Evaluation of the Weather Research and Forecasting Model on Forecasting Low-level Jets: Implications for Wind Energy

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Nocturnal low-level jet (LLJ) events are commonly observed over the Great Plains region of the USA, thus making this region more favorable for wind energy production. At the same time, the presence of LLJs can significantly modify vertical shear and nocturnal turbulence in the vicinities of wind turbine hub height, and therefore has detrimental effects on turbine rotors. Accurate numerical modeling and forecasting of LLJs are thus needed for precise assessment of wind resources, reliable prediction of power generation and robust design of wind turbines. However, mesoscale numerical weather prediction models face a challenge in precisely forecasting the development, magnitude and location of LLJs. This is due to the fact that LLJs are common in nocturnal stable boundary layers, and there is a general consensus in the literature that our contemporary understanding and modeling capability of this boundary-layer regime is quite poor. In this paper, we investigate the potential of the Weather Research and Forecasting (WRF) model in forecasting LLJ events over West Texas and southern Kansas. Detailed observational data from both cases were used to assess the performance of the WRF model with different model configurations. Our results indicate that the WRF model can capture some of the essential characteristics of observed LLJs, and thus offers the prospect of improving the accuracy of wind resource estimates and short-term wind energy forecasts. However, the core of the LLJ tended to be higher as well as slower than what was observed, leaving room for improvement in model performance. Copyright © 2008 John Wiley & Sons, Ltd.

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Introduction and Motivation

Low-level jets (LLJs) are wind maxima typically centered around 100–1000 m above ground level (AGL). LLJs have been observed on every continent, with frequent occurrences on North America, South America, portions of Africa, southern Asia, Europe (specifically near the Baltic sea) and Australia. In the USA, common
occurrences of LLJs have been documented over the Great Plains (e.g. Bonner, Mitchell et al., Whiteman et al., Song et al.), as well as along the Californian coast (e.g. Burk and Thompson, Parish).

LLJs have direct ramifications for renewable wind energy production (e.g. Sisterson and Frenzen), as will be highlighted throughout this paper. Apart from their role in wind energy generation, LLJs strongly assist in initiation and sustenance of convective weather (e.g. Maddox), pollutant dispersion (e.g. Banta et al.), and migrations of birds and insects (e.g. Liechti and Schaller). In the literature, LLJs have also been linked to widespread flooding events (e.g. Arritt et al.). In theory, an LLJ can even cause premature touchdown of an aircraft during landing (e.g. Wittich et al.). Thus, researchers across multiple disciplines are interested in the prospect of having improved modeling capabilities of LLJs.

Over the past 50 years, several physical mechanisms were proposed in the literature to explain the development and intrinsic characteristics of LLJs. They include (but not exclusively) inertial oscillations, baroclinicity generated by sloping terrain and large-scale coupling. Over the USA’s Great Plains, LLJs are quite common at night in stably stratified conditions. Under stable stratification, turbulence is usually generated by shear, but is destroyed by negative buoyancy and viscosity. Because of this competition between shear and buoyancy effects, the strength of mixing in the nocturnal stable boundary layer is typically weak. Lack of vertical mixing sometimes leads to decoupling of the outer (Ekman) boundary layer from the inner (surface) layer. This decoupling allows the outer layer wind speed to accelerate, since this layer is not anymore affected by surface friction, and to become a (supergeostrophic) LLJ. The existence of mild sloping terrain over the Great Plains further increases the strength of these jets.

High wind speeds associated with LLJs make the Great Plains’ wind resources more favorable for wind energy production. At the same time, the presence of LLJs can significantly modify the vertical wind shear and nighttime turbulence in the vicinity of the wind turbine hub height; thus, LLJs may have detrimental effects on rotors. It is important to emphasize that the existing codes (e.g. the International Electrical Commission’s Normal Turbulence Models), which traditionally provide inflow conditions for wind turbine design, neither represent strong wind shear nor turbulence bursting events associated with stable boundary layers and LLJs. Thus, it is not surprising that suboptimal wind energy generation and turbine failures due to nighttime turbulence have been reported in several wind farms in the Great Plains.

At present, numerical weather prediction (NWP) models face a challenge in forecasting the development, magnitude and location of LLJs with precision. This could be partially attributed to our limited understanding and modeling capability of nocturnal stable boundary layers. A next-generation NWP model, the Weather Research and Forecasting (WRF) model, was developed by a collaborative effort. Several studies have demonstrated the ability of this model to forecast severe weather events. However, to date, the capability of this state-of-the-art model in forecasting LLJs is mainly undocumented. The present study attempts to fill that void. If the WRF model is found to be reliable in forecasting LLJs and their morphological characteristics, as well as the low-level wind fields, it could potentially reduce (or even replace) the need for expensive observational (tall) towers in a variety of forthcoming wind energy projects.

The organization of this paper is as follows. Descriptions of our modeling approach and the observational data used to validate the model are provided in Data and Methodology. In Results, detailed WRF modeling results of LLJ events, over West Texas and southern Kansas, are presented. Lastly, conclusions and future works are delineated in Conclusions.

Data and Methodology
To test the capabilities of the WRF model in forecasting LLJs, two pronounced LLJ events observed over West Texas and southern Kansas were simulated in this study. The LLJ event over West Texas was observed from 00:00 to 12:00 UTC, 2 June 2004 at Texas Tech University’s Wind Science and Engineering (WISE) Research Center field site. The LLJ event over southern Kansas was observed on the night of 2 October 2006 at the Atmospheric Radiation Measurement (ARM) facility in Beaumont. These specific sites were selected because of their simple topographic setting, high frequency of strongly stratified boundary
layers and LLJs, and because extensive observational datasets from advanced monitoring systems exist for both these locations.

The WISE Research Center field site includes a boundary-layer wind profiler, and the Reese Mesonet station from the West Texas Mesonet (WTM) network (http://www.mesonet.ttu.edu/).28 The boundary-layer wind profiler (Vaisala LAP-3000 915 MHZ Doppler radar vertical profiler, Vaisala Inc, Boulder, CO, USA) has a vertical resolution of 55 m, with the first level reported at 124 m AGL, and an output of 30 min averaged data. The WTM consists of 50 automated surface meteorological stations (10 m tall towers) with an average spacing of 35 km. Each surface station measures up to 15 meteorological (e.g. wind speed, wind direction, temperature, humidity, barometric pressure, precipitation and solar radiation) and 10 agricultural (e.g. soil moisture and soil temperature) variables every 5 and 15 min, respectively.28 The boundary-layer profiler at the ARM facility in Beaumont is a 915 MHz radar profiler with the first level being reported at 87 m AGL, and a vertical spacing of 58 m.29

In this work, version 2.2 of Advanced Research WRF (referred to as WRF from hereon) was evaluated.25 The WRF model is computationally efficient, and its two-way nesting capabilities allow extremely fine grid resolutions at the regions of interest. The WRF pre-processing system also allows various resolutions of terrain and land datasets to be used. Various model and physical parameterization configurations (Table I) were evaluated to determine if any one configuration showed a clear benefit over the others. A 500 × 500 horizontal grid with a 4 km spacing and 36 vertical levels (13 levels below 1 km AGL: approximately at 10, 40, 85, 125, 180, 255, 340, 430, 515, 605, 695, 785 and 900 m AGL at the grid points evaluated) were used. The number of vertical levels in the lowest 1 km is greater (almost double) than typically used in operational NWP models.

Common features between the model runs presented in this paper include 30 s U.S. Geological Survey (USGS) land use and topographic height data interpolated onto the modeled domain, National Centers for the Environmental Prediction (NCEP, Oregon State University, Air Force, and Hydrological Research Lab) (NOAH) land-surface model,30 and Ferrier microphysics scheme.31 The cumulus parameterization was turned off because of the fine grid spacing used in this study. The vertical mixing and diffusion was solely performed by the planetary boundary-layer (PBL) schemes (YSU32 or MYJ33-37 in this study). In other words, no additional explicit diffusion or numerical filters were involved in either the horizontal or the vertical direction. This approach allowed us to conduct a better evaluation of the WRF–PBL schemes themselves.

Two combinations of longwave and shortwave radiation schemes were used: (i) the Dudhia38 simple cloud interactive shortwave scheme, along with the rapid radiative transfer model (RRTM) longwave radiation39 scheme, and (ii) the Geophysical Fluid Dynamics Laboratory (GFDL) shortwave scheme,40 in conjunction with the GFDL longwave scheme41 (Table I). The initialization and lateral boundary conditions for all the runs were provided by The North American Meso (NAM, formerly ETA) model Advanced Weather Interactive Processing Systems archived dataset. The NAM uses a 40 km grid and provides lateral boundary conditions every 6 h.

Results

The following subsections compare the WRF-based model output with available field observations from both the West Texas and southern Kansas cases. Emphasis is given on timing, magnitude and location of the LLJs,

<table>
<thead>
<tr>
<th>Model run</th>
<th>Grid center</th>
<th>PBL</th>
<th>LW/SW radiation</th>
<th>Initialization date and time</th>
</tr>
</thead>
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<tr>
<td>YSU_rrtm_TX</td>
<td>WISE</td>
<td>YSU</td>
<td>RRTM/Dudhia</td>
<td>1 June 2004 18:00 UTC</td>
</tr>
<tr>
<td>MYJ_rrtm_TX</td>
<td>WISE</td>
<td>MYJ</td>
<td>RRTM/Dudhia</td>
<td>1 June 2004 18:00 UTC</td>
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<td>YSU_gfdl_TX</td>
<td>WISE</td>
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<td>GFDL/GFDL</td>
<td>1 June 2004 18:00 UTC</td>
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<td>MYJ_gfdl_TX</td>
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<td>YSU_rrtm_KS</td>
<td>ARM</td>
<td>YSU</td>
<td>RRTM/Dudhia</td>
<td>1 Oct 2006 18:00 UTC</td>
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<tr>
<td>MYJ_rrtm_KS</td>
<td>ARM</td>
<td>MYJ</td>
<td>RRTM/Dudhia</td>
<td>1 Oct 2006 18:00 UTC</td>
</tr>
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since these attributes have the largest implications for wind resource assessments and for short-term wind energy predictions.

**West Texas Case**

Two LLJs with wind speeds greater than 16 m s\(^{-1}\) were observed on 2 June 2004 over the West Texas panhandle region (Figure 1(e)). The first LLJ occurred between 05:30 and 06:30 UTC, spanning from just above the ground to approximately 0.5 km AGL. The second maximum occurred between 08:30 and 09:30 UTC, spanning between 0.3 and 0.9 km AGL. The first jet had a predominantly easterly direction, while the second jet was more southerly (Figure 1(f)). The forcing mechanisms of these jets are not entirely clear at this time. Preliminary analysis of surface maps and visible satellite imageries revealed that the easterly jet was likely associated with a dry line in Texas regressing westward (not shown). The southerly LLJ could be a result of either the inertial oscillation or the baroclinicity created from the sloping terrain of the southern Great Plains. Reliable identification of the forcing mechanism for an observed LLJ is not a trivial task and is beyond the scope of this paper. Interested readers are encouraged to peruse the works of McNider and Pielke,\(^42\) McCorcle,\(^43\) Fast and McCorcle,\(^44\) Zhong et al.,\(^45\) and Wu and Raman.\(^46\) Some of these numerical studies have further investigated the sensitivities of LLJ evolution to topography, land-surface heterogeneity, soil moisture, etc.

In Figure 1, wind speed and direction time–height profiles from the WRF grid point closest to the WISE field site are compared to the corresponding profiles from the Texas Tech wind profiler. Since no distinct differences were found between the RRTM and GFDL runs with either boundary-layer parameterizations, only model runs using the RRTM radiation scheme are presented in this paper. According to Figure 1, both the MYJ\(_{\text{rrtm}}\)\(_{\text{TX}}\) and YSU\(_{\text{rrtm}}\)\(_{\text{TX}}\) runs represented the vertical and temporal characteristics of the observed LLJs fairly well. However, at the WISE field site location, the MYJ\(_{\text{rrtm}}\)\(_{\text{TX}}\) run forecasted slightly stronger, and somewhat more accurate wind speeds for the first LLJ event in comparison with the YSU\(_{\text{rrtm}}\)\(_{\text{TX}}\) run (Figure 1). On the other hand, the YSU\(_{\text{rrtm}}\)\(_{\text{TX}}\) run captured the wind speeds of the LLJ event occurring at 09:00 UTC more precisely, though the timing of the YSU\(_{\text{rrtm}}\)\(_{\text{TX}}\) run was slightly delayed (Figure 1(a),(e)). Unfortunately, all the runs failed to reproduce the strong winds (>14 m s\(^{-1}\)) that were observed below 0.2 km AGL during 05:00 and 06:00 UTC. Significant differences between the MYJ\(_{\text{rrtm}}\)\(_{\text{TX}}\) run and the profiler wind direction were also observed, while the YSU\(_{\text{rrtm}}\)\(_{\text{TX}}\) run represented the wind direction quite accurately with a slight temporal displacement (Figure 1(b),(d),(f)).

The power law relation

\[
U(z) = U_r \left(\frac{z}{z'}\right)^\alpha,
\]

where \(U_r\) is the wind speed at a reference height (typically 10 m), and \(U(z)\) is the wind speed at height \(z\) above ground, is commonly used in the wind energy community to estimate the wind speed in the boundary layer. In wind energy literature,\(^47\) the shear exponent, \(\alpha\), is typically assumed to be equal to 1/7 (also known as the 1/7th power law). In Figure 2, the observed \(\alpha\) time series (calculated from the Texas Tech boundary-layer profiler’s 124 m wind speed and the Reese WTM station’s 10 m wind speed time series) is compared to the WRF-simulated \(\alpha\) time series (calculated from the wind speed time series at the 127 and 10 m grid levels) and the conventional 1/7th power law (as reference). For the entire night, the observed \(\alpha\) values were larger than the conventional value of 1/7. The YSU\(_{\text{rrtm}}\)\(_{\text{TX}}\) and MYJ\(_{\text{rrtm}}\)\(_{\text{TX}}\) runs captured the evolution of \(\alpha\) reasonably well, albeit underestimating the magnitude. The MYJ\(_{\text{rrtm}}\)\(_{\text{TX}}\) simulation slightly underestimated the shear exponent at the peak of the two LLJs (e.g. 06:00 and 09:00 UTC). Similar conclusions can also be made from Figure 3. This figure highlights that if the observed 10 m wind speed is extrapolated using the conventional 1/7th power law, it is very likely to under-predict the outer layer wind speeds in the presence of LLJ events. In comparison, the WRF model can forecast wind speeds considerably closer to the observations (Figure 3).

Over the Great Plains, high values of \(\alpha\) are common during nighttime hours,\(^48\) especially when LLJs are present. These high values should be appropriately taken into account during wind resource assessment, short-
Figure 1. Simulated and observed wind speed and wind direction for 04:00–12:00 UTC on 02 June 2004. The left column shows wind speed time–height plots (unit: m s$^{-1}$) of (a) hourly output from the YSU_rrtm_TX run, (c) hourly output from the MYJ_rrtm_TX run and (e) half-hourly averages from the Texas Tech boundary-layer wind profiler. The right column is the wind direction time–height plots (unit: meteorological degrees) of (b) hourly output from the YSU_rrtm_TX run, (d) hourly output from the MYJ_rrtm_TX run and (f) half-hourly averages from the Texas Tech boundary-layer profiler.

term wind power prediction and wind turbine design. High values of $\alpha$ imply that wind turbines can generate a substantial amount of energy, even when the wind speed near the ground is minimal. At the same time, larger $\alpha$ will introduce higher fatigue loads on the turbine blades.49

So far, we have compared a single grid point output from the WRF runs with collocated field observations. However, flow visualizations of the modeled fields reveal that the forecasted LLJs portray considerable spatial variabilities (see Figure 4). For example, at 06:00 UTC, slightly to the south and west of the WISE field site, quite strong winds were forecasted by the YSU_rrtm_TX run. If these winds were observed over the WISE field site, the YSU forecasted profiles would have been much closer to the observations. To the best of our knowledge, it is not known in the literature whether such large spatial variabilities, as observed in the modeled cross sections and horizontal plan-view maps (Figure 4), are observed in the real-world LLJs. What little observational evidence that exists suggests that LLJ properties may be relatively uniform over distances of up
Figure 2. Vertical wind speed (m s$^{-1}$) profiles from the YSU_rrtm_TX (dotted lines in gray) and MYJ_rrtm_TX (dashed lines in black) runs at 05:00 (left) and 06:00 (right) UTC on 2 June 2004. Observed wind speed profiles from Texas Tech boundary-layer profiler are depicted as solid gray lines. Please note that the profiler observations are not available below 124 m. In order to facilitate the comparisons, 10 m Reese WTM and 124 m profiler wind speed values are joined using the power law relationship (equation (1)) and the observed $\alpha$ values (long dashed lines in gray). The extrapolated wind speed profiles utilizing ‘only’ the observed 10 m Reese WTM wind speed and the conventional 1/7th power law are also shown as reference (dashed-dotted lines in black).

Figure 3. Vertical shear exponent ($\alpha$) time series calculated from the YSU_rrtm_TX (dotted line) and MYJ_rrtm_TX (dashed line) runs (utilizing wind speed time series at the 113 m grid level and at the 10 m level) between 03:00 and 12:00 UTC on 2 June 2004. The Texas Tech boundary-layer profiler’s 124 m wind speed and the Reese WTM station’s 10 m wind speed time series were utilized to estimate the observed $\alpha$ time series (solid line). The 1/7th power law exponent is also shown for comparison (dashed-dotted line).

to 100 km (e.g. Banta et al.$^{10}$ and Song et al.$^5$), in contrast to the results presented here. The WISE Research Center, along with the Texas Tech Atmospheric Science Group, is currently constructing two mobile Ka-band radars, which will be able to give large spatial coverage of three-dimensional velocity fields, and consequently morphological properties of the Great Plains’ LLJs.

Southern Kansas Case
In order to establish the generality of our conclusions from the 2 June 2004 case, a second LLJ event that occurred on 2 October 2006 over southern Kansas was simulated. A southerly LLJ jet with wind speeds over
Figure 4. Wind speed (m s\(^{-1}\)) fields from the YSU\_rrtm\_TX run at 06:00 UTC, 2 June 2004. The cross sections are taken (a) at 1.3 km Mean Sea-Level height, (b) at 0.955 sigma level (~350 m AGL), (c) along 33.3\(^\circ\)N latitude (line 1 shown in (a)) and (d) along 102\(^\circ\)W longitude (line 2 shown in (a)). The X marks the approximate location of the WISE field site in (c) and (d). The field site is approximately at the intersection of the two white lines in (a). Reference arrow for wind vector is given on the right.

24 m s\(^{-1}\) and centered between 0.3 and 0.4 km AGL developed around 02:00 UTC, and was persistent through 10:00 UTC (Figure 5(c),(d)). Wind turning with height was also observed throughout the night (Figure 5(d)). Both the YSU and MYJ PBL parameterizations were investigated for this case (Table I). Since the MYJ-based run produced results very similar to the YSU-based run, we only report the YSU\_rrtm\_KS results. The YSU\_rrtm\_KS run qualitatively reproduced the vertical and temporal characteristics of the observed LLJ reasonably well (Figure 5). However, as with the West Texas case, the WRF runs overestimated the LLJ heights and at the same time underestimated the wind speeds. These behaviors could be due to enhanced mixing by the PBL schemes and, undoubtedly, need systematic evaluation in the near future.

Conclusions
In this study, we investigated various model configurations in order to determine if the WRF model is able to forecast the Great Plains’ LLJs. Our general conclusion is that all the WRF configurations evaluated do have the capability to capture some of the essential characteristics (e.g. location and timing) of the observed LLJ events. Unfortunately, all the WRF configurations tested also have the tendencies to overestimate the LLJ heights and to underestimate the LLJ wind speeds. These results are likely related to the ‘enhanced mixing’ of the PBL schemes. It is worth mentioning that most of the present-day mesoscale and large-scale atmospheric models use PBL parameterizations, which are not physically based but are ‘inspired by model performance’. Some of these ad hoc parameterizations alleviate problems, such as ‘runaway cooling’, by (artificial) enhanced mixing. At the same time, these ‘fixes’ create unphysical consequences, such as unrealistically deep boundary layers and weaker LLJs. The wind energy industry may desire more accurate wind speeds than currently
forecasted by different WRF configurations, but we emphasize that all of these forecasts were significantly more accurate than conventional extrapolation using the 10 m wind speed and the 1/7th power law.

We found that no particular WRF configuration is clearly better or worse than the others. For example, in the West Texas case, the YSU PBL scheme-based runs captured the wind direction profiles better than the MYJ-based runs. On the other hand, the MYJ runs forecasted the wind speed profiles more accurately at this location. Given the significant spatial variabilities we found in the forecasted wind fields, it is very likely that at a different validation point, the relative performances of various WRF configurations will vary. We believe that high-resolution spatiotemporal observations and innovative forecast verification metrics (accounting for both the magnitude and displacement errors) will be needed before one can conclusively identify the ‘best’ WRF configuration for forecasting LLJs over the Great Plains.

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**References**

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