A NUMERICAL STUDY OF SURFACE AIR TEMPERATURE RESPONSE TO VERTICAL MIXING AND MOMENTUM EXTRACTION BY WIND FARMS AND THE IMPACTS OF WIND FARMS ON MESOSCALE BOUNDARIES

BY

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THESIS

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ABSTRACT

Wind turbines have been shown to impact their local microclimate. With the increasing areal coverage of wind farms it has become increasingly important to answer scientific questions regarding these impacts. In this thesis, a high resolution numerical model is employed to explore the response of land surface and near surface air temperatures within and in the immediate vicinity of large wind farms in west central Texas to changes in the turbines’ thrust and TKE coefficients during meteorological summers. A control run with no wind turbines is compared to three experimental tests, each with differing thrust and TKE coefficients. The experimental tests are first compared to observed data from the Moderate Resolution Imaging Spectroradiometer (MODIS) data on the Terra and Aqua Satellites. It is shown that the observed impact of wind farms is greater than the numerically modeled impact. Second, the control run is compared to the experimental tests. The non-linear interaction of hub height wind speeds, thrust coefficients, and TKE coefficients along with the wind turbine layer static stability determine the temperature change impact. During night, statically stable conditions result in strong warming signals while during the day near-neutral conditions result in insignificant impacts. The magnitude of the signal is determined by non-linear interactions between the wind turbines’ thrust coefficient and the vertical wind speed.

The high resolution numerical model is also used to analyze the propagation of mesoscale boundaries near and through the wind farm. When compared to the control run, the experimental simulation shows an acceleration of the propagation of the mesoscale boundaries when the boundaries approached the wind farms and a deceleration as the boundaries propagated away from the wind farms. Due to the reduction of winds by the wind farms, boundaries propagating away from the wind farms experience less winds behind the boundaries and propagation speeds
are reduced. Boundaries propagating towards wind farms experience less winds ahead of the
wind farms and propagation speeds increase.
TABLE OF CONTENTS

CHAPTER 1: INTRODUCTION ........................................................................... 1
CHAPTER 2: ATMOSPHERIC MODEL ................................................................. 6
CHAPTER 3: SURFACE AND NEAR SURFACE TEMPERATURE RESULTS ....... 12
CHAPTER 4: MESOSCALE BOUNDARY RESPONSE ......................................... 20
CHAPTER 5: CONCLUSIONS AND DISCUSSION ........................................... 26
LITERATURE CITED ................................................................................... 30
TABLES AND FIGURES ............................................................................. 33
1.1 Literature Review of wind farm impacts on near surface meteorology

Wind energy is widely acknowledged to be a key strategy to combat climate change, air pollution, energy security and other problems causing wind power to experience remarkable growth in the recent years worldwide. It is currently the fastest growing energy resource in the US (American Wind Energy Association, 2012). Much of the growth is in the utility sector consisting of large industrial-scale wind farms that are often sited over farmlands, especially in the Midwest and the Great Plains. Agricultural activity in these farms may be sensitive to microclimate changes due to wind turbine operations (Armstrong et al., 2013). These changes likely result from the interactions between wind turbines and the atmospheric boundary layer (ABL), the lowest layer of the atmosphere in contact with and directly influenced by the earth surface. Hence, understanding the dynamics and thermodynamics of wind turbine-ABL interactions and quantifying the effects of wind farms on surface/near-surface hydrometeorology is a growing area of research.

Baidya Roy and Traiteur (2010) used in situ observations from a wind farm in California to explore the relationship between ABL stability and change in near-surface air temperature. They concluded that turbulence in the wake of the rotors increase vertical mixing of air between the turbine hub height and the surface. In a stably stratified environment where the vertical potential temperature gradient is positive, there is a net downward transport of warmer air causing an increase in surface temperature of up to 2°C. In an unstable atmosphere with negative
vertical potential temperature gradient, a net downward transport of cooler air causes a surface cooling of up to 0.4°C.

Zhou et al. (2012) used Moderate Resolution Imaging Spectroradiometer (MODIS) data from the NASA Terra and Aqua satellites to study the land surface temperatures (LST) in wind farms in central Texas. They observed a summer (June-July-August, JJA) warming of 0.724°C per decade at night, but no significant trends during daytime. Zhou et al.’s (2012) results are qualitatively similar to Baidya Roy et al (2010) but cannot be quantitatively compared because, amongst other reasons, the former is a study of LST while the latter is a study of air temperature near the surface.

Rajewski et al. (2013) measured air temperature, stability, surface fluxes and other variables in an Iowa wind farm as a part of the Crop/Wind-Energy Experiment (CWEX) campaign, the first comprehensive meteorological field campaign in a wind farm. They found a small cooling (< 0.75°C) in 9 meter air temperatures downwind of wind turbines during the day and a strong warming (up to 1.5°C) at night. In spite of the high variability, they concluded that their observations were consistent with that of Baidya Roy and Traiteur (2010).

Smith et al. (2013) conducted a field campaign in a large wind farm in the Midwestern U.S during the spring of 2012. They do not report any strong signal at hub heights. However, their results show a strong surface warming of 1.6 °C warming in the wake of a single turbine and a 1.9 °C warming in the wake of the wind farm at night. They did not find any significant warming or cooling signal during the day.

Due to limited availability of field data, numerical models have been extensively used to study the effects of hypothetical wind farms on hydrometeorology at a wide range of spatial and temporal scales. Baidya Roy et al. (2004) first explored this question for a wind farm in
Oklahoma using a mesoscale model. They developed a parameterization that approximates a wind turbine as a sink of momentum and source of turbulent kinetic energy (TKE). Subsequent studies (Baidya Roy, 2011; Fitch et al., 2012; Adams and Keith, 2013; Cervarich et al., 2013) have used a fundamentally similar approach but with increasing degree of sophistication to study wind farms of different sizes in the US. In general, these studies found a mean warming signal up to 1°C averaged over days-months within the wind farms. Typically the warming occurred during the night and early mornings when the environment is stably stratified. Occasionally, a small cooling signal was also observed during the day in a statically unstable environment.

Global climate models have also been used to study extremely large futuristic wind farms (Wang and Prinn, 2010; Keith et al, 2004; Kirk-Davidoff and Keith, 2008). These studies found a warming of 1-2°C averaged over decades. The climate models simulated wind farms by altering the roughness length, $z_0$, to recreate the momentum sink observed in wind farms. Although computationally efficient, this method may not accurately recreate turbulence in the turbine wakes, consequently exaggerating the effects of wind farms on surface sensible heat fluxes and surface air temperatures (Fitch et al., 2013).

The goal of this study is to estimate the impacts of a collection of large wind farms located in west-central Texas on land surface and near-surface air temperatures. This area is particularly rich in wind resources. Four of the world’s 10 wind largest wind farms are located here. This study is an extension of a preliminary study (Cervarich et al., 2013) that was the first to simulate real-world wind farms under realistic boundary conditions in contrast with previous works that all used hypothetical wind farms. The Advanced Research Weather Research and Forecasting Model (WRF) (Skamarock et al., 2008) is used to simulate the regional climate for the meteorological summers of 2010, 2011, and 2012. The effects of wind farms are simulated
using 3 different wind turbine parameterizations. Two of the parameterizations are based on typical commercial wind turbine data while a third is the default parameterization available in WRF. The parameterizations are evaluated by comparing simulated LST from WRF with MODIS LST data.

1.2 Literature Review of wind farm impacts on mesoscale boundaries

Transient synoptic-mesoscale boundaries, such as fronts and dry lines, provide a significant amount of precipitation to the agriculture land where wind farms are often located. The propagation of fronts is best correlated with the wind component normal to the front in the cold air (Bluestein, 1992). The magnitude of the component is in part determined by the strength of the ageostrophic circulation along the boundary (Murkowski and Richardson, 2010).

Idealized numerical modeling studies have shown momentum deficits of 1 ms\(^{-1}\) are present at least 50 km downstream from wind farms (Fitch et al., 2012; Fitch et al., 2013). However, to the best of my knowledge, there have been no assessments of the role the momentum deficit would play in the components that determine the propagation of fronts. An interference of the ageostrophic circulation near the front via the reduction of momentum indicates that it is possible for wind farms to influence the local propagation of frontal boundaries.

Surface and boundary layer impacts on frontal propagations have been investigated with regards to changes in land surface characteristics (Gallus and Segal, 1999). A pronounced frontal acceleration was simulated over Lake Michigan. The authors concluded the reduction in turbulence over the lake resulted in increased wind speeds and convergence which increased the temperature gradient along the front. This led to an increase of frontal propagation speed from 6 ms\(^{-1}\) to 12 ms\(^{-1}\).
The propagation of synoptic-mesoscale boundaries will be qualitatively assessed using WRF over the wind farms described above. Four boundaries are analyzed using the default parameterization in WRF.

This paper is structured as follows: Chapter 2 comprises of the WRF configuration and physical parameterizations with a focus on the three wind turbine modifications used to test the sensitivity of the wind turbine parameterization. Chapter 3 compares the results of each modeled wind farm to the control run. Chapter 4 qualitatively assesses the propagation speed of synoptic-mesoscale boundaries in a control run and wind turbine run. Chapter 5 presents a summaries and conclusions of the two studies.
2.1 Model Description and Configuration

WRF is employed to simulate the 2010-2012 meteorological summers (June, July, and August) over a group of large wind farms consisting of 2359 wind turbines in central Texas (Figure 1). The simulations are performed with 3 nested grids centered on -100.375° longitude, 32.50° latitude. Grid 1, the coarsest grid, consists of 55x46 grid points with horizontal grid spacing of 25 km. The two nested grids have resolutions of 5 km and 1 km, respectively and consist of 91x76 grid points and 151x126 grid points, respectively. The 3 grids communicate via an interactive two-way nesting scheme. A stretched vertical grid consisting of 29 levels is employed with finer resolution at lower levels and coarser resolution at higher levels. The grid contains 7 levels in the lowest 1000 meters and 4 levels in the lowest 300 meters. This high spatial resolution is required to adequately represent vertical transport in the wind turbine layer. The soil model is 2 m deep with 4 levels stretched in the vertical with higher resolution near the surface and lower resolution at deeper levels. The simulations are initialized at 0000 UTC 01 June and run for 92 days until 0000 UTC September 01. A Runge-Kutta 3rd order scheme is used to integrate the equations with time steps 80s, 20s, and 5s for grids 1, 2 and 3, respectively. Model specifications are summarized in Table 1.

WRF solves for a complete set of discretized Eulerian partial differential equations that describe the spatiotemporal evolution of atmospheric dynamic and thermodynamic variables including 3 velocity components, perturbation potential temperature, perturbation geopotential, and perturbation surface pressure of dry air. The system is closed with the MYNN 1.5 order
scheme as it has been shown to have success in modeling wind turbine turbulence in previous studies (Fitch et al., 2012). In this scheme, TKE is prognosed but all other second-order moments are parameterized. Cumulus convection is resolved in Grid 3 but in the other grids it is parameterized using the Kain-Fritsch scheme that uses a mass flux approach with downdrafts and CAPE removal time scale. Microphysical processes are represented by the WRF Single-Moment 3-class simple ice scheme which is a simple efficient scheme with ice and snow processes appropriate for mesoscale simulations. Shortwave radiative transfer is parameterized with the Dudhia scheme that involves a simple downward integration allowing for efficient cloud and clear-sky absorption and scattering. Longwave radiation is parameterized with the RRTM scheme that uses look-up tables accounting for multiple bands, trace gases, and microphysics species. Model physics parameterizations are summarized Table 2.

The model is initialized using meteorological data from the North American Regional Reanalysis (NARR, www.emc.ncep.noaa.gov/mmb/rreanl/). The same data set is used to provide lateral atmospheric boundary conditions during the simulation period by nudging the boundaries of the coarsest grid towards the observations every 6 hours. The topography, soil characteristics and MODIS-based land cover data are obtained from WRF standard datasets. The bottom boundary conditions in terms of surface fluxes of heat moisture and momentum are simulated using the NOAH Land Surface module that calculates soil moisture and temperature profiles.

2.2 Wind Farm Parameterization

Three turbine parameterizations are used to explore the impacts of turbines on surface/near-surface air temperatures while only the default parameterization is used to explore the impacts on boundary propagation. In each case, a wind turbine is assumed to be a sink of
kinetic energy (KE) and a source of TKE in the ABL. The drag caused by a wind turbine is given by:

\[ F_{\text{drag}} = \frac{1}{2} C_T \rho V^2 A \]

(1)

where, \( V \) is the horizontal velocity, \( C_T \) is the turbine thrust coefficient, \( \rho \) 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:

\[ \frac{\partial KE_{\text{drag}}}{\partial t} = -\frac{1}{2} C_T \rho V^3 A \]

(2)

A part of the KE extracted is converted into electrical energy \( E \) according to the following equation:

\[ \frac{\partial E}{\partial t} = \frac{1}{2} C_p \rho V^3 A \]

(3)

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

\[ \frac{\partial TKE}{\partial t} = \frac{1}{2} C_{TKE} \rho V^3 A \]

(4)

where \( C_{TKE} \) is the TKE coefficient. It should be noted \( C_p + C_{TKE} = C_T \).

The three parameterizations are mathematically similar but differ with regards to their power and thrust coefficients (Figure 2) because they are based on data for turbines developed by different manufactures. The three parameterizations are: (i) The default parameterization (DEF)
scheme in WRF. (ii) A parameterization (AK) that approximates the data presented in Adams and Keith (2013) using the following 6\textsuperscript{th}-order polynomial fit to estimate the thrust and power coefficients:

\[ C_p = 1.4423 \cdot 10^{-8} \cdot |V|^6 - 1.2559 \cdot 10^{-6} \cdot |V|^5 + 2.6912 \cdot 10^{-5} \cdot |V|^4 + 4.8238 \cdot 10^{-4} \cdot |V|^3 - 2.513 \cdot 10^{-2} \cdot |V|^2 + 2.773 \cdot 10^{-1} \cdot |V| - 4.856 \cdot 10^{-1} \]  

(5)

and

\[ C_T = 2.1538 \cdot 10^{-8} \cdot |V|^6 + 1.9344 \cdot 10^{-6} \cdot |V|^5 + 5.0217 \cdot 10^{-5} \cdot |V|^4 - 1.078 \cdot 10^{-4} \cdot |V|^3 - 2.06 \cdot 10^{-2} \cdot |V|^2 + 2.013 \cdot 10^{-1} \cdot |V| + 3.335 \cdot 10^{-1} \]  

(6)

(iii) The Cervarich and Baidya Roy parameterization (CBR) applies the following rational fraction approximation to the data presented in Baidya Roy (2011) and Nivedh (2011):

\[ C_p = ((2.528 \cdot |V|^3 - 44.9 \cdot |V|^2 + 305.3 \cdot |V| - 642.1) / (|V|^3 - 8.583 \cdot |V|^2 + 83.72 \cdot |V| - 947.8)) \cdot ((2 \cdot 10^6) / (|V|^3 \cdot A)) \]  

(7)

and

\[ C_T = (-1.936 \cdot 10^{-2} \cdot |V|^3 + 1.142 \cdot |V|^2 - 21.41 \cdot |V| + 135.4) / (|V|^2 - 26.13 \cdot |V| + 185.3). \]  

(8)

There are significant differences between the power and TKE coefficient curves of the 3 parameterizations. DEF has the highest thrust and TKE coefficients over most of the operational range. The thrust coefficient for CBR is lower than DEF at light wind speeds (3-8 ms\textsuperscript{-1}) but higher for stronger wind speeds. The TKE coefficient of CBR is highest of the 3 parameterizations at moderate and strong wind speeds of 8-15 ms\textsuperscript{-1} but very close to AK otherwise.

For uniformity, all wind turbines are assumed to have a 100 meter hub height, 100 meter rotor diameter, 0.158 standing thrust coefficient, 3 ms\textsuperscript{-1} cut-in speed and 25 ms\textsuperscript{-1} cut-out speed.
Frequently there are multiple turbines in a grid cell. In that case, 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. The response of the LST simulations to the parameterizations is tested by comparing with the control (CTRL) simulation where the wind turbine parameterization is switched off. When applied, each turbine parameterization is applied to all domains.

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.

2.3. MODIS data

The Collection 5 MODIS 8-day average 1-km LST images downloaded from (https://lpdaac.usgs.gov/get_data) are aggregated spatially and temporally into meteorological summer means and anomalies at 0.01° resolution for the period of 2010-2012 as done in Zhou et al. (Zhou et al., 2012). As the direct driving force in determining the exchange of longwave thermal radiation and turbulent heat fluxes at the surface–atmosphere interface, LST is one of the most important variables for studying a wide variety of Earth surface processes and surface-atmosphere interactions in the physical processes of surface energy, radiation budget, and water balance at local through global scales (Li et al., 2013). MODIS is a key scientific satellite instrument launched into Earth orbit by NASA on board the Terra and Aqua platforms. The MODIS LST images consist of four acquisition times (local solar time ~10:30 and ~13:30 at daytime and ~22:30 and ~1:30 at nighttime). The MODIS LST data represent the best quality
retrieval possible from clear-sky conditions over each 8-day period and have been proven to be of high quality in a variety of validation studies (Wan et al., 2006).
Chapter 3
SURFACE AND NEAR SURFACE TEMPERATURE RESULTS

3.1 Model Evaluation

The performance of the WRF model is evaluated by comparing simulated LST with MODIS data (Figure 3). WRF daytime plots are the average of the simulated LST at 10:30 and 13:30 local time while nighttime signals are the average of simulated LST at 1:30 and 22:30. These times correspond to the observation time of MODIS Terra and Aqua satellites for the study region. For brevity, only the comparison between DEF and MODIS 2010-2012 average are shown in Figure 3. Similar patterns are also seen for the individual years and the CBR and AK cases.

Both WRF and MODIS depict similar spatial patterns with slightly warmer regions in the southwestern and northeastern regions of the study domain. The simulated temperatures lack the finer details of the observations due to smoothing by the model. The observed and simulated values are well-correlated with $r^2 = 0.8$ for day and $r^2=0.85$ at night, both significant at $p<0.01$. However, the simulated values show a positive bias during the night and a negative bias during the day compared to the observations. In other words, the diurnal cycle of temperature simulated by WRF has smaller amplitude than MODIS. This is due to a number of reasons. The likely primary cause is that LST is retrieved only in clear sky conditions causing MODIS to sample LST during night with least obstructed radiative cooling and days with least obstructed incoming solar radiation (Wan et al., 2004). Errors due to estimations made in the retrievals, and satellite downtime may have played a role. A damped diurnal cycle may also be due to errors intrinsic in the WRF surface layer and ABL schemes that have been shown to overestimate the mixing in the
ABL (Holtslag et al., 2013). Finally, heterogeneity in turbine attributes and downtime due to breakdown and scheduled maintenance in real-world wind farms also contribute to the difference between simulated and observed LST signals.

3.2 Wind and Static Stability

The impact of wind farms on land surface and near-surface air temperature is a function of the non-linear relationships between the static stability in the wind turbine layer, wind speed at the turbine hub height and power and TKE coefficients at the respective wind speeds. Turbulence generated by a wind turbine is determined by the hub height wind speed and the TKE coefficient at that wind speed. This turbulence enhances vertical mixing that affects the vertical temperature gradient quantified by the static stability parameter within the wind turbine layer. Hub height wind speeds, in turn, are affected by the power coefficients of the upwind turbines that extract kinetic energy from the wind field and reduces wind speeds for downstream wind turbines.

First, the climatologies of wind speed and ABL stability are explored and next the combined effects of these 2 variables on temperatures are analyzed. These climatologies are generated from data at 1:30 and 22:30 local time to be consistent with the Terra and Aqua satellite passes. Large-scale background winds at hub height show significant diurnal variation in speed and direction. Daytime winds for the CTRL are predominantly from the south with an average speed of 6 ms\(^{-1}\). There is little variation year to year; each year experienced greater than 80% of winds from 150° and 210°. Night time winds are predominantly from the southeast with an average speed of 10 ms\(^{-1}\) with little year to year variation; greater than 80% of the winds were between 135° and 150°.
The domain-average wind speeds in the wind farm simulations are similar to the CTRL. However, the wind speeds averaged over the wind farm locations are significantly less than the CTRL, more so during the night than the day. DEF, AK, and CBR runs show a wind speed reduction of 4.1%, 4.9%, and 5.2% respectively, during the day and 14.2%, 15.3%, and 16.7% reduction, respectively, during the night with minimal change in wind direction. These results appear to be counter-intuitive. Even though DEF has the highest thrust coefficient, it generates the weakest impact while the strongest impacts are observed for CBR with the lower thrust coefficient. This is because if the thrust coefficient is high, the turbines at the leading edge of the wind farms extract a portion of KE equal to their thrust coefficient and the wind speeds rapidly fall below the operational range. During this time the wind turbines remain non-operational. If the thrust coefficient is low, the hub height wind speeds stay above the 3 ms\(^{-1}\) cut-off and the turbines continue to operate for a longer time period. Indeed, light winds in the 3-5 ms\(^{-1}\) range are observed only 38.1% of the time for DEF but 40.2% and 43.7% of the time for AK and CBR, respectively. DEF, AK, and CBR are below the cut-off speed 9.1%, 7.3% and 6.0%, respectively. As a consequence, the impacts during light wind speed are greater in CBR and AK than DEF.

The relationship between hub height wind speed and static stability is shown in Figure 4. The static stability parameter \(\sigma\) (K hPa\(^{-1}\)) is calculated from the change of potential temperature with height through the wind turbine layer (Bluestein, 1992):

\[
\sigma = -T \frac{\partial \ln \theta}{\partial p}
\]

where \(T\) is temperature (K), \(\theta\) is potential temperature (K) and \(p\) is pressure (hPa). Static stability is divided into four stability classes: (i) unstable (\(\sigma < -0.005\)), (ii) near-neutral (-0.005<\(\sigma<0.005\)), (iii) stable (0.005<\(\sigma<0.03\)), and (iv) very stable (\(\sigma>0.03\)).
Hub height wind speed is divided into five categories: (i) off (<3 ms\(^{-1}\)); wind turbines are not operational, (ii) light (3-5 ms\(^{-1}\)); DEF has the greatest thrust coefficient and winds can easily drop below the cut-off speed, (iii) at moderate (5-8 ms\(^{-1}\)) winds DEF has the greatest thrust coefficient; AK has a greater thrust coefficient than CBR, (iv) during high (8-15 ms\(^{-1}\)) AK has the lowest thrust coefficient and CBR has a local TKE coefficient maximum, and (v) very high (>15ms\(^{-1}\)) winds DEF has the greatest thrust and TKE coefficients; AK has the least thrust and TKE coefficients. Results show that statically stable cases are the most frequent, especially under moderate and high wind speeds. Very high wind speeds are extremely rare. Unstable environments are quite infrequent as well.

3.3 Surface and near-surface temperature

Earlier studies (Baidya Roy and Traiteur, 2010; Baidya Roy, 2004) have shown that enhanced turbulent mixing due to the turbine rotors changes the vertical temperature profile in the wind turbine layer thereby changing near-surface air temperatures as well. The mixing creates a warming effect under stable environmental conditions, a cooling effect under unstable conditions, but under neutral conditions no significant impact can be expected. In the current study, the effects of wind turbines on hub height temperatures are extremely small. At night, the wind turbines produce a cooling effect in the 0.04 to 0.07°C range that are statistically significant at \(p<0.01\). No significant temperature changes are produced during the day. These results are consistent with the small nocturnal effects at the hub height level observed in Smith et al. (2013) but with a higher magnitude. Hence, the remainder of the analysis focuses on near-surface air temperatures.

Figure 5i illustrates the impacts wind farm parameterizations have on 2 meter temperatures at night. The plots show the difference between the CTRL and the wind farm runs
averaged over JJA 2010-2012. The plot times correspond with the passes of the Terra and Aqua satellite and therefore MODIS observations. All parameterizations induce a nighttime warming (Fig. 5i) within the wind farm. The signals are significant at p<0.001 using the Wilcoxon-Mann-Whitney two sample rank sum test. The wind farms generate a warming signal because the environment is typically stable at night. These results are consistent with the observed warming in the study area (Rajewski et al, 2013). A nighttime warming is also seen to the northeast of the wind farms, especially in the AK and CBR cases. This is likely due to downstream advection because the synoptic-scale winds are predominantly from the southwest.

Mean nighttime impacts averaged over the wind farms are summarized in Table 3. CBR and DEF cause a 0.168°C and 0.165°C increase respectively in 2 meter temperatures at night but AK is less, causing about 0.13°C increase. These differences between different parameterizations are due to the turbulence generated by the turbines. Averaged over all summer, CBR and DEF create more turbulence than AK within the wind farm due to its interaction with moderate and stronger winds. During moderate winds DEF has the greatest TKE coefficient causing it to induce the most mixing at a given wind speed. Counter intuitively, DEF also has the highest thrust coefficient causing the DEF parameterization to extract more momentum from the wind field than the other two parameterizations. TKE production increases exponentially with wind speed so while TKE production in DEF is enhanced by the greater TKE coefficient it is also limited by the greater thrust coefficient. CBR has the lesser thrust coefficient and greater TKE coefficient than AK during moderate winds causing greater warming in the CBR run than the AK run. In the high wind regime, AK has the lowest TKE coefficient resulting in the least turbulence generated. A local maximum of TKE coefficient in the CBR parameterizations leads
to the greatest production of TKE. The strong DEF warming signal during high winds is supported by high TKE coefficient in that wind range.

Surface warming is a function of static stability and TKE which is a function of the TKE coefficient at the given wind speed. Figure 4 summarizes the 2 meter temperature warming within each static stability and wind speed bin. Only changes that are that statistically significant (p < 0.01) are shown. It can be seen that warming increases as static stability increases. In addition, warming is maximized where each parameterization produces the most TKE; for AK that is with very high winds (>15 ms\(^{-1}\)) and for CBR and DEF it is with high winds (8-15 ms\(^{-1}\)). DEF and CBR produce stronger warming than AK during light and moderate winds. The most frequent winds are those that contribute the most to the total warming via TKE produced for DEF and CBR. Likewise, AK produces the greatest TKE and the most warming during the most infrequent wind group. Light to moderate winds are more likely to have stronger static stability because they are associated with clear and calm conditions that allow radiational cooling to set up strong temperature inversions.

Increase in near-surface air temperature affects the flux of sensible heat from the surface to the atmosphere. At night, the atmosphere is warmer than the ground. Hence, this flux is usually negative, indicating a net transport of sensible heat from the atmosphere to the surface (Baidya Roy and Pacala, 2004). Figure 5(ii) illustrates effect of wind farms on the sensible heat flux. Blue (red) colors indicate an increase (decrease) in downward heat flux or a decrease (increase) in upward heat flux. Results show that the near-surface warming increases the downward flux of sensible heat for all 3 parameterizations. This is because near-surface warming increases the atmosphere-land temperature gradient leading to more heat transfer from the atmosphere into the ground. There are small regions with increased downward sensible heat flux
signals in the immediate wake of the turbines. These regions are likely due to decrease in TKE in these regions.

The change in surface heat flux impacts the LST. Since more energy is transferred into the ground, the LST within the wind farms increases (Fig. 6iii). This increase in LST at night is consistent with MODIS observations in this region (Zhou et al, 2012). The magnitude of the simulated changes appears to be smaller than Zhou et al. (2012). It is important to note that the 2 studies cannot be directly compared. This study is a numerical sensitivity experiment where the background synoptic meteorology is identical between the simulations. Zhou et al. (2012) compared “before” and “after” scenarios where the synoptic meteorological conditions are likely different between the scenarios.

Unlike the nocturnal environment, no significant impacts of wind farms are observed on 2 meter temperatures during the day. Figure 6, showing the daytime averaged over the 2010-2012 summers, illustrates this effect. The average 2 meter air temperature change for DEF, AK, and CBR are 0.041°C, -0.006°C, and 0.05°C, respectively. However, none of these differences are statistically significant according to the Wilcoxon-Mann-Whitney two sample rank-sum test; all have p-values greater than .05. Earlier studies have conjectured that the lack of impacts during the day is because the static stability of the wind turbine layer tends to be near-neutral and observational studies have mixed changes during unstable conditions.

Baidya Roy and Traiteur (2010) suggested that surface temperature signals are weaker during the day because the environment is NN and vertical mixing does not change the temperature profile. However, in my simulations, we see that the environment is frequently non-neutral during the day. During unstable conditions, turbine-induced mixing induces a net downward energy transport leading to a cooling signal near the surface. Simultaneously, solar
diabatic heating of near-surface air causes buoyant vertical mixing and a net upward heat transport. These two processes likely offset each other generating a mixed, weak signal on surface temperatures. Table 4 presents the percent occurrences of the different stability conditions during operational wind speeds for the DEF case. During the daytime the wind turbine layer tends to be either unstable or near-neutral (σ<.005 K) with these conditions present 94.1% of the time. Additionally, environmental conditions allowed for the turbines to be operational (> 3 ms⁻¹) and have a stable wind turbine layer (σ > .005 K hPa⁻¹) 4.36% of the time; in contrast, during the nighttime these conditions were met 96.9% of the time. The DEF case is representative of all the parameterized runs as there are no significant differences in static stability or daytime hub height wind speeds.

To further investigate daytime impacts we compared climatological impacts at 10:30 AM and 1:30 PM LST. At the 10:30 AM hour, 2 meter air temperature increases were .06 K, .04 K, and .07 K for DEF, AK, and CBR respectively. The 1:30 PM LST hour yielded changes of .02 K, -.01 K, and .03 K, respectively. The results were compared using a student’s t-test to test for significance. The p-values for 10:30 AM LST were all less than .01 while at 1:30 PM LST all p-values were greater than .05 indicating impacts at 10:30 AM LST had dissipated by early afternoon. The change in morning near surface air temperature is due to the residual nighttime stable boundary layer as shown in Table 4 (10:30 AM). Table 4 shows that by 1:30 PM LST the boundary layer has become well mixed and any turbulence would mix a homogenous temperature profile leading to no change in the near surface air temperature. Wind turbine layer static stability favorable for warming (σ > .005 K/hPa⁻¹) was present 11.51% of the time during the morning and less than .003% of the time during the afternoon.
CHAPTER 4
MESOSCALE BOUNDARY RESPONSE

Consistency amongst mesoscale boundaries simulated in WRF suggests propagation speeds are altered by the extraction of momentum by the wind farms. Boundaries approaching the wind farm region propagate faster when the wind farm is present as the wind turbines extract momentum from the boundary layer and reduce convergence along the front. Boundaries propagating away from the wind farms are slowed as the wind turbine extract momentum from the atmosphere that would otherwise go to advecting the front. Four cases will be presented: two cold fronts an outflow boundary and a shear line.

A front is not defined in the traditional synoptic sense; rather a front is considered a cold front if the air on the cold side of the boundary is advancing during a majority of the event. A boundary is considered a shear line if there is an advancing boundary of distinct wind direction change and an outflow boundary if precipitation cooled air that moves into a region of warmer air.

4.1 Case A: A Cold Front

At 5:00 PM LST on June 14th, 2010 a simulated cold front entered the inner-most domain from the northwest. The cold front exhibited a steep temperature gradient with temperatures gradient of 3°C km\(^{-1}\). Northwest winds in the cold sector propagated the front towards the northeast. Southerly winds in the warm sector provided convergence along the front and inhibited the progress of the front. The CTRL and DEF simulations simulated the front nearly identically during the front’s entrance into the domain. CTRL and DEF simulations diverge
once the front enters the northwest wind farm. The front in the DEF simulation slows down relative to the CTRL front due to the extraction of momentum on the cold side of the front.

Figure 7(a, c) shows the front in the northwest corner of the domain at 8:00 PM LST on June 14th, 2010 for CTRL and DEF, respectively. Wind speeds in the cold sector are about 15 ms$^{-1}$ for both the CTRL (Figure 7a) and the DEF (Figure 7c) simulations. Surface temperatures range from 24°C in the cold sector to 36°C in the warm sector in both simulations. At this time, the spatial distribution of wind speeds, wind direction, and temperature are very similar. Figure 7(b, d) shows the progression of the front two hours later at 10:00 PM LST. Largely, the temperature and wind fields are similar between the CTRL and DEF simulations. In the northwest corner of the wind farms the front has progressed less in the DEF simulation than in the CTRL simulation. The front in the CTRL simulation has propagated 3 km farther in the 2 hours in the immediate vicinity of the wind farm. Momentum from the wind in the cold air is extracted by the wind turbines in the DEF simulation retarding the front’s advance through the domain.

At 11:00 PM, the front in both cases progresses southeastward. Difference plots, CTRL subtracted from DEF, show (Figure 8a) winds have decreased ahead of the front, reducing convergence along the front. The momentum extraction of the southern wind farms is affecting the propagation of the front. Figure 8b shows difference in vertical velocity by subtracting the CTRL simulation from the DEF simulation, therefore strong negative vertical velocities indicate upward motion and the location of the front in the CTRL simulation and strong positive vertical velocity differences are indicative of the upward motion and the location of the front in the DEF simulation. Spatial discrepancies in the vertical velocity fields are largest in the central part of the domain where the DEF simulation extracts momentum ahead of the front but does not impact
winds behind the front. The net result is reduced convergence along the front and increased propagation speed of the front. Where the turbines are both ahead of and behind the front the spatial discrepancy of the front is smaller.

4.2 Case B: A Cold Front

On June 15th at 3:00 PM LST a cold air mass entered the domain from the northwest. The associated front propagates southeastward before reversing direction, transitioning into a warm front as the cold air begins to retreat at 8:00 PM LST. The cold front in the CTRL simulation does not penetrate as far into the domain as the cold front in DEF simulation due to the strong winds in the warm sector coming from the southeast. Southeasterly winds in DEF simulation are reduced due to the presence of the turbines southeast of the front.

Figure 9(a, c) shows a cold air mass entering the northwest corner of the domain at 5:00 PM LST for the CTRL and DEF simulation, respectively. The boundary extends from the west central portion of the domain northeastward to the northeast corner in both cases. The CTRL simulation has the front advanced by 2 km relative to the DEF simulation. Surface temperatures in both simulations range from 20-28°C and 30-35°C in both simulations while exhibiting similar spatial characteristics. 30 meter winds also exhibit similar spatial characteristics between both simulations. Winds are around 10 ms\(^{-1}\) in the warm sector for the CTRL simulation and 3 ms\(^{-1}\) slower downwind of the wind farms in the DEF simulation. Winds in the cold sector are near 5 ms\(^{-1}\) in both simulations. Figure 9 (b, d) presents the front at 10:00 PM LST. Temperatures in the warm sector have decreased. Temperatures in the warm sector and the cold sector still maintain similar spatial characteristics between runs. The location of the cold front in the DEF simulation progressed farther southeast than in the CTRL case.
Figure 10 illustrates the difference in progression between the front in the CTRL and DEF simulations. Vertical velocity differences (Figure 10a) and wind speed differences (Figure 10b) are plotted in the same manner as figure 8. The front in the DEF case propagate farther into the domain. Large changes in the hub height wind field are due to the two reasons: the different locations of the front and the reduction of wind speeds. The fronts are not collocated due to the reduced convergence along the front in the DEF case allowing the front to progress farther southeastward. The southeastern wind farms reduce winds by up to 4 ms$^{-1}$. The reduced convergence also manifests itself in the strength of the vertical motions where the CTRL simulation exhibits stronger upward motion due to greater convergence.

4.3 Case C: An Outflow Boundary

The 5 km domain developed a convective system immediately north of the innermost domain at 6:00 PM on August 14$^{th}$ LST, 2010. Outflow from the convective system caused cool northerly winds to enter the innermost domain from the north. Warm southerly winds, due to the larger synoptic flow, occupied the southern portion of the domain at this time. The cool outflow boundary pushed south displacing the warmer air. The outflow boundary advanced farther in the CTRL simulation than in the DEF simulation due to the extraction of momentum from the turbines to the south of the outflow boundary.

The state of hub height level winds and temperature on August 14$^{th}$, 2010 at 5:00 PM LST are plotted in Figure 11 (a, c). The outflow boundary is identified by the rapid change in temperature and wind direction. Temperatures in the outflow boundary are 27-29°C and the temperatures in the warm sector are from 32°C in the southwest to 36°C in the northeast. Winds in the outflow boundary are divergent at the location of the convective cells with a generally northerly flow into the domain. The CTRL and DEF simulations have similar spatial
characteristics for the wind direction and temperature at this time. Figure 11(b, d) show the same atmospheric variables as Figure 11 (a, c) but 4 hours later at 9:00 PM LST. Temperatures in the warm sector have decreased due to radiational cooling and the outflow boundary has propagated southward. Temperatures and the wind field maintain similar characteristics between the CTRL and DEF simulation with the exception of subtle changes along the outflow boundary. The outflow boundary has progressed farther southward in the CTRL simulation than in the DEF simulation.

The difference in propagation speed is shown in Figure 12. The difference in vertical velocity at hub height is plotted in Figure 12a and the difference in hub height wind speed is plotted in Figure 12b. The figures are plotted in the same manner as Figure 8. The vertical velocity plot shows the front has propagated farther southward in the DEF simulation than in the CTRL simulation by 5 km in the center of the domain. Differences in wind speed are seen to the south of areas of maximum vertical velocity change and north of the wind farms. Wind speeds are reduced by up to 2 ms\(^{-1}\). Reduced winds south of the outflow boundary in the DEF case are associated with a greater advance of the boundary.

4.4 Case D: A Shear Line

A boundary separating dry air from moist air propagated into the southeast of the domain on August 18\(^{th}\), 2010 at 1:00 PM LST. The boundary propagated to the northwest and is characterized by the rapid change in wind direction and moisture with vertical distance with a moisture gradient of 1 g kg\(^{-1}\) km\(^{-1}\). The propagation speed of the boundary away from the south central wind farms is decreased in the DEF simulation. Energy is extracted from the wind field decreasing the amount of advection behind the front boundary. In contrast, the CTRL simulation advances at a faster rate due to higher wind speeds behind the front.
Figure 13 (a, c) show the placement of the boundary at 5:00 PM LST on August 18th, 2010. The boundary extends from the southern portion of the domain east northeastward through the southernmost wind farms and into the east central part of the domain. At this hour, the boundary is slightly more advanced in the DEF simulation than in the CTRL simulation. This may be due to the faster propagation of the boundary while upwind of the wind farm as seen in the other cases. The moist side of the boundary has convective activity with 30 meter moisture values ranging from 14 g kg\(^{-1}\) to 17 g kg\(^{-1}\) with winds from the east and north. The dry sector contains mixing ratios below 10 g kg\(^{-1}\) with winds predominantly from the southeast. Away from the boundary, the CTRL and DEF simulations exhibit similar moisture and wind characteristics. Figure F7 (b, d) shows the boundary at 11:00 PM LST. The dry air has moved into the southeast half of the domain. The boundary has advanced in a different manner in the simulations. The DEF simulation has the boundary located to the southeast of the boundary in the CTRL simulation. The magnitude of the gradient along the front is unchanged.

Difference plots (Figure 14) at 11:00 PM LST on August 18th, 2010 show the difference in wind speed, wind direction, and moisture at 30 meters AGL. Red (blue) shading in Figure 14a represents areas where the DEF (CTRL) simulation is moister. The red ribbon indicates the DEF boundary has not progressed as far as in the CTRL simulation. Figure 14b shows hub height meter winds downwind of the wind far are decreased by up to 5 ms\(^{-1}\). The decrease in wind speeds is associated with the retardation of the propagation of the front. The CTRL simulation is moister than the DEF simulation to the east of the west central wind farms.
CHAPTER 5
CONCLUSIONS AND DISCUSSION

This study investigates the effect of wind farms on surface and near-surface air temperatures and the impacts wind farms have on the propagation of mesoscale boundaries. WRF is employed as a regional climate model to simulate the summers of 2010, 2011, and 2012 over west-central Texas. This region is rich in wind resources and 4 of the world’s 10 largest wind farms are located here. Three wind turbine parameterizations with different thrust and TKE coefficient curves are used to investigate the effect on surface and near-surface air temperature. These include the WRF default parameterization and 2 other parameterizations based on functional wind turbine data. Only the WRF default parameterization is used to explore the impacts on mesoscale boundaries.

The simulated LSTs show good spatial correlation with observed LSTs from the MODIS imager on the Terra and Aqua satellites. However, the simulated diurnal cycle is smaller than observed. It is important note that the simulated and observed temperature retrievals cannot be directly compared for a number of reasons. MODIS only retrieves during clear sky conditions while WRF simulated data represents all sky conditions. Real world wind farms are a mix of different types of turbines that are occasionally shut down due to breakdown, maintenance or curtailment but the parameterizations in WRF are spatially homogenous and operate continuously. Finally, errors intrinsic to WRF cause the model to under-simulate the magnitude of the diurnal cycle also may contribute to the differences with the MODIS data.

The wind turbine parameterizations generate a significant warming effect on 2 meter temperatures and LST at night. This is due to the increase in net downward sensible heat.
transport in the stably stratified nocturnal environment induced by the turbulence in turbine wakes. The magnitude of the warming is dependent on the non-linear interaction of the thrust coefficient and TKE coefficient curves with the wind field and wind turbine layer static stability. Maximum warming is associated with high TKE generation during moderate to high winds and high values of static stability. In contrast, no significant effect is found during the day, especially in the afternoon. This is because due to light winds, the turbines do not operate frequently during the day. Even when the turbines are operating, the turbulent mixing does not lead to a net sensible heat transport because the static stability profiles are near neutral or unstable. Overall, all 3 parameterization successfully capture the pattern of LST signals observed in MODIS LST data. Thus, parameterizing wind turbines as sinks of momentum and sources of TKE appears to be a better approach than as surface roughness elements (Fitch et al, 2013).

There are significant differences in impacts from different parameterization. The CBR parameterization produces the greatest impacts and AK produces the least impacts. This is because (i) the low thrust coefficient at light wind speeds in CBR prevents winds from decreasing to below the cut-off speed when the other two parameterizations decreased winds below the cut-off, and (ii) moderate to very high winds reduce to a wind speed that coincide with the maximum production of TKE for CBR and a minimum for AK.

The simulations cause warming and cooling outside of the immediate vicinity of the wind farms. It is suspected this is caused by changes in the precipitation patterns and the passage of fronts and other mesoscale boundaries.

Mesoscale boundaries are shown to be impacted by the presence of wind farms. Wind farms extract momentum from the boundary layer which can either impede or accelerate the propagation of the boundary depending on where the boundary is relative to the wind farms. If
the boundary is upwind of the wind farm then boundary propagation accelerates; if the boundary is downwind of the wind farm, the boundary propagation is impeded. It is suspected the mechanism causing the acceleration of boundaries involves reduction of convergence along the boundary. This is supported by the decrease in vertical velocity along the boundary when turbines are present. Simulations with higher vertical resolution are needed before conclusive statements can be made regarding the mechanism and are currently part of an ongoing study.

Future work should include improving understanding of the ABL and mesoscale boundary dynamics and implementation of these phenomena in atmospheric models, especially during statically stable conditions. Additionally, the sensitivity of land surface temperatures and near surface temperatures should be compared to a wide range of turbines with varying thrust and TKE coefficients. Surface temperatures are also highly influenced by precipitation patterns and investigations into the impact of wind farms on precipitation patterns may provide further explanation into the observed change of land surface temperatures. Regarding mesoscale boundaries many science questions are available to be explored: How do the wind farms affect the vertical structure of boundaries? What role does the creation of TKE play in propagation of the boundaries? And how sensitive is boundary propagation to different types of turbines?

Future experiments should focus on using higher vertical resolution, simulating boundaries that can be verified with observations. Results should be quantified and relationship should be developed between energy extracted and the change in propagation speed. The change in propagation should be reconciled with the current theory of the propagation of fronts and the effect of wind turbines on the isallobaric wind and the ageostrophic circulation that accompanies air mass boundaries.
Overall, this study shows wind farms impact their local microclimate and transient features such as mesoscale boundaries in addition to showing wind turbine parameterizations in WRF are capable of simulating the pattern of the impacts. Increasingly, wind farms are being placed on agricultural land that is sensitive to atmospheric changes. This and similar studies can provide a thorough understanding of how wind farms affect their surrounding and thereby help develop optimal strategies for the growth of wind energy.
LITERATURE CITED


Fitch A, Lundquist J, Olson J. Mesoscale Influences of Wind Farms throughout a Diurnal Cycle. MWR. 2013;7;2173-2198. http://dx.doi.org/10.1175/MWR-D-12-00185.1


Fitch, Anna C., Joseph B. Olson, Julie K. Lundquist, 2013: Parameterization of Wind Farms in Climate Models. J. Climate;26; 6439–6458. doi: http://dx.doi.org/10.1175/JCLI-D-12-00376.1


Rajewski D, Tackle E, Lundquist J, Oncley S, Prueger J, Horst T, Rhodes M, Pfeiffer R, Hatfield


Table 1

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<thead>
<tr>
<th>Domains</th>
<th>Outer (1)</th>
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Table 1: Summary of the structure of the domains.
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Table 2: Summary of physics parameterizations.
### Table 3
Summary of pertinent variables

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Table 3: Summary of pertinent variables.
### Table 4

Percent occurrence of the different stability conditions at operational wind speeds.

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Table 4: Percent occurrences of the different stability conditions at operational wind speeds for 1:30 AM, 10:30 AM, 1:30 PM, and 10:30 PM, respectively in the DEF case over wind farm grid cells. Bin values are light (3-5 ms\(^{-1}\)), moderate (5-8 ms\(^{-1}\)), high (8-15 ms\(^{-1}\)), and very high (>15 ms\(^{-1}\)). Static Stability bin values are U (unstable; $\sigma < -.005$ °C hPa\(^{-1}\)), NN (near-neutral; -.005°C hPa\(^{-1}\) $< \sigma < -.005$ °C hPa\(^{-1}\)), S (stable; -.005 °C hPa\(^{-1}\) $< \sigma < .03$ °C hPa\(^{-1}\)), SS (strongly stable; $\sigma > .03$ °C hPa\(^{-1}\)).
Figure 1: WRF simulation domain showing the 3 nested grids. Red asterisks mark the locations of the wind turbines. The bold arrow shows the prevailing wind.
Figure 2

Figure 2: Thrust and TKE coefficients of the 3 difference wind turbine parameterizations
Figure 3

Figure 3: 2010-2012 summer average land surface temperature for (top) day and (bottom) night. Panels are (a) MODIS retrieved temperatures and (b) WRF simulated temperatures.
Figure 4

Figure 4: A cross tabulation and impacts graphic of change (CTRL – experimental) in 2 meter temperatures (°C). Only changes that are statistically significant at p<0.01 are shown. Green shading represents probability of occurrences of each environmental condition. Wind speeds bin values are off (<3 ms⁻¹), light (3-5 ms⁻¹), moderate (5-8 ms⁻¹), high (8-15 ms⁻¹), and very high (>15 ms⁻¹). Static Stability bin values are U (unstable; σ < .005 °C hPa⁻¹), NN (near-neutral; .005°C hPa⁻¹ < σ<.005 °C hPa⁻¹), S (stable; .005 °C hPa⁻¹< σ<.03 °C hPa⁻¹), SS (strongly stable; σ>.03 °C hPa⁻¹).
Figure 5

i) 2010-2012 night time averages of CTRL run minus parameterized run for i) 2 meter air temperature (°C) ii) surface to air sensible heat flux (w m\(^{-2}\)) iii) LST (°C).

Figure 5: 2010-2012 night time averages of CTRL run minus parameterized run for i) 2 meter air temperature (°C) ii) surface to air sensible heat flux (w m\(^{-2}\)) iii) LST (°C).
Figure 6: Same as 5i but for daytime
Figure 7: Simulated wind and temperatures at 30 meters AGL on (a, c) June 14, 2010 at 8:00 PM LST and (b, d) June 14, 2010 at 10:00 PM LST for CTRL (a, b) and DEF (c, d). Color scale is temperature and arrows represent wind direction and speed.
Figure 8

Figure 8: Simulations for June 14, 2010 at 11:00 PM LST for (a) 30 meter AGL simulated vertical velocity difference and wind difference and (b) 30 meter AGL wind difference and magnitude of winds. The differences are calculated by subtracting CTRL from DEF.
Figure 9: Simulated wind and temperatures at 30 meters AGL on (a, c) June 15, 2010 at 5:00 PM LST and (b, d) June 15, 2010 at 10:00 PM LST for CTRL (a, b) and DEF (c, d). Color scale is temperature and arrows represent wind direction and speed.
Figure 10

Figure 10: Same as figure 9 for June 15, 2010 at 10:00 PM LST.
Figure 11: Hub height simulated wind and temperatures on (a, c) August 14, 2010 at 5:00 PM LST and (b, d) August 14, 2010 at 9:00 PM LST for CTRL (a, b) and DEF (c, d). Color scale is temperature and arrows represent wind direction and speed.
Figure 12: Simulations for August 14, 2010 at 9:00 PM LST for (a) 100 meter AGL simulated vertical velocity difference and wind difference and (b) 100 meter AGL wind difference and magnitude of winds. The differences are calculated by subtracting CTRL from DEF.
Figure 13: 30 meter simulated wind and moisture on (a, c) August 18, 2010 at 5:00 PM LST and (b, d) August 18, 2010 at 11:00 PM LST for CTRL (a, b) and DEF (c, d). Color scale is moisture and arrows represent wind direction and speed.
Figure 14

Figure 14: Simulations for August 18, 2010 at 11:00 PM LST for (a) 30 meter AGL simulated mixing ratio difference and wind difference and (b) 100 meter AGL wind difference and magnitude of winds. The differences are calculated by subtracting CTRL from DEF.