The effect of atmospheric stability on wind-turbine wakes: A large-eddy simulation study

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Abstract. In this study, large-eddy simulation is used to investigate the influence of atmospheric stability on wind-turbine wakes. In the simulations, tuning-free Lagrangian scale-dependent dynamic models are used to model the subgrid-scale turbulent fluxes, while the turbine-induced forces are parameterized with an actuator-disk model. Emphasis is placed on studying the structure and characteristics of turbine wake in the cases where the incident flow to the turbine has the same mean velocity at the hub height but different thermal stability condition. The simulation results show that the atmospheric stability has a significant effect on the spatial distribution of the mean velocity deficit and turbulent fluxes in the wake region. In particular, in the convective boundary layer, the wake recovers faster, and the locations of the maximum turbulence intensity and turbulent stresses are closer to the turbine compared with the neutral and stable cases.

1. Introduction
Wind turbines operate in the lowest region of the atmospheric boundary layer (ABL). As a result, the structure and evolution of wind-turbine wakes are affected by the characteristics of the ABL flow such as the wind speed, wind shear and turbulence levels. Besides land or sea surface characteristics such as the roughness and topography, the thermal stratification has an important effect on the wind characteristics by changing the length and velocity scales of the ABL turbulence. Evidence of significant thermal stability effect on wind-turbine wake structures and power harvesting has been reported in full-scale field measurements as well as wind-tunnel tests of down-scaled wind-turbine models. Baker and Walker [1] carried out measurements behind a 2.5-MW wind turbine at Goodnoe Hills, Washington. Their results showed a slower wake recovery under the stable nighttime conditions characterized by relatively lower turbulence levels. Later, Magnusson and Smedman [2] investigated the structure of the wakes downwind of a wind turbine in the Alsvik wind farm during different atmospheric stability conditions. They showed that the velocity deficit is a function of atmospheric stratification with larger values in the stable air. Barthelmie and Jensen [3] estimated wind-farm efficiency reductions up to 9% in the stable conditions compared with the unstable ones for the wind-speed range of 9-10 m/s for the Nysted wind farm in the Danish Baltic Sea. Iungo and Porté-Agel [4] performed wind velocity measurements of the wake downwind of a 2 MW Enercon E-70 wind turbine with three scanning Doppler wind LiDARs under different atmospheric conditions. They showed that the wakes recover faster under the convective conditions compared with the neutral and stable cases. Recently, Zhang et al. [5] carried out wind-tunnel experiments of the down-scaled wind-turbine
models to investigate the effect of thermal stability on wind-turbine wakes under the convective and neutral conditions. They found a smaller velocity deficit (about 15% at the wake center) in the CBL compared with the wake of the same wind turbine in the neutral boundary layer.

As illustrated above, atmospheric thermal stability cannot be viewed as a small perturbation to a basic neutral state, thus, a detailed comprehension of the variability of wind turbine wakes under different ABL regimes is crucial. The present work aims at simulating the wind-turbine wakes under different stability conditions using a recently-developed LES framework. In this framework, a Lagrangian scale-dependent dynamic model [6] is used to parameterize the sub-grid-scale (SGS) fluxes and an actuator-disk model with rotation is applied to calculate the turbine-induced lift and drag forces [7, 8]. Numerical experiments are carried out under different atmospheric stability conditions in order to investigate the effect of thermal stratification on wind-turbine wakes. A short introduction of the LES framework and the numerical setup are presented in Section 2. The spatial distribution of the mean velocity, turbulence intensity, and turbulent shear stresses obtained from the turbulence statistics are shown and discussed in Section 3. Last, a summary and conclusions are provided in Section 4.

2. Large-Eddy Simulation Framework

2.1. LES Governing Equations

LES solves the filtered continuity equation, the filtered Navier-Stokes equations (written here using the Boussinesq approximation), and the filtered transport equation for potential temperature:

$$\frac{\partial u_i}{\partial x_i} = 0, \quad \frac{\partial u_i}{\partial t} + \tilde{u}_j \frac{\partial u_i}{\partial x_j} = - \frac{\partial p^s}{\partial x_i} + \delta_{ij} \tau_{ij} + \delta_{i3} g \frac{\tilde{\theta} - \langle \tilde{\theta} \rangle}{\theta_0} - f_i + F_p \delta_{i1}, \quad \frac{\partial \tilde{\theta}}{\partial t} + u_j \frac{\partial \tilde{\theta}}{\partial x_j} = - \frac{\partial q_j}{\partial x_j} + S_q,$$

where the tilde represents a spatial filtering at scale $\Delta$, $t$ is time; $\tilde{u}_i$ is the instantaneous resolved velocity in the $i$–direction (with $i = 1, 2, 3$ corresponding to the streamwise ($x$), spanwise ($y$) and vertical ($z$) directions, respectively); $\tilde{\theta}$ denotes the resolved potential temperature; $\theta_0$ is the reference temperature, the angle brackets represent a horizontal average; $g$ refers to the gravitational acceleration; $\delta_{ij}$ is the Kronecker delta; $\tilde{p}^s = \tilde{p}/\rho + \frac{1}{2} \tau_{kk}$ is the modified kinematic pressure; $f_i$ is a body force (per unit volume) used to model the effect of the turbine on the flow; $\rho$ is the fluid density; $F_p$ is an imposed pressure gradient; $S_q$ is an imposed heat-flux gradient; $q_j$ denotes the SGS heat flux; $\tau_{ij}$ represents the kinematic SGS stress; and $\tau_{ij}^d$ is its deviatoric part. Note that $\tau_{ij}^d$ and $q_j$ are unknown and need to be parameterized as a function of filtered (resolved) fields. A common parameterization strategy in LES consists of computing the deviatoric part of the SGS stress with an eddy-viscosity model [9], $\tau_{ij} - \frac{1}{2} \tau_{kk} \delta_{ij} = -2 \Delta^2 C_S^2 \tilde{S} \delta_{ij}$, and the SGS heat flux with an eddy-diffusivity model, $q_j = -\Delta^2 C_S^2 P_{r_{sgs}}^{-1} \frac{\partial \tilde{\theta}}{\partial x_j}$, where $\tilde{S}_{ij} = \langle \partial \tilde{u}_i / \partial x_j + \partial \tilde{u}_j / \partial x_i \rangle / 2$ is the resolved strain-rate tensor whose magnitude is $|\tilde{S}|$, $\Delta$ is the filter width, $C_S$ is the Smagorinsky coefficient, $C_S^2 P_{r_{sgs}}^{-1}$ is the lumped coefficient, where $P_{r_{sgs}}$ is the SGS Prandtl number. Here, we employ the scale-dependent Lagrangian dynamic models [6] to compute the local optimized value of the model coefficients without any ad hoc tuning. In contrast with the traditional dynamic models [10, 11], the scale-dependent dynamic models compute dynamically not only the value of the model coefficients in the eddy-viscosity and eddy-diffusivity models, but also the dependence of these coefficients with scale. More details on the formulation of scale-dependent dynamic models for the SGS fluxes can be found in Porté-Agel et al. [12], Porté-Ágel [13], and Stoll and Porté-Ágel [6].

To parameterize the turbine-induced forces, the actuator-disk model with rotation [7] is used. Through this model, the aerodynamic forces are determined using the lift and drag characteristics of the airfoil type as well as the local flow conditions. Unlike the standard
actuator-disk model, which assumes the loads are distributed uniformly over the rotor disk and acting only in the axial direction, the actuator-disk model with rotation includes the effect of turbine-induced flow rotation as well as the non-uniform force distribution. Figure 1 shows a cross-sectional element of radius $r$ in the $(\theta, x)$ plane, where $x$ is the axial direction. Different forces, velocities and angles are shown in this figure. $V_x = V_x(r, \theta)$ and $V_\theta = V_\theta(r, \theta)$ are axial and tangential velocities of the incident flow at the blades, respectively, in the inertial frame of reference. The local velocity relative to the rotating blade is defined as $V_{rel} = (V_x, \Omega r - V_\theta)$, where $\Omega$ is the turbine angular velocity. The angle of attack is defined as $\alpha = \varphi - \gamma$, where $\varphi = \tan^{-1}(V_x/(\Omega r - V_\theta))$ is the angle between $V_{rel}$ and the rotor plane and $\gamma$ is the local pitch angle. To determine the forces acting on the rotor disk, we consider an annular area of differential size $dA = 2\pi rdr$. The resulting force per unit rotor area is given by:

$$f_{disk} = \frac{dF}{dA} = \frac{1}{2} \rho V_{rel}^2 \frac{B c}{2\pi r} (C_L e_L + C_D e_D),$$

(2)

where $B$ is the number of blades, $C_L = C_L(\alpha, Re_c)$ and $C_D = C_D(\alpha, Re_c)$ are the lift and drag coefficients, respectively, $Re_c$ is the Reynolds number based on relative velocity and chord length, $c$, and $e_L$ and $e_D$ denote the unit vectors in the directions of the lift and the drag, respectively. Through the simulation, the tangential ($V_\theta$) and the axial ($V_x$) velocities at the rotor plane are known. Hence, the local velocity relative to the rotating blade ($V_{rel}$) and the angle of attack $\alpha = \varphi - \gamma$ can be computed. Then, the resulting force is obtained using Equation 2.

2.2. Numerical Setup

The LES code used in this study is a modified version of the one described by Albertson and Parlange [14], Porté-Agel et al. [12], Stoll and Porté-Agel [6] and Wu and Porté-Agel [7]. In the simulations, tuning-free Lagrangian scale-dependent dynamic models are used to model the subgrid-scale turbulent fluxes, and the turbine-induced forces are parameterized using the above-mentioned actuator-disk model. Since the Reynolds number of the ABL is very high, no near-ground viscous processes are resolved, and the viscous term is neglected in the momentum equation.

The domain is divided into $N_x$, $N_y$, and $N_z$ uniformly spaced grid points in streamwise, spanwise and wall-normal directions, respectively. The grid planes are staggered in the vertical direction, with the first vertical velocity plane at a distance $\Delta_z = L_z/(N_z - 1)$ from the surface, and the first horizontal velocity plane $\Delta_z/2$ from the surface. The filter width is computed using the common formulation $\delta = (\Delta_x \Delta_y \Delta_z)^{1/3}$, where $\Delta_x = L_x/N_x$ and $\Delta_y = L_y/N_y$. Here, the horizontal spans, $L_x$ and $L_y$ of the domain are parallel and perpendicular to the mean.
wind direction, respectively. $L_z$ is the height of the computational domain, which is different for different stability conditions. The chosen values for the height of the boundary layer are consistent with the boundary-layer depth reported by Peña et al. [15] at the National Test for Wind Turbines at Hovsøre, Denmark. It is worth mentioning that the grid resolution is chosen such that 10 points in the spanwise direction and 16 points in the vertical direction cover the turbine rotor diameter. Based on previous resolution sensitivity results [7, 16], as long as we have at least 5 points in the spanwise direction and 7 points in the vertical direction over the turbine rotor, the grid resolution is well suited for the LES framework to account for the most significant characteristics of wind-turbine wakes.

The vertical derivatives are approximated with second-order central differences and the horizontal directions are discretized pseudo-spectrally which requires periodic boundary conditions. Full dealiasing of the nonlinear terms is obtained by padding and truncation according to the 3/2 rule [17]. To avoid the downwind flow affecting the flow upwind of the wind turbine due to the periodic boundary conditions, a buffer zone upstream the turbine is employed to adjust the flow from the downwind condition to that of a fully turbulent boundary-layer inflow condition. The inflow condition is obtained from separate (without turbine) simulations of fully-developed ABL flows over horizontally-homogeneous flat surfaces [18, 7]. The time advancement is carried out using a second-order-accurate Adams-Bashforth scheme [19]. The upper boundary condition consists of a stress/flux-free condition. At the bottom surface, the standard formulation based on local application of Monin-Obukhov similarity theory [20] is used. Although this theory was developed for mean quantities, it is a common practice in LES of atmospheric flows to compute the instantaneous filtered surface momentum flux [21, 22] as follows, 

$$
\tau_{33}|_w = -u_3^2 \frac{\partial u_3}{\partial z} = -\left(\frac{\partial u_3}{\partial z}\right) \frac{\partial u_3}{\partial z},
$$

where $\tau_{33}|_w$ is the instantaneous local wall stress; $u_3$ is the friction velocity; $z_o$ is the aerodynamic surface roughness; $\kappa$ is the von Kármán constant; and $\bar{u}_3$ is the local filtered horizontal velocity at the first level $z = \Delta z/2$. In a similar manner, the surface heat flux is computed as, $q_3|_w = \frac{u_3 \phi (\theta_o - \bar{\theta})}{\ln(z_z/z_o) - \Psi_M}$, where $\Psi_M$ and $\Psi_H$ are the stability corrections for momentum and heat, respectively, and are defined as follows [23, 24]:

$$
\Psi_M = \begin{cases} 
-4.7 \frac{x}{L} \\ 2 \ln[\frac{1}{2}(1 + x)] + \ln[\frac{1}{2}(1 + x^2)] - 2 \tan^{-1}[x] + \frac{\pi}{2}
\end{cases} \text{ for stable conditions,}
$$

(3)

and

$$
\Psi_H = \begin{cases} 
-7.8 \frac{x}{L} \\ 2 \ln[\frac{1}{2}(1 + x^2)]
\end{cases} \text{ for stable conditions,}
$$

(4)

where $L = -(u_3^2 \theta_0)/(\kappa g q_3|_w)$ is the local Obukhov length, $\theta_0$ is the reference temperature and is set to $\theta_0 = 293K$, and $x = (1 - 15 z/L)^{1/4}$. In the present work, we directly specify the values of the imposed heat-flux gradient ($S_q \eq \frac{\tau_{33}|_w}{L_z}$) and the imposed pressure gradient ($F_p \eq u_3^2/L_z$) such that the incoming flows have the same mean velocity at the hub height equal to $U_{hub} = 8 ms^{-1}$ but different stability conditions. The surface potential temperature and the aerodynamic surface roughness are 293K and 0.05m, respectively. In the simulations, the Vestas V80-2MW wind turbines, with a rotor diameter ($D$) of 80m and a hub-height ($z_h$) of 70m, are immersed in the flow. The wind turbines operate with the same mean angular velocity of 16.1 rpm in different ABL flows. Wu and Porté-Agel [25] provided details of the Vestas V80-2MW wind turbine in a simulation of stand-alone wind-turbine wake. The code is run for a long-enough time to guarantee that quasi-steady conditions are reached. The key parameters of the various LES cases are summarized in Table 1.
Table 1. Key parameters of the various LES cases.

| ABL cases | Stability condition | $L$ (m) | $u_*$ (m s$^{-1}$) | $q_{\beta w}$ (K m s$^{-1}$) | $L_x \times L_y \times L_z$ (m$^3$) | $N_x \times N_y \times N_z$ |
|-----------|---------------------|--------|------------------|---------------------|---------------------------------|---------------------|
| CBL       | Convective          | -150   | 0.46             | 0.048               | $3000 \times 1500 \times 750$   | $200 \times 150 \times 150$ |
| NBL       | Neutral             | $\infty$ | 0.4             | 0                   | $3000 \times 1500 \times 500$   | $200 \times 150 \times 100$ |
| SBL       | Stable              | 150    | 0.31             | -0.015              | $3000 \times 1500 \times 250$   | $200 \times 150 \times 50$  |

3. Results

The vertical profiles of the inflow for different stability conditions are shown in Fig. 2. In all the cases, the incoming wind has the same wind speed $U_{hub} = 8$ m s$^{-1}$ at the hub height. As expected, for the same $U_{hub}$, stronger vertical mixing in the CBL results in a higher turbulence intensity. The turbulence intensity (TI) is computed by:

$$TI = \sqrt{2\overline{k}/3U_{hub}},$$

where $\overline{k} = 0.5\overline{u_i' u_i'}$ is the time-averaged resolved-scale turbulent kinetic energy. Similarly, the kinematic shear stress $-\overline{u'w'}$ in the unstable condition is higher compared with the neutral and stable ones (Fig. 2d).

The vertical profile of the turbulent kinematic heat flux $\overline{w'\theta}$ is also plotted in Fig. 2c. These simulated velocity and temperature fields are then used as inflows to the wind-turbine wake simulations.

Figure 2. Vertical profiles of a) the time-averaged streamwise velocity $U$ (m s$^{-1}$), b) the time-averaged potential temperature $\Theta$ (K), c) the kinematic heat flux $\overline{w'\theta}$ (K m s$^{-1}$), d) the kinematic shear stress $-\overline{u'w'}$ (m$^2$ s$^{-2}$), e) the streamwise turbulence intensity $I_u$, and f) the total turbulence intensity $TI$ of the incoming ABL flows. The horizontal dotted lines show the top-tip, hub, and bottom-tip heights.

Figure 3 displays the time-averaged streamwise velocity contours in a vertical $xz$ plane through the center of the turbines as well as in a horizontal $xy$ plane at the turbine hub height, respectively. As can be seen in the figure, the simulation results indicate that the upwind flows with different stability conditions result in significant differences in the mean velocity distribution of the turbine wakes. In particular, in the convective boundary layer with a higher level of turbulence, the wake recovers faster which is attributed to the increased momentum
transport and turbulent mixing induced by convection. In contrast, in the stable condition, it takes a longer distance for mixing to be complete in the wake (i.e., larger wake region).

![Figure 3](image)

**Figure 3.** Contours of the time-averaged streamwise velocity $U$ (ms$^{-1}$) in the middle vertical $x-z$ plane perpendicular to the turbines (a) and in the horizontal $x-y$ plane at the turbine hub height (b) for different stability conditions.

The lateral and vertical profiles of the velocity deficit $\Delta U/U_{hub}$ through the center of the wakes are shown in Fig. 4, where $\Delta U = U_{inflow} - U$ is the time-averaged velocity deficit, and $U_{inflow}$ is the time-averaged streamwise inflow velocity shown in Fig. 2a. Again we can see that the magnitude of the velocity deficit increases with increasing the atmospheric stability for all distances downstream of the turbine. The reason is the mixing between the wake and the ambient air is less efficient during the stable condition than during the neutral and unstable ones. Magnusson and Smedman [2] reported similar trends using the filed data downwind of a wind turbine in the Alsvik wind farm during different atmospheric stability conditions. It is also found that, the velocity deficit in the wake has an approximately Gaussian shape after some downwind distances. This behavior in the turbine wakes was reported in previous numerical and experimental studies by Wu and Porté-Agel [25], Rados et al. [26], Chamorro and Porté-Agel [27], and Zhang et al. [5].

Figure 5 shows contours of the turbulence intensity $TI$ in a vertical $x-z$ plane through the center of the turbines as well as in a horizontal $x-y$ plane at the turbine hub height, respectively.
As can be understood from these contours, an obvious enhancement of the turbulence intensity is observed at the top-tip level and also near the two side-tip positions, which is related to the intense production of turbulent kinetic energy associated with the strong shear at those locations. It is also evident that the exact location and magnitude of the maximum turbulence intensity is clearly affected by the stability condition. In particular, the higher turbulence level in the incoming flow leads to also a larger maximum wake turbulence level, which occurs closer to the turbine for the convective condition, compared with the neutral and stable ones. This is consistent with the faster recovery of the wake observed in the convective condition.

Figure 6 displays contour plots of the kinematic shear stress $\tau_{xz}$ in a vertical $x - z$ plane through the center of the turbines. This term is mainly responsible for the vertical kinetic energy entrainment into the wake. From this figure, it is evident that $\tau_{xz}$ has positive values around the upper edge of the wake and negative values around the lower edge. It should be noted that the magnitude of the momentum flux is larger in the upper part of the wake, where the shear is strongest. In addition the magnitude of the shear stress is higher in the unstable condition compared with the neutral and stable ones, which leads to a higher kinetic energy entrainment into the wake. The higher kinetic energy entrainment into the wake in the convective condition is consistent with the above-described faster wake recovery in that condition. From Fig. 6, the position of the maximum turbulent stress is found closer to the turbine under the unstable condition and further downstream under the stable one, coinciding with the location of the maximum turbulence intensity for those cases (Figure 5).

4. Conclusion
In this study, large-eddy simulation (LES), coupled with a turbine model, was used to investigate the effect of atmospheric stability on wind-turbine wakes. In the simulations, the tuning-free Lagrangian scale-dependent dynamic models were used to model the subgrid-scale turbulent fluxes, while the turbine-induced forces (e.g. lift and drag) were parameterized with the actuator disk model with rotation.
Figure 5. Contours of the time-averaged turbulence intensity $T I$ in the middle vertical $x - z$ plane perpendicular to the turbines (a) and in the horizontal $x - y$ plane at the turbine hub height (b) for different stability conditions.

Figure 6. Contours of the kinematic shear stress $\tau_{xz} \ (m^2 s^{-2})$ in the middle vertical $x - z$ plane perpendicular to the turbines for different stability conditions.
The simulation results show that the atmospheric thermal stability has a significant influence on the spatial distribution of the mean velocity deficit, turbulence intensity, and turbulent shear stresses in the turbine wakes. In particular, the wake recovers faster under the convective condition compared with the neutral and stable ones. This enhancement in the wake-recovery rate is most likely related to the higher turbulence level of the incoming wind in the unstable condition, which leads to a higher turbulent entrainment flux into the wake. In addition, the maximum turbulent stresses and turbulence intensity in the wake occur around the top-tip level, where the mean shear is largest and their magnitudes are larger in the unstable condition compared with the neutral and stable cases.

The results presented in this work provide unique datasets for the improvement and validation of analytical models of wind-turbine wakes by taking into account the effect of atmospheric stability similar to the one performed by Bastankhah and Porté-Agel [28] for neutrally-stratified ABLs. Future research will address the effect of thermal stratification on the structure and characteristics of wind-turbine wakes and their interaction with the ABL inside wind farms.

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