In situ observations of the influence of a large onshore wind farm on near-surface temperature, turbulence intensity and wind speed profiles

Craig M Smith¹, R J Barthelmie and S C Pryor

Atmospheric Science Program, Department of Geological Sciences, Indiana University, Bloomington, IN, USA

E-mail: craig.smith@dri.edu

Received 19 March 2013
Accepted for publication 2 July 2013
Published 16 July 2013
Online at stacks.iop.org/ERL/8/034006

Abstract
Observations of wakes from individual wind turbines and a multi-megawatt wind energy installation in the Midwestern US indicate that directly downstream of a turbine (at a distance of 190 m, or 2.4 rotor diameters (D)), there is a clear impact on wind speed and turbulence intensity (TI) throughout the rotor swept area. However, at a downwind distance of 2.1 km (26 D downstream of the closest wind turbine) the wake of the whole wind farm is not evident. There is no significant reduction of hub-height wind speed or increase in TI especially during daytime. Thus, in high turbulence regimes even very large wind installations may have only a modest impact on downstream flow fields. No impact is observable in daytime vertical potential temperature gradients at downwind distances of >2 km, but at night the presence of the wind farm does significantly decrease the vertical gradients of potential temperature (though the profile remains stably stratified), largely by increasing the temperature at 2 m.

Keywords: lidar, wind turbine wakes, surface temperature profiles, turbulence intensity, wind shear

Online supplementary data available from stacks.iop.org/ERL/8/034006/mmedia

1. Introduction
Consistent with historical and continuing use of wind propellers to prevent freezing in vineyards by enhancing vertical exchange of warmer air from aloft (e.g. Crawford 1965), reduction of wind speed and enhancement of turbulence in the lee of wind turbines (i.e. wind turbine wakes) (e.g. Barthelmie et al 2010), modifies the planetary boundary layer and surface-atmosphere fluxes of momentum, sensible heat and latent heat. These changes may have implications for crop yields if wind farms are located in agricultural regions (e.g. by changing water availability), and may alter downstream atmospheric properties (see detailed literature review provided in the supplementary materials available at stacks.iop.org/ERL/8/034006/mmedia).

Idealized mesoscale models, in which wind turbines are parameterized as sinks of momentum and sources of turbulent kinetic energy (Baidya Roy 2011), and large eddy resolving simulations (LES) of an idealized infinite wind farms (Lu and Porté-Agel 2011, Calaf et al 2011), have been used in efforts to quantify the impact of wind turbines on atmospheric properties within and downstream of multi-MW
wind turbine deployments. Results from these studies are to some degree inconsistent; while some modeling groups have found 'statistically significant impacts on near-surface air temperature and humidity as well as surface sensible and latent heat fluxes' (Baidya Roy 2011), the simulations of an infinite wind farm for tall (120 m) turbines presented in Lu and Porté-Agel (2011) show no significant effect on surface temperatures. As discussed in the supplementary materials, there are relatively few in situ observational data sets with which to evaluate these and other model simulations. In this paper we present data from a large operational onshore wind farm located in flat homogeneous terrain with uniform land use and analysis to quantify the impact of this development on near-surface profiles of wind speed, turbulence intensity and temperature.

2. Data and methods

2.1. Observational data

Data analyzed herein were collected during 4 April–20 May 2012, at a large wind farm in the Midwest (table S1 and supplementary materials available at stacks.iop.org/ERL/8/034006/mmedia). The array comprises ~300 1.5+ MW wind turbines with a hub height of 80 m. Confidentiality agreements prohibit discussion of some details, but the overall shape of the installation is roughly rectangular, and the layout is such that in the west–east direction the wind turbine spacing is ~5 rotor diameters (D) (where D = 80 m, and the range of spacing is 3.8–5.5D), and in the south–north direction the turbine spacing is ~20D (range: 18–22D) (figure 1). Meteorological data were collected on or near two 80 m masts located in the southwest (SW) and northeast (NE) corners of the wind farm which is collocated with soy and corn crops (which were between 5 and 25 cm tall during the field campaign). Widely scattered houses and poplar trees exist throughout the farm as well, but none were located nearby our measurement sites, and soil and crop conditions close to both meteorological masts were relatively similar throughout the campaign. Duplicate anemometers deployed on different sides each meteorological mast allowed for identification and reduction of mast shadow effects (in which the tower superstructure upwind of a sensor perturbs the flow field) by conditionally sampling the data to select measurements from the sensor upwind of the tower. Additional data from two vertically pointing continuous wave ZephIR lidars and a Galion scanning pulsed lidar are presented for 7–20 May. As discussed further below, wind speeds estimated using these lidars exhibit very good agreement with data from the cup anemometers (Peña et al 2009) and sonic anemometers (Sathe et al 2011). Further, scanning lidars have been shown to be capable of capturing the −5/3 Kolmogorov spectrum (Iungo et al 2013). However, estimates of turbulence intensity (TI) (and momentum flux, e. g. Mann et al 2010) measured by the ZephIR lidars over a scanning volume is attenuated relative to point measurements, and the degree of attenuation varies with mean wind speed (Peña et al 2009), height (scanning volume) and stability (Sathe et al 2011). For the purposes of this paper all wind speed and direction measurements taken between 75–80 m are referred to as representing a nominal height of 80 m (i.e. turbine hub height). Unless otherwise stated, all times quoted are in local standard time (LST), the date format is month/day/year, the data integration period is 10 min, and all data have been conditionally sampled to select

Figure 1. Overview of the wind farm, including close-up views of the NE and SW locations, and schematic of the unwaked (#1, black), SW farm-waked (#2, red), SW direct-waked (#3, blue), NE farm-waked (#4, green) and NE direct-waked (#5, magenta) wind direction bins. The frequency with which flow greater than 4 m s−1 was observed in the five directional sectors during 04/04/2012–05/20/2012 is 6.9, 16.6, 7.9, 14.2 and 1.8%, respectively.
periods when the wind farm was operating and producing power (i.e. free-stream hub-height wind speeds >4 ms$^{-1}$). In operational wind farms, including the one studied herein, it typical that a small percentage of wind turbines will not be operational due, for example to maintenance issues or curtailment events by the grid operator, however, in the data period shown here the turbines closest to the meteorological masts were fully operational.

Characteristics of wind turbine wakes, such as the incremental increase in TI, are non-linear functions of incident wind speed due to the dependence on the wind turbine thrust coefficient. Wake induced TI is generally maximized for wind speeds between the cut-in wind speed (when the wind turbine starts turning) and the rated wind speed (when power output ceases to be a function of wind speed) (Barthelmie et al 2012). The median free-stream wind speed for data presented herein is 7.5 ms$^{-1}$, which is associated with the highest thrust coefficients for turbines on this farm, and hence the measurement period is characterized by a high frequency of conditions during which wakes will be pronounced and the largest relative velocity deficits will be observed. Thus the results presented herein may slightly over-estimate downstream effects relative to wind farms in higher wind speed regimes.

2.2. Differentiating unwaked, near wake and wind farm wake conditions

Wind farm geometry was used to identify wind direction sectors associated with outflow from the entire wind farm (wind farm wake), with a direct wake from the nearest wind turbine (near wake) and with flow that represents free-stream conditions (unwaked). The nearest turbines to the SW mast are located 2.4D (193 m) to the northwest (299°), 2.4D (189 m) to the northeast (62°), and 6.8D to the east (81°) (figure 1). Thus for the SW location a direct wake (sector 3 shown in figure 1) is characterized by flow centered on turbines 1 and 2 (where each sector is assumed to have a ~15° half width, see figure S1 (available at stacks.iop.org/ERL/8/034006/mmedia) for further evaluation of the wind direction sectors). For wind directions between 35° and 035° the SW location is fully unwaked (sector 1) (figure 1). Flow through a large portion of the wind farm with the closest turbines displaced 26D (2.1 km) away (with the next row located 44–48D (~3.8 km) away). Thus, flow from these directions is used to describe the entire wind farm wake (SW farm waked, sector 2). Wind directions from 318° to 350° are fully unwaked at both the SW and NE meteorological masts, and thus are used to define ‘unwaked’ (i.e. sector 1) conditions. For the NE location, there is a line of turbines aligned at ~255° (with the closest turbine at 2.4D). This direction represents the centerline of the NE direct-waked sector (#5). The nearest row south of the NE mast does not have turbines extending all the way to the wind farm eastern boundary, and the nearest wind turbine is located 33D (2.7 km) away at 218°. Thus the sector from 190° to 240° is used to define the wind farm wake for the NE location (sector 4). For the SW farm-waked and direct-waked bins, the SW location is fully unwaked. Thus, in each case (2–5) one meteorological mast location can be used to provide ‘free-stream’ (i.e. unwaked) conditions, while the other mast can be used to characterize conditions in the wake of an individual turbine, or the entire wind farm. To avoid situations in which the downstream edge of wind turbines was not operating when free-stream wind speed was near cut-in, we present data only from periods when the hub-height wind speed at both the NW and SE meteorological masts exceeded 4 ms$^{-1}$. These criteria ensured that the wind turbines proximal to the SW meteorological mast (#1 and #2, see figure 1) were operating and producing power >99% of the time for the waked cases studied herein, which we verified through inspection of power production from each of these two turbines (not shown). The frequency with which flow greater than 4 ms$^{-1}$ was observed in the five directional sectors (1: both masts unwaked, 2: wind farm wake at SW, 3: direct wake at SW, 4: wind farm wake at NE, 5: direct wake at NE) during 04/04/2012–05/20/2012 is 6.9, 16.6, 7.9, 14.2 and 1.8%, respectively.

3. Results

3.1. Average conditions in the near wake, wind farm wake and unwaked sectors

Low level wind shear ($\alpha$) is characterized using the power law:

\[
\frac{u_2}{u_1} = \left(\frac{z_2}{z_1}\right)^{\alpha},
\]

where $u$ is the wind speed, $z$ is the height, and subscripts 1 and 2 indicate 40 m and 80 m measurements, respectively. In the unwaked wind directions the average shear exponent at SW = 0.05 during the day (11:00–17:00 LST, hereafter referred to as daytime) and 0.36 at night (00:00–06:00 LST, hereafter referred to as nighttime), while at the NE mast $\alpha = 0.05$ during the day and 0.33 at night (table 1). Both are thus consistent with low shear (high turbulence regimes) in the day and higher shear at night. The average shear exponent from all unwaked data is 0.13 and 0.13 at the SW and NE locations, respectively, which is consistent with the value of 0.14 used in the wind turbine design standards (IEC standard 61400-3), but lower than the shear exponent of 0.23 computed from measurements at 50 and 90 m from an Indiana tall tower in a low roughness regime (Elliott et al 2008).

Negative shear (decreasing wind speeds between 40 and 80 m) is clearly evident in the near wake wind directions (i.e. sector 3 at the SW mast, and sector 5 at the NE mast) (table 1 and figure S1 available at stacks.iop.org/ERL/8/034006/mmedia) consistent with the hub-height maximum velocity deficit (Politis et al 2012). Also consistent with detailed wind turbine wake studies which have indicated relatively rapid recovery of wind turbine wakes in high turbulence regimes (Barthelmie et al 2012), the shear exponent in the farm-waked sectors is only modestly lower than that for the unwaked sectors (median daytime values for unwaked and wind farm-waked sectors are; 0.05 versus 0.07 for SW, and 0.05 versus 0.07 for NE, see table 1).
Table 1. Median values of daytime (11:00–17:00 LST) and nighttime (00:00–06:00 LST) turbulence intensity (TI) (%), shear exponent (α) (unitless), and vertical potential temperature gradient (Δθ/Δz) (°C m⁻¹) for each wind sector (see figure 1).

| Mast & wind direction sector | Day TI | Night TI | Day α | Night α | Day Δθ/Δz | Night Δθ/Δz |
|------------------------------|--------|----------|-------|---------|-----------|-------------|
| SW: Sector #1 unwaked       | 14.2   | 5.7      | 0.05  | 0.36    | −0.018    | 0.048       |
| SW: Sector #2 farm wake     | 14.8   | 7.7      | 0.07  | 0.20    | −0.020    | 0.022       |
| SW: Sector #3 direct wake   | 25.7   | 24.7     | −0.05 | −0.24   | −0.021    | 0.026       |
| SW: Sector #4 unwaked       | 12.3   | 4.5      | 0.08  | 0.35    | −0.015    | 0.036       |
| SW: Sector #5 unwaked       | 20.6   | 6.9      | 0.04  | 0.16    | −0.005    | 0.047       |
| NE: Sector #1 unwaked       | 12.5   | 5.4      | 0.05  | 0.33    | —         | —           |
| NE: Sector #2 unwaked       | 15.0   | 7.8      | 0.05  | 0.30    | —         | —           |
| NE: Sector #3 unwaked       | 15.9   | 7.3      | 0.09  | 0.33    | —         | —           |
| NE: Sector #4 farm wake     | 12.5   | 6.6      | 0.07  | 0.23    | —         | —           |
| NE: Sector #5 direct wake   | 25.3   | 24.3     | 0.01  | 0.02    | —         | —           |

Figure 2. Mean (a) hub-height difference in wind speed (SW–NE), (b) difference in hub-height TI (SW–NE) and (c) mean potential temperature gradient for the SW location only, binned as an average of each two hours as a function of local hour of day (LST) for the unwaked (#1, black) SW farm-waked (#2, red), SW direct-waked (#3, blue), NE farm-waked (#4, green) and NE direct-waked (#5, magenta) wind direction bins. The error bars denote one standard deviation from the mean. Also plotted in (c) are events for which α < 3 ms⁻¹ for the SW farm-waked (#2, yellow) and SW direct-waked (#3, cyan) direction sectors.

For a wind speed at 40 m of 6.0 ms⁻¹, this change in shear exponent due to farm waking, from 0.05 to 0.07, equates to an absolute change in wind speed at hub height of <0.1 ms⁻¹ which is near measurement uncertainty for wind speeds from cup anemometers, and is thus close to the limit of detection. Thus, the inference is the whole wind farm wake is virtually undetectable in wind speed shear between 40 and 80 m.

Data from cup anemometers mounted on the meteorological masts (i.e. SW location minus NE for all sectors), indicate that for the unwaked directions (sector 1) mean wind speeds are almost identical (figure 2(a)). No horizontal velocity gradient is present during either the day or night according to the Wilcoxon rank sum test applied with 95% confidence level. This is consistent with the flat terrain and uniform land use, and validates use of this location for an assessment of the magnitude of whole wind farm wake effects on the near-surface layer. For wind directions associated with direct wakes at SW but no wake at NE (sector 3), wind speeds at the SW mast are significantly lower (according to the Wilcoxon rank sum test) for all hours of the day, especially during the nighttime. The difference is smallest in the mid-afternoon when wake recovery due to vertical momentum transfer is maximized, presumably due to the unstable conditions and efficient vertical mixing. Similar behavior (NE mast measured wind speeds are lower than SW) is also noted when the NE mast is direct waked and the SW location is unwaked (sector #5), for bi-hourly bins containing more than 8 data points. For sectors associated with whole wind farm wake conditions (sectors 2 and 4), horizontal differences of hub-height wind speed during the daytime are fairly small, but at least for sector 4 mean wind speed difference is 1.0 ms⁻¹ during nighttime, when stable conditions and low ambient TI tend to limit wake recovery (Schepers et al 2012, Barthelmie et al 2012). The horizontal wind speed differences for the direct-waked sector are in agreement with previous wind tunnel studies (Zhang et al 2013) and field data (Magnusson and Smedman 1994, Jungo et al 2013). The horizontal wind speed differences at wind turbine hub height shown in figure 2(a) are also qualitatively in agreement with predictions from the simplified Park model (Katic et al 1986), which describes wake deficits, Δu_wd (i.e. the difference between the free-stream velocity at hub height, u_hub, and the velocity in the wake at a given downstream distance) as:

\[
\triangle u_wd(x) = u_{hub} \times \frac{1 - \sqrt{1 - \frac{C_T}{D}}}{(1 + \frac{2k}{D})^{\frac{1}{3}}},
\]

where C_T is the thrust coefficient and k is an empirically determined linear expansion coefficient (here k = 0.07), and x/D is the rotor normalized distance downstream from the turbine, equal to 26 and 2.4 for sectors 2 and 3, respectively. For \( u_{hub} = 6 \text{ m s}^{-1} \) and \( C_T = 0.75 \), the wake deficit for a single turbine at hub height calculated from (2) is 0.14 and 1.7 ms⁻¹ for downwind distances equal to those for sectors 2 and 3, respectively (cf values shown in figure 2). This implies
that the mean hub-height velocity deficit derived from these measurements in sector 3 (where wind speeds from the NE mast is used as the free-stream and the SW mast is used to characterize the wake depth) is dominated by the influence of the closest wind turbine, and shows little additional impact of the entire wind farm. This is consistent with analyses from offshore wind farms which have shown that the wake velocity deficit at hub height is dominated by the impact of the nearest turbine (Barthelmie et al. 2009).

TI is defined as the ratio of the standard deviation ($\sigma$) of horizontal wind speed to the mean value ($u$) during the (10 min) sampling interval

$$TI = \frac{\sigma}{u}.$$ (3)

Previous investigations (Yahaya and Frangi 2004) have shown that TI derived from cup anemometers can exhibit bias at low wind speeds relative to sonic anemometers due to inertia, and at high wind speeds due to over-speeding. TI estimates from a cup or sonic anemometer and those derived using the ZephIR are not directly comparable because the ZephIR scans one height for 3 s over an 18 s repeat cycle. During each 3 s cycle, 150 line of site measurements are taken over the scanning volume and averaged together to find one mean wind speed and horizontal velocity variance. Thus 10 min mean estimates of the mean and variance of horizontal wind speed derive from sampling during only 1 min and 40 s. Further, the scanning volume increases with height. For an 80 m measurement height, the horizontal diameter of the scanning volume is 80 m (the scanning angle of the ZephIR is roughly $30^\circ$ from vertical), and the Doppler returns are considered from an along-beam Lorentzian-weighted range gate. The large scanning volume means there may be substantial variations of streamwise velocity within the sampled volume. Thus care should be taken in interpreting TI and mean velocity measurements from the ZephIR particularly for the direct-waked bins since the $30^\circ$ wake widths shown in figure S1 imply a full wake width of 100 m (190 m downstream of the proximal wind turbines). TI at 80 m from the ZephIR and cup anemometer on the SW mast exhibits a relatively high degree of accord (for $u > 4$ ms$^{-1}$, $R^2 = 0.77$) (figure S2 available at stacks.iop.org/ERL/8/034006/mmedia), as in Peña et al. (2009 figure 9), but again re-emphasizes that there are differences in TI in a scanned volume versus a point measurement. TI from the ZephIR generally exceed those from cup anemometers during the daytime (figure S2, red circles) when turbulence length scales can be larger than the scanning volume, but ZephIR derived TI are generally less than those from the cup anemometer during night (figure S2, blue circles), when stable stratification reduces turbulence length scales. The values of TI shown here are larger than typically seen in offshore wind farms, but are consistent with previous reports for onshore wind farms (cf figure 7, Wharton and Lundquist 2012). Thus, in the following we only compare wind speed and TI derived from identical instruments (i.e. cup anemometers or ZephIR lidars).

TI from cup anemometers in the unwaked sector exhibits a typical diurnal pattern with an afternoon maxima (median TI of 12–15%, similar to those shown in Schepers et al. 2012), and lowest values overnight (TI ~ 5–7%) (table 1). Consistent with models of rotor induced turbulence and previous work (Barthelmie et al. 2007), TI is significantly higher in the direct wake (sectors 3 and 5) in all hours of the day. For example, median TI for the direct wake sector at the SW location is much greater than that at the NE location during both nighttime hours (median TI at night = 24.7% SW versus 5.4% NE) and during the day (25.7% SW versus 12.5% NE) (table 1). Conversely, conditions in the wind farm-waked sectors (#2 and #4) show little enhancement of TI relative to the unwaked (ambient) TI (sector 1). The enhancement of nighttime TI in farm-waked conditions relative to unwaked conditions is relatively small (5.7 versus 7.7% at the SW mast, and 5.4 versus 6.6% at the NE mast). Comparable values for daytime are 14.2–14.8% and 12.5–12.5%, respectively. Thus, wind farm waking generates at most only a modest increase in TI (~2.0% difference between waked and unwaked values, see figure 2(b) and table 1). This implies the cumulative turbine-added turbulence is small relative to the ambient TI at a downwind distance from the wind farm edge of ∼20–30D.

Probability distributions of TI show a clear signal of higher TI for the direct wake sectors but, consistent with the discussion above, the impact of the entire wind farm wake (where all turbines are displaced at least ten-times as far away from the measurement point, i.e. 26D downwind, versus for the direct wake when the downstream distance is 2.4D) is not detectable (figure 3 and table 1). Direct waking is characterized by higher median TI, and a broader distribution of TI, both day and night (figure 3). The majority of nighttime direct-waking events were characterized by high TI and negative shear (figure S3 available at stacks.iop.org/ERL/8/034006/mmedia). Both at night and during the day the modal value of TI is shifted to higher values in sectors impacted by the wind farm wake than in unwaked
conditions. However, consistent with the median TI values shown in table 1, the overall change in the modal value is small. Taken in combination these analyses thus indicate that stochastic variability in TI (i.e. difference in median TI between the two mast locations for unwaked sectors of 1–2%, see table 1) is of similar magnitude to the wind farm effect at a downstream distance of >26D, or 2.1 km, from the closest turbine (i.e. median farm-waked TI versus median unwaked TI at both the NE and SW mast is also 1–2%). These results indicate slightly more rapid dissipation of the wake than is evident in analysis of data from wind tunnels which suggest the added streamwise TI behind the turbine rotor is ∼8% at a downstream distance of 10D under unstable and neutral stratification (Zhang et al 2013) and is ∼8% at 20D downstream under stable conditions (Chamorro and Porté-Agel 2010). A partial explanation for this difference is that the ambient TI in the wind tunnel experiments was considerably lower (<10%) than the values experienced in the field observations.

The vertical potential temperature gradient ($\frac{\Delta \theta}{\Delta z}$) is quantified using:

$$\frac{\Delta \theta}{\Delta z} = \frac{\theta_2 - \theta_1}{z_2 - z_1},$$

(4)

where $\theta_1$ and $\theta_2$ denote the air potential temperature computed from temperature measurements at $z_1 = 2$ m, and $z_2 = 75.7$ m at the SW mast. $\Delta \theta/\Delta z$ for the unwaked direction sector indicates unstable conditions during the daytime (∼0.018 °C m⁻¹) consistent with positive sensible heat flux, and stable (+0.048 °C m⁻¹) at night consistent with negative sensible heat flux (figure 2(c) and table 1). Consistent with remote sensing data (Zhou et al 2012), the largest changes in $\Delta \theta/\Delta z$ due to wind turbine wakes are observed late at night (figure 2(c)), and during the daytime the change in median $\Delta \theta/\Delta z$ between the farm-waked, direct-waked and unwaked sector is too small to be able to detect any impact of adjacent wind turbines or the wind farm. The $\Delta \theta/\Delta z$ overnight in the direct wake and wind farm wake sectors (+0.026 °C m⁻¹ and +0.022 °C m⁻¹) differ at the 95% confidence level from those in the unwaked sectors (+0.036 to +0.047 °C m⁻¹, see table 1). However, it must be noted that: (i) the individual temperature measurements have an accuracy of ±0.1 °C (∼0.002 °C m⁻¹ in our vertical potential temperature gradient calculations) and (ii) these potential temperature gradients are not compared to the free-stream and therefore might be related to the larger scale synoptic meteorology instead of, or in addition to, the wind turbine/wind farm. Thus this relatively weak signal in direct wakes and farm wakes on daytime vertical potential temperature gradients (of ∼0.002 °C m⁻¹) is barely above the limit of detection. Nevertheless, vertical potential temperature gradients (figure 2(c)) for SW farm-waked and SW direct-waked direction sectors during calm conditions ($u < 3$ ms⁻¹) are considerably larger than those during wind farm operation (figure 2(c)). Hence this is consistent with the reduction of $\Delta \theta/\Delta z$ for farm-waked and direct-waked bins being due to the effect of wind turbines when the farm is operating ($u > 4$ ms⁻¹), and not being due to synoptic scale effects on free-stream vertical potential temperature structure. Contrary to the observed signals of TI and shear, which are highest for the individual wake at 2.4D and appear to decay rather rapidly downstream from the wind farm, the influence of the entire wind farm (as manifest in wind direction sector 2) on nighttime vertical potential temperature gradients is larger than for the individual direct wake case (sector 3) (see figure 2(c)).

3.2. Case studies

To further illustrate the differences in flow characteristics associated with impacts from direct wind turbine wakes versus whole wind farm effects, a number of case studies were analyzed. Two are discussed in detail here.

Flow during 04/20/2012 illustrates an example of direct waking on TI and shear. Initially the wind direction was southerly, veering to become westerly and then northerly by noon (figure 4(b)). Between 11:00 and 12:30 the SW mast was waked by turbine #1, located 2.4D away. During this time power production at the turbines nearest to the SW and NE locations was relatively constant, and hub-height wind velocity at the NE location was between 8 and 10 ms⁻¹ while hub-height velocity at the SW location dropped to 4–5 ms⁻¹ (figure 4(a)). At the same time, TI at the SW location increased from 10% to 30% (figure 4(d)) and low level shear became negative (figure 4(c)). Before and after this direct waking there was relatively little difference between velocity at hub height at the SW and NE locations. Profiles from the
Figure 5. Vertical profiles of (a) wind speed ($u$) (ms$^{-1}$), (b) turbulence intensity (TI) (%) from the ZephIR lidar at SW mast on 04/20/2012 at 09:05 (red), 10:45 (blue) and 14:25 (green). Profile times are indicated in figure 4(a).

ZephIR lidar show a reduction of wind speed (figure 5(a)) and increase in TI$_{ZephIR}$ (figure 5(b)) at hub height and further aloft at approximately 10:45 AM, but not before or after the direct-waked event. The time at which the direct-waked profile is taken is consistent with the change in wind direction during this event and small offset between the SW mast and the ZephIR lidar. The change in wind direction during this period was due to the passage of a cold front, which also strongly influenced air temperatures, and thus no temperature data are presented for this case study, since synoptic scale thermal advection rather than local influences dominated air temperature variability.

The period 05/16/2012 22:00–05/17/2012 10:00 is characteristic of periods during which unwaked, wind farm waked and direct wake conditions were observed. During this time the wind direction veered from northerly to easterly (figure 6(b)). Thus before midnight the SW location was subject to wind directions associated with impact from the whole wind farm wake, and from 01:00 to 05:00 (LST) the SW location was impacted by a direct wake. Prior to the direct waking, shear and TI conditions at the SW mast were similar to those at the NE mast, and there was little difference in hub-height velocity between the two locations. As the wind continued to veer, the SW mast experienced a direct wake from the proximal turbine, and a large drop in hub-height wind speed was observed (figure 6(a)) simultaneously with a decrease in low level shear (figure 6(c)) and increase in hub-height TI (figure 6(d)) relative to the NE location. Between 01:00 and 05:00 (LST), there was an increase in near-surface (i.e. 2 m) temperature at the SW mast by 1.0–1.5°C which was not seen at the NE location or at hub height at either location (figure 6(e)). The magnitude of increase in surface temperature during the event is consistent with the mixing of warmer air aloft down to the surface and partially eroded the vertical gradient of 2.5–3.0°C (and thus stable stratification) seen before and after the event at the SW and NE masts to 1.5–2.0°C during the event. Hourly mean vertical profiles of wind speed (figure S4(a) available at stacks.iop.org/ERL/8/034006/mmedia) and TI$_{ZephIR}$ (figure S4(b)) from the ZephIR just before (05/16/2012 23:00), during (05/17/2012 04:00) and after the event (05/17/2012 08:00) reveal the extent to which direct waking by the adjacent wind turbine 2.4D away changed the structure of the boundary layer (N.B.: further details of the wind turbine wake during this time is shown by the plan position indication scan from the Galion lidar collected at 01:06 on 05/17/2012 (figure S5)). Direct waking at the SW mast led to a large decrease in hub-height velocity, creating negative shear between 40 and 80 m (figure 6(c)), and increasing shear in the 80–120 m level. The increase in shear in both layers at 04:00 at the SW location led to enhanced TI at the SW location (i.e. hub-height TI was 14% greater at the SW location than at NE, see figures 6(d) and S4(b)), throughout the rotor swept area (40–120 m). Before and after the event, there was relatively little difference for TI and velocity between the SW and NE locations.

4. Concluding remarks

This study presents observations of flow in the near-surface layer close to a large Midwestern wind farm co-located with
corn and soybean crops during spring. Data are conditionally sampled to examine gradients of wind speed, turbulence intensity, shear and potential temperature under conditions of free-stream flow (unwaked conditions), downstream of the entire wind farm, and for direct impingement of wakes from proximal wind turbines. In accord with a priori expectations and a wealth of prior research, for direct wake cases (i.e. where measurements are taken 2.4D (192 m) downstream of a turbine), there is a clear signal of a decreased wind speeds and increased TI at hub height and throughout the rotor swept area. However, the impact of the whole wind farm wake on vertical shear and TI is virtually indistinguishable from background stochastic variability at distances of 2.1 km or greater.

Vertical potential temperature gradients were not strongly affected by direct wake impingement or whole wind farm waking during the daytime, but nighttime potential temperature gradients were reduced relative to unwaked conditions. Mean $\Delta \theta / \Delta z$ was 0.026 $^\circ$C m$^{-1}$ for the direct wake, 0.022 $^\circ$C m$^{-1}$ in the wind farm wake and 0.048 $^\circ$C m$^{-1}$ in unwaked wind directions. Hub-height temperatures varied little with wind direction, thus the change in nighttime vertical potential temperature gradients was due almost solely to an increase in 2.5 m temperature, which was +1.6 $^\circ$C greater in the direct-waked case than in the unwaked case, and +1.9 $^\circ$C greater in the farm-waked case than in the unwaked cases. The increases in air temperature are consistent with case studies presented in Rajewski et al (2013) who reported warming at 9 m height of 0–1.5 $^\circ$C in direct wakes during the nighttime, and the analysis of MODIS data in Zhou et al (2012), who reported winter nighttime warming due to wind farms of ~0.45 $^\circ$C.

Our observations suggest that wind speed deficits and increases in turbulence intensity created by very large onshore wind farms co-located with agricultural crops during the spring recovery rapidly, likely within 2 km of the downstream edge and have little impact on the potential temperature structure from the surface to hub height or by association surface sensible heat fluxes (for a 80 m hub height) during the day. However, operating wind turbines may reduce nighttime vertical potential temperature gradient within and downstream (<2 km) of large wind farms potentially altering near-surface scalar fluxes and reducing risk from early season freezing events. Thus, in this study the influence of the downstream influence of the wind farm on atmospheric properties and profiles was relatively modest, but further investigations during other seasons are warranted.

Acknowledgments

This research was supported in part by the National Science Foundation (grant no. 1067007), by the Department of Energy under Award Number #DE-EE0005379, and by the Nell J Redfield Foundation.

Disclaimer: ‘This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof’. This manuscript was greatly improved by the constructive comments of three reviewers who are gratefully acknowledged.

References

Baidya Roy S 2011 Simulating impacts of wind farms on local hydrometeorology J. Wind Eng. Ind. Aerodyn. 99 491–8

Barthelmie R J, Frandsen S T, Nielsen M, Pryor S, Rethore P E and Jørgensen H 2007 Modelling and measurements of power losses and turbulence intensity in wind turbine wakes at Middelgrunden offshore wind farm Wind Energy 10 517–28

Barthelmie R J, Hansen K S and Pryor S C 2012 Meteorological controls on wind turbine wakes Proc. IEEE 99 1–10

Barthelmie R J et al 2009 Modelling and measuring flow and wind turbine wakes in large wind farms offshore Wind Energy 12 431–44

Barthelmie R J, Pryor S C, Frandsen S T, Hansen K S, Schepers J G, Rados K, Schlez W, Neubert A, Jensen L E and Neckelmann S 2010 Quantifying the impact of wind turbine wakes on power output at offshore wind farms J. Atmos. Ocean. Technol. 27 1302–17

Calaf M, Parlange M and Meneveau C 2011 Large eddy simulation study of scalar transport in fully developed wind-turbine array boundary layers Phys. Fluids 23 126603

Chamorro L P and Porté-Agel F 2010 Effects of thermal stability and incoming boundary-layer flow characteristics on wind-turbine wakes: a wind-tunnel study Bound.-Layer Meteorol. 136 515–33

Crawford T T 1965 Frost protection with wind machines and heaters Meteorol. Monogr. 6 81–7

Elliot D, Schwartz M and Scott G 2008 Wind shear and resources at elevated heights: Indiana and Iowa case studies Presented at WINDPOWER 2008 (Houston, TX)

Iungo G V, Wu Y and Porté-Agel F 2013 Field measurements of wind turbine wakes with lidars J. Atmos. Ocean. Technol. 30 274–87

Katic I, Hojstrup J and Jensen N O 1986 A simple model for cluster efficiency Proc. EWE’86 (Rome) vol 1, pp 407–10

La H and Porté-Agel F 2013 Large-eddy simulation of a very large wind farm in a stable atmospheric boundary layer Phys. Fluids 23 065101

Magnusson M and Smedman A S 1994 Influence of atmospheric stability on wind turbine wakes Wind Energy 18 139–52

Mann J, Peña A, Bingöl F, Wagner R and Courtney M S 2010 Lidar scanning of momentum flux in and above the atmospheric surface layer. J. Atmos. Ocean. Technol. 27 959–76

Peña A, Hasager C B, Grying S, Courtney M, Antoniou I and Mikkelsen T 2009 Offshore wind profiling using light detection and ranging instruments Wind Energy 12 105–24

Politis E S, Prospathopoulos J, Cabezón D, Hansen K S, Chaviaropoulos P K and Barthelmie R J 2012 Modeling wake
effects in large wind farms in complex terrain: the problem, the methods and the issues *Wind Energy* **15** 161–82

Rajewski D *et al* 2013 Crop Wind Energy Experiment (CWEX): observations of surface-layer, boundary-layer, and mesoscale interactions with a wind farm *Bull. Am. Meteorol. Soc.* **94** 655–72

Sathe A, Mann J, Gottschall J and Courtney M S 2011 Can wind lidars measure turbulence? *J. Atmos. Ocean. Technol.* **28** 853–68

Schepers J G, Obdam T S and Prospathopoulos J 2012 Analysis of wake measurements from the ECN Wind Turbine Test Site Wieringermeer, EWTW *Wind Energy* **15** 575–91

Wharton S and Lundquist J K 2012 Assessing atmospheric stability and its impacts on rotor-disk wind characteristics at an onshore wind farm *Wind Energy* **15** 525–46

Yahaya S and Frangi J P 2004 Cup anemometer response to the wind turbulence—measurement of the horizontal wind variance *Ann. Geophys.* **22** 3363–74

Zhang W, Markfort C D and Porté-Agel F 2013 Wind-turbine wakes in a convective boundary layer: a wind-tunnel study *Bound.-Layer Meteorol.* **146** 161–79

Zhou L, Tian Y, Roy S B, Thorncroft C, Bosart L F and Hu Y 2012 Impacts of wind farms on land surface temperature *Nature Clim. Change* **2** 539–43