Interaction between large wind farms and the atmospheric boundary layer

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Abstract

Accurate prediction of atmospheric boundary layer (ABL) flow and its interactions with wind turbines is of great importance for optimizing the design and efficiency of wind farms. This study first focuses on recent efforts to develop and validate a large-eddy simulation (LES) framework for wind-energy applications. The subgrid-scale turbulent fluxes of momentum and heat are parameterized using tuning-free dynamic models. The turbine-induced forces are parameterized using two types of models: an actuator disk model that allows for non-uniform force distribution and includes rotational effects, and an actuator line model. The LES framework is validated against wind-tunnel measurements collected inside and above a large model wind farm. Further, this framework is used to study wind-farm effects. Comparison of simulations of flow through both aligned and staggered wind farms shows important effects of farm layout on the flow structure and wind-turbine performance. We also investigate the impacts of wind farms on a stable ABL and a convective ABL.

Keywords: atmospheric turbulence, large-eddy simulation, wind turbine

Nomenclature

ABL      atmospheric boundary layer
RANS     Reynolds-averaged Navier–Stokes
LES      large-eddy simulation
SGS      subgrid scale

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1. Introduction

With the fast growing number of wind farms being installed worldwide, the interaction between atmospheric boundary layer (ABL) turbulence and wind turbines, and the interference effects among wind turbines, have become important issues in both the wind energy and the atmospheric science communities [1–3]. Accurate prediction of ABL flow and its interactions with wind turbines at a wide range of spatial and temporal scales is of great importance to optimize the design (turbine siting) of wind energy projects. In particular, flow prediction can be used to maximize wind-energy production and minimize fatigue loads in wind farms. Numerical simulation can also provide valuable quantitative insight into the potential impacts of wind farms on local meteorology. These are associated with the significant role of wind turbines in slowing down the wind, generating turbulence, and enhancing vertical mixing of momentum, heat, moisture and other scalars [4].

During the last decade, numerical simulation of wind-turbine wakes has become increasingly popular. Most of the previous studies of ABL flow through isolated wind turbines or wind farms have parameterized the turbulence using a Reynolds-averaged Navier–Stokes (RANS) approach [5–7]. However, as repeatedly reported in a variety of contexts [8], RANS is too dependent on the characteristics of particular flows to be used as a method of general applicability. Large-eddy simulation (LES) can potentially provide the kind of high-resolution spatial and temporal information needed to maximize wind energy production and minimize fatigue loads in wind farms. Only recently there have been some efforts to apply LES to simulate wind-turbine wakes [4, 9–12].

The accuracy of LES in simulations of ABL flow with wind turbines hinges on our ability to parameterize subgrid-scale (SGS) turbulent fluxes as well as turbine-induced forces. These forces are responsible for the development of the turbine wakes. In the next session, different wind-turbine models are discussed. This work is dedicated mainly to the study of the characteristics of wind-turbine wakes and their aggregated effect on wind-turbine performance as well as land-atmosphere exchanges (momentum and heat fluxes). We describe our LES framework in Sect. 2. The LES results are presented and discussed in Sects. 3 and 4, and a summary is provided in Sect. 5.
2. Large-eddy simulation framework

2.1 LES governing equations

LES solves the filtered continuity equation, the filtered momentum conservation equations (written here in rotational form and using the Boussinesq approximation), and the filtered heat equation

\[ \frac{\partial \tilde{u}_i}{\partial t} = 0, \]

\[ \frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \left( \frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i} \right) = -\frac{\partial p^*}{\partial x_i} + \delta_{ij} v \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} + \delta_{ij} g \frac{\partial \theta}{\partial x_i} + f_c \varepsilon_{ij} \tilde{u}_j - \frac{f_i}{\rho} + F_i, \]

\[ \frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \alpha \frac{\partial^2 \tilde{u}_j}{\partial x_j^2}, \]

where the tilde represents a three-dimensional spatial filtering operation at scale \( \Delta \), \( u_i \) is the velocity in the \( i \)-direction (with \( i = 1, 2, 3 \) corresponding to the streamwise (x), spanwise (y) and vertical (z) directions), \( \theta \) is the potential temperature, \( \theta_0 \) is the reference temperature, the angle brackets represent a horizontal average, \( g \) is the gravitational acceleration, \( f_c \) is the Coriolis parameter, \( p^* \) is the modified pressure, \( \rho \) is the air density, \( v \) is the kinematic viscosity of air, \( \nu \) is the thermal diffusivity of air, \( f_i \) is an immersed force (per unit volume) for modeling the effect of wind turbines on the flow, and \( F_i \) is a forcing term (e.g., a mean pressure gradient). Based on the Boussinesq approximation, both \( \rho \) and \( \theta_0 \) in Eq. (2) are assumed to be constant. \( \tau_{ij} \) and \( q_{ij} \) are the SGS stresses and fluxes, respectively. These SGS terms are parameterised using Lagrangian scale-dependent dynamic models [13, 14].

2.2. Wind-turbine parameterizations

Using an actuator-disk approximation is a common approach to parameterize the turbine-induced forces (e.g., thrust, lift, and drag) in numerical models of flow through propellers and turbines. This approach assumes the flow surrounding a wind turbine to be inviscid and does not require resolving the boundary-layer flow around the surface of the turbine, which decreases greatly the computational cost. Betz [15] first applied a Rankine–Froude actuator disk method to determine the thrust force and the power production on an ideal turbine rotor and, thus, derived the well-known Betz limit for the maximum achievable efficiency of a wind turbine (maximum power coefficient of \( C_{P,max} = 16/27 \)). Since this method only considers a uniform thrust load over the rotor disk and ignores the wake rotation effect, here we refer to this method as the actuator-disk model without rotation (ADM-NR).

A major advancement in wind-turbine modeling was the introduction of the blade-element momentum (BEM) theory. This theory considers that each blade of a wind turbine can be divided into \( N \) blade elements (see Fig. 1), which are assumed to behave aerodynamically as two-dimensional aerofoils and to
have no radial action on the flow. Based on momentum balance around the aerofoils, the aerodynamic forces are determined using the lift and drag characteristics of the aerofoil as well as the local flow conditions. Note that, for each blade element, the lift and drag forces are perpendicular and parallel, respectively, to the direction of the local relative velocity. The resultant force is non-uniformly distributed on the blade surface or over the rotor-disk area, and produces thrust as well as rotation of the flow. This BEM approach can be applied into two types of wind-turbine models: actuator-disk model with rotation (ADM-R) and actuator-line model (ALM). More details regarding the three wind-turbine models can be found in [4, 12, 16–18].

3. Simulation of turbulent flow inside and above wind farms

To validate this recently-developed LES framework, we choose a simulation case study, corresponding to a wind-tunnel wind-farm experiment performed by Chamorro and Porté-Agel [19] in an ABL wind tunnel under neutral stratification. In that experiment, a turbulent boundary-layer flow was developed in the 16 m × 1.7 m × 1.7 m test section of the tunnel. At the downwind part of the test section, the flow had a free-stream velocity of $U_f \approx 3.0 \text{ m s}^{-1}$ and a boundary-layer depth of $\delta \approx 0.68 \text{ m}$; the friction velocity and surface roughness length are $u_* = 0.12 \text{ m s}^{-1}$ and $z_o = 0.03 \text{ mm}$, respectively. The wind farm had an aligned configuration and consisted of 30 miniature, horizontal-axis, three-bladed wind turbines arranged in 10 rows and three columns that were spaced $S_x = 5$ apart in the streamwise direction and $S_y = 4$ apart in the spanwise direction, where $d = 0.150 \text{ m}$ is the rotor diameter (see Fig. 2). Each turbine consists of a three-bladed GWS/EP-6030×3 rotor attached to a small DC generator motor at a hub height ($H_{hub}$) of 0.125 m. The normalized angular velocity distribution measured in the aligned wind farm is shown in Fig. 2. Moreover, the effect of the wind-farm configuration on the flow is investigated using LES. To achieve that, a staggered wind farm, where the even turbine rows are shifted laterally by $2d$ with respect to the aligned layout, is also considered. The angular velocity of the turbines in the staggered farm was measured (see Fig. 2) under the same inflow condition.

To simulate the entire wind-farm wake, the horizontal computational domain spans a distance $L_x = 72d = 10.8 \text{ m}$ in the streamwise direction and $L_y = 12d = 1.8 \text{ m}$ in the spanwise direction. In the experiment, the boundary-layer depth $\delta = 0.68 \text{ m}$ grew slightly along the streamwise direction due to the increased effective surface roughness induced by the wind farm. To allow for this effect in the simulations, the computational domain has a vertical height $L_z = 0.89 \text{ m}$, which is slightly higher than the depth of the incoming boundary-layer flow. A constant streamwise pressure gradient is used to drive the flow within the boundary layer. The domain is uniformly divided into $(N_x \times N_y \times N_z) = (648 \times 108 \times 108)$ grid points in the streamwise, spanwise and wall-normal directions, respectively. More detail regarding the numerical set-up can be found in [16].

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Fig. 2. (a) Schematic of the aligned wind-farm configuration; (b) Normalized measured angular velocity distribution of the wind turbines at different downwind positions
3.1. Model validation

Figure 3 shows contours of the normalized time-averaged streamwise velocity and the streamwise turbulence intensity obtained from the wind-tunnel experiment and the simulations with the ADM-R and the ADM-NR. As expected, the turbine wakes (regions of reduced mean velocity) are clearly visible behind each turbine. Also evident is the cumulative effect of multiple wakes, leading to the formation of a “wind-farm wake” with two distinct regions: in the first region, below the top-tip level, the mean velocity deficit adjusts relatively rapidly and reaches an equilibrium after only two–three rows of wind turbines. This is consistent with field observations showing that the power output from operational offshore aligned wind farms decreases significantly (with respect to the first row) for the second and, to a lesser extent, the third row of turbines, while it remains relatively unchanged after that [e.g., [20]]. In the second region, above the turbines, the flow experiences a larger downwind variation as the cumulative farm wake expands. The edge of the farm wake, defined here as the height where the time-averaged wake velocity is 99% of the mean inflow velocity at that height, is shown in Fig. 3. The location of the simulated wake edge is very similar for both turbine models and it is in good agreement with the measurements. The wake edge grows with downwind distance and reaches a height of about 0.4 m (twice the turbine height) behind the tenth row of turbines $(x / d \geq 45)$.

![Figure 3](image-url)

The simulation results in Fig. 3 show clear differences between the predictions of the wake velocity by the two wind-turbine models. In particular, the LES with the ADM-R produces velocity profiles that are in good agreement with the measurements throughout the wind farm. In contrast, the ADM-NR clearly overpredicts the mean velocity (i.e., it underpredicts the velocity deficit) in the wake behind each turbine. This is consistent with the previous simulations of the wake of a stand-alone turbine presented by [12, 17]. It should be noted that the thrust coefficient $C_T$ used for each turbine in the ADM-NR is obtained based on the overall thrust force computed using the BEM theory in the ADM-R. Consequently, the failure of the ADM-NR model to reproduce the velocity magnitude in the wake regions is attributed to the limitations of two major assumptions made in the ADM-NR (but not in the ADM-R): (a) the turbine-
induced rotation effect is ignored, and (b) the axial thrust force is uniformly distributed over the rotor disk area, thus ignoring the radial variation of the force. As pointed out by [12], the latter assumption has the stronger effect of the two.

Due to the cumulative effect of the multiple wakes from upstream wind turbines, the maximum level of the turbulence intensity found behind the wind turbines increases substantially in the wakes behind the first four rows of turbines, and reaches a plateau after the fifth row. That maximum turbulence intensity is found behind each turbine at the top-tip level. This is due to the high mean shear (see Fig. 3) and associated mechanical (shear) turbulence production in that region. In particular, a peak of turbulence is found at approximately three rotor diameters behind each of the turbines, except for the first one. This is due to the fact that the inflow to the first row of wind turbines is much less turbulent, leading to a slower recovery of the wake (due to less efficient mixing with the surrounding flow), compared with the wakes of the other turbines. This also explains why the turbulence intensity peak is found further downwind from the turbine in the case of a stand-alone wind turbine [12, 17].

The distribution of the simulated turbulence intensity obtained with the two turbine models (ADM-NR and ADM-R) shows a similar qualitative behaviour as the one reported in the experiment. However, significant differences are found in the ability of the two models to match quantitatively the measured turbulence intensity levels. The magnitude of the turbulence intensity obtained with the ADM-R, and particularly its maximum value at the top-tip level, is found to be in acceptable agreement with the wind-tunnel measurements. The ADM-NR tends to systematically underestimate the peak of turbulence intensity behind most of the turbines. Below the top-tip height, and further than two rotor diameters downwind of the turbines, both models underestimate the turbulence intensity, with a slightly worse prediction from the ADM-NR model.

3.2. Layout effects

In this subsection, a comparison of the LES results for the aligned and staggered wind farms is presented. The numerical set-up in the previous model validation case is adopted in the staggered wind-farm wake simulation, except for the horizontal position and the angular velocity of the turbines.

Figure 4 shows contour plots of the normalized time-averaged streamwise velocity and the streamwise turbulence intensity on a horizontal $x$-$y$ plane at the hub level and in a vertical $y$-$z$ plane at $3d$ downstream behind the third and ninth turbines for the two farms. In this figure, it is clear that the farm layout has a strong effect on the structure of the cumulative wakes and, consequently, on the distribution of the different turbulence statistics. In the aligned case, the wake regions are centred around the turbine rows and grow radially with distance downwind, only interacting laterally after approximately the eighth row. In the staggered farm, lateral wake interactions are obvious even after the third row of turbines due to the fact that the wind farm offers a larger “frontal area” to the incoming flow. Moreover, since the effective distance between downwind turbines is now $10d$, the wakes have a longer distance to recover before the next turbine, which results in a higher efficiency of the turbines (i.e., faster rotating speed) in extracting momentum from the flow, compared with the aligned counterpart. This explains the higher angular velocity of the turbines and the more uniform distribution of the velocity within the wind farm.

Important differences between the two layouts are also found in the turbulence intensity distribution. The enhancement of turbulence intensity and, consequently, the potential negative impacts of the associated fatigue loads are much higher in the aligned farm. In the staggered farm, the distance between “immediately downwind” turbines is longer, which allows for the turbulence to dissipate to lower levels before reaching the next downwind turbine, thus reducing the cumulative turbulence enhancement effect. It should be noted that the maximum turbulence intensity region corresponds to a U-shaped area at the rotor edge and above hub height, where the local shear and associated production of kinetic energy are high.

In order to further illustrate the growth of the cumulated farm wakes and their dependence on farm layout, Fig. 5 depicts a three-dimensional representation of the distribution of the simulated wake edge over the aligned and staggered wind farms. The wake edge is defined as the location where the time-
averaged wake velocity is 99% of the mean flow velocity at height. From this figure, it is obvious that in
the aligned wind farm there is no lateral interaction between the turbines until the eighth row of turbines.
In contrast, the wakes merge relatively soon, leading to a more uniform spanwise distribution of the wake
edge. As a result, the growth of the cumulated farm wake resembles more a classical “internal boundary
layer” in the case of the staggered farm than in the case of the aligned farm.

Fig. 4. Contours of the normalized time-averaged streamwise velocity (left panel) and the streamwise turbulence intensity (right
panel) on the horizontal \(x-y\) plane at the turbine hub height (top) and in a vertical \(y-z\) plane at \(3d\) downstream behind the third and
ninth turbines (bottom) for the both aligned and staggered wind farms

Fig. 5. Isosurface of internal wake layer distribution: (a) Aligned and (b) staggered wind-farms

4. Wind farms in stable and unstable boundary layers

4.1. Wind farms in a stable boundary layer

Of special interest for wind-energy applications is the study of thermally stratified stable boundary
layers (SBLs). SBLs are relatively shallow and are characterized by strong shear and a relatively high
wind near the top. At that height, the wind can become super-geostrophic and form the so-called low-
level jet. As a result, compared to neutral and convective ABLs, SBLs provide larger energy potential, but
also larger structural fatigue loads associated with the strong shear. SBLs are particularly challenging to
simulate accurately due to the large shear and anisotropy of the flow. An LES inter-comparison study was
carried out in the context of the global energy and water cycle experiment atmospheric boundary layer
study (GABLS) initiative [21] to simulate a moderately stable boundary layer. This case is used here as a
baseline case.

In order to study the effect of a wind farm on the GABLS case, we have “immersed” (using the ALM) a
V112-3.0MW wind turbine in the GABLS domain. This wind turbine has a rotor diameter of \(d = 112\) m. Two
\(x\)-direction dimensions, corresponding to two typical wind-turbine spacings, are studied: (1) \(L_x = 8d = 896\) m
(the corresponding LES is abbreviated as the 8d case); (2) $L_x = 5d = 560$ m (the corresponding LES is abbreviated as the 5d case). Periodic boundary conditions are applied horizontally to simulate an infinitely large wind farm. Readers can find more numerical details from previous articles [4, 21]. It should be noted that the baseline case attains a quasi-steady state in 8–9 h [21]. Therefore, in order to examine the wind-turbine effects relative to the baseline case, we introduce the wind turbines only in the last hour of simulation.

Figure 6a shows the formation (initial stages) of blade-induced three-dimensional helicoidal tip vortices, detected using vorticity iso-surface. Due to the strong shear and non-uniformity of the incoming boundary-layer flow, helicoidal vortices are stretched as they travel faster at the top tip level compared with the bottom tip level. Figure 6b shows the mean vertical profiles of wind speeds. In agreement with other studies [22], when wind turbines are installed, there is an increase of the boundary height. The baseline case clearly shows a super-geostrophic nocturnal jet peaking near the top of the boundary layer. However, the extraction of energy by the turbines, leads to a distortion of the velocity field (compared with the baseline case) and an elimination of the low-level jet in the wind farm simulations. Also, as expected, the closer the distance between the wind turbines, the larger extraction of kinetic energy from the flow.

![Fig. 6. (a) Vorticity isosurface of the 5d case at $t = 30$ s; (b) Vertical distributions of mean x-direction velocity $U$ and y-direction velocity $V$](image_url)

Besides extracting kinetic energy and generating turbulence, wind-turbine blade motions also mix fluid parcels. Figure 7a compares the potential temperature profiles obtained from the baseline case and two wind-turbine cases. Blade motions enhance the vertical mixing and transfer more thermal energy from higher levels to lower levels. This leads to an increase of temperature (about 0.5 K warming) below the top tip level and a decrease between the tip-height and the SBL height. The investigation of fluxes is of interest because local meteorology is considerably affected by the overall exchanges of momentum, heat, moisture, etc. The magnitude of the surface buoyancy flux decreases with time as shown in Fig. 7b. Specifically, over the last 15 min, the 8d case yields a buoyancy-flux magnitude of approximately $-3.8 \times 10^{-4}$ m$^2$s$^{-3}$ (reduced $\approx$15%), corresponding to a heat flux of $-13.5$ W·m$^{-2}$; the 5d case yields a buoyancy-flux magnitude of approximately $3.2 \times 10^{-4}$ m$^2$s$^{-3}$ (reduced $\approx$28%), corresponding to a heat flux of $-11.4$ W·m$^{-2}$. Regarding the overall thermal-energy budget, this reduced heat flux is consistent with the increase of air temperature in the boundary layer as shown in Fig. 7a.

### 4.2. Wind farms in a convective boundary layer

Though a very-coarse-resolution simulation [2] reported cooling effects by wind farms in a daytime ABL, a high-fidelity study of wind-farm effects on day-time convective atmospheric boundary layers (CBLs) has yet to be performed. In CBL flows, the surface of atmospheric boundary layer is warmer than the surrounding air, in response to solar heating. The warmer surface leads to a positive (upward)
buoyancy flux, which creates a thermal instability and generates turbulence. In order to reduce uncertainties when studying the interactions between a wind farm and a CBL, we start with a CBL baseline case (without wind turbines) that has been well tested with LES. We conduct three-dimensional LESs with the actuator disk model with rotation [12] to investigate the impact of wind farms on this CBL case. Siemens SWT-2.3-93 wind turbines, with a rotor diameter of 93 m and a hub height of 80 m, are “immersed” in the flow, as shown in Fig. 8a. The horizontal domain is larger than four boundary layer depths, which is enough to resolve large waves. In order to understand farm layout effects, the framework is applied to study several cases of aligned wind farms with different streamwise and spanwise spacings.

Fig. 7. (a) Vertical profiles of potential temperature; (b) Surface buoyancy flux evolutions

As an example, Fig. 8b shows vertical profiles of averaged (horizontally and over a certain time period) wind speed obtained from the aligned $S_x \times S_y = 5 \times 5$ case and the baseline case. In line with the situation in the stable condition, results reveal the extraction of momentum by the turbines. However, the boundary layer height in the CBL flow is relatively larger, thus wind turbines cause a relatively smaller increase of 2.5% in comparison with 10% in the stable condition.

Fig. 8. (a) Instantaneous streamwise velocity contours and turbine-induced vortex structures; (b) Wind speed profiles obtained from the aligned $S_x \times S_y = 5 \times 5$ case and the baseline case

In contrast to the warming effects under stable conditions, the wind farm leads to a slight decrease of temperature in the CBL as shown in Fig. 9a. The magnitude of cooling is about 0.040 K near the surface.
and about 0.025 K throughout the entire boundary layer, which is even less than a tenth of magnitude of warming in stable condition. The warming effect in stable condition is most likely caused by the enhanced mixing, which pulls down warmer air from higher altitudes. Under unstable conditions, turbulent wakes mix cool air down and warm air up, producing a cooling near the surface. In comparison with the ABL flows under stable conditions, the existing mixing under unstable conditions is already very large. Hence, the turbine-enhanced turbulent mixing may play a smaller role. However, as shown in Fig. 9b, the vertical profiles of the heat flux reveal largely enhanced entrainment fluxes, indicating that the cooling below the entrainment zone has created substantial negative heat flux (downward warming). The entrainment/surface flux ratio has been increased approximately from 0.29 to 0.48. Regarding the overall thermal-energy budget, the cooling throughout the entire boundary layer is consistent with the reduced surface heat flux as shown in Fig. 10. The discrepancy between the surface heat fluxes obtained from baseline case and each wind farm case is increasing with time, and all wind farm cases yield approximately 5% reductions in the surface-heat-flux magnitude.

![Fig. 9. Vertical profiles of (a) potential temperature and (b) heat flux obtained from the aligned $S_x \times S_y = 5 \times 5$ case and the baseline case.](image)

![Fig. 10. Time evolution of the area-averaged surface buoyancy flux.](image)

### 5. Summary

This paper presents recent efforts to develop and validate a large-eddy simulation framework for wind energy applications. The tuning-free dynamic models are used to parameterize the SGS stress tensor and
the SGS heat flux. Two types of models are used to parameterize the turbine-induced forces: actuator disk models and actuator line models.

The proposed LES framework is validated against high-resolution velocity measurements inside and above the aligned wind farm in an ABL wind tunnel. In general, the characteristics of the simulated turbine wakes (average velocity and turbulence intensity distributions) are in good agreement with the measurements. In the case of the ADM-R, accounting for rotation and non-uniform distribution of the forces yields improved predictions.

Comparison of the simulation results for the aligned and staggered wind-farm cases shows a strong effect of wind-farm layout on the turbulent flow structure inside and above wind farms. In particular, the cumulative wakes are found to have little lateral interaction (with no interaction before the eighth row of wind turbines) in the case of the aligned wind farm. In contrast, the lateral interaction between the wakes is much stronger and happens throughout most of the wind farm in the case of the staggered wind farm. As a result, the growth of the cumulative wake from the staggered farm resembles more a classical internal boundary layer compared with that from the aligned farm.

Further, we investigated the impacts of wind farms on a stable ABL and a convective ABL. Our results clearly show that the largest discrepancies appear in the distribution of momentum. The differences in the distribution of potential temperature are relatively smaller. Previous studies at relatively low resolutions have shown that wind farms could have noticeable effects on the global climate [3], and on local meteorology [2]. In agreement with these studies, our results show that the wind-turbine motions enhance the vertical mixing of heat, resulting in near-surface warming under stable conditions and cooling under convective conditions. They also lead to lowered surface heat flux magnitudes.

The wind in the lowest part of the atmosphere is the most important atmospheric variable for wind-power meteorology. The results presented in this paper show that LES has the potential provide reliable detailed information of wind-turbine wakes, which is needed to optimize wind-farm design (maximize energy output and minimize fatigue loads) and also to develop more accurate parameterizations of turbulent fluxes in weather/climate models.

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