sonic anemometers and gas analysers were made available from the National Center of Atmospheric Research (NCAR). The instruments were operating at 4.5 m above ground level (AGL). The Obukhov length was calculated as

$$L = -\frac{u_*^3 T_v}{k \, g \, w' T_v'} \tag{1}$$

using the friction velocity  $u_*$ , derived from the vertical fluxes of momentum in the streamwise and spanwise directions, the vertical kinematic heat flux  $\overline{w'T'_v}$  and the virtual temperature  $T_v$ measured by the sonic anemometer. The factors k and g are the von-Kármán constant and the gravitational acceleration, respectively. The bulk Richardson number (Ri) was calculated as an alternative measure for atmospheric stability following Stull [11].

$$Ri = \frac{g \Delta \Theta_v \Delta z}{\Theta_v \left[ (\Delta u)^2 + (\Delta v)^2 \right]}$$
(2)

with  $\Delta\Theta_v$ ,  $\Delta u$  and  $\Delta v$  the difference between the virtual potential temperature  $\Theta_v$ , the streamwise velocity u and the cross-stream velocity v at two different measurement heights separated by  $\Delta z$ . As temperature measurements were not available above 10 m, Ri could only be calculated from the model results. The bulk Richardson number was calculated between the surface and the hub of the simulated turbine  $(Ri_0^{90})$  and between the lower and upper rotor tip  $(Ri_{30}^{150})$ 

#### 2.2. Models

The model chain for the simulation of the case consisted of two models. The Weather Research and Forecasting (WRF) model [12] was used to simulate the changing wind conditions at the site during the day, required as large-scale forcing input [8] for the PArallelized Large-Eddy Simulation Model (PALM) [13].

Model version 3.6.1 of WRF was used for a 30 h simulation starting at 00 UTC (five hours ahead of local standard time LST) on 9 July [14]. Initial and boundary conditions for the oneway-nested domains were derived from the Global Forecast System (GFS) reanalysis, using the standard procedures as defined in Skamarock et al. [12]. The smallest domain covered the entire state of Iowa with 990 m horizontal resolution and a dimension of 571 x 511 grid points. Vertical levels were stretched towards the top with 70 levels in total and a vertical spacing of about 22 m in the lower 300 m AGL. The MYNN Level 2.5 scheme [15] was used for the TKE closure in the planetary boundary layer. A more detailed description and analysis of the WRF simulation is presented in Lee and Lundquist [14].

To create the large-scale forcing profiles for the LES, the hourly model results from WRF were horizontally averaged on a domain of 80 km x 80 km to average out pressure perturbations on smaller scales (See Vollmer et al. [8] for a discussion on the necessary size of the averaging domain). The domain was centered around the turbine, where the lidar measurements were made. The mean geostrophic wind vector at this location was calculated from the large-scale pressure gradients over the domain. The vertical profiles of the horizontal advection

of temperature, humidity and horizontal momentum as well as the geostrophic wind speed components were used for the large-scale forcing of PALM. To prevent the LES from drifting from the WRF results, a nudging scheme was used with a relaxation time constant of  $\tau = 4$  h. Nudging was applied to the domain averaged vertical profiles of potential temperature, humidity and the horizontal wind components. More details about the preparation and application of the large-scale forcing can be found in Vollmer et al. [8].

Revision 1928 of PALM [13] was used with the same numerical schemes as in Vollmer et al. [16]. Simulations were run on a 640 x 640 x 160 grid with 5 m resolution. Above 600 m, vertical stretching of the grid was applied. The highest grid point is centered at 1715 m. Monin-Obukhov similarity theory is used at the bottom boundary with a surface roughness length of momentum of  $z_0 = 0.14$  m, which represents the average roughness length inside of the WRF averaging domain. Roughness lengths of scalars were a factor of ten times smaller.

Sufficient information to implement the GE turbine was not available. However, to allow for a qualitative comparison of the wake behaviour, an ADM-R [17] representation of the NREL 5MW [9] research turbine model was used for wake simulations. The turbine has a rated power of 5 MW, a rotor diameter of 126 m and its hub is located at 90 m.

Adaptation of the rotor speed of the NREL 5MW turbine to the changing wind is ensured by a generator torque controller below rated wind speed (11.4 ms<sup>-1</sup>) and a collective pitch controller above rated wind speed. The turbine orientation is controlled by a yaw controller based on a 30second running average of the wind direction at the turbine hub. The yaw actuator is activated for a misalignment of more than 5 degrees. As the turbine influences the turbulence and fluxes inside the cyclic LES domain, the maximum length of individual turbine simulations was 35 minutes, of which the first 5 minutes were discarded as the wake was still developing. From the total 30 h of simulation, the first eight hours were discarded as they are used for the spin-up of both the WRF model and the LES.

#### 3. Results

In the following we will discuss the performance of the model chain to simulate the state and development of the atmospheric boundary layer, followed by an analysis of the wake simulations. Figure 2 compares the results of the simulation of the ambient flow with the large scale forcing input data, the lidar measurements and the flux measurements. The wind speed and wind direction follow the trend of the input data, but deviations from the measurements can reach more than 2 ms<sup>-1</sup> and 20° for wind speed and wind direction, respectively. The measured surface kinematic heat flux (Fig. 2g) is well replicated by the WRF simulation with a negative heat flux during nighttime and a positive one during daytime between 08:00 LST and 18:00 LST. The LES kinematic heat flux almost equals that of WRF. The diurnal cycle of the 2-min turbulence intensity (I) is well reproduced in magnitude, and the moment of restratification, quantified by the sign change of L, during the evening transition matches very well. The largest deviation of the LES from the WRF input is found in the measures for the vertical wind profile (Fig. 2e,f). The LES does a better job to simulate the veer of the wind profile of the nocturnal boundary layer than the mesoscale model, which appears to be limited to a maximum veer of  $\Delta WD = 10^{\circ}$  between the two selected heights. The shear of the wind profile on the other hand is well replicated by WRF with the exception of a period at the end of the night where the measured wind shear increases in the measurements. A low-level jet occurs in the simulation between 03:00 LST and 07:00 LST with a core height between 200 m and 300 m (not shown), thus clearly above the maximum rotor height. The core height is consistent with the lidar measurements, as no local maximum of the wind speed can be found in the measured profiles below 220 m.

Based on the results of the simulation of the ambient flow, three periods of 1.5 hours, marked by the shaded areas in Fig. 2, were selected in which a simulation with a turbine was conducted.

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**Figure 2.** Comparison between one-hour running means (black bold), short-term averages (grey) of measurements, the large-scale forcing input from WRF (dots) and the domain averaged LES results (blue thin). (a) Two-minute hub-height wind speed, (b) hub height turbulence intensity, (c) hub-height wind direction and (d) hub-height standard deviation of the wind direction. (e) Two-minute vertical power law coefficient and (f) change of wind direction, both between 40 m and 140 m. (g) Five-minute surface kinematic heat flux, (h) Obukhov length and bulk Richardson number between surface and hub height (solid) and between lower (30 m) and upper (150 m) rotor tip (dashed). Shaded areas mark the selected periods for the turbine simulation. From left to right: SBL, CBL and NNBL.

The periods (Tab. 1) were selected to represent different meteorological conditions. During the first period, the turbine operates in a strongly sheared and veered wind profile with low turbulence that is created by the strong nocturnal stable stratification (SBL). The second period during the day is characterized by a convective boundary layer (CBL) with nearly no vertical shear but vigorous short scale fluctuations of wind speed and direction (Fig. 2b,d). The evening transition from the daytime to the nighttime layer with a near neutral stratification (NNBL) is selected as the third period. While the measures of the wind profile differ considerably between SBL and NNBL, the mean Obukhov length is almost equal and the negative heat flux is even lower during the NNBL period (Fig. 2g,h, Tab. 1). The long build-up of the strong shear of the nocturnal boundary layer can thus not be captured with the instantaneous measure of Obukhov length and heat flux at the surface. Using the bulk Richardson number as an alternative measure for the classification of the stability conditions during the periods allows to differentiate between the SBL and NNBL period only when using measurements at the heights of the rotor tips.

The wakes in the three situations exhibit very different characteristics, that appear in both, the measurements and the simulations. Fig. 3 shows the two-minute averaged profiles from the lidar measurements and from the simulations at the upwind and downwind lidar position. Even though the wind turbines in reality and in the LES model are different, and the ambient flow fields are not exactly equal, either, the defining wake characteristics are identical. During the IOP Conf. Series: Journal of Physics: Conf. Series 854 (2017) 012050

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**Figure 3.** Temporal development of the horizontal velocity profile at the position of WC1 (top row) and WC2 (middle row) and difference between the two profiles (bottom row), (a) from the lidar measurements and (b) from the LES. The dashed lines mark the vertical boundaries of the respective rotor.

SBL period the wake is weaker and at a lower height than during the NNBL period, while the wake during the CBL period is just intermittently discernible. However, the vertical profiles of course only visualise a fraction of the full wake. Especially in the strong fluctuating wind conditions of the convective boundary layer it is impossible to localise the position inside the wake where it is sliced by the scan.

To gain further insight into the wake characteristics and behaviour, vertical cross-sections of the wake derived from the simulations were used. For this purpose the wind field was averaged along a half-circle downstream of the wind turbine with the radius of 3.22 D, corresponding to the distance of the downstream lidar from the turbine (Fig. 3b). This procedure was chosen to retrieve sections of the wake at the same distance for every wind direction. Example crosssections for the three time intervals are shown in Fig. 4. The strong veer of the nocturnal boundary layer leads to a strong cross-stream stretching of the wake. Thus, the vertical profile at the lidar position only captures the lower left corner of the wake. The example wakes during the CBL and NNBL both have a more circular shape.

**Table 1.** Average quantities from the PALM simulations during the three periods for which wake simulations were run. Mean and turbulent quantities are at hub height. Vertical temperature flux and Obukhov length are calculated at the vertical center of the lowest grid cell at z = 2.5 m.

	Start [LST]	End [LST]	$\overline{WS}$ $[ms^{-1}]$	$\overline{WD} \\ [°]$	$\overline{I}$ [%]	$\overline{\sigma WD} \\ [^{\circ}]$	$\overline{\Delta WD} \\ [^{\circ}]$	$\overline{\alpha}$ [-]	$\overline{w'T'}$ [K ms <sup>-1</sup> ]	$\overline{L}$ [m]	$\overline{Ri}_0^{90}$ [-]	$\overline{Ri}_{30}^{150}$ [-]
SBL CBL NNBL	05:30 13:30 19:00	07:00 15:00 20:30	7.5 9.0 7.6	194 197 186	$3.4 \\ 10.7 \\ 4.9$	$1.5 \\ 5.0 \\ 2.0$	$22.8 \\ 0.5 \\ 3.3$	$0.65 \\ 0.08 \\ 0.26$	-0.006 0.095 -0.025	87 -172 93	0.13 -0.12 0.11	$0.35 \\ -0.75 \\ 0.16$

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Figure 4. (a) LES wind speed average at hub height at 19:45 LST during the SBL period with the positions of the lidars marked as circles. Marked as black line is the line of constant distance to the turbine along which the velocities are analysed in Fig. 4 (b) Examples of the 2-min averaged wind speed along a constant distance (3.22 D) downstream of the turbine during the three simulation intervals. The vertical line denotes the position of WC2. The circle denotes the surface used for the calculation of the REWS at WD =  $180^{\circ}$ .

A direct comparison of the wakes based on the wind speed is difficult as the wakes can not be easily fitted to any geometric structure, e.g. a Gaussian-like shape, due to their asymmetry. To simplify the wake representation, the wind speeds downstream of the turbines were converted to rotor equivalent wind speeds (REWS) [18] as a function of the cross-stream coordinate x as in Vollmer et al. [16]. For this purpose the cube of the wind speed is averaged on virtual rotor surfaces of the diameter D of the NREL 5MW turbine and converted back to a wind speed.

$$\operatorname{REWS}(x) = \left(\frac{1}{A} \int_{x1}^{x2} \int_{z1}^{z2} u^3(x', z') \cos(\beta(x', z')) dz' dx'\right)^{1/3}, \ (x' - x)^2 + (z' - z_h)^2 \le (D/2)^2$$
(3)

The wind veer  $\beta$  over the rotor area A is defined as the difference between the wind direction at hub height and at the specific coordinate [19]. Here we use the assumption that the virtual rotor is aligned with the wind direction at hub height. By calculating the REWS the wakes are reduced to two-dimensional structures and can be compared easier.

The REWS for all individual 2-minute averages is shown in Fig. 5a. Figure 5b shows a time series of the deficit position defined as the minimum of the REWS and the 2-minute average of the LES wind direction at the rotor center of the turbine. The analysis shows that the REWS shows a strong asymmetry in the SBL, with a sharp gradient on the right side of the wake and a flat slope on the left side. As the simulated wind veer increases during the SBL period (Fig. 2f), the difference between the wind direction of the REWS minimum and the hub height wind direction also increases. This difference reaches a value of 10 degrees by the end of the stable simulation. Though the effect is regarded to depend on both shear interacting with the wake rotation and the veer of the wind profile [16], it is mainly dependent on wind veer in the analysed case as shown in Fig. 5c.

The wake during the NNBL period appears to be more symmetric. While the wake shapes of NNBL and CBL appear similar in Fig. 4a, the main difference between the two periods is the strong fluctuation of the wind direction during the CBL period which leads to a permanent

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Figure 5. (a) REWS as function of wind direction of each 2-min timeframe. (b) Position of the minimum of the REWS (blue) and LES wind direction at the rotor center (red). (c) Difference between wake position and hub height wind direction  $\Delta \mu$  plotted over the wind veer and the wind shear coefficient.

cross-stream meandering of the wake. During the NNBL period the REWS minimum generally coincides with the measured wind direction at hub height.

#### 4. Discussion

Mesoscale to microscale flow modeling is regarded as one of the main research topics for the next generation of wind condition assessment and wind farm design tools [20]. The methodology to use a background state derived from mesoscale simulations for cyclic LES, presents an alternative to the so-called nesting of LES in mesoscale simulations. The advantage of the method is that only a limited amount and only low resolved mesoscale data is necessary for the setup of the LES boundary conditions. Thus, the simulations can be run from a database of temporally resolved mesoscale model data like planned e.g. in the New European Wind Atlas (NEWA) project. The disadvantage of the method is that the spatially resolved advection of turbulent structures, for example from orography or from upstream wind farms can not be included in the simulation. Here, nesting presents an advantage, even though the best practices of turbulence instigation and mesh refinement from the meso- to the microscale regime are still under discussion [21].

The results of this paper indicate that the model chain of WRF and PALM is generally able to replicate the state of the atmospheric boundary layer during the selected day. As also concluded in Vollmer et al. [8], the more important model for a good replication of wind speed and wind direction is the mesoscale model. However, in the given case with a strong diurnal cycle, we find the LES model capable of improving the vertical wind speed and wind direction profile of a strongly-stratified nocturnal boundary layer. The reason may be primarily related to the lower vertical resolution of the mesoscale model and the consequential parametrization of the boundary layer fluxes. To improve the match between measurements and simulations it might be worth incorporating the measurements into the large-scale forcing and nudging data as in Rodrigo et al. [19].

The wake simulations performed in the transient flow conditions present a method to enhance the understanding of the measured wake flow. This procedure can be regarded as an alternative or a supplement to long-term measurements that are typically classified in classes of wind speed, wind direction and stability [4, 22, 23]. While we were not able to replicate the wake in this

study due to the lack of sufficient details about the wind turbine, we were still able to show the fundamental differences in wake behaviour and shape in the three periods of different atmospheric stability.

The differences can be related to the vertical profile of wind speed and direction and to the fluctuations of these parameters. The wind veer reaches values of up to 35° over the rotor surface during stable stratification, which leads to a wide stretching of the wake. During the daytime convective period the fluctuation of wake position and intensity is dominating the wind field. The bulk Richardson number, calculated from the vertical wind shear and the temperature difference over the rotor surface allows a categorization of the three periods of different wake behaviour. Atmospheric stability measured in the constant flux layer close to the surface, i.e. characterized by the Obukhov length, on the other hand, appears to be insufficient to differentiate between the periods as it is not able to capture the time history of the evolving flow. Thus, for a classification of wake measurements or performance measurements of wind turbines in stability classes the Richardson number is more suitable.

Abkar et al. [24] have shown in a simulation of an idealized diurnal cycle in LES how the wind farm power varies with the wind conditions influenced by atmospheric stability. For more sophisticated wind farm control like curtailment or wake steering, a precise knowledge about the wake deficit position is also crucial. Our results show that wind veer needs to be considered as it can indeed influence the wake deficit position.

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