The Iowa Atmospheric Observatory: Revealing the Unique Boundary Layer Characteristics of a Wind Farm

Eugene S. Takle

Department of Agronomy, Iowa State University, Ames, Iowa

Daniel A. Rajewski and Samantha L. Purdy

Iowa State University, Ames, Iowa

Received 27 September 2017; in final form 20 November 2018

ABSTRACT: The Iowa Atmospheric Observatory was established to better understand the unique microclimate characteristics of a wind farm. The facility consists of a pair of 120-m towers identically instrumented to observe basic landscape–atmosphere interactions in a highly managed agricultural landscape. The towers, one within and one outside of a utility-scale low-density-array wind farm, are equipped to measure vertical profiles of temperature, wind, moisture, and pressure and can host specialized sensors for a wide range of environmental conditions. Tower measurements during the 2016 growing season demonstrate the ability to distinguish microclimate differences created by single or multiple turbines from natural conditions over homogeneous agricultural fields. Microclimate differences between the two towers are reported as contrasts in normalized wind speed, normalized turbulence intensity, potential temperature,

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DOI: 10.1175/EI-D-17-0024.1
and water vapor mixing ratio. Differences are analyzed according to conditions of no wind farm influence (i.e., no wake) versus wind farm influence (i.e., waked flow) with distance downwind from a single wind turbine or a large group of turbines. Differences are also determined for more specific atmospheric conditions according to thermal stratification. Results demonstrate agreement with most, but not all, currently available numerical flow-field simulations of large wind farm arrays and of individual turbines. In particular, the well-documented higher nighttime surface temperature in wind farms is examined in vertical profiles that confirm this effect to be a “suppression of cooling” rather than a warming process. A summary is provided of how the wind farm boundary layer differs from the natural boundary layer derived from concurrent measurements over the summer of 2016.

**KEYWORDS:** Atmosphere; Atmosphere–land interaction; In situ atmospheric observations; Measurements

1. Introduction

The Iowa Atmospheric Observatory (IAO) was established through collaboration among Iowa State University, The University of Iowa, and the University of Northern Iowa to improve understanding of the wind resources and microclimates within utility-scale wind farms in an agricultural region. The widespread expansion of wind farms in Iowa is the most recent in a long series of landscape transformations of the U.S. Midwest since the European settlement began in the early nineteenth century. This most recent transformation, like those before it, is creating measurable changes to local microclimates. As the number of wind farms continues to grow, turbines could influence regional (Vautard et al. 2014) and perhaps even global (Keith et al. 2004; Wang and Prinn 2010) climates, although a later study suggests the effect is exaggerated (Fitch 2015).

The landscape of Iowa has undergone major transformations since the European settlement that began in the early nineteenth century. By the early twentieth century, a majority of the original marshy, prairie-pothole-dominated central and northern regions and the rolling hill areas of the remainder of the state had been drained and converted to farmland (New York Times 1910). The presettlement forested area of Iowa, estimated to be about 6 million acres, was reduced by half by the end of the twentieth century (Gallant et al. 2011). These changes of the surface and subsurface hydrology and vegetation have had profound influences on the exchange of energy, water vapor, and carbon dioxide between the atmosphere and the surface. Furthermore, because of the change from largely perennial vegetation to largely annual vegetation, the linkage between the atmosphere and the deep soil has been altered.

In the twenty-first century, the landscape of Iowa is undergoing another transformation of land use from the installation of several thousand wind turbines over agricultural cropland. Utility-scale wind farms typically occupy 200–500 km², or even more, with 100–200 turbines. These low-density wind farms [distance between turbines generally greater than 15D (where D is the turbine rotor diameter; currently D ~ 80 m) in prevailing wind directions] are designed with the intent of reducing turbine–turbine interactions. With 4145 turbines in Iowa as of 2018, most of which are located within 25 large utility-scale wind farms (>100 MW) of aggregate power capacity of over 5600 MW, the Iowa land area influenced by Iowa wind farms has become comparable to the size of its cities or forests (AWEA
The impact from the production of wind energy on the prevailing land use (intensive agriculture) has not been fully evaluated (Rajewski et al. 2013, 2014).

Wind turbines convert a fraction of the mean kinetic energy flowing through the wind farm to electrical energy and convert another fraction to turbulence, with the remainder leaving the wind farm as a reduced amount of kinetic energy (Christiansen and Hasager 2005; Adams and Keith 2007). The reduction in mean kinetic energy (i.e., mean wind speed) and increase in turbulence downwind of turbines, commonly referred to as turbine wakes (Högström et al. 1988; Magnusson and Smedman 1999; Hirth and Schroeder 2013), have a direct influence on the exchange of heat, moisture, and carbon dioxide in the wind farm (Rajewski et al. 2013, 2014, 2016; Takle 2017) and may create an aggregate wind farm effect beyond the boundary of the wind farm (Baidya Roy 2011; Baidya Roy et al. 2004; Keith et al. 2004; Adams and Keith 2007; Rajewski et al. 2013; Smith et al. 2013; Armstrong et al. 2014).

The shape, internal characteristics, and downwind extent of wakes are highly dependent on the thermal stratification of the lowest 200 m of the ambient atmosphere. Simulations with energy-conserving parameterizations of individual wind turbines and wind farm wakes reported by Adams and Keith (2007), Fitch (2015), Fitch et al. (2012, 2013a,b), Lu and Porté-Agel (2011), Mirocha et al. (2014), Sescu and Meneveau (2015), and others have provided additional insight on structure and processes in wind farms.

In situ measurements of fluxes and near-surface temperature and humidity taken within wind farms report nighttime temperatures above the surface that are about 0.2–1.0 K higher (Baidya Roy and Traiteur 2010; Henschen et al. 2011; Rajewski et al. 2013, 2014, 2016; Smith et al. 2013; Takle et al. 2014), soil temperatures that are a few tenths of kelvins higher, and absolute humidity above the surface that is a few tenths of grams per cubic meter lower (Armstrong et al. 2016). Satellite measurements over agricultural regions of the central United States (Zhou et al. 2012, 2013a,b; Harris et al. 2014; Slawsky et al. 2015; Xia et al. 2016) also indicate that surface skin temperatures are 0.3–1.0 K higher at satellite fly-over times deep within and downwind of utility-scale wind farms compared to cropland outside of wind farms.

Turbulence is the fundamental process that regulates fluxes throughout the lower boundary layer. These fluxes regulate the interception of light (through plant movement that illuminates lower leaves) and transport of heat, water, and carbon dioxide within the crop canopy and drive the biophysical processes that influence vegetative growth, reproductive development, and overall yield (Campbell and Norman 2000). Commodity crops currently grown in the United States have been finely tuned for optimal growth and yield in a specific climate region. More measurements are needed to characterize the variability of microclimate fluxes and turbulence, especially deep within utility-scale wind farms that are collocated with commodity-crop agriculture, roughly 5%–15% of the total cropland acres especially in the state of Iowa (USDA 2012). Measurements of the three-dimensional turbulence conditions inside a wind farm with concurrent turbulence conditions in the nearby natural boundary layer offer a method to clarify the role of wind farms in modifying wind farm microclimates.

In this report, we provide an overview of the characteristics of the boundary layer that are being created by this new and expanding establishment of large utility-scale wind farms. These results provide a delineation of how single and multiple wakes aggregate to characterize wind and turbulence conditions that define vertical profiles of meteorological conditions within a wind farm.
We conceptually summarize in Figure 1 the impacts on surface microclimate and boundary layer conditions deep in the wind farm during the day (Figure 1a) and during the night (Figure 1b) from our assessment of microclimate changes in the leading few lines of turbines (Rajewski et al. 2016) and from recent profiling measurements taken with unmanned aerial vehicles in the near wake of single turbines (Adkins and Sescu 2017). We adopt the terminology of Newman et al. (2013) for describing the wind farm boundary layer by labeling its three sublayers as the layer swept by the rotor [rotor-swept layer (RSL)] and layers below and above the rotor area called the below-rotor layer (BRL) and the above-rotor layer (ARL), respectively. In Figure 1, we note, by use of light-blue-striped bars above and below the single-wake boundaries, the effect that multiple wakes have toward creating an aggregated wind farm boundary layer. Larger or smaller flux departures within the wind farm from fluxes outside the wind farm are indicated with wide or narrow arrows.

A description of the IAO’s twin-tall-tower network and instrumentation is provided in section 2. In section 3, we characterize the data processing, filtering procedures, and sorting metrics used to interpret wind farm impacts on the boundary layer. Our analyses of the tall-towers’ data compare wind, turbulence, temperature, and humidity conditions both with and without the influence of the wind farm in section 4. In section 5, we summarize and interpret our findings with a table describing how turbines change individual meteorological variables in the wind farm boundary layer. We provide overall conclusions and suggestions for future research in section 6.

2. IAO twin-tall-tower network

2.1. Site description

The IAO consists of two 120-m towers: one located inside a 200-turbine wind farm in central Iowa (denoted by A1) and one approximately 22 km to the northwest of A1 and outside of the wind farm (denoted by A2; Figure 2). The terrain for both sites is flat with about 13-m-higher elevation at A2 versus A1 (356.6 vs 343.8 m). Within 1 km of A1, the land slopes gently upward (≤1.0%) to the west, north, northwest, southwest, and south of the tower. Surrounding A2, slopes within 1 km of the tower are ±0.1% to the northwest, southwest, south, and west of the tower and −0.3% to the north of the tower. Both sites feature slopes of less than ±0.3% at the 4-km distance from each tower for each of the following directions (A1 vs A2)—north: <0.1% vs 0%; south: −0.3% vs −0.2%; east: <0.1% vs <0.1%; west: <−0.1% vs −0.2%.

Both towers are sited in agricultural fields that are planted on a corn–soybean annual rotation. In 2016, the first agricultural year the towers were operational, A1 had a triangular area, defined by the guy wire anchors, of grass around its base within a field of corn (Zea mays L.). A2 had soybeans [Glycine max (L.) Merr.] planted in a ~191 m × 199 m patch around the tower base, while the rest of the field was planted with corn.

The nearest public roads are approximately 137 m to the south at A1 and to the west at A2. The triangular towers are identical with 0.91-m faces and are oriented with vertices to the northeast, southeast, and west. Each site also has a 2.4 m × 3 m × 3.0-m-high shelter located 3 m to the east of the tower base. The tower base and shelter occupy part of an 11.3 m × 12.2 m graveled compound area. A 3.7-m-wide gravel road connects each site to a public road.
Figure 1. Conceptualization of wind farm modification of surface and boundary layer microclimate for (a) daytime/unstable conditions and (b) nighttime/stable conditions based on available field measurements, wind tunnel measurements, and numerical simulations. Wider arrows denote larger values in heat (red) and water vapor (blue) fluxes, and narrower arrows denote smaller values in fluxes. Double-headed arrows denote fluxes could be either direction, zero, or unknown. Scales of turbulence are denoted by light blue swirls, with the top portion of the largest daytime eddy having a dashed line to infer boundary layer depth of several hundreds of meters or a few kilometers above the wind farm boundary layer.
Figure 2. Site comparison of identically configured tall towers: (a) A1 located within the 200-turbine wind farm vs (b) A2 located 6.9 km outside of the wind farm at a distance of 22 km from A1. Photo source: Iowa NAIP 2017 Orthophotos. USDA-FS-APFO Aerial Photography Field Office Image created from the Iowa State University GIS Facility Iowa Geographic Map Server (https://isugisf.maps.arcgis.com/apps/webappviewer/index.html?).
2.2. Instruments

The two towers are instrumented identically at six levels: 5, 10, 20, 40, 80, and 120 m (Figure 3a). Each level has one sonic anemometer, two three-cup anemometers, two wind vanes, and one temperature–relative humidity probe (with a duplicate temperature–relative humidity probe at 120 m). In addition, barometers are located at 10 and 80 m. See Figure 3b for instrument and mounting specifications for each sensor. The identical cup anemometers and wind vanes are mounted on the west-northwest (WNW) and south (S) booms with a temperature–relative humidity probe also located on the WNW boom. The sonic anemometers are mounted at the end of the west-southwest (WSW)-pointing booms and are oriented with sensor arms pointing due west (270°). This allows for the least amount of tower influence in the data, as the prevailing winds are from the northwest in the winter and from the south to southeast in the summer in this region.

2.3. Data collection

The sonic anemometers measure three-dimensional wind speed and virtual temperature. Additional sensors report 1-Hz measurements of wind speed, wind direction, air temperature, relative humidity, and air pressure. Raw data are sent in 10-min files on a 10-min delay so that there is, at most, a 12-min real-time data delay from either site to the server on the Iowa State University campus. Microclimate differences between the towers are evaluated from measurements taken from 5-min averages of the slow-rate (1 Hz) measurements during 10 June–30 September 2016. Data from the sonic anemometers were not available at both towers until 30 November 2016. All data are archived at the Iowa Environmental Mesonet (IEM 2017).

3. Data metrics and analysis methods

3.1. Measurement quality control methods

3.1.1. Precipitation periods and turbine operation

For analyses reported herein, we removed periods of rain (identified by radar) for quality control of the data, which eliminates ~10% of the total observations. As we assume that wakes from the wind farm will not influence measurements at A2 for the directional window of 165°–338°, we determined periods when turbines were on or off from the 80-m ambient hub-height wind speed \( U_H \) on the WNW boom at A2. We define wind farm operation as on when \( U_H \geq 3.5 \text{ m s}^{-1} \) and off when \( U_H < 3.5 \text{ m s}^{-1} \) or \( U_H > 20.0 \text{ m s}^{-1} \). These upper and lower thresholds approximate the cut-in and cut-out speeds, respectively, from the GE 1.5 XLE turbines installed in the wind farm (GE Energy 2009). We recognize nacelle speeds would be a better indicator of when turbines were on or off, but these data were not available.

3.1.2. Designation of tower wake

We determined the influence of the tower cross section on measurements from the WNW and S booms by comparing the turbulence intensity (TI; \( TI = \sigma_U U^{-1} \)) of wind speed at the 80-m level (McCaffrey et al. 2017). We use a 5° directional bin with staggering of ±2.5° of each bin from the WNW boom wind vane to determine the directional window for the wake of the tower on each boom. We consider the tower
Figure 3. Conceptual layout of (a) vertical locations of instruments on each identically configured tall tower and (b) tower cross-sectional diagram of boom orientation, length, and placement of instruments on each tower.
wake to be affecting the WNW and S booms when the speed difference between the two boom measurements is \( > \pm 5\% \) and the TI is \( > \pm 5\% \) (Figure 4). Measurements from 165° to 338° are not influenced by the tower wake for either boom. Therefore, we further divide this region into additional categories of no turbine influence (e.g., no wake) and turbine influence (discussed in section 3.2). We use measurements from the WNW boom to provide a complete profile of wind speed from both towers because data were missing from the A2 S boom at the 10- and 120-m levels for a substantial portion of the analysis period.

### 3.2. Turbine/wind farm wake attribution

We define directional categories relating to downwind distance from a single turbine or multiple turbines within the northwest portion of the 200-turbine wind farm as indicated in Figure 5. We determine bulk averages of the wind farm by
considering each observation from 302° to 338° to be a member of the bulk-wake category describing flow downwind of 50+ turbines to the northwest of tower A1. We also specify a category for the single wakes to include three leading-edge turbines about 1 km to the south-southwest of A1, which have no turbines beyond them in this direction (173°–215°). We use data from southwest, west, and west-northwest of the A1 tower, with the exceptions of small sectors containing non-wind-farm turbines, to
define the natural boundary layer for this tower. The region for no influence of the wind farm (i.e., no-wake category) is determined by the wind direction sectors from 215° to 218° and from 229° to 258°.

We apply a 5° wake expansion factor from each leading turbine or groups of turbines to determine the relevant wake angles as described by Barthelmie et al. (2009) and adopted in subsequent wake analysis techniques for measurements taken during the Crop Wind Energy Experiment (CWEX; Takle et al. 2014; Rajewski et al. 2013, 2014, 2016). Wake angles and distances from each grouping of turbines are determined from Google Earth and then proscribed on ArcGIS (ESRI 2016) to generate a wake attribution diagram as in Figure 5. In addition to the wake attribution from turbines, we also designate the tower-waked area that was previously described in section 3.1.

3.3. Derived variables and bin categories

We calculate the 40–5-m Richardson number from measurements of wind speed, air temperature, relative humidity, and air pressure at A2 to relate the ambient thermal stratification to the variability of wake impacts on microclimate. We interpolate pressure measurements between 10 and 80 m to determine pressure at 40 and 5 m using the hypsometric equation (Wallace and Hobbs 1977):

\[
z_2 - z_1 = \frac{R_d T_v}{g} \ln \left( \frac{p_1}{p_2} \right),
\]

where \(R_d\) is the gas constant for dry air, \(g\) is the gravitational acceleration, and \(T_v\) is the mean virtual temperature of the layer between \(z_2\) and \(z_1\). Virtual temperature is approximated at each tower level for unsaturated humidity conditions according to Rogers and Yau (1996) as

\[
T_v \approx T(1 + 0.61 r_v),
\]

where \(r_v\) is the mixing ratio calculated from the temperature and relative humidity measurements at each tower level. We reference the virtual potential temperature by the lowest tower measurement at 5 m, instead of the commonly used reference to \(p_0\) (100 kPa), as

\[
\theta_v = T_v \left( \frac{p_{5m}}{p} \right)^\kappa,
\]

where \(\kappa = 0.287\) and represents the Poisson constant (Wallace and Hobbs 1977).

The gradient Richardson number is then calculated from the 40–5-m differences in virtual potential temperature and the 40–5-m difference in wind speed (Stull 1988):

\[
Ri = \frac{g}{\theta_v} \left( \frac{\partial \theta_v}{\partial p} \right) \left( \frac{\partial U}{\partial z} \right)^2.
\]

Categories of stability are adapted from Stull (1988) for very unstable (\(\text{vu}; \ Ri < -1.0\)), unstable (\(\text{u}; -1.0 \leq Ri < -0.25\)), weakly unstable (\(\text{wu}; -0.25 \leq Ri < -0.05\)),
near-neutral (n; $|\text{Ri}| / C20 \leq 0.05$), weakly stable (ws; $0.05 < |\text{Ri}| / C20 < 0.25$), stable (s; $0.25 < |\text{Ri}| / C20 < 1.0$), and very stable (vs; $|\text{Ri}| / C20 \geq 1.0$) conditions. The number of observations for each wake attribution category and stratification category is indicated in Table 1. We distinguish natural variability “no wake” conditions from wind farm “wake” conditions by tower differences ($A1 - A2$) from $u_{5m}$ and $r_{5m}$ and normalized tower differences $[(A1 - A2) / A2]$ for normalized wind speed ($U / U_{120m A2}$) and normalized turbulence intensity ($\Delta T_{I} / T_{I120m A2}$).

### 3.4. Surface condition bias correction

We consider the A2 tower outside the wind farm (Figure 5) to be our best representation of natural conditions and therefore refer to it as the “reference tower.” If the surface was perfectly homogeneous (no terrain and uniform crops), measurements taken from a precisely defined southwest sector from tower A1 located within the wind farm, as previously described when no synoptic differences existed, would offer a set of concurrent observations of the natural boundary layer in the region. We use these A1 tower data to assess biases and natural variability (for this direction sector) of measurements from the reference tower. Wind speed and turbulence intensity profiles from this sector will be impacted by upwind terrain, surface roughness, and displacement height that are slightly different for the two towers. For towers A1 and A2, we determined roughness $z_o$ to be 0.17 and 0.10 m, respectively, and displacement $d$ to be 0.65 and 1.49 m, respectively, from a log-displacement fit comparing theoretical and measured normalized wind speed profiles ($U / U_{120m A2}$) in neutral flow ($|\text{Ri}| \leq 0.01$). The theoretical profiles for each tower are determined from a neutral flow bin-averaged $z_o$, calculated from a linear fit of wind speed and height profiles such that

$$
\frac{U(z)}{U_{120m A2(z_o,d)}} = \ln \left( \frac{z - d}{z_o} \right) \left[ \ln \left( \frac{z_{120m} - d_{A2}}{z_{o A2}} \right) \right]^{-1}.
$$

Similarly, we represent normalized turbulence intensity with the assumption $\sigma_U = 2.5 u_*$ for neutral conditions (Counihan 1975; Frandsen 2007; Gualtieri 2015) such that

Table 1. Number of observations from single-wake, bulk-wake, and no-wake sectors and stability categories determined from the 80-m wind direction and the 5–40-m-layer Richardson number at A2. Observations with higher uncertainty due to low sample size (<20 observations) are denoted in italics and not used in the analysis. See section 3.3 for definitions of stability abbreviations.

<table>
<thead>
<tr>
<th>Wake category</th>
<th>Wind farm status</th>
<th>Wind direction bin (°)</th>
<th>Stability</th>
<th>Stable</th>
<th>Neutral</th>
<th>Unstable</th>
</tr>
</thead>
<tbody>
<tr>
<td>No wake</td>
<td>On/off</td>
<td>215–218, 229–258</td>
<td>vs s ws</td>
<td>n ($</td>
<td>\text{Ri}</td>
<td>/ C20$ ≤ 0.05)</td>
</tr>
<tr>
<td>No wake</td>
<td>On</td>
<td>215–218, 229–258</td>
<td>51 177 283</td>
<td>137</td>
<td>31</td>
<td>152 226 137</td>
</tr>
<tr>
<td>Single wake</td>
<td>On</td>
<td>173–215</td>
<td>8 143 266</td>
<td>121</td>
<td>27</td>
<td>136 169 40</td>
</tr>
<tr>
<td>Bulk wake</td>
<td>On</td>
<td>302–338</td>
<td>32 284 2346</td>
<td>1451</td>
<td>274</td>
<td>971 405 43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 91 612</td>
<td>360</td>
<td>83</td>
<td>420 264 24</td>
</tr>
</tbody>
</table>
\[ TI(z) = \left[ \ln \left( \frac{z - d}{z_o} \right) \right]^{-1}, \]  

and therefore

\[ \frac{TI(z)}{TI_{120m_A2[z_o,d]}} \approx \ln \left( \frac{z_{120m} - d_{A2}}{z_{o,A2}} \right) \left[ \ln \left( \frac{z - d}{z_o} \right) \right]^{-1}. \]  

The theoretical profiles do not agree as well with measured profiles for turbulence intensity as they do for wind speed. Use of a 1/7 power law (Hui et al. 2009; Gualtieri 2015), rather than the log function, did not improve the fit for near-neutral conditions, so we retain the log-displacement law profile fit (valid during neutral conditions) for turbulence intensity in our remaining analyses.

We refer to the A1 \( \rightarrow \) A2 differences in the normalized wind speed (\( \Delta U/U_{120m_A2[z_o,d]} \)) and normalized turbulence intensity (\( \Delta TI/TI_{120m_A2[z_o,d]} \)) profiles, determined from the roughness and displacement heights of both towers, and as the “surface-condition bias” arising from the contrast in crops near the two towers in this particular growing season. It is likely that modest terrain influence from west of A1 may contribute to uncertainty in this comparison, and this uncertainty may be stability dependent. Fortunately, flows from prevailing directions (generally SSE and NW) encounter very little difference in terrain, as the overall difference in elevation between the towers is only 13 m over a distance of 22 km (0.06%).

Theoretical profiles for potential temperature calculated according to a log-displacement law (e.g., Campbell and Norman 2000) are inadequate to represent the natural variability between the two tower sites. We will focus only on measured tower differences in \( \theta \) and \( r \) in our remaining analyses of the natural and wind farm boundary layers. In our evaluation of differences within the wind farm boundary layer, we isolate the effect of turbines by removing the surface condition bias from the measured differences as described in section 4.3.

4. Results

We first describe the characteristics of the natural boundary layer from tower measurements in the vicinity of the wind farm as a point of departure for assessing the changes created by turbines (section 4.1). Tower profiles of concurrent differences for neutral and nonneutral flow in section 4.2 provide metrics of natural uncertainty. Profiles in section 4.3 for directions of single wakes and bulk wakes reveal isolated and aggregated impacts of wind turbines.

4.1. Vertical profiles of the natural boundary layer

We first examine stability-dependent vertical profiles of wind speed, turbulence intensity, potential temperature, and water vapor mixing ratio from A2 for the condition of no turbine influence, starting with the neutral conditions.

Wind speed and turbulence intensity at 120 m and potential temperature and mixing ratio at 5 m will be used as reference values for normalizing differences between the two sites under neutral conditions (Table 2). Over the period of record,
neutral wind speed is higher by about $0.6 \pm 1.6 \text{ m s}^{-1}$ at A2 (outside the wind farm), while mixing ratio is higher by $0.34 \pm 1.1 \text{ g kg}^{-1}$. By removing the surface condition bias determined in section 3.4, we can look for other biases in wind speed and turbulence intensity. Differences ($A1 - A2$) in profiles of neutral wind speeds normalized by the 120-m wind speed at the reference tower (Figure 6a) indicate that for two classes of neutral flow ($|Ri|/C_{20} < 0.01$ and $|Ri|/C_{20} < 0.05$), the vertical profiles of wind speed lie very close to the difference profile corrected for surface condition bias (dashed profile). The separation between the dashed curve ($DU/U_{120m\_A2}[zo, d]$) and the actual measured difference ($DU/U_{120m\_A2}[meas]$) represents the unexplained normalized biases between the measurements on the two towers, which are 2%–3% of the normalizing wind speed, compared to the 4%–7% negative bias at tower A1 due to the surface condition.

For the turbulence intensity (Figure 6b), the surface condition bias ($\Delta TI/TI_{120m\_A2}[zo, d]$) at A1 is 8%–19% of the 120-m TI, leaving unexplained biases of about 0%–22%. Surface condition bias does not apply to potential temperature or mixing ratio (Figures 6c,d). Instead, other land management and soil factors not quantified in our measurements are responsible for a potential temperature bias at A1 of $-0.16$ to $-0.21 \text{ K}$ (except for an anomalous extra $-0.22-\text{K}$ bias at 20 m) and a mixing ratio bias of $-0.08$ to $0.35 \text{ g kg}^{-1}$. Comparison of the two ranges of Ri shows that the wider window around zero of $|Ri| < 0.05$ (which allows for 106 more observations) reduces the biases between the towers. Various tests on the temperature data from the 20-m level have so far failed to expose any explanation other than that the sensor evidently has a negative bias of 0.2–0.3 K.

### 4.2. Uncertainty in the natural boundary layer for nonneutral stratification

Comparison of data when neither tower is influenced by turbines (Figure 7) revealed that profiles for all stabilities have wind speeds (Figure 7a) exceeding the profile attributed to the surface condition bias $\Delta U/U_{120m\_A2}[zo, d]$ (dashed line). This exceedance increases systematically for more extreme departures from neutral, with the very stable condition creating a jet-like structure with maximum speed increase of over 45% at 40 m. We attribute this anomaly to the slight ridge of terrain 6 m higher than the elevation at the base of the A1 tower in a 2.5-km-wide by
A 2.0-km-long strip from west-northwest to southwest at a distance of about 1 km from the tower. Turbulence intensity (Figure 7b) reaches a peak in the region of highest wind speed gradient, as expected. It is noteworthy that the TI is enhanced substantially for the stable profiles while being affected little for even the most extreme unstable profile.

The potential temperature profiles (Figure 7c) follow the expected departures from neutral, except for the anomalously low temperatures reported by the 20-m sensor at the A1 tower previously discussed. The mixing ratio difference profiles (Figure 7d) have more complicated dependence on stability but generally decrease with height, indicating a general tendency for lower humidity at the surface but higher humidity at upper levels at the A1 tower when compared to the A2 tower. Nonneutral stabilities show drier conditions throughout the profile by up to

Figure 6. Measured A1 – A2 differences of the natural boundary layer vertical profiles for periods of no turbine or no wind farm influence (i.e., no wake) under neutral stratification (\(|R_i| \leq 0.05\) and \(|R_i| \leq 0.01\)) for (a) normalized horizontal wind speed \((\Delta U/U_{120m})\), (b) normalized TI \((\Delta TI/TI_{120m})\), (c) potential temperature \((\Delta \theta)\), and (d) mixing ratio \((\Delta r)\). The estimated surface-condition bias is plotted for normalized wind speed and normalized turbulence intensity in (a) and (b). Error bars indicate the standard deviation of the differences. Symbol sizes are scaled by number of samples for each category.
We have no specific explanations for these changes with height and differences between towers, but provide these as a background upon which the turbines may have an influence.

4.3. Wind farm wake characteristics

We illustrate a “bulk” or aggregate impact of wakes from about 50 turbines distributed from 2 to 14 km from the A1 tower in the prevailing northwest direction. For southerly winds, a windward-edge line of turbines 14.3D to the south of tower A1 provide the data for single wakes (Figure 5). The surface condition bias-corrected differences $\left( \Delta U/U_{120m_A2[meas]} - \Delta U/U_{120m_A2[zo,fil]} \right)$ are plotted for two near-neutral stability windows to provide a measure of uncertainty of stability categorization (Figure 8a). In the following analysis, we use the $|\text{Ri}| \leq 0.05$ window.
for comparison to nonneutral conditions. Wind speed enhancements of 6% in the lowest 20 m for bulk wakes stand out as a departure from no-wake (A2 tower) conditions. Nearly no enhancement near the surface is revealed for single wakes, and single wakes have a maximum decrease at hub height of 4%.

Surface bias-corrected turbulence intensity (Figure 8b) is reduced substantially near the surface, more so for the bulk-wake condition (58%) than for single wakes (25%). It may seem counterintuitive that within turbine wakes, TI decreases as wind speed increases. However, we note that the data of Figure 8a, taken together with the normal logarithmic increase with height of wind speed in neutral conditions, mean that the wind speed becomes more uniform with height (less wind shear) near the surface, and hence there is less mechanical turbulence. Turbines increase the turbulence intensity above 40 m to a maximum (20%) at hub height for single wakes, which is consistent with the findings of Porté-Agel et al. (2011) and Abkar and
Porté-Agel (2015), but a continued level of 15% higher than the no-turbine boundary layer for the bulk wakes, suggesting that both single and bulk wakes have a strong interaction with the layer above our 120-m A1 tower. Temperatures (Figure 8c) are uniformly higher (~0.4 K) at all heights leeward for bulk wakes, whereas single turbines have a very weak enhancement. The elevated temperatures detected in our profile are also in agreement with numerical parameterization of wind farms (e.g., Calaf et al. 2011), although comparisons are limited in other neutral boundary layer simulations because temperature changes were not reported. Mixing ratio profiles (Figure 8d) within bulk wakes show similar vertical change as the natural boundary layer, with slightly drier conditions for single wakes.

Thermodynamically unstable conditions create high turbulence due to convection, while neutral stability often is associated with moderate and high winds that create high turbulence due to mechanical mixing in high-shear layers. In unstable conditions (figure not shown), profiles are quite similar to the near-neutral results shown in Figure 8, except the magnitudes are larger for wind speed and lower for turbulence intensity: single turbines decrease winds above 20 m by 5%, while bulk-wake conditions increase winds in the lowest 20 m by 4%–9%, and profiles for turbulence intensity are about half those for neutral conditions. Potential temperature and mixing ratio show patterns similar to the neutral conditions shown in Figure 8. Our measurements indicate similar near-surface and rotor-layer positive temperature departures from the natural boundary layer reported in wind tunnel simulations of a single turbine (Hancock and Zhang 2015) or a small array of turbines (Hancock and Farr 2014) and in large-eddy numerical simulations of wind farms (Lu and Porté-Agel 2015; Sharma et al. 2017). This is in contrast to slightly lower temperatures in the infinite wind farm wake reported from single-column models (Sescu and Meneveau 2015) and from a wind tunnel simulation in the near wake (2–3D) of a single turbine (Zhang et al. 2013).

We attribute our small differences in moisture from the ambient profile to the possibility of wake meandering during unstable stratification. Unlike a snapshot detection of a wake meander as in numerical simulations of single wakes (Machefaux et al. 2016; Keck et al. 2014a), our composites represent a spatiotemporal average of each wake category.

It is well known from modeling studies (Chamorro and Porté-Agel 2010; Hansen et al. 2012; Odemark 2012; Iungo and Porté-Agel 2014; Keck et al. 2014b; Abkar and Porté-Agel 2015; Abkar et al. 2016; Larsen et al. 2015; Machefaux et al. 2016; Vanderwende et al. 2016; Lee and Lundquist 2017a,b) and observations (Hirth and Schroeder 2013; Rajewski et al. 2013, 2016; Rhodes and Lundquist 2013; Smith et al. 2013; Lundquist et al. 2014; Bodini et al. 2017) that wakes with reduced mean wind speed persist long distances downwind of turbines under stable conditions, although field measurements of aggregate wakes of wind farms are sparse. The bulk effect of multiple turbines in weakly stable conditions (Figure 9a) is to enhance near-surface winds by up to 10% and decrease winds by 7%–12% in the wake region at and above 80 m, compared to no-wake conditions. For strong stratification, there is a much shallower layer of weaker surface speedup. Single turbines have lower speedup near the surface and slightly larger speed reduction above 20 m. Strong stratification in Figure 9b gives less near-surface speedup for multiple turbines than weak stratification, and single turbines have up to 20% decrease in wind speed above 40 m.

Turbulence intensity varied from being lower by 55% in the surface layer in neutral flow (Figure 8b) to as much as 140% higher under strong stability (Figure
Figure 9. Measured difference departures from the surface-condition bias of vertical profiles between the wind farm (A1) and no wind farm (A2) locations during conditions of single-wake, bulk-wake, and no-wake categories when turbines are on for (a),(b) normalized wind speed ($\Delta U_{120 m}/U_{120m}$), (c),(d) normalized TI ($\Delta TI/\Delta TI_{120 m}$), (e),(f) potential temperature ($\Delta \theta$) and (g),(i) mixing ratio ($\Delta r$). (a),(c),(e),(g) Weakly stable stratification ($0.05 < Ri \leq 0.25$); (b),(d),(f),(h) stable stratification ($0.25 < Ri \leq 1.0$). Symbol sizes are scaled by number of samples for each category.
In the rotor layer, turbulence intensities are 15%–20% higher in neutral flow but 40%–160% higher under weak and strong stabilization for both single and bulk wakes, more so for low Ri (Figure 9c) than high Ri (Figure 9d). TI may reach 120%–200% of no-wake conditions at 80 m (Figure 9c). High TI at the 120-m level, especially for weakly stable conditions, suggests a strong interaction with the layer above our 120-m A1 tower.

Under near-neutral conditions for bulk wakes, the potential temperature at A1 revealed a uniformly higher value at all levels, with a difference of about 0.4 K. Bulk wakes weaken thermal stabilization (Figure 9e) by warming (or, more precisely, preventing the cooling of) the surface by about 0.7 K under weakly stable conditions and less for strong stability (Figure 9f). Single wakes have the same height dependence as bulk wakes but half the magnitude. Our measurements indicate slightly lower temperatures above hub height in single wakes, which is consistent with numerical simulations of single wakes (Xie and Archer 2017) and of large wind farms (Lu and Porté-Agel 2011; Fitch et al. 2013a; Dörenkämper et al. 2015). Additional study is needed to explain the higher temperatures throughout our measured 120-m profile in bulk wakes.

Mixing ratio showed essentially no difference inside and outside the wind farm for neutral conditions. However, Figure 9g indicates the wind farm has a higher moisture condition, increasing with height for weak stable stratification, suggesting that dew formation has been suppressed. For strong stability (Figures 9h, 7d), the available data (note that the number of data points is low for this category) suggest a sharp deficit in humidity at 20 m and below, with nearly as strong of an increase at 120 m for the bulk-wake condition. This feature was not evident for the single-wake profiles. Numerical simulations of large wind farms report a similar pattern of lowering of surface humidity and increasing the humidity above hub height for low wind speeds (Waggy et al. 2015; El Fajri 2016), but this dipole is also observed from profile measurements taken within the near wake (<2D) of a single turbine (Adkins and Sescu 2017) and from multiple ground-level measurements in a wind farm (Armstrong et al. 2016). We also observe lower surface moisture within bulk wakes for low hub-height wind speeds (figure not shown) and, given the potential agricultural significance, consider it a factor needing further research.

5. Discussion

The overall effects of wind farms on microclimate conditions are summarized qualitatively in Figure 10. We return to our conventions from Figure 1 of defining the below-rotor layer as the 0–40-m layer underneath the RSL. In the RSL, turbines are in direct contact with the 40–120-m boundary layer. We indicate a return to natural boundary layer conditions with the use of a horizontal double-sided brown arrow, whereas wind farm effect is denoted with an upward red arrow for an increase or a downward blue arrow for a decrease. Wakes are most evident in the RSL of a single wake and at nighttime when thermal stratification suppresses turbulent mixing of the natural boundary layer turbulence into the wind farm boundary layer turbulence. Our measurements indicate the highest turbulence and speed reduction within single wakes rather than bulk wakes because wake dissipation is lower within single wakes than within bulk wakes. In the daytime, single wakes generally do not intersect the surface (Rajewski et al. 2013; Takle et al. 2013).
whereas the bulk wake does make contact with the lowest tower heights. At night, turbulence intensity in the BRL is weakly coupled to the RSL in the natural boundary layer. Therefore, the turbulence intensity of bulk wakes near the surface is of similar magnitude as for conditions outside of the wind farm. Within single wakes, turbulence intensity is also decoupled between the BRL and RSL, but the speed profile is less changed near the surface than in the rotor layer.

The data suggest that single wakes reduce daytime humidity both near the surface and in the RSL, whereas bulk wakes possess moisture near that of the natural boundary layer. At night, single wakes move surface moisture from the BRL into the RSL, causing a lower BRL humidity and a higher RSL humidity. Additional work is needed to address the specific mechanisms that modify moisture within wind farms.

The bulk-wake effects on profiles for weakly stable conditions suggest that these ambient conditions are most vulnerable to turbine influence on thermal stratification. The data of Figure 9e indicate that the effect of both individual turbines and of many turbines is to create a higher temperature within the wind farm than is observed beyond the wind farm boundary. This should not be physically considered heating, but rather suppression of surface stabilization of near-surface air through forced downward mixing of warm air and reduction of the cooling rate of the

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Figure 10. Summary of wake influences within the BRL and RSL of single wakes and bulk wakes for typical neutral, unstable, and stable conditions. Brown two-sided arrows denote no change of differences from no-wake conditions, red upward arrows denote a positive effect by turbines, and blue downward arrows denote a negative effect by turbines. Thicker black outlining of arrows denotes a stronger difference.
radiating surface temperature (Figure 9e). Enhanced mixing of air in the rotor layer and below leads to a downward heat flux that partially replenishes surface energy radiated to space under stable (nighttime) conditions. This difference in the stratification from measured values at tower A2 is associated with enhanced wind farm wind speed at levels below 40 m above natural conditions (Figure 9a) and suppresses onset of the low-level jet above 40 m, thereby allowing high turbulence (Figure 9c) through the entire 120-m depth of the wind farm boundary layer. This is true for both single wakes (with maximum at hub height) and bulk wakes.

The suppression of natural cooling of the surface in wind farms has an agricultural significance. High nighttime temperatures during the pollination and grain-filling periods are known to reduce yields of corn (Peters et al. 1971; Badu-Apraku et al. 1983; Canterer et al. 1999; Elmore 2010; Lutt et al. 2018). The rise of nighttime temperatures due to climate change (Hatfield et al. 2014) has been cited as a potential limiting factor for much of the U.S. Midwest. In some years, the suppression of nighttime cooling due to wind farms might be 1.2 K (0.7-K mean from Figure 9 plus one standard deviation (not shown) of 0.5 K) during the reproductive period for corn, which would add to the adverse effect of climate change in the U.S. Midwest (Zhou et al. 2012).

We recognize that there are many limitations of this description of this wind farm microclimate. First, although the region is quite flat, small-scale terrain features, together with soil heterogeneities, contribute uncertainty not captured by our use of only two identical towers. We are able to sample only a limited sector of wind directions to establish the wind farm scale uncertainty of the natural boundary layer. Second, our data are limited to 1-Hz resolution and do not fully capture the changes to directly measured fluxes and turbulence to fully describe microclimate conditions. Vertical profiles of turbulence and fluxes will be described in future reports. Third, heterogeneity in crop type and seasonal changes in crop phenology influence interactions with turbines from season to season and year to year. Fourth, uncertainty measures, such as error bars of one standard deviation, would indicate that there is too much uncertainty to support some of our conclusions. However, we note that numerous figures (e.g., Figure 8) show profiles of mean values having expected dependence on stability and height.

Results from our low-density wind farm with irregularly spaced wind turbines, all having the same hub height, may not be applicable to high-density wind farms with regular or irregular arrays and wind farms with more terrain or landscape heterogeneity, different soils, or agricultural management practices. Despite these limitations, we assert that the summary in Figure 10 provides a basis for understanding the unique boundary layer of a low-density utility-scale wind farm.

6. Conclusions

We compare microclimate conditions in the lowest 120 m of the atmospheric boundary layer at two locations separated by 22 km in an intensively managed agricultural landscape. Locations of the towers allow us to determine spatial variability of the natural boundary layer as well as (from data for carefully selected wind directions) the aggregate influence of ~50 turbines in contrast to a single line of windward-edge turbines of a wind farm having a low-density distribution of turbines. Our results show how this twin-tower observatory adds a third dimension to our understanding of the wind farm boundary layer that affects crops and natural
ecosystems. Furthermore, from Figure 10, it is evident that conditions leeward of a single turbine and at different elevations can differ substantially from conditions observed leeward of multiple turbines where the flow is aggregated to create a bulk effect. Therefore, caution must be exercised in extrapolating measurements behind a single turbine to represent the wind farm boundary layer.

Future reports will continue analysis and interpretation of past and future data from this continuously operating tower network. Our future analysis also will include results from sonic anemometers on the towers, as well as a shorter tower with a high vertical density of sonic anemometers and gas analyzers for measuring very near-surface turbulent fluxes. Data retrieval beyond 120 m will also be provided by an operational sodar starting in spring 2018.

Acknowledgments. The authors acknowledge assistance from Tom Wind in the planning and preparation of activities leading to the construction of the tall towers. The authors also acknowledge Daryl Herzmann for providing the data files used in the analysis and Russell Doorenbos for developing the wake attribution diagram. Financial support for the tower construction was provided from the State of Iowa Power Fund and the National Science Foundation Iowa EPSCoR Grant 1101284. Additional funding for data support, data analysis, and interpretation is provided by the National Science Foundation Wind-Energy Science, Engineering and Policy IGERT Grant 1069283, National Science Foundation Grant 1701278, the Howard Hughes Medical Institute grant, and Pioneer Hi-Bred Professorship in Agronomy Grant and the Iowa Energy Center Opportunity Grant OG-17-001. The authors acknowledge cooperation with the land owners and the wind farm manager.

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