Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 40 (2013) 530 – 536

Energy Procedia

European Geosciences Union General Assembly 2013, EGU

Division Energy, Resources & the Environment, ERE

Spatiotemporal structure of wind farm-atmospheric boundary layer interactions

Matthew Charles Cervarich[a], Somnath Baidya Roy[a,]*,Liming Zhou[b]

[a]University of Illinois, 105 S. Gregory St, Urbana IL 61801 USA
[b]University at Albany, State University of New York, 1400 Washington Avenue, Albany, NY 12222 USA

Abstract

Observations and modelling studies show that wind farms can alter their local microclimate. This study examines the effect of real-world wind farms on land surface temperatures in West Central Texas using the Weather Research and Forecasting model under realistic boundary conditions. Three wind turbine parameterizations, including two developed in this study, are used for model sensitivity experiments. The simulated effects of wind farms on temperatures match the spatial patterns observed in satellite data but are weaker in magnitude. The magnitudes of the temperature changes depend on the power coefficients used in the parameterizations.

Keywords: Wind energy; wind energy impact; wind turbine parameterization; mesoscale model

1. Introduction

Wind energy is one of the most rapidly growing energy resources in the world. Wind farms extract kinetic energy (KE) from the atmosphere and create turbulent kinetic energy (TKE) in their wakes. These processes affect the transport of mass, momentum and energy within the lower atmospheric boundary layer (ABL) and modify land-atmosphere interactions. As wind farms continue to increase in areal coverage, atmospheric and environmental impacts are expected to increase. Observational studies have shown that wind farms influence downwind temperatures [1], momentum deficits in the wake [2], and

* Corresponding author. Tel.: +1-217-244-1123; fax: +1-217-244-4393.
E-mail address: sbroy@atmos.uiuc.edu.

doi:10.1016/j.egypro.2013.08.061

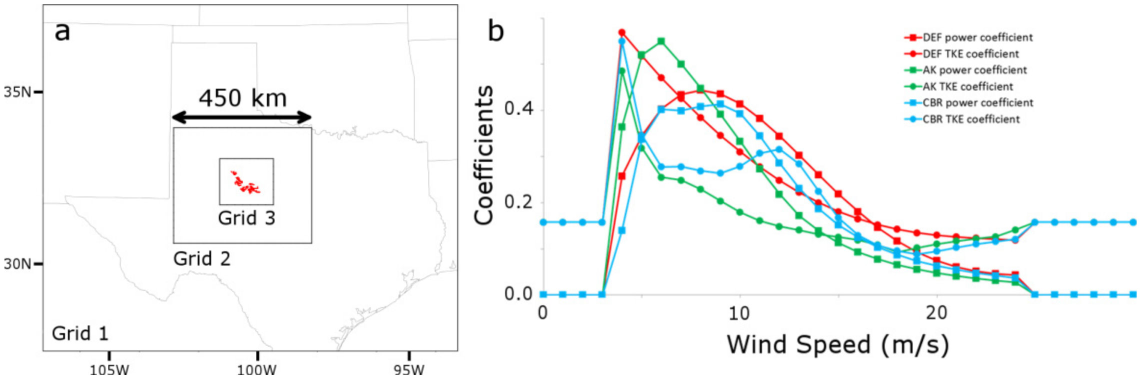


Figure 1: (a) WRF simulation domain showing the 3 nested grids. Red asterisks mark the locations of the wind turbines. (b) Power and TKE coefficients of the 3 different wind turbine parameterizations.

land surface temperatures [3]. These impacts have been simulated using atmospheric models at global [4, 5], regional [6, 7, 8, 9] and local scales [1, 10, 11].

Zhou et al. [3] used satellite data to investigate changes in regional land surface temperature (LST) near a grouping of large wind farms in West Central Texas which consists of 2358 wind turbines in total. They compared Moderate-resolution Imaging Spectroradiometer (MODIS)-derived LSTs between two periods (before and after most of the wind turbines were installed) and between wind farm pixels and nearby-non-wind farm pixels. They observed a warming of 0.724°C per decade in summer (June – July – August, JJA) at night but no significant trends during the day for the period of 2003-2011. They conclude that the difference in signal between night and day is a function of the stratification in the lower ABL and the diurnal variation of wind speed. During the night, the ABL is generally stable with warmer air residing over cooler air. Increased vertical mixing due to turbulence in the turbine wakes causes warmer air aloft to be mixed down to the surface. This increases downward heat flux from the atmosphere into the land surface causing land surface temperatures to increase. During the daytime, convection associated with strong surface heating generates a neutrally stratified ABL. Additional turbulent mixing in such a well-mixed layer does not significantly alter vertical temperature transport.

The goal of this study is to evaluate if numerical models can simulate the wind farm-induced temperature signal observed by Zhou et al. [3]. For this purpose, numerical experiments are conducted with the Advanced Research version of the Weather Research and Forecasting model (WRF) [12], a state-of-the-art regional climate model. Two new wind turbine parameterizations are developed and implemented in WRF to compare with the default scheme available in the model. This study is the first to explore seasonal-scale changes in LST due to real-world wind farms under realistic boundary conditions. It will improve our understanding of wind farm-ABL interactions and advance our capability to simulate these interactions using regional atmospheric models.

2. Atmospheric model

2.1 Model Description and Configuration

WRF is used to simulate the 2010 summer over a group of large wind farms in West Central Texas. The simulations are initialized at 0000 UTC 01 June 2010 and run for 92 days until 0000 UTC September 01 2010 (Figure 1a). The simulation domain consists of 3 nested grids centred at -100.375° longitude, 32.50° latitude. Grid 1 consists of 55x46 grid points with horizontal grid spacing of 25 km; Grid 2 has 91x76 grid points spaced 5 km apart; and Grid 3 is 151x126 grid points with 1km spacing. A stretched vertical grid consisting of 29 levels is employed with higher resolution at lower levels and lower resolution at higher levels. The grid contains 4 levels in the lowest 300 meters and 7 levels in the lowest 1000 meters to adequately represent vertical transport in the wind turbine layer. There are 4 soil levels stretched in the vertical with higher resolution near the surface and lower resolution at deeper levels. A Runge-Kutta 3rd order integration scheme is used with time steps 80s, 20s, and 5s, respectively, for grids 1, 2 and 3. Two-way nesting is employed allowing solutions from the finer grids to feed into the coarser grids. Meteorological data from the North American Regional Reanalysis (NARR) data set is used to initialize as well as provide lateral atmospheric boundary conditions during the simulation period.

The MYNN 1.5 order scheme is used for the planetary boundary layer and the surface layer as they have been shown to have success in modelling wind turbine turbulence in previous studies [11]. NOAH Land Surface Model is used to simulate subsurface soil moisture and temperatures. Precipitation is resolved in the Grid 3 but parameterized using the Kain-Fritsch cumulus scheme in grids 1 and 2. The WRF Single-Moment 3-class scheme is used to parameterize microphysics. The Rapid Radiative Transfer Model and Dudhia scheme are used to model longwave and shortwave radiation, respectively.

2.2 Wind Farm Parameterization

Three turbine parameterizations are used to explore the impacts of turbines on land surface temperatures. In each case, a wind turbine is assumed to be a sink of KE and a source of TKE in the ABL. The drag caused by a wind turbine is given by:

$$F_{drag} = \frac{1}{2} C_T \rho V^2 A \tag{1}$$

where, V is the horizontal velocity, C_T is the turbine thrust coefficient, ρ is the air density, and A is the cross sectional rotor area. The rate of loss of KE from the atmosphere due to this turbine drag is given by:

$$\frac{\partial KE_{drag}}{\partial t} = -\frac{1}{2} C_T \rho V^3 A \tag{2}$$

A part of the KE extracted is converted into electric power P according to the following equation:

$$\frac{\partial P}{\partial t} = \frac{1}{2} C_p \rho V^3 A \tag{3}$$

where C_p is the power coefficient. The rest of the extracted KE is converted into TKE as follows:

$$\frac{\partial TKE}{\partial t} = \frac{1}{2} C_{TKE} \rho V^3 A \tag{4}$$

where C_{TKE} is the TKE coefficient. It should be noted $C_P + C_{TKE} = C_T$.

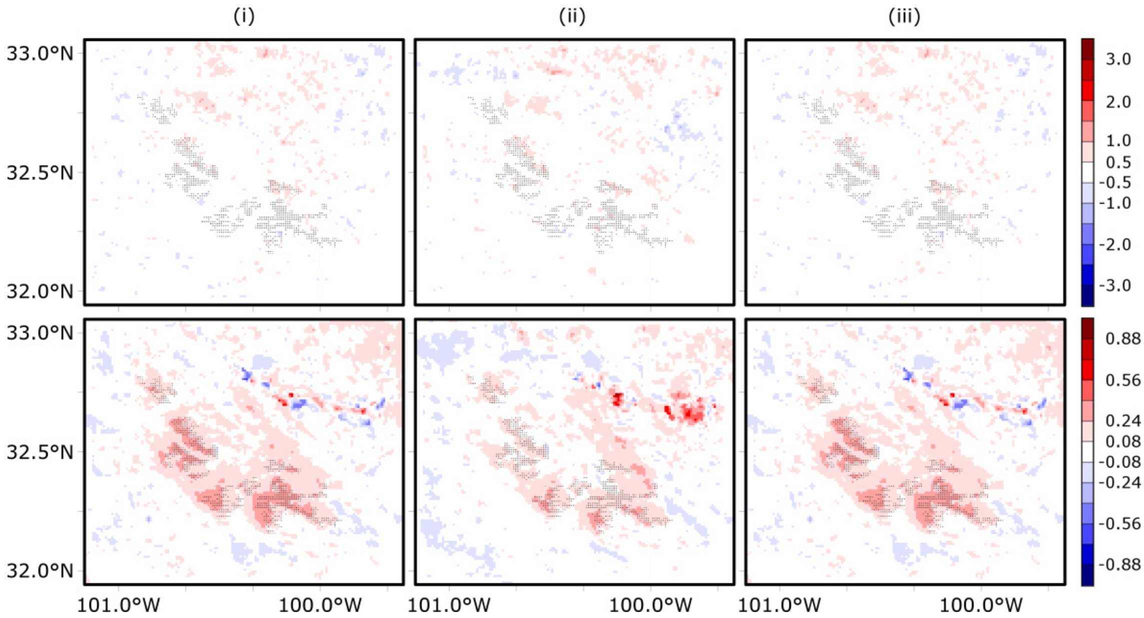


Figure 2: Simulated impacts of wind farms on LST (ΔT K) during the day (top) and night (bottom) with the (i) DEF, (ii) AK and (iii) CBR parameterizations in the finest grid. Black dots mark the locations of the wind turbines.

Even though mathematically similar, the 3 parameterizations significantly differ in terms of power and thrust coefficients (Figure 1b) because they represent different turbines from different manufacturers. The first parameterization (DEF) is the default parameterization in WRF [11]. The second parameterization (AK) is implemented in WRF for this study. The coefficients in this parameterization are estimated using a 6^{th}-order polynomial fit to the data presented by Adams and Keith [13]. The third is the Cervarich and Baidya Roy parameterization (CBR) developed for this study where the coefficients are obtained by a rational fraction approximation of the data in Baidya Roy [10] and Nivedh [14]. For uniformity, all wind turbines are assumed to have a 100 m hub-height, 100 m rotor diameter, 0.158 standing thrust coefficient, 3 m/s cut-in speed and 25 m/s cut-out speed. If there is more than one turbine per grid cell then the changes in KE, power, and TKE are multiplied by the number of turbines in the cell and integrated over the cell. The turbine blades are assumed to be oriented perpendicular to the wind as this is how most large turbines operate. Sensitivity of the LST simulations to the parameterizations is tested by comparing with the CONTROL simulation where the wind turbine parameterization is switched off.

Wind turbine locations are obtained from FAA Obstruction Evaluation/Airport Analysis dataset. The location of the finest domain is determined so turbines are located at least 25km from the domain edge to ensure that numerical boundary feedback issues do not create artificial signals.

3. Results

Figure 2 shows the simulated impact of wind farms on JJA average LST using the 3 different wind turbine parameterizations. In each case, the simulated LST in the CONTROL run is subtracted from the LST in the experimental runs. Daytime signals are the average of simulated LST at10:30 and 13:30 local time while LST at 1:30 and 22:30 local time are used for the nocturnal average. These times correspond roughly to observation times of MODIS Terra and Aqua satellites Figure 3 shows the MODIS JJA LST

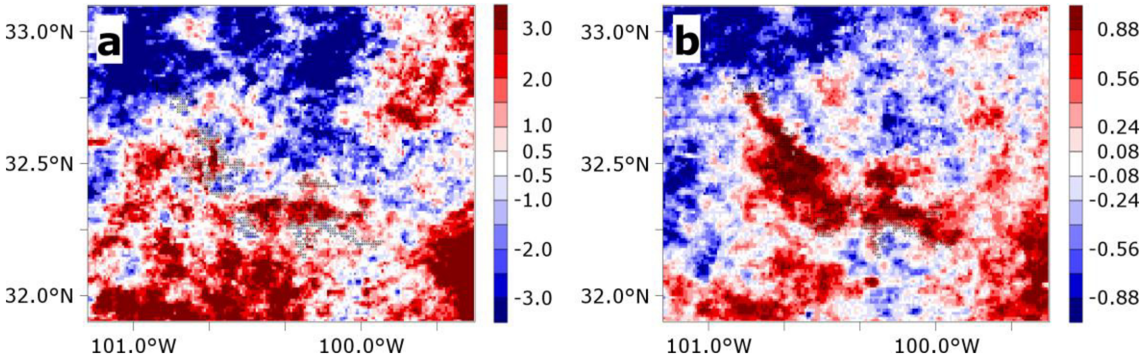


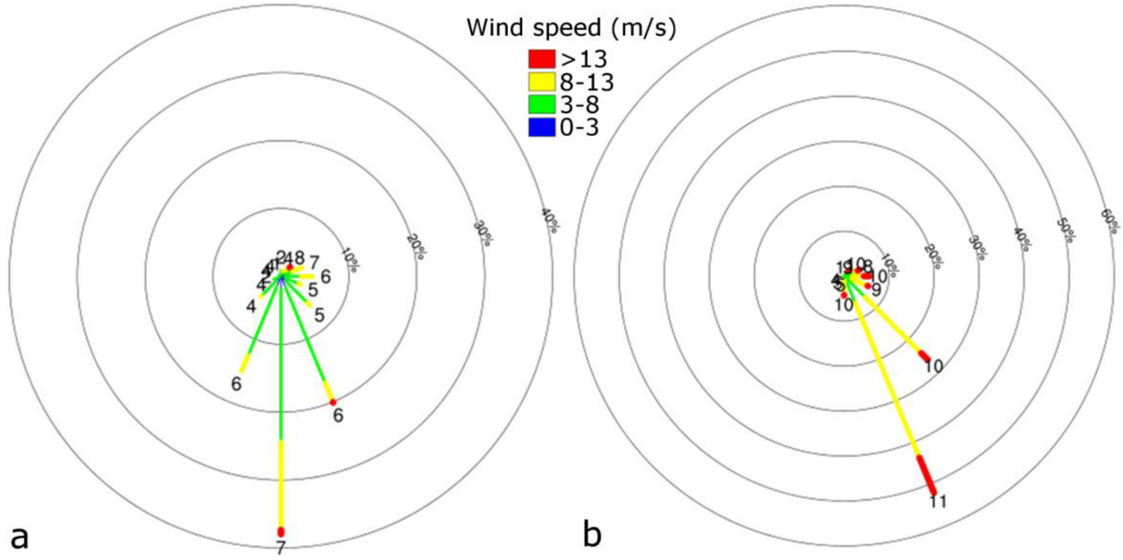
Figure 3: Observed impacts of wind farms on MODIS LST (K) during (a) day and (b) night. Black dots mark the locations of the wind turbines.

differences between 2010 and 2003. The 2003 data is analogous to the CONTROL case because very few wind turbines were operational then [3]. Hence, Figure 3 can be considered to be a qualitative representation of the impact of wind farms on LST.

The observed and simulated signals show a remarkable similarity in terms of the spatial pattern of nocturnal warming within and downwind of wind farms at night but a mixed signal during the day. However, the temperature differences are much stronger in the observations than the simulations. It is important to note that figures 2 and 3 cannot be quantitatively compared for at least three reasons. First, the observed signal in Figure 3 is influenced by the difference in the large-scale meteorological conditions between 2003 and 2010 summers although a simple regional mean LST for each year is removed from MODIS LST at pixel level to reduce the impact of this interannual LST difference. In contrast, the numerical experiments in Figure 2 all use the same meteorological boundary conditions from summer 2010. Second, the MODIS LSTs are retrieved from clear-sky conditions while the model simulations include all-sky conditions. Third, the simulated turbines are assumed to be identical and always working at full capacity. In reality, the makes and models of the turbines are different and they are often turned off to mitigate issues associated with turbine loading, maintenance or export to the grid.

Stronger and more consistent warming signals are seen during the night because of the stronger and more consistent nocturnal winds shown in the wind roses (Figure 4). As discussed earlier, the nocturnal warming in LST is due to downward heat transport by wake turbulence. According to Equation 4, higher winds induce greater increases of TKE making the wakes more turbulent. Consequently, higher winds lead to stronger impacts on LST.

The nocturnal impact of the AK parameterization is less than that of the DEF and CBR parameterizations. The AK parameterization yielded a mean 0.127 K warming while DEF and CBR yielded a mean increase of 0.161K and 0.160K, respectively. Spatially, the warming in the AK parameterization is limited to the immediate wind farm area. The DEF and CBR parameterizations cause warming in and downwind of the wind farms. The AK parameterization had a lesser TKE coefficient and greater power coefficient than the other two parameterizations in the 4-17 m/s hub-height wind speed range (winds were within this range over 80% of the time). Decreased mixing coupled with greater momentum removal in the AK parameterization limited turbulent through the boundary layer in addition to providing less wind resources for downwind turbines further limiting turbulence added to the boundary layer. The greater turbulence experienced in the DEF and CBR wind farms allowed for vertical mixing to occur in more strongly stable regimes which increased the magnitude of the vertical temperature advection.



In contrast to night-time, during the daytime there is low spatial correlation between LST and wind turbines. The DEF and CBR simulations produce an increase of 0.159 K and 0.140 K, respectively while the AK simulation produce a decrease of 0.159 K. LST can be modified by three factors: land surface properties, incoming surface radiation, and boundary layer conditions near the surface; all of which should be explored in further studies. During both night and day, LST are affected away from the wind farms. It is expected that these changes are indirectly caused by changes in cloud cover, precipitation patterns, and net radiative forcing at the surface. A thorough analysis of these processes is the subject of an ongoing study.

4. Summary and discussions

In this study, the Weather Research and Forecasting Model is used to examine how change in wind turbine parameterization affect land surface temperatures. Three different schemes, DEF, AK and CBR, are used to test the sensitivity of the model to different wind turbine parameterizations. Simulations are conducted over central Texas for the 2010 summer where many of the world's largest wind farms are located. The results confirm the findings of Zhou et al. [3] that wind turbines in central Texas can affect local and regional LST.

Night-time temperatures are seen to increase within and immediately downwind of the wind farms in all cases. In contrast, daytime LST signals are weak and do not show any clear correspondence between the LST patterns and turbine locations. This phenomenon is consistent with the hypothesis that turbulence in wind turbine wakes increase downward transport of heat in the nocturnal stable environment generating a strong warming signal in near-surface air temperatures and LST. Since the daytime neutrally-stratified ABL is well-mixed, additional wake turbulence does not significantly affect temperature and heat transport profiles. The AK simulation yield much weaker warming than the other two cases. The AK parameterization produces less turbulent kinetic energy within the range of wind speeds most common at hub height (4-17 ms^{-1}). Less TKE causes less mixing which leads to less vertical advection through the stably stratified night-time boundary layer.

The simulated LST changes are much smaller than MODIS data in magnitude. One possible cause is that WRF may be underestimating surface air temperatures and/or NOAH could be underestimating LST. This can occur due to many reasons including a cool bias in NARR data. Errors in estimating the lapse rate due to the coarse vertical resolution of WRF can be a contributing factor. It is also likely that WRF is underestimating the hub-height wind speeds because the WRF outputs are Reynolds' averaged over the entire 1 sq. km grid cell. Most importantly, there could be deficiencies in the wind turbine parameterizations, especially in the characterization of the turbulence in turbine wakes. Further analysis is required to identify the cause of the differences in the observed and simulated signals.

Ultimately, this study shows that wind farms alter their local microclimate. More and more wind farms are being constructed on agricultural land that is sensitive to changes in the microclimate. Accurate and realistic understanding of how wind farms and surrounding areas are altered is critical for determining the impact wind turbines have on the natural and human environment. This study will advance our ability to quantitatively estimate the impacts and thus play an important role in developing wind farm siting strategies.

Acknowledgements

This research was funded by the US National Science Foundation (NSF AGS-1247137).

References

[1] Baidya Roy S, Traiteur J. Impacts of wind farms on surface air temperatures. *PNAS* 2010; **107**:17899-1704.

[2] Hirth B, Schroeder J, Gunter W, Guynes J. Measuring a utility-scale turbine wake using the TTUKa mobile research radars. *J. of Atmopheric and Oceanic Technology* 2012; **29:**765-771.

[3] Zhou L, Tian Y, Baidya Roy S, Thorncroft C, Bosart L, Hu Y. Impacts of wind farms on land surface temperature. *Nature Climate Change* 2012;**2**:539-543

[4] Wang C, Prinn RG. Potential climatic impacts and reliablility of very-large scale wind farms. *Atmos. Chem. Phys* 2010;**10**:2053-2061.

[5] Keith D, DeCarolis J, Denkenberger D, Lenschow D, Malyshev S, Pacala S, Rasch P. The influence of large-scale wind power on global climate. *PNAS* 2004;**101:**16115-16120.

[6] Kirk-Davidoff D, Keith D. On the climate of surface roughness anomalies. *JAS.* 2008;**65**:2215-2234.

[7] Barrie D, Kirk-Davidoff D. Weather response to a large wind turbine array. *Atmos. Chem. Phys.* 2010; **10**:769-775

[8] Fiedler B, Bukovsky M. The effect of a giant wind farm on precipitation in a regional climate model. *Enviro. Res. Lett.* 2011;**6**:1-7

[9] Baidya Roy S, Pacala S, Walko R. Can large wind farms affect local meteorology?. *JGR*. 2004;**109**:1-6.

[10] Baidya Roy S, Simulating impacts of wind farms on local hydrometeorology. *J. Wind Eng. Ind. Aerodyn.*2011;**99**:491-498

[11] Fitch A, Olson J, Lundquist J, Dudhia J, Gupta A, Michalakes J, Barstad I. Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. *MWR* 2012;**148**:3017-3038

[12] NCAR Technical Note: Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda M, Huang X-Y, Wang W, Powers JG. A description of the Advanced Research WRF Version 3.Boulder: National Center for Atmospheric Research; 2008. *NCAR/TN–475+STR* 2008

[13] Adams A, Keith D. Are global wind power resources estimates overstated?. *Eniron. Res. Lett.*2013;**8**:015021

[14] Nivedh BS. Repowering wind farms. Chennai India, Anna Univ, ME Thesis, 2011.