Turbulent flow and scalar transport through and over aligned and staggered wind farms

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Wind farm–atmosphere interaction is complicated by the effect of turbine array configuration on momentum, scalar and kinetic energy fluxes. Wind turbine arrays are often arranged in rectilinear grids and, depending on the prevailing wind direction, may be perfectly aligned or perfectly staggered. The two extreme configurations are end members with a spectrum of infinite possible layouts. A wind farm of finite length may be modeled as an added roughness or as a canopy in large-scale weather and climate models. However, it is not clear which analogy is physically more appropriate. Also, surface scalar flux, including heat, moisture and trace gas (e.g. CO\textsubscript{2}), are affected by wind farms, and need to be properly parameterized in large-scale models. Experiments involving model wind farms, in aligned and staggered configurations, were conducted in a thermally controlled boundary-layer wind tunnel. Measurements of the turbulent flow were made using a custom x-wire/cold-wire probe. Particular focus was placed on studying the effect of wind farm layout on flow adjustment, momentum and scalar fluxes, and turbulent kinetic energy distribution. The flow statistics exhibit similar turbulent transport properties to those of canopy flows, but retain some characteristic surface-layer properties in a limited region above the wind farms as well. The initial wake growth over columns of turbines is faster in the aligned wind farm. However, the overall wake adjusts within and grows more rapidly over the staggered farm. The flow equilibrates faster and the overall momentum absorption is higher for the staggered compared to the aligned farm, which is consistent with canopy scaling and leads to a larger effective roughness. Surface heat flux is found to be altered by the wind farms compared to the boundary-layer flow without turbines, with lower flux measured for the staggered wind farm.

Keywords: atmospheric boundary layer (ABL); canopy turbulence; roughness transition; scalar transport; wake–turbine interaction; wind farm layout; wind-tunnel experiment

1. Introduction

With increased interest in developing sustainable renewable energy, wind farms are being built larger and in more locations. Whether onshore or offshore, wind farms now occupy a significant amount of the earth’s surface and invariably have an impact on surface-atmosphere fluxes of momentum, moisture and trace gases (e.g. CO\textsubscript{2}). To account for wind
farm–atmosphere interaction in large-scale weather and climate models, new or improved parameterizations need to be developed. As the interaction between the atmospheric boundary layer (ABL) and wind farms is multiscale and fully coupled, it is also necessary to develop improved methods for designing wind farms to optimize the power output and minimize fatigue loads on the turbines for different wind farm configurations, atmospheric stability and complex land cover and terrain characteristics. Energy converted to power by a wind farm is derived from the available energy of the wind. This energy is primarily available as total kinetic energy in the ABL, and is extracted in two primary ways, from the incoming wind at the leading edge of the wind farm and from above the farm. For very large wind farms where the distance across the farm is much larger than the characteristic flow development length scale, nearly all of the energy must be extracted from flow above the farm [1–4].

A challenging problem for the design of wind farms is balancing the need for adequate spacing between turbines to extract the maximum amount of energy per turbine, while at the same time limiting the amount of land used for power production and ensuring that wakes–turbine interaction does not lead to fatigue failure [5]. The most important aerodynamic considerations in the design of wind farms is the velocity deficit within the farm and the enhancement of turbulence intensity, which primarily occurs near the top-tip height of the farm [6]. The velocity deficit within the farm is linked to the amount of power which can be extracted from the flow, while turbulence generated by strong shear and tip vortex shedding at the top of the farm can lead to structural fatigue and possibly failure of wind turbine components. In addition, it has been found that the current models used for wind farm design tend to overpredict the power that a farm will generate [7, 8]. This is likely due to incomplete and/or incorrect turbine parameterizations of wake–turbine interactions within wind farms as well as errors in representations of the effect of atmospheric stability [9]. Individual wind turbine efficiency and turbine spacing are parameters which engineers control in the design of wind farms. Therefore, it is important to understand how wind-turbine wakes interact and combine, and how wind farm layout may affect the velocity deficit and turbulence intensity in the farm. When there are multiple turbines aligned with the wind, it has been observed that while the first row of turbines produces the maximum power, similar to standalone turbines, there is a significant decrease in power production for the second row of turbines downwind, with limited additional losses for successive turbines [10]. Vermeulen and Buitjé [11] found that turbulence intensity increases to a maximum behind the second row of turbines and then relaxes until reaching an equilibrium by the third or fourth rows.

Large wind farms can affect local meteorology and possibly even the global climate system. First attempts to predict the effect of wind farms on regional-scale weather patterns assumed wind farms increase the effective surface roughness and turbulent kinetic energy (TKE) in the logarithmic layer, resulting in a measurable response in regional weather and climate [12–14]. The surface-layer approximation for modeling wind farms was introduced by Frandsen [15]. Alternatively, wind farms may be modeled using a distributed drag approach, taking into account the large vertical extent of turbines and treating the wind farm as a tall canopy [16]. This can be incorporated into Reynolds averaged Navier–Stokes (RANS) simulation frameworks, or at even finer scales, high-resolution large-eddy simulations (LESs), using turbine parameterizations based on blade element momentum theory (e.g. drag disk or actuator line models), are able to resolve detailed fluid dynamics in the wakes of turbines and provide important information about how multiple turbines and wakes interact in a turbulent flow, as shown by Lu and Porté-Agel [3], Porté-Agel et al. [17] and Wu and Porté-Agel [18].
Much work has been done recently by a number of researchers to understand wind farm–atmosphere interactions and in-farm fluid dynamics. Research by Frandsen et al. [1, 16], Cal et al. [19], Chamorro and Porté-Agel [6], Porté-Agel et al. [17] and others involve theoretical model development, laboratory experiments and field scale experiments and simulation of flow in wind farms. All have provided insights into how wind turbines affect the ABL, and how they may be parameterized in wind turbine siting models as well as large scale weather and climate models. In particular, Corten et al. [20] presented an early wind tunnel experiment measuring the flow through a scaled-down wind farm. Studying boundary-layer interaction with a wind farm consisting of 28 turbines for both onshore and offshore conditions, they found that it takes far more than five rows of turbines for the flow to reach equilibrium. Recently Chamorro and Porté-Agel [21] showed the importance of an incoming boundary layer with varying surface roughness on the wake of a single wind turbine. Zhang et al. [22] revealed the effect of the boundary layer on near wake turbulence for a similar wind turbine. In addition, Chamorro and Porté-Agel [23] and Zhang et al. [24] showed the effects of stable and convective incoming boundary layers, respectively, on the wake recovery for a single turbine. Hancock and Pascheke [25] also investigated the effect of a moderately stable ABL on wind-turbine wake recovery. Cal et al. [19] presented wind tunnel experiments for a $3 \times 3$ wind-turbine array and argued that large wind farms extract most of the energy from the flow above the farm. Chamorro and Porté-Agel [6] presented wind tunnel experimental results describing the flow in and around an aligned wind turbine array, and Chamorro et al. [26] studied the flow through a staggered wind turbine array, both in isothermal conditions. However, it is still not clear if current parameterizations accurately represent wind farm–atmosphere interaction, and development and testing of improved parameterizations are needed to increase confidence in our ability to accurately represent wind farms in models. It is also not well understood how wind turbine array arrangement and wake–turbine interactions affect the overall absorption of momentum, the distribution of added turbulence and turbulent transport, nor the distribution of TKE within large wind farms.

To date, results have not been reported directly comparing the flow within and over aligned and staggered wind farms, nor has there been work to examine whether flow through and over a wind farm is best represented as a rough surface layer or as a canopy flow. Also experimental measurements of passive scalar transport in wind farms have not been performed. This study presents wind tunnel experiments to examine the turbulence characteristics in and over aligned and staggered model wind farms, consisting of 12 rows of horizontal axis wind turbines, in a deep turbulent boundary-layer flow. We characterize the wake development within and over the wind farms as well as the horizontally averaged vertical momentum flux and effective roughness for the quasi-fully-developed flow in wind farms. We also characterize the overall momentum absorption, heat flux, TKE budget and the scaling parameters of canopy turbulence to assess the appropriateness of the rough surface layer versus canopy model analogies for describing large wind farm flows. The paper is organized as follows: Added roughness and canopy models are presented in Section 2 as an underlying framework for the analysis; the experimental facility, the measurement methods and the experimental conditions are then described in Section 3; Section 4 compares the flow development within the two wind farm configurations, characterization of the wake expansion above the wind farms and presents the spanwise-averaged flow statistics of the developed flow, including the mean velocity, turbulence intensity, momentum flux, TKE and passive scalar transport. Section 5 discusses observed characteristics of the flow and assesses models for added roughness and canopy flows. Finally, Section 6 provides a summary of the key results and conclusion.
2. Wind farm models

2.1. Added roughness model

The added roughness model is commonly used to describe flow over wind farms [1, 2, 9]. A general model proposed by Lettau [27] is based on the geometry of roughness elements and a drag coefficient. Reformulating the model utilizing properties of wind farms, including the turbine thrust coefficient $C_T$ and the streamwise and spanwise wind turbine spacing $S_x \times S_y$, in terms of multiples of the rotor diameter $D$, is

$$
\frac{z_{0.L}}{Z_{hub}} = C_T \frac{Z_{hub} \pi}{4S_x S_y} = \frac{c_{f.t}}{Z_{hub}},
$$

where the important vertical length scale for describing momentum extraction from the flow is assumed to be the hub height $Z_{hub}$ and $c_{f.t} = \frac{\pi C_T}{4S_x S_y}$ is the drag coefficient for the wind farm drag per-unit surface area of ground or ocean.

Frandsen et al. [1] introduced the hypothesis that wind farms can be modeled as a combination of two log layers intersecting at the hub height, which takes into account the roughness of the surface as well as the momentum extracted by the wind farm, resulting in an effective roughness due to the turbine array. The resulting roughness $z_{0,F}$ model follows as

$$
\frac{z_{0,F}}{Z_{hub}} = \exp \left( -\kappa \left[ \frac{1}{2} c_{f.t} + \left( \frac{\kappa}{\ln(Z_{hub}/z_{0,gnd})} \right)^{-2} \right]^{-1/2} \right),
$$

where $z_{0,gnd}$ is the roughness of the underlying surface.

A recent refinement of the model was developed, supported by LES results for a suite of 14 hypothetical wind farms using a drag disk wind turbine parameterization, that incorporates a rotor-induced wake region buffering the two log layers [2]. The resulting model takes the form

$$
\frac{z_{0,C}}{Z_{hub}} = (1 + B) \beta \exp \left( -\frac{c_{f.t}}{2\kappa^2} + \left( \frac{\ln(Z_{hub}/z_{0,gnd}) (1 - B) \beta}{Z_{hub}/z_{0,gnd}} \right)^{-2} \right)^{-1/2},
$$

where $B = D/2Z_{hub}$, the exponent $\beta = v_{w}^2/(1 + v_{w}^2)$ and $v_{w}^2$ is a wake eddy viscosity estimated by Calaf et al. [2] as $v_{w}^2 \approx 28 \sqrt{c_{f.t}/2}$. To estimate roughness using the above models, an accurate thrust coefficient must be determined for wind turbines within a farm. Typically, a single representative value of $C_T$ is used, based on the performance of individual turbines and invariant of wind turbine array configuration. This is problematic because $C_T$ is expected to depend on the configuration of the turbines within the farm, due to in-farm flow organization resulting in variable degrees of wake interaction and sheltering from upwind turbines.

2.2. Wake growth model

For wind farms of a finite length, the flow transitions from the upwind water or land surface to the wind farm leading to the expansion of interacting wakes. Frandsen et al. [1] suggested
the flow through and over wind farms can be separated into two distinct layers, the flow inside the farm and the internal boundary layer above due to the transition from a relatively smooth to a rougher surface. Wake development within the wind farm can be characterized by the velocity deficit, and the level of turbulence can be characterized as added turbulence intensity due to the wind farm.

To represent the wind farm as a roughness transition, lateral ensemble-averaged velocity profiles are required to track the internal boundary-layer adjustment. However, due to the large distance between roughness elements leading to a long drag development scale, which is a measure of the distance required for the flow to adjust to the imposed drag inside the wind farm, the roughness transition model may break down as an equilibrium sublayer cannot develop above the wind farm until the flow within the farm reaches equilibrium. This means the flow within the wind farm is coevolving with the flow above and is characterized by complex three-dimensional wake interactions (cf. [28]). It may be more important, from the standpoint of wake–turbine interaction, to determine the rate of wake growth along columns of turbines. The flow adjustment above a wind farm can be characterized using mean and turbulence flow statistics. Wake expansion is typically modeled using one of two approaches: empirically with a power law following, e.g. Elliott [29] and Wood [30], or the more complex model based on the diffusion analogy following Panofsky and Dutton [31]. The diffusion analogy is based on the principle of limited diffusion of momentum. The model proves useful for modeling complex wake expansion and will be used to evaluate the wake growth rate over the wind farm. The wake growth rate is controlled by the relative level of shear stress or vertical turbulence intensity within the wake. A proportional relationship between wake growth and shear or vertical turbulence intensity follows as

\[
\frac{d\delta_{\text{wake}}}{dx} \propto \frac{\sigma_w}{U(\delta_{\text{wake}})} \propto \frac{u^*}{U(\delta_{\text{wake}})}. 
\]

(4)

2.3. Canopy model

An alternative to the added roughness model is the canopy-type model, which resolves the effect of the vertical extent of the wind farm. Wind farms are fundamentally made up of distributed momentum-absorbing elements, that have a significant vertical extent, distorting the flow. Such complex flows can be described as canopy turbulence or as obstructed shear flows [32–34]. They are common in the ABL as well as other engineering and environmental flows. The salient feature of a canopy flow is an inflection point in the mean velocity profile, which consequently results in dynamically different transport process from that of surface-layer-type flows. The resulting inviscid instability leads to enhanced turbulence and two integral length scales to emerge, including the shear length scale \( L_s \) that describes the characteristic scale of coherent Kelvin–Helmholtz (K-H)-type eddies at the top of the canopy, and the canopy drag development length scale \( L_c \). The shear length scale can be defined as

\[
L_s = \frac{U_H}{(dU/dz)_{z=Z_H}}, 
\]

(5)

where \( U_H \) is the mean velocity at the top of the canopy, and \( Z_H \) is the aerodynamic canopy height, defined by the height of the inflection point in the mean velocity profile. The shear length scale \( L_s \) is the characteristic depth K-H-type eddies penetrate into a canopy. If present in a wind farm, K-H eddies may represent a significant potential source of turbulent
loading on the wind turbines. The drag development length scale is defined as

$$L_c = (C_d a)^{-1},$$

where $C_d$ is the drag coefficient, and $a$ is the canopy area density or projected frontal area per unit volume, which is proportional to the distance required for the momentum within the wind farm to come into balance with the drag force. Coceal and Belcher [35] estimated that the flow within a canopy is fully developed when the drag force is balanced by the vertical momentum flux at approximately $3L_c$. However, the flow development length has been shown to depend on the configuration and drag characteristics of obstacles in the flow, as well as the turbulence statistics being considered. Higher order flow statistics may require a longer distance to adjust. Cheng and Castro [36] and Coceal et al. [37] presented results from wind tunnel experiments and LESs, respectively, for flow in and above a model urban canopy. They found the flow in a staggered array of cubes adjusted more rapidly than in the aligned array due to the effect of wake sheltering. It is expected that similar results may be found for wind farms. The drag coefficient is difficult to know a priori for a complex array of roughness elements like turbines in a wind farm. Coceal et al. [37] showed that the drag characteristics of the aligned and staggered cube arrangements were quite different because of distinct differences in the three-dimensional structure of the flow.

Frandsen et al. [16] presented a framework for modeling wind farm flow in terms of a canopy-type flow following theoretical work on urban canopies by Belcher et al. [38], and found good results comparing with field data from an offshore wind farm. The linearized model and scaling relies on a relatively sparse canopy to ensure that nonlinear terms may be considered negligible. As identified by Frandsen et al. [16], the linearized canopy model is particularly useful as an intermediate model for accurately representing the mean velocity deficit within the relatively sparse wind farm array (intermediate in the sense that it is between the complexity of the added roughness model and more detailed explicitly resolved turbine modeling employed in computational fluid dynamics (CFD) models). The canopy model has not been rigorously tested for sparse canopies or for wind farms. This is particularly true with regard to second-order moments and turbulent transport. The flow over a wind farm may behave similar to a canopy flow; however, in general, canopies are denser than the typical wind farm. Wind farms may be considered sparse canopies; however, research on sparse canopies to date is limited, and it is unresolved whether length scales (e.g. $L_s$) for dense canopies apply to sparse canopies and by extension to wind farms.

The momentum equation for a fully developed canopy flow residing within the surface layer of the ABL, with zero longitudinal pressure gradient, and horizontal averaging simplifies to the form

$$-\frac{d}{dz} \left( \langle u'w' \rangle_{xy} + \langle \bar{u}'' \bar{w}'' \rangle_{xy} \right) = \langle f_x \rangle_{xy}. $$

The meteorological convention is used where $x_i$ is the direction in Cartesian coordinates with $i = (1, 2, 3)$ or $(x, y, z)$, the $z$-coordinate oriented vertically and with the corresponding velocity $u_i$. The overbar signifies time averaging, $\langle \cdot \rangle_{xy}$ represents spatial averaging in the streamwise and spanwise directions, as identified by the subscripts, and $f_x$ is the turbine-induced force. The total wall-normal shear stress is defined as

$$\tau_{xz} = \langle u'w' \rangle + \langle \bar{u}'' \bar{w}'' \rangle,$$
where we assume viscous effects are negligible and \( \langle \overline{u''} \overline{w''} \rangle \) is the dispersive flux of momentum. The dispersive flux or stress is the horizontally unresolved subgrid-scale quantity that arises from horizontal spatial filtering of the momentum equation and represents the contribution to momentum transfer from correlations between spatial variations in the time-averaged flow where \( \overline{u''_i} = \overline{u_i} - \langle \overline{u_i} \rangle \) [39]. The turbine-induced drag force is

\[
F = \frac{1}{2} \rho C_T A_r U |U|, \tag{9}
\]

where \( \rho \) is the density of the air, \( A_r \) is the rotor swept area and \( U \) is the mean streamwise velocity. The force, per unit mass, distributed over the unit volume occupied by turbines in a wind farm is

\[
\langle f \rangle_{xy} = \frac{F}{Z_H A_f}, \tag{10}
\]

where \( Z_H \) is the representative height of the wind farm and \( A_f = S_x S_y D^2 \) is the unit ground area per turbine. The distributed force is the volume average force in Equation (7), which can be modeled as the square of the mean velocity divided by the canopy drag length scale,

\[
\langle f \rangle_{xy} = \frac{U |U|}{L_c}, \tag{11}
\]

where \( L_c \) can be rewritten in terms of wind farm parameters as

\[
L_c = \frac{2Z_H A_f}{C_T A_r} = \frac{8Z_H S_x S_y}{\pi C_T} = \frac{2Z_H}{c_{f1}}. \tag{12}
\]

An accurate \( C_T \) is required to make predictions of the distance for the flow to develop inside a wind farm. In addition, the shear penetration length scale has been found for many obstructed shear layer flows to be \( L_s \approx 1/3 L_c \) [33]. The dispersive flux is generally not important in canopy flows as it has typically been found to be about 1% of the shear stress [40, 41]. However, it is likely significant for sparse, heterogeneous canopies or wind farms and is known to be important near the leading edge \( x \lesssim O(L_c) \) of a canopy where advective flux is significant [42].

3. Experimental setup

3.1. Atmospheric boundary-layer wind tunnel

Experiments were conducted at the St. Anthony Falls Laboratory (SAFL) thermally stratified boundary-layer wind tunnel at the University of Minnesota. The low speed tunnel has a plan length of 37.5 m and was operated in closed loop return mode. The main test section is approximately 16 m long, has a cross-section of 1.7 m \( \times \) 1.7 m and has a 6.6:1 area contraction ratio. A 200 HP fan drives the flow and turning vanes along with screens and honeycomb flow straighteners help train the flow. The resulting freestream turbulence intensity is less than 1% at 3.2 m s\(^{-1}\). The flow was tripped by a 4 cm \( \times \) 8 cm picket fence, which initiates the growth of a deep turbulent boundary layer, and an adjustable roof allows
for zero pressure gradient conditions. The surface layer exhibits good statistical properties with logarithmic mean and linear stress profiles.

The air temperature was controlled with an automated water heater/chiller and heat exchanger at the expansion region downwind of the fan. Aluminum panels on the floor are thermally controlled to maintain the floor temperature independent of the air, within \( \pm 0.25^\circ\text{C} \), using automated valve controllers. Nominally, a \( 60^\circ\text{C} \) differential can be maintained, which allows for well-controlled simulation of neutral, stable and convective boundary layers. Secondary false walls were installed along the inner sides of the test section to reduce heat transfer with the outside and prevent secondary circulations from forming. A similar approach was employed by Ohya and Uchida [43] to study stratified-boundary-layer dynamics in the wind tunnel at Kyushu University, Japan. More details about the SAFL wind tunnel configuration and operation can be found in Carper and Porté-Agel [44] and Chamorro and Porté-Agel [45].

### 3.2. Model wind farm

The model wind turbine arrays consisted of 36 (aligned) and 30 (staggered) miniature wind turbine models (see Figure 1) with three-blade, GWS EP-5030 \( \times 3 \), rotors attached to adjustable load resistance SGST DC microgenerators (model SRF-1220CA-15085) which were immersed in a turbulent boundary layer. The nacelle around the generator has a 12 mm diameter and extends 3 cm behind the rotor hub. The maximum rated power output from the generator was 0.6 W. The rotor diameter \( D = 12.8 \text{ cm} \) with the bottom tip of the turbine at a height of 3.8 cm (0.3\( D \)) and the top-tip at \( z = 16.8 \text{ cm} \) (1.3\( D \)). The hub height was 10.4 cm, resulting in the turbine rotor swept area within the lowest 1/3 of the turbulent boundary layer, ensuring geometric similarity with prototype scale wind farms. Specific details about the blade geometry are provided in Table 1, including chord length \( (c) \), max thickness \( (t_{\text{max}}) \) and twist angle \( (\alpha_r) \) at various positions along the radius \( (r/R) \), where \( R \) is the rotor radius (6.4 cm). At a freestream velocity of 3.2 m s\(^{-1}\), the turbine operated at 1710–1760 rpm. The resulting tip speed ratio \( (\lambda = \Omega(2\pi/60)(D/2)/U_{\text{hub}}) \) is approximately 4.2. The tip speed ratio generally falls within the values of previous experiments involving 3-blade wind turbine models (between 3 and 6.7) reported by Vermeer et al. [46]. Typical field scale wind turbines operate at an optimal \( \lambda \) between 6 and 8. Experiments using similar turbines include Chamorro and Porté-Agel [6,21] and Zhang et al. [22,24].

<table>
<thead>
<tr>
<th>( r/R )</th>
<th>Chord length ( c/R )</th>
<th>Max thickness ( t_{\text{max}}/c )</th>
<th>Twist angle ( \alpha_r ) (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>0.222</td>
<td>0.092</td>
<td>14.8</td>
</tr>
<tr>
<td>0.31</td>
<td>0.235</td>
<td>0.084</td>
<td>18.0</td>
</tr>
<tr>
<td>0.47</td>
<td>0.235</td>
<td>0.075</td>
<td>19.6</td>
</tr>
<tr>
<td>0.63</td>
<td>0.219</td>
<td>0.067</td>
<td>17.6</td>
</tr>
<tr>
<td>0.79</td>
<td>0.183</td>
<td>0.050</td>
<td>12.4</td>
</tr>
<tr>
<td>0.94</td>
<td>0.135</td>
<td>0.051</td>
<td>8.7</td>
</tr>
<tr>
<td>0.99</td>
<td>0.105</td>
<td>0.048</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Note: Twist angle is relative to the rotor plane.
Two wind farm layouts, with perfectly aligned and staggered configurations, were investigated. The aligned layout consists of a rectilinear grid of turbines with 13 rows and 3 columns. The rows have a streamwise spacing of $S_x = 5D$ and the columns are separated in the spanwise direction by $S_y = 4D$ resulting in a unit turbine area density of $S_x S_y = 20D^2$. The staggered array has the same spacing; however, the even numbered rows have only two turbines and are laterally staggered by $2D$ with respect to the aligned configuration (see Figure 2). A similar 2–3 column arrangement was investigated in [26]. The equal turbine density allows for direct comparison of the turbine layout effect on the wind farm performance, flow and turbulent transport characteristics. Solid blockage effects are estimated based on the ratio of the rotor disk area and projected area of the tower to the wind tunnel cross-sectional area. For the aligned case, three turbines span the tunnel resulting in a blockage of 1.3%. For the staggered case, a total of five turbines span the tunnel resulting in a blockage of 2.1%. Many investigators have assessed the effect of blockage and found that solid blockage should be less than 5%–10% to insure unimpeded expansion of wakes [47].
Figure 2. Schematic diagram of the aligned (top) and staggered (bottom) wind farms. Profiles collected behind the twelfth and eleventh row, respectively, at selected spanwise locations were used to characterize the quasi-developed flow. Note that the even numbered rows in the staggered farm have two turbines, while the odd-numbered rows have three turbines.

3.3. Hot-wire anemometry

High-resolution turbulence measurements were made using a custom three-wire (x-wire and cold wire) probe. The x-wire is a standard type, which allows for measurements of instantaneous streamwise and vertical velocities as well as evaluate the wall normal momentum fluxes. The hot wires are 5.0 μm diameter platinum-coated tungsten wires separated by 0.7 mm and the cold wire is a 2.5 μm diameter wire, 1.7 mm in front of the x-wires. An A.A. Lab System AN-1003 10 channel CTA/CCA system was used to capture the voltage signal with an overheat ratio of 1.2 to minimize interference between the x-wire and cold-wire sensors. The collocation of a cold-wire and x-wire sensor allowed for point-by-point temperature correction of the x-wire measurements as well as wall normal heat flux to be measured. The sensor was calibrated in a custom calibration unit against a Pitot–static tube and a copper-constantan thermocouple at four temperatures,
seven inclination angles and seven velocities. A look-up table calibration method, using cubic spline interpolation, was used to determine the two instantaneous velocity components from the two instantaneous voltage signatures. Calibration was performed at the beginning of the experiment and a postexperiment calibration was carried out to check the validity of the calibration throughout the experiment. During the calibration and measurements, the air and floor temperatures were maintained within a range of ±0.25°C to avoid bias errors caused by thermal drift of the voltage signal. More details on the calibration procedure can be found in [48] and [49]. The sensor was mounted on a traversing system (Velmex, Inc), controlled with a custom Labview program, so that multiple locations could be precisely measured. Measurement uncertainty for mean velocities is within 1%, while turbulence statistics are accurate to approximately 3%–5% depending on turbulence level in the flow and distance to the wall or to the wind turbine models.

Measurements were taken at selected locations within the wind farm to characterize the flow development along the centerline $y = 0$ inside and over the two wind farm configurations. The profiles have a vertical spacing $\Delta z = 1$ cm, and a streamwise spacing $\Delta x = 1D$. Profiles were also taken at various spanwise locations $y/D = -1, 0, 1$ and 2 within the wind turbine arrays, at $x/D = 3$ behind the twelfth row of the aligned layout and the eleventh row of the staggered layout (Figure 2). These measurements characterize the spatially averaged flow statistics within and over the wind farms. Time series of $u$, $w$ and $\theta$ were collected at each point for 90 s to 120 s at a frequency of 2000 Hz.

3.4. Boundary-layer characterization

A thick turbulent boundary layer is generated in the wind tunnel test section. Over a homogeneous flat surface, the mean velocity in the surface layer (the lowest 10%–15% of a fully developed turbulent boundary layer) follows a log-law profile modified with a stability correction, and is written as

$$U(z) = \frac{u_*}{\kappa} \left[ \ln \frac{z - d}{z_0} + \Psi_m \left( \frac{z - d}{L} \right) \right],$$

(13)

where $u_*$ is the friction velocity defined as $u_* = (-\bar{u}'w')^{1/2}$, the surface kinematic shear is taken as the minimum value at the surface, $\kappa$ is the von Karman constant ($\approx 0.4$), $z_0$ is the roughness length, $d$ is the zero-plane displacement and

$$\Psi_m((z - d)/L) = -2 \ln \left( \frac{1 + X}{2} \right) - \ln \left( \frac{1 + X^2}{2} \right) + 2 \tan^{-1}(X) - \pi/2$$

(14)

is the diabatic term. In Equation (14), $X = (1 - 15((z - d)/L))^{1/4}$ is a function of the Obukhov length, $L = -(u_*^3 \Theta_0)/(\kappa g Q_s)$ [50]. The Obukhov length scale corresponds to the height where buoyancy production of turbulence overcomes the shear production, $\Theta_0$ is the reference temperature, often taken as the mean value measured in the surface layer, $g$ is gravitational acceleration, and $Q_s = (w'\theta')_s$ is the surface heat flux. $Q_s$ is taken as the maximum value at the surface. Thermal stability can be quantified by the Richardson number $Ri$, the ratio of the buoyancy production to shear production terms of the TKE budget. It is more common to use the bulk Richardson number $Ri_b = g \delta \Delta \Theta / (\Theta U_0^2)$ as the measure of atmospheric stability for complex boundary layers with surface heterogeneity.
and topography. It is negative for the unstable or convective boundary layer, zero for neutral conditions and positive for stable conditions.

In this study, a nearly neutral boundary layer was developed over a smooth surface and grew to a depth of $\delta = 50$ cm where $U(\delta) = 0.99 U_0$. The aerodynamic roughness and friction velocity were $z_0 = 0.08$ mm and $u_* = 0.12$ ms$^{-1}$, respectively. The heat source was achieved by maintaining the floor temperature at 72°C and a freestream temperature at 12°C. Figure 3 shows the profiles of the mean velocity, turbulence intensity and fluxes as well as the flux Richardson number profile in the surface layer. The velocity profiles with and without a heat source were measured and were found to be very similar with the same boundary-layer thickness, roughness and friction velocity. The bulk Richardson number $Ri_b = -0.09$ and Obukhov length $L = -0.4$ m. Therefore, $L$ is 80% of the boundary-layer thickness for the flow entering the wind farm. The diabatic term in the Monin–Obukhov profile was evaluated and found to be negligible. There still may be a small buoyancy enhancement effect on the turbulent dynamics of the first couple of rows of turbines; however, shear and wake generation of TKE quickly overwhelm any buoyancy effect within the wind farms, as
will be shown in Section (4.4). Therefore, it follows that the heat source does not have an
effect on the dynamics of the flow within the wind farms, which allows for the examination
of the effect of the wind farm on the flux of heat as a passive scalar quantity.

The Reynolds number, based on freestream velocity and boundary-layer thickness,
is approximately $\text{Re}_s = 1 \times 10^5$, and based on turbine height is approximately
$\text{Re}_Z = U_0 Z_H / \nu = 3.6 \times 10^4$. Reynolds numbers in the field are typically two to three orders of
magnitude larger. Despite a mismatch in dynamic scaling between model and prototypical
wind farms, the detailed physics characterized in these experiments provide valuable information about the flow behavior within wind farms immersed in a turbulent boundary layer,
and high-resolution spatial and temporal data that can be used to validate CFD frameworks
including RANS and LES models with turbulent transport and wind turbine parameterizations. It has been shown that, although it is not possible to reproduce the Reynolds numbers
of field-scale flows in a wind tunnel, using the selected wind turbine it is possible to reproduce key characteristics of the wakes, including wake rotation, and the tip/root helicoidal vortex system [22, 51].

4. Results

4.1. Angular velocity

The angular velocity of a wind turbine rotor is a surrogate for power generation. Angular velocity was evaluated as a function of row number for the aligned and staggered wind farms. It is well known that power generation decreases with successive downwind rows of turbines and the rate of decrease depends on the spacing between downwind turbines [1, 9]. Figure 4 shows a comparison between the results for the aligned and staggered wind farms. It is notable that the rotation rate drops quickly for the aligned case by the second row; however, the staggered case exhibits a more gradual decrease. At approximately 10 rows, the staggered case exhibits greater rotation rate than the aligned farm, while at 13 rows

![Figure 4](image)

Figure 4. Angular velocity of each row of wind turbines in the aligned and staggered wind farm normalized with the first row.
they are nearly equal. Therefore, the overall power generated by the staggered wind farm is greater than that of the aligned farm.

4.2. In-farm wake development

4.2.1. Mean velocity

Wind turbines extract kinetic energy from the incoming flow, which results in a wake of reduced velocity behind the turbines. To examine the development of the flow within the wind farms, velocity profiles were measured at selected positions \((x/D = 3)\) downwind of each row of turbines along the center span \((y/D = 0)\). Vertical profiles of the mean streamwise velocity \(U\) compared with the undisturbed incoming flow are shown in Figure 5. For even numbered rows, the closest direct upwind turbine in the staggered configuration is \(x/D = 8\). The velocity profiles follow a similar trend, including large departures from the inflow in the two cases between the bottom-tip and top-tip heights. A key difference between the two cases is that there is a significant wake recovery behind the even number rows in the staggered farm, due to a larger distance along streamlines between turbines and funneling of the flow between the staggered turbines.

The velocity deficit at the center of the wake (around the hub height) is an important parameter to estimate power production and predict overall wake development characteristics. With the assumption of self-similar behavior, the wake profile can be expressed as a function of the velocity deficit at the hub height and radial distance away from the wake center (cf. [1,21,24]). The velocity deficit is calculated by

\[
\frac{\Delta U_s}{U_{hub}} = \frac{U_0(z) - U(x,z)}{U_{hub}},
\]

where \(U_0(z)\) is the incoming mean streamwise velocity, and \(U_{hub}\) is the incoming mean wind speed at the hub height.

![Figure 5](image)

**Figure 5.** Normalized mean streamwise velocity profiles \((U/U_{hub})\) at center span \(y = 0\) and \(x/D = 3\) behind consecutive rows: aligned (left), staggered (right). Horizontal dotted lines represent the top and bottom rotor tip heights. The dash-dotted line indicates the hub height level.
Figure 6. Streamwise mean velocity deficit ($-\Delta U/U_{\text{hub}}$) within the wind farm at center span $y = 0$ and $x/D = 3$ behind consecutive rows: (a) aligned and (b) staggered. Horizontal dotted lines represent the top and bottom rotor tip heights. The dash-dotted line indicates the hub height level. (c) Streamwise velocity deficit ($-\Delta U_{\text{hub}}/U_{\text{hub}}$) at the hub height within the wind farm.

Figure 6 shows the velocity deficit in the wake behind each row of turbines in the wind farm. In the aligned farm case, the velocity deficit at hub height quickly increases to the maximum deficit by the second row and decreases until about the eleventh row where it stabilizes. The trend in the velocity deficit within the staggered farm is nearly constant after the third row, and is greater than the aligned case. Because there is no turbine at the centerline for the second nor subsequent even numbered rows in the staggered arrangement, the flow has a greater distance to recover before the next immediately downwind turbine extracts momentum. In addition, due to the lateral offset of turbines in the second and to a lesser extent in subsequent rows, a Venturi effect is created causing more momentum to recover in front of the second and subsequent rows of turbines. This allows the staggered farm to extract more momentum from the flow. In contrast, in the aligned farm for which the turbines are effectively closer together along streamlines, the wakes shed from upwind rows of wind turbines have less distance to recover. This is significant because it limits the amount of energy the turbines in the aligned case can extract from the flow and conversely
optimizes the amount of energy that can be extracted in the staggered case for a given
turbine density. The results agree with the rotor angular velocity measurements compared
in Section 4.1. On the basis of the results we can conclude that for a given turbine density,
the configuration of wind turbines controls the amount of kinetic energy the wind farm can
extract from the flow.

4.2.2. Turbulence intensity
As pointed out by Rosen and Sheinman [52] and Thomsen and Sørensen [53], turbulence
intensity is the primary cause of fatigue failure and is commonly used as a surrogate
measure of the fatigue loads on wind turbines. Turbulence intensity $I_u$ is commonly defined
as the standard deviation of the wind velocity in the primary wind direction $\sigma_u$ divided by
the mean velocity at the turbine hub height:

$$ I_u = \frac{\sigma_u}{U_{hub}}. $$

(16)

The streamwise turbulence is caused by several coupled mechanisms, including the ambient
boundary-layer turbulence $I_{u0}$, turbulence generated by the shear layer of the turbine wakes,
coherent tip vortex shedding from turbine blades and potentially turbulence generated or
suppressed by thermal stratification, i.e. positive or negative buoyancy, respectively.

It is common practice to consider turbulence intensity at the hub height as representative
of the whole rotor. However, possibly more important is the region around the top-tip height,
where shear generation and tip vortex shedding are significant. Figure 7 shows the turbulence
intensity profiles at the center span, at $x/D = 3$, behind consecutive rows of wind turbines
in the aligned case and behind the odd numbered rows for the staggered case. It is clear that
the turbulence intensity is highest near the top tip height throughout both the wind farms.
It reaches an equilibrium between the third and fourth rows for the aligned case and is
increasing throughout the farm in the staggered case. There is a secondary peak just above
the bottom tip height as well, with lower turbulence intensity at the center of the wakes
and near the surface. The turbulence intensity is higher for the aligned case compared to
the staggered case. This is likely due to greater wake recovery behind consecutive turbines
in the staggered case compared to the aligned case. Overall, wind turbines in the staggered
configuration experience less turbulence than in the aligned case.

It is useful to understand how the added turbulence intensity compares in the two wind
farm configurations. The effective wake or added turbulence intensity $I_{add}$ is defined as a
function of the ambient turbulent intensity $I_0$, and the turbulence intensity in the wind farm
$I_{wf}$ as

$$ I_{add} = \sqrt{I_{wf}^2 - I_0^2}. $$

(17)

Frandsen and Thogersen [54] proposed a model for the added turbulence that takes into
account wind farm density, but does not consider the effects of configuration. The model is
based on the geostrophic drag law and takes into account the additional surface roughness
generated by the turbines:

$$ I_{add,F} = \frac{a \sqrt{C_T}}{b \sqrt{C_T} + \sqrt{S_x S_y}}, $$

(18)
where \( a \) and \( b \) are generic empirical coefficients. Fitting the model to data from various unpublished field experiments, cited in [54], the following relationship has been found to be an adequate approximation,

\[
I_{\text{add}, F} = \frac{0.36}{1 + 0.2 \sqrt{S_x S_y / C_T}},
\]

where the model applies above the hub height.

In the current experiments \( I_{\text{add}} \) adjusts with the same trend as the turbulence intensity shown in Figure 7. Previous experiments have shown that the maximum turbulence intensity occurs near the top tip height and about \( x/D = 3 \) behind turbines, i.e. [6, 26]. Taking the maximum value near the top tip, at the centerline and a distance \( x/D = 3 \) behind the eleventh row turbine as the representative added turbulence for the wind farms, \( I_{\text{add}} = 0.15 \) for the aligned farm and 0.14 for the staggered farm. As will be shown in Section 5 the thrust coefficient, \( C_T \) required to test Equation (19) is 0.18 for the aligned case and 0.47
for the staggered case. The model predicts $I_{\text{add}, F} = 0.12$ for the aligned case and 0.16 for the staggered case. The model generally gives good estimates considering experimentally determined values for $C_T$. As the aligned case is the limiting scenario, practitioners should design for this case. However, while turbines are closer together in the aligned case, the added turbulence experienced by turbines in the wind farm will be higher than in the staggered configuration. The current models do not account for how configuration effects turbulence levels in wind farms. In addition, to understand and model transport of momentum, moisture and other trace gases within the wind farm, more work is required to accurately predict the turbulence levels, taking into consideration wind farm configuration. There are other similar empirical models summarized in [46], but currently there is no theoretical model for the prediction of turbulence intensity inside wind farms that has been well validated against data from wind farms with varying turbine density and configuration [55].

4.2.3. Helicoidal tip vortices

Wind turbines induce a complicated wake vortex system, including coherent helicoidal tip vortices within the ambient turbulence of a turbulent boundary layer. These vortices are associated with enhanced turbulence level, noise generation and structural fatigue due to vortex-induced vibration. Coherent tip vortex structures were characterized for a stand-alone wind turbine wake within a turbulent boundary layer by Zhang et al. [22] and Hu et al. [56]. Tip vortices are strongest near the top tip level behind turbines where background turbulence is lowest, and were only apparent in velocity power spectra to about two to three rotor diameters downwind of the turbine. Here, we examine the persistence of and compare the signature of tip vortices in the aligned and staggered wind farms.

Power spectra of the velocity fluctuations ($u'$ and $w'$) were analyzed for time-series measured at the top-tip height at $x/D = 1$ behind selected rows of turbines. Figure 8 displays the spectra behind the first row, which are the same for both the aligned and staggered wind

![Figure 8](image-url)

Figure 8. Power spectrum of the streamwise and vertical velocity fluctuating components at the top-tip height, center span $y = 0$ and $x/D = 1$ behind the first row of turbines.
farms. The power spectra show the classical production and inertial subranges with $-1$ and $-5/3$ slopes, respectively, for boundary-layer turbulence. However, superimposed is a concentration of energy at a specific frequency, which is associated with tip vortices at the top-tip height. Multiple spectral peaks are detected, including the primary frequency of the top-tip vortex shedding ($3f_t$) and the first harmonic frequency ($6f_t$), where $f_t$ is the rotation frequency of the three-blade turbine.

Some clear differences can be seen between the two wind farm layouts after the second and third rows as well as deep within the wind farms (Figure 9). Particularly in the staggered

![Figure 9](image_url)

Figure 9. Power spectrum of the streamwise and vertical velocity fluctuating components at the top-tip height, center span $y = 0$ and $x/D = 1$ behind the second, third and ninth rows: aligned (left) and staggered (right).
case, the spectra behind the second row, R2, (measured at $x = 6D$, $y = 0$, and $z = Z_H$; referenced to the leading edge of the wind farm) exhibits no peak in energy due to the longer distance to the closest upwind turbine ($6D$) compared to the aligned case ($1D$). However, due to lower turbulence at the next closest downwind turbine, in row R3, the peak is larger for the staggered compared to the aligned case. This result is consistent with earlier findings that higher turbulence intensity leads to a weaker tip vortex signature [24]. This pattern continues throughout the farm and leads to stronger tip vortex signatures behind turbines in the staggered configuration, even far within the wind farm, e.g. behind the ninth row. In addition, the peak signature for both configurations is muted compared to the first row and the second harmonic frequency of the tip vortex signature is undetectable without filtering out the background turbulence signal. This is likely due to the increase in the overall energy concentrated around the peak, exhibited by a wide range of scales and spectral slope that deviates from the inertial $-5/3$ scaling. This may be related to the formation of a shear layer at the top of the wind farm, which may lead to coherent vortex structures and higher turbulence levels compared to boundary-layer turbulence. This behavior is similar to that in and above canopies, as the peak frequency often occurs due to complex fluid–structure interaction involving wake shedding, and the movement of canopy elements, leading to a short-circuiting of the energy cascade [32]. In the case of a wind farm, the fast moving turbines blades chop the air, shedding relatively smaller vortices compared to inertial scale eddies in the flow, expected for a flat boundary layer.

4.3. Vertical wake expansion

The mean velocity just above the two wind farm configurations decreases with downwind distance; however, the rate of decrease is greater for the staggered farm. This reduction in velocity above the wind farms is an indication of a growing wake region as the wakes of consecutive downwind turbines interact (see Figure 5). Wake expansion is characterized to compare the rate of flow development over the wind farms. Here, we focus on turbulence measurements taken along the centerline $y = 0$, over the central column of wind turbines, at a streamwise spacing of $\Delta x = 1D$ and at four heights above the wind farms, from the top tip $z/Z_H = 1$ to $z/Z_H = 2$.

As introduced in Section 2.2, an expanding wake can be modeled as proportional to the vertical turbulence intensity and kinematic shear stress (Equation (4)). Figure 10 shows the streamwise distribution of wall-normal turbulence intensity above the centerline of the two wind farms. The wake growth is evident by the increase in turbulence intensity, compared to the inflow, at each level with increasing downwind distance. As expected for a growing wake, there is a delay in the growth downstream with increasing height. This same pattern holds true for shear stress as well as the streamwise turbulence intensity.

Turbulence levels exhibit clear adjustment from inflow conditions to an equilibrium at varying rates. The wake growth rate can be characterized either by the inception of disturbance or the point of equilibrium. The point downstream where the turbulence or shear stress reaches equilibrium can be defined as the distance where the turbulence reaches 99% of the final equilibrated value. However, the flow over the sparsely spaced turbine arrays is not monotonic from point to point, as the wakes adjust significantly between turbines, making it difficult to identify where equilibrium occurs. One option to aid in the quantification is to smooth or filter the data; however, the specific filter can affect the results. Another option is to fit a smooth function to the data that characterizes the process and assess equilibrium based on adjustment of that function. An appropriate model to describe the growth of wakes is a logistic growth model. Because the wake growth rate is dependent
on the amount of turbulence present (Equation (4)), a logistic growth model is a physically realistic representation to describe the wake growth process. Fitting the growth model to measurements of vertical wake growth, we can determine the wake growth rate, \( d\delta_{\text{wake}}/dx \).

The general form of the logistic growth model, considering the turbulent stress as the characteristic of the flow that is growing, follows as

\[
d(\overline{u_i u_j})/dx = b \overline{u_i u_j} (1 - \overline{u_i u_j}/K),
\]

and integrating results in

\[
\overline{u_i u_j} = K/(1 + \exp[-(a + bx)]),
\]

with three parameters: \( K \) is the asymptotic maximum value and \( a \) and \( b \) are generic coefficients that shift and rescale the \( x \) variable. By algebraic manipulation this model can be transformed into

\[
\ln[\overline{u_i u_j}/(K - (\overline{u_i u_j}))] = a + bx.
\]

Knowing \( K \) based on the initial inflow profile and the equilibrium values of the turbulence stresses, we can analyze the log ratio to estimate the parameters \( a \) and \( b \) using a least
Figure 11. Over-farm wake height based on turbulent stress adjustment characterized with a logistic function for aligned and staggered farms. The slope of the regressed linear functions reveal the rate of wake growth over the farms.

squares approach. The result provides a realistic and quantitative approach for determining the wake expansion rate.

Figure 11 shows the equilibrium wake growth over the two wind farm configurations. Regression of the wake layer growth for the three turbulence quantities provides an estimate of the growth rate, $d\delta_{\text{wake}}/dx = 0.016$ for the aligned case and 0.024 for the staggered case. The growth rate over the center column of turbines is initially faster over the aligned case compared to the staggered configuration. However, after the initial growth at the leading edge, the growth rate is subsequently faster over the staggered farm as exhibited by the steeper slope of the growth curve.

4.4. Characterization of wind farm turbulence

The spanwise ensemble average profiles collected within and over the aligned and staggered wind farms are compared, and characterized to determine key turbulence properties of the wind farms, including the aerodynamic roughness and friction velocity. Also presented are the turbulence intensity, kinematic shear stress, dispersive stress, scalar flux, turbulent momentum and heat transport efficiency, as well as key TKE terms. The data were collected at selected locations within the quasi-developed region of the wind farms as presented in Section 3. To summarize, the spanwise-averaged vertical profiles used to characterize the wind farm flow were collected at four locations along the span ($y/D = -1, 0, 1, 2$) and at the streamwise position $x/D = 3$ behind the wind turbines of the corresponding targeted row, the eleventh and twelfth row of turbines for the staggered and aligned cases, respectively. These profiles were averaged horizontally and deemed to be representative of the horizontally averaged flow. This strategy was determined initially by trial and error, as we tested averaging various combinations of profiles taken at different locations to determine
the optimum number and location of profiles required. A challenge for collecting true spatially averaged data in complex flows is that it is not feasible to collect data everywhere. This is particularly true close to turbines where errors of the measurement technique make data unreliable. This is also an issue in the field, where often a limited number of sampling stations are available. We have investigated this strategy further using a validated LES framework to simulate wind farms with similar characteristics and found averaging the four selected profiles represented the spatially averaged data well (see Wu and Porté-Agel [57]). The results from this section will be employed in Section 5 to determine the thrust coefficient for the wind farms, and evaluate the models outlined in Section 2. In addition, turbulent flow properties of wind farms will be compared with those of surface-layer- and typical canopy-type flows, to assess which flow type is physically more similar to turbulent flow in and above wind farms.

4.4.1. Mean flow properties

Spanwise, ensemble-averaged streamwise velocity and temperature profiles are shown in Figure 12 for the aligned and staggered wind farms. The mean velocity is normalized by the velocity at the top of each wind farm. For the same freestream velocity, the velocity is higher in the aligned versus the staggered farm, and an inflection point in the profile is evident just below the top tip height. This is characteristic of canopy-type flows where inviscid instability typically leads to the generation of a mixing layer, with K-H-type eddies [58]. The temperature profiles are similar between the two configurations, with a variation of about 7°C between the bottom-tip height of the wind farm and the freestream flow. Therefore, there is a 53°C change between the surface and the bottom tip height.

A thick boundary layer over the wind farm ($\delta/Z_H \approx 3$) allows for a limited log layer to develop over the farm, as can be identified from the mixing length profile in Figure 13, where the mixing length is defined as

$$L_m \equiv -\langle u'w' \rangle^{1/2}/(dU/dz).$$  \hspace{1cm} (23)

Figure 12. Laterally averaged vertical profiles of (a) mean streamwise velocity and (b) mean temperature in the aligned and staggered wind farm.
Figure 13. Effective mixing length profiles for the aligned and staggered wind farms, used to determine the region of the flow that satisfies linear mixing length scaling. Dashed lines are linear fits extrapolated to determine the zero-plane displacement.

The linear region of the $L_m$ profile corresponds to a log-linear region in the velocity profiles, which is only present in a limited region near the top of the wind farms, from $z/Z_H = 0.8$ to 1.0 for the aligned farm and $z/Z_H = 1$ to 1.2 for the staggered farm. The linear variation of the mixing length may be written as

$$L_m = \kappa (z - d).$$

Extending the linear fit of the mixing length to the ordinate axis, the zero-plane displacement $d$ is determined. The aligned case exhibits a small displacement $d = 0.005$ m, while the staggered case has a significant displacement $d = 0.065$ m. On the basis of the log-linear fit of the velocity profiles, following Equation (13), the effective roughness for the aligned case is found to be $z_0(\text{aligned}) = 1.5$ mm with a corresponding friction velocity $u_* = 0.20$ m s$^{-1}$, and for the staggered case the roughness is $z_0(\text{staggered}) = 2.5$ mm with a friction velocity of $u_* = 0.26$ m s$^{-1}$.

A summary of the mean wind farm flow characteristics for the aligned and staggered configurations are listed in Table 2. The momentum flux is about 1.7 times greater for the staggered compared to the aligned case. The resulting effective roughness for the staggered case is about 70% greater than that of the aligned wind farm, and the roughness length relative to wind farm height is 1% and 1.5% for the aligned and staggered wind farms, respectively. This is within the range simulated in the study by Calaf et al. [2]. The effective wind farm roughness is 18 to 31 times that of the surface below the turbines, respectively. The resulting stability effect on the flow is characterized for the wind farm cases by $L_{\text{aligned}} = -1.3$ m and $L_{\text{staggered}} = -1.4$ m, or $-L/Z_H$ is 7.7 for the aligned case and 8.3 for the staggered case. Because the boundary layer only extends up
Table 2. Comparison of wind farm flow characteristics and effective roughness for the aligned and staggered wind farms.

<table>
<thead>
<tr>
<th>Wind farm configuration</th>
<th>$U_H$ (m s$^{-1}$)</th>
<th>$d$ (cm)</th>
<th>$d/Z_H$</th>
<th>$u_*$ (m s$^{-1}$)</th>
<th>$u_*/U_H$</th>
<th>$z_0$ (mm)</th>
<th>$z_0/Z_H$</th>
<th>$z_0/z_0$ ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td>2.4</td>
<td>0.5</td>
<td>0.03</td>
<td>0.20</td>
<td>0.08</td>
<td>1.5</td>
<td>0.009</td>
<td>18</td>
</tr>
<tr>
<td>Staggered</td>
<td>2.2</td>
<td>6.5</td>
<td>0.38</td>
<td>0.26</td>
<td>0.11</td>
<td>2.5</td>
<td>0.015</td>
<td>31</td>
</tr>
</tbody>
</table>

to approximately $3Z_H$, we can reason that buoyancy has a negligible effect on the flow in the wind farm cases. Therefore, although the flow for the case without a wind farm may be slightly convective, buoyancy is negligible for the wind farm cases.

4.4.2. Turbulence and flux characteristics

Figure 14 shows the streamwise and vertical normal stress profiles, which are maximum just below the top tip height of the wind farms. Near the top of the wind farm, the profiles collapse when normalized by $u_*$. The maximum streamwise value is about 1.7, and the maximum vertical value is 1.5 in both cases. It is notable that the turbulence levels within the wind farms are different likely due to the configuration of the turbines. Figure 15 shows the normalized kinematic shear stress profiles, the dispersive stress component and total stress profiles. The total stress profiles collapse well with a maximum near the top of the aligned and staggered wind farms. The shear stress reduces quickly below the top of the farm to about 40% of the maximum value at about the hub height and near zero close to the bottom tip height for the aligned farm and 20% for the staggered farm. There is significant dispersive stress measured for the two wind farms. The dispersive stress is 40% of the max shear stress near the hub height for the aligned wind farm, and 10% for the staggered wind farm. The lower dispersive stress in the staggered farm is due to the wakes of offset turbines which aid to homogenize the mean flow and lead to more efficient lateral mixing compared to the aligned case.

Figure 14. Vertical profiles of the (a) streamwise and (b) wall-normal turbulence for the aligned and staggered wind farms.
Figure 15. Vertical profiles of (a) kinematic shear stress, (b) dispersive stress and (c) total stress for the aligned and staggered wind farms.

Figure 16 shows the scalar flux profiles, which are the sum of kinematic heat flux and the dispersive heat flux $Q = \left\langle w'\theta' \right\rangle + \left\langle \bar{w}''\bar{\theta}' \right\rangle$ normalized by the surface flux $Q_{s0}$ in the boundary layer without a wind farm. In both the wind farm cases, the heat flux is higher in the region above the hub height and lower in the region below the hub height of the wind farms, compared to the case without a wind farm. Near the surface, the profiles diverge slightly, with the staggered case exhibiting the lowest flux. Lu and Porté-Agel [3] showed similar decreasing behavior in LES cases under stable conditions, while Calaf et al. [59] reported enhanced surface flux for LES cases with scalar source at the surface. The dispersive flux is less than 10% of the total flux. Further study is planned to investigate the surface scalar flux in more detail, but we can infer notable differences in the surface heat flux for the two farms and also note an important difference compared to the flat boundary-layer case.

Profiles of the spatially averaged correlation coefficient $r_{uw} = \frac{\overline{uw}}{\sigma_u \sigma_w}$ in the wind farms are shown in Figure 17. The correlation coefficient is a measure of the efficiency of the turbulence in transporting momentum relative to the absolute amount of turbulence present. The profiles follow similar trends, with magnitudes near the top of the wind farms between 0.3 and 0.4 for the aligned and staggered cases, respectively. In flat boundary-layer-type flows, it is expected to be around 0.3. Therefore, flow over the staggered wind farm is more efficient at absorbing momentum than a flat boundary layer, while the aligned...
case is similar to a flat boundary layer. Figure 17 also shows Prandtl number profiles for the two wind farm configurations. The values are similar near the top tip height of the wind farm at approximately 0.7. This means that the wind farm is about 1.5 times as efficient at transporting heat compared to momentum. For a flat boundary layer under neutral conditions, $Pr_t$ is expected to be about 1.0, while for mixing layers and canopy flows $Pr_t$ is approximately 0.5.

### 4.4.3. Turbulent kinetic energy budget

The TKE budget consists of the different physical mechanisms contributing to turbulence generation, consumption and transport of TKE and follows as

$$
\left( \frac{g}{\theta_0} \langle w'\theta'' \rangle \right) - \langle \bar{u}' w' \frac{\partial \bar{u}'}{\partial z} \rangle - \langle \frac{\partial \bar{k} w}{\partial z} \rangle - \langle \frac{1}{\rho} \frac{\partial p' w'}{\partial z} \rangle + \langle \frac{1}{\rho} \frac{d' u'_i}{x_i} \rangle - \langle \frac{\partial \bar{k}'' \bar{w}''}{\partial z} \rangle - \langle \left( \bar{u}' u'' j \right) \frac{\partial u''}{\partial x_j} \rangle - \langle \varepsilon \rangle = 0,
$$

(25)

where $\bar{k} = \frac{1}{2} \bar{u}'^2$ is the time-averaged TKE, $p'$ is pressure fluctuation, $\rho$ is fluid density, $d'_i$ is fluctuations of the drag and $\varepsilon$ is dissipation. Index notation is only used for terms where all components are likely significant. From left to right, the terms represent (1) production due to buoyancy, (2) shear production, (3) turbulent transport, (4) pressure transport, (5) waving production, (6) dispersive transport, (7) wake production and (8) viscous dissipation. In canopies, waving production is associated with moving canopy elements. Here, waving production is due to the moving blades of wind turbines. Wake production has the same form as shear production but depends on local variation in shear stress doing work against local variations in mean strain rates. In a wind farm, this is caused by vortex shedding from
wind turbine components, including the tower, nacelle and blades (e.g. tip vortices). For a homogeneous array of turbines and steady flow conditions, wake production simplifies to

\[ P_w = -\langle \bar{u} \rangle \frac{\partial}{\partial z} \left( \langle u'w' \rangle + \langle \bar{u}'\bar{w}' \rangle \right) \]

(cf. [40, 60]).

Here, we are able to compare the shear, vertical turbulence transport, wake production and buoyancy production terms of the TKE budget for the aligned and staggered cases (Figure 18). The profiles are normalized by \( u^3/Z_H \). The shear production is maximum near the top tip height where mean velocity gradients are greatest, and the profiles are similar between the two wind farm configurations with higher shear near the top tip height in

![Figure 18. TKE budget term profiles in the aligned and staggered wind farm. (a) Shear production, (b) vertical turbulent transport, (c) wake production and (d) buoyancy production.](image)

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the staggered case. There is a significant sink in vertical turbulent transport for which the maximum of both cases is near the top tip height and is approximately the same magnitude as the shear production. The transport sink is greater for the aligned compared to the staggered configuration. Wake production is the largest of the measured components, and is greatest between $Z_{hub}$ and $Z_H$. Due to the large pressure drop across wind turbines it is expected that the pressure redistribution term balances the wake production term. However, the pressure term was not measured in this study. Wake and waving production tend to short circuit the spectral energy cascade by converting larger scale eddy motion, with length and time scales in the energy containing range to smaller eddies. The result is an increase in dissipation rate compared to the flat boundary-layer flow without wind turbines [32]. This can be seen in the energy spectra far within the wind farms, in Figure 9. The buoyancy production is very small for both cases, less than an order of magnitude compared to shear production. The aligned case has higher buoyancy production than the staggered case, possibly due to more efficient wake interaction in the staggered farm leading to a reduction in surface flux, as seen in Figure 16.

5. Discussion

The models for added aerodynamic roughness and canopy length scales require an estimate of the drag due to the wind farm, and the related thrust coefficient $C_T$. One method to determine the turbine-induced drag force is to measure and take an ensemble average of all of the terms in the momentum equation and set their sum equal to the drag term. However, we lack adequate three dimensional data coverage to ensure a good estimate. Another approach involves using a well-known canopy model, which relates the exponential decay of mean velocity within a canopy to the momentum flux, developed by Inoue [61] and recently revisited by Yi [62]. The model follows as

$$U(z) = U_H \exp \left[ \alpha \left( \frac{z}{Z_H} - 1 \right) \right], \quad (27)$$

where $\alpha = \beta' Z_H / \lambda$, $\beta' = u_s / U_H$ and $\lambda = 2 \beta'^3 / L_c$. Fitting the exponential model to the ensemble streamwise velocities, presented in Figure 12, leads to an estimate of the overall drag within the wind farms. The model fits the profiles, with an $R^2 = 0.99$ across the rotor swept region, between $z/Z_H = 0.3$ and 1.0. With direct measurements of $\beta'$ and fitting a regression to the mean velocity profiles, we can determine $L_c$ and calculate $C_T$ following Equation (12). We find that the thrust coefficient $C_T$ for the aligned farm case is 0.18 and for the staggered case is 0.47. The difference in $C_T$ between the two configurations is remarkable. However, this is not unexpected since the array configuration has a significant effect on the three-dimensional flow within the wind farms, and the aligned array exhibits greater wake sheltering from upwind turbines compared to the staggered farm. This is supported by Nepf [63] who studied the effect of layout pattern on the drag coefficient of cylinder arrays. A similar effect was reported for arrays of blocks in the study by Coceal et al. [37]. The estimation of $C_T$ is sensitive to measurements of mean velocity, friction velocity and the representativeness of the horizontally averaged profiles. We estimate the uncertainty of $C_T$ to be approximately 5% based on estimated measurement uncertainty (Section 3) and evidence that the profiles represent horizontally averaged profiles (Section 4.4). The drag development length scale $L_c = 43$ m was determined for the aligned case and 16 m for the staggered case. Therefore, the flow within the staggered case adjusts, on a spanwise-averaged bases, much faster than the aligned case. This is due to the more
efficient mixing of wakes horizontally and vertically within the staggered farm, and is in agreement with the results of the velocity deficit, wake growth rate and the vertical transport of momentum and TKE budget.

Using the estimates of $C_T$, we compare the effective roughness lengths of the two wind farm configurations with the added roughness models introduced in Section 2.1 as well as with previous experiments. As determined in Section 4.4, the effective roughnesses for the two wind farm configurations were $z_0(\text{aligned}) = 1.5 \text{ mm}$ and $z_0(\text{staggered}) = 2.5 \text{ mm}$. By comparison, in previous experimental studies of aligned wind farms, Cal et al. [19] found a roughness, $z_0 = 0.4 \text{ mm}$, for a $3 \times 3$ array of model turbines with a spacing of $S_x = 7D$ and $S_y = 3D$, and Chamorro and Porté-Agel [6] found the same roughness, $z_0 = 36 \text{ mm}$, for two model wind farms with $S_x = 5D$, $S_y = 4D$ and $S_x = 7D$, $S_y = 4D$. The result of Cal et al. [19] is based on spatially averaged velocity measured with particle image velocimetry around the third row. However, the wind farm extent was much smaller than the drag development length scale and, as pointed out by the authors, an adjusted surface layer was unable to developed over the wind farm. This supports the need to characterize the flow for very large wind farms to determine the effective roughness. Chamorro and Porté-Agel [6], on the other hand, determined the roughness based on velocity profiles collected at the centerline of the two turbine arrays, albeit after 10 rows of turbines. The combination of wakes along the centerline of a turbine array results in a very different velocity profile, which is not representative of the spanwise-averaged profile required to characterize the flow using a top-down approach [4]. Only considering the velocity profile at the centerline results in an artificially large apparent roughness.

Comparing our experimental results to model predictions, we can evaluate the performance of the various roughness models (see Section 2.1). The results from the three added roughness models, Equations (1)–(3) [1, 2, 27], are summarized in Table 3. Overall, the models produce a large range of effective roughness estimates, with the model by Calaf et al. [2] providing the closest estimates to the experimental results for the aligned farm, while the model by Frandsen et al. [1] is closest for the staggered farm. The results reveal the sensitivity of the models especially to $C_T$. Deviations of model predictions from experimental results may be due to a number of factors. Although the experimental results reflect flow in and above large wind farms, the flow may not be fully developed, indicated by the large estimated drag development length scales $L_c$. This is particularly important with regard to the aligned farm for which the estimated $L_c$ is a factor of four greater than the length of the model wind farm. The flow within the farm must be fully developed for the flow above to reach equilibrium. Another possible reason for errors in effective roughness estimations may be due to assumptions made in the model formulations, including the existence of two log layers that intersect at the hub height and simplification of the wake eddy viscosity model. In addition, the models do not explicitly account for wind turbine array configuration. As shown in Section 4.4, dispersive flux is significant in wind farms, making up as much as 40% of the total momentum flux for the aligned case. Strong and

### Table 3. Results for effective roughness models compared with experimental data.

<table>
<thead>
<tr>
<th>Wind farm configuration</th>
<th>$z_0,\text{exp}$ (mm)</th>
<th>$z_0,L$ (mm)</th>
<th>$z_0,F$ (mm)</th>
<th>$z_0,C$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned</td>
<td>1.5</td>
<td>1.2</td>
<td>0.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Staggered</td>
<td>2.5</td>
<td>3.2</td>
<td>2.9</td>
<td>4.5</td>
</tr>
</tbody>
</table>
varying levels of inhomogeneity of the flow, which depends on wind farm configuration (i.e. wind direction) and leads to variable momentum flux, presents a challenge for developing a robust model for effective roughness independent of flow information.

In addition to the drag development length scale, the shear penetration scale is a key length scale that describes mixing processes inherent to canopy flows. It has been proposed that the ratio between the height of the roughness elements and the drag length scale $C_d h$ needs to be greater than 0.1 for canopy flow properties to emerge [64–66]. This includes characteristics, such as an inflected mean velocity profile, and mixing-layer (shear-layer)-type K-H eddies near the top of the array. In this study the canopy scales are both well below this criterion with $C_d h = 0.004$ for the aligned case and $C_d h = 0.009$ for the staggered case. Ghisalberti [33] reports that flows with such low canopy scales should not exhibit canopy flow characteristics, but instead can be characterized as rough surfaces. Evidence based on the turbulence and transport statistics presented here suggest this limit may not hold. Both wind farm configurations exhibit an inflection point in the ensemble-averaged velocity profiles near the top tip height $Z_H$. The length scale for the penetration of K-H eddies into a canopy is based on the ratio of the mean velocity and the velocity gradient at the top of the wind farm (Equation (5)). The result for the aligned case is $L_s = 0.6$ m, and for the staggered case is $L_s = 0.4$ m. In both cases, the scale of eddy penetration is larger than $Z_H$. This implies that eddies generated by the shear layer at the top of the wind farms, for the turbine distribution density studied here, directly interact with the surface, likely distorting any K-H eddy development.

We find that some properties of the flow follow characteristics of a surface layer while others are similar to canopy flows. It is evident, based on the mixing length profiles (Figure 13), that the mixing length is proportional to vertical distance within a limited region, which depends on turbine configuration. Conversely, many bulk turbulence statistics more closely resemble typical values reported for canopy turbulence. Table 4, partially reproduced from Raupach et al. [58] and Finnigan [32], summarizes a comparison between standard flow properties of surface layers and canopies with those observed from the two wind farm configurations studied here. It is clear that, based on the classical turbulence statistics for surface layer and canopy flows, wind farm flows are more similar to canopy flows. In addition, many terms of the TKE budget, which have been shown to be important in canopy flows, are also significant in wind farm flows. However, the integral scales, drag development length scale and shear length scales, examined earlier, do not strictly exhibit typical behavior of a dense canopy flow. The wind farms appear to have integral scale turbulence characteristics that exhibit a combination of surface layer and canopy flow

<table>
<thead>
<tr>
<th>Property</th>
<th>Surface layer</th>
<th>Canopy</th>
<th>Wind farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflection in U profile</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$\sigma_u/u_*$</td>
<td>2.5 – 3.0</td>
<td>1.8 – 2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>$\sigma_w/u_*$</td>
<td>1.2 – 1.3</td>
<td>1.0 – 1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>$r_{uw} = -\langle u'w' \rangle/\langle u_* w_* \rangle$</td>
<td>$\sim$0.3</td>
<td>$\sim$0.5</td>
<td>$0.3 – 0.4$</td>
</tr>
<tr>
<td>$Pr_t = K_M/K_H$</td>
<td>$\sim$1.0</td>
<td>$\sim$0.5</td>
<td>$\sim$0.6 – 0.7</td>
</tr>
<tr>
<td>Integral length scale</td>
<td>$\propto (z - d)$</td>
<td>$\propto L_s$</td>
<td>$\propto Z_H$ and $L_s$</td>
</tr>
<tr>
<td>TKE budget</td>
<td>$Ps = \epsilon$</td>
<td>Large $Ps$, $Tt$, $Tp$</td>
<td>Large $Ps$, $Tt$, $Tp$ and $Pw$</td>
</tr>
</tbody>
</table>

Note: the TKE budget terms are shear production ($Ps$), turbulence transport ($Tt$), pressure transport ($Tp$) and wake/waving production ($Pw$).
characteristics, while the bulk turbulence statistics and transport behavior more closely follow the characteristics of canopy flows.

6. Summary and conclusions

Wind-tunnel experiments were performed to study the effect of wind-farm configuration on flow development in and over wind farms, and to investigate the validity of surface-layer-versus canopy-flow-type models for wind farms. The addition of a heat source at the surface, while maintaining neutral conditions, allowed for the study of scalar transport through the wind farms. High-frequency hot-wire/cold-wire anemometry was used to quantify mean wind velocity, turbulence intensity, turbulent stress and kinematic scalar fluxes within the flow development region as well as deep within the quasi-developed wind farms. Focus was put on revealing the difference in the magnitude and spatial distribution of the velocity deficit and the turbulence intensity in the turbine wakes, characterization of wake expansion above the wind farms and on characterization of the spatially averaged wind-farm turbulent flow, including mean velocity, normal and shear stresses, momentum and heat flux and key terms of the TKE budget.

The effective aerodynamic roughness of the wind farms, canopy drag length scale, shear-layer thickness and bulk turbulence statistics were compared to determine whether flow in and over wind farms is more appropriately modeled as a surface layer with added roughness or as a canopy. We conclude that neither flow paradigm strictly typifies wind-farm flows. Many flow properties follow those of canopy-type flows; however, a well-defined shear layer with K-H-type eddies is not observed and unlike most canopy flows, the drag development length scale is very long. The length scale was of the order of 100–250 times the height of the wind farms, compared to forest canopies where the length scale is on the order of the canopy height. The implication is that the thrust force on individual turbines within a wind farm may vary for many rows downwind of the first row and strongly depends on wind farm configuration. This was the first comprehensive study to experimentally examine wind farm turbulence in such detail, which fills an important gap in our knowledge about how wind farm flows behave and provides valuable information from which to improve wind farm parameterizations. The data are also useful for validation of existing parameterizations.

In addition, key differences in the three-dimensional flow field indicate the momentum absorption and therefore energy generation characteristics are very different in the two wind farms. The main differences found between aligned and staggered wind-farm flows are summarized as follows:

1. The staggered wind farm turbines operate with higher angular velocity than those in the aligned wind farm. This leads to a greater overall power generation potential in the staggered wind farm.
2. The mean velocity profiles exhibit strong wake regions behind wind turbines. The velocity deficit is greater within the staggered wind farm due to more efficient absorption of momentum.
3. The turbulence intensity is greatest around the top tip region for both wind farms. The peak turbulence intensity is greater within the aligned farm. Available empirical models to estimate added turbulence are sensitive to estimates of $C_T$ and cannot account for different wind farm configurations.
4. The velocity spectral signature of tip vortices behind turbines is stronger in the staggered wind farm than in the aligned farm. However, due to the larger distance to successive downwind turbines, allowing greater dissipation of coherent structures,
turbines experience lower turbulence-induced fatigue loads in the staggered configuration.

(5) The wake growth over the wind farms can be modeled using a logistic growth model. The wake growth rate is initially faster over turbines in the aligned farm; however, the overall wake growth rate is greater over the staggered wind farm due to increased momentum absorption and turbulence production.

(6) The spanwise-averaged mean velocity profiles of the quasi-developed wind farm flow exhibit an inflection point instability, commonly seen in canopy flows. The staggered wind farm flow has lower mean velocity within and just above the wind farm caused by greater momentum absorption compared to the aligned farm case.

(7) The effective roughness of the staggered wind farm is 1.7 times greater than that of the aligned wind farm. The staggered wind farm exhibits a significant zero-plane displacement, whereas there is only a small displacement for the aligned case. The log-layer region, exhibited by a region of linear mixing length is limited to a region near the top of the wind farms, which is approximately 20% of the total wind farm height.

(8) Similar turbulence intensity and shear stress profiles are found for the two configurations, with significantly larger dispersive stresses measured in the aligned wind farm, $\sim 40\% u^2$ compared to the staggered wind farm, $\sim 10\% u^2$. The friction velocity is 30% greater for the staggered wind farm compared to the aligned farm.

(9) Profiles of kinematic heat flux indicate a reduction of surface scalar (heat) flux within wind farms compared to a flat boundary layer without wind turbines, for the studied wind farm density. A greater reduction was measured in the staggered wind farm.

(10) The turbulent correlation coefficient and Prandtl number profiles follow similar trends between the two wind farm configurations, with levels near the top tip height compatible to those found near the top of canopies.

(11) Compared to a flat boundary layer where shear production is balanced by dissipation, the TKE budget involves a number of significant terms in the wind farm flows, including shear production, vertical turbulent transport, wake production and pressure transport, which are similar to that of canopy-type flows. The wake production and vertical transport terms are particularly significant, especially for the aligned farm. Buoyancy production is negligible for both wind farms.

(12) The thrust coefficient is approximately two to three times greater in the staggered wind farm compared to the aligned wind farm, revealing that wind farms with the same turbines and the same turbine distribution density but different configurations exhibit different aerodynamic loading characteristics due to varying wake interaction causing variation in sheltering of downwind turbines.

(13) The added roughness models exhibit a wide range of estimates and do not account for turbine array configuration. The more complex model of Calaf et al. [2] provided the closest estimate for the aligned farm, while that of Frandsen et al. [1] provided the best estimates for the staggered configuration.

This study provides new insights into the effects of wind-farm configuration on turbulent flow and transport of momentum and scalars in wind farms. It also provides detailed data for validating and motivating the development of improved models for the turbulent momentum and heat fluxes, and the turbine-induced forces in numerical models of wind farms (e.g. computational fluid dynamics models such as LES). Measurement strategies presented here provide useful knowledge about the minimally required data that must be gathered, which can prove useful in planning field campaigns where often a limited number
of sampling stations are available. Future work will include model validation as well as further investigation and analysis of scalar transport in wind farms. Understanding the effects of wind farms on surface fluxes is important and new studies are currently underway with detailed surface flux information to better understand the sign and distribution of heat flux changes after the installation of a wind farm. Further investigation of wind farms with varying turbine density and configuration are required to develop models to predict $C_T$, which is a critical parameter in course-resolution weather and climate models. Characterizing lateral wake interaction is important for predicting power production as well as total turbulence intensity within the developing flow of a wind farm. Work to better characterize the scales of interaction will be important and help fill a critical need for improved models to predict turbulence intensity, which take into account turbine density and wind farm configurations.

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References


