EVALUATING HIGH-RESOLUTION NWP FORECASTS OF THE NOCTURNAL LOW LEVEL JET FOR IMPROVING WIND POWER FORECASTS

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ABSTRACT

The Nocturnal Low Level Jet (NLLJ) is a significant contributor to overnight wind power production in the Southern Great Plains. This region of the United States is expecting wind farm growth over the coming decades and therefore it is important to better understand how to forecast wind energy, and hence forecast the location and strength of the NLLJ. The Weather Research and Forecasting Model (WRF) is one tool that can be used for forecasting winds. This study investigates performance of a real-time, high-resolution (3-km grid spacing) configuration of the WRF for several NLLJ cases in southwest Oklahoma. Forecast location and intensity of the NLLJ and its interaction with moderate terrain features around the Blue Canyon Wind Farm, particularly the Wichita Mountains and Slick Hills, were evaluated. These model forecasts also provide insight into the relationship between NLLJ behavior as a function of wind magnitude and atmospheric stability. The study finds that errors in model forecasted boundary layer stability coupled with NLLJ terrain interactions could be the reason for wind forecast errors at Blue Canyon.

1. INTRODUCTION

1.1 Wind Energy in the Southern Plains

The U.S. wind industry, the largest national wind industry in the world, has been growing at an increasing rate over the last several years. In 2009, the United States wind industry set new growth records by installing nearly 10 GW of generating capacity, bringing the nation's total capacity to over 35 GW. (AWEA, 2010). This growth is expected to continue as the U.S. Department of Energy (DOE) has set a goal of increasing the percentage of total U.S. power derived from wind from 2% in 2009 to 20% by 2030 (AWEA, 2009).

The Southern Great Plains is expected to have some of the largest growth in wind farm development. Installed Capacity, which is the potential megawatts of rated capacity that could be installed in the areas that are suitable for wind energy, is a way of determining which states will be the largest wind producers in the future. For this, Texas is ranked first with 1902 GW, Kansas second with 952 GW, and Oklahoma ninth with 517

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GW (DOE, 2010). Texas is already the largest producer of wind energy in the country, containing nearly 10 of the 35 GW of generating capacity in the nation. (AWEA, 2009).

For wind energy to be reliable and cost effective, precise and accurate forecasts are required. Unlike the current prominent energy resources such as coal and natural gas, wind energy has a weather forecast element. Wind energy production at any wind farm varies with the amount of wind the turbines collectively are exposed to. Accurate wind and power forecasts that go out at least several hours are going to become increasingly more important as wind energy becomes more prominent. Otherwise, the unforeseen variability that occurs will lead to grid operators struggling to keep power loads balanced by needing to quickly fire up or shut down coal or natural gas generators. Not only does this make the grid potentially unreliable, but it also makes wind power more costly. If high quality wind farm power forecasts can be made, then grid operators can plan ahead of time how much power production will need to come from other sources (Lerner et al., 2009)

Weather Decision Technologies (WDT), a Norman, OK, based company, has developed a unique approach to wind power forecasting. Their product, WindPredictor™, creates forecasts by using two models, The Uncoupled Surface Layer Model (USL) and Weather Research and Forecasting Model (WRF) (Carpenter et al., 2009). Both are deterministic models that have simulated physical and dynamical processes to achieve accuracy and precision. This paper investigates where improvements in the WRF model's depiction of the Nocturnal Low Level Jet can potentially be made by assimilating data from Blue Canyon Wind Farm in southwestern Oklahoma with WRF model forecasts, surface observations, and Rapid Update Cycle (RUC) analysis.

1.2 NLLJ, Terrain, and Blue Canyon

The Nocturnal Low Level Jet (NLLJ) is a large factor in overnight wind power production in the Southern Great Plains, which is where Blue Canyon Wind Farm is located. The NLLJ is characterized by a fast moving stream of air that is usually located between 100 and 1000 m above the ground. The NLLJ in the Southern Great Plains takes southerly flow. (Banta et al., 2010)

There is a cubic relationship between wind speed, U, and the available wind power, P,:

$$P = \frac{1}{2}\rho A U^3 \qquad (1)$$

where A is the rotor swept area and ρ is air density.

It can be seen in Figure 1 that potential power forecast errors are greatest the wind speed falls in the *typical average wind speed* section of the graph as compared to the *cut-in wind speed* section or just prior to the *rated wind speed*. Most observed nighttime wind speeds at Blue Canyon fall into the *typical average wind speed* for this study.

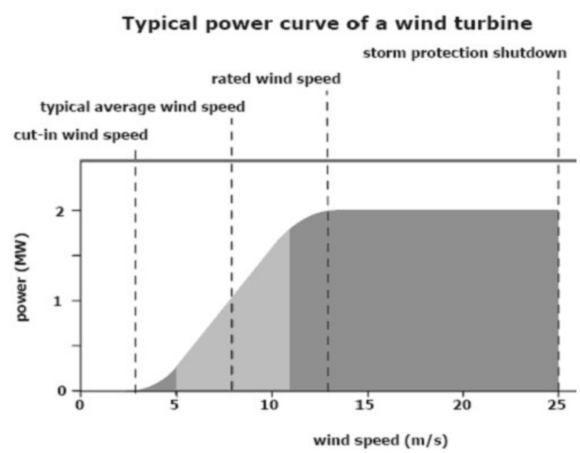


Figure 1. Typical wind turbine power curve. Figure from HiWinds Program, University College Dublin.

Blue Canyon Wind Farm is located in the Slick Hills of Caddo and Comanche Counties in southwest Oklahoma. The Slick Hills are about 20 km long and run along a west-northwest track, parallel to the Wichita

Mountains, which are located about 10 km south. With the NLLJ having a large southerly component and with the Wichita Mountains directly south of Blue Canyon, the question arises as to whether the WRF model can accurately depict interactions between the NLLJ and these mountains, and whether this has an effect on Blue Canyon. WDT runs a configuration of the WRF with 3-km grid spacing. The model resolves the overall profile of the Wichita Mountains and Slick Hills although it does not resolve individual peaks.

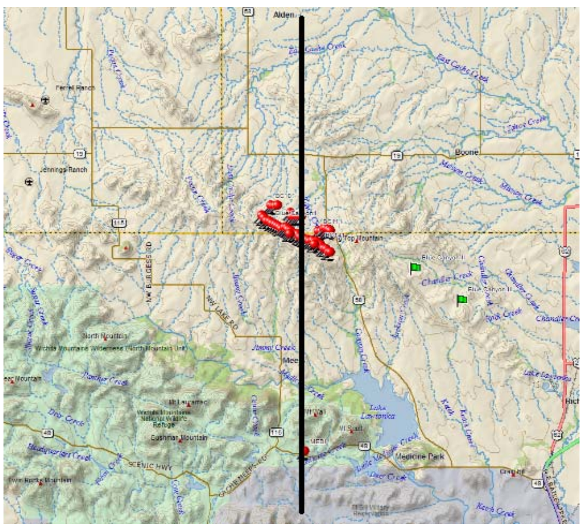


Figure 2. Red pushpins indicate the turbines at Blue Canyon Wind Farm, which are located in the Slick Hills of southwestern Oklahoma. The black line represents the position of the transect used in future figures. The Wichita Mountains are located about 10 km to the south and southwest of the wind farm.

1.3 Mountain Waves

The effect of topographic features on airflow is a function of the speed and direction of the flow relative to the feature as well as atmospheric stability. (Linacre and Geerts, 1998) In some circumstances, mountain waves can develop if there is a significant vector component of the wind perpendicular to the mountain. Although mountain waves are usually associated with large scale topographical features such as the Rocky Mountains or the Alps, smaller scale mountain waves can occur in areas like the Wichita Mountains if atmospheric stability and wind speed are within a certain range. Examining whether mountain wave development occurs can be done through the Froude number, Fr:

$$\mathbf{Fr} = \frac{U}{NH} \qquad (2)$$

$$N = \sqrt{\frac{|g|}{Tv}\left(\frac{\partial \theta v}{\partial z}\right)} \qquad (3)$$

where N is the Brunt–Väisälä frequency, H is the height of a topographical feature, g = 9.8 m s^{-1} is gravitational acceleration, and θ is potential temperature

If Fr << 1, such as when the airflow is slow, the air is stably stratified, or if there is a large topographical feature, air will flow around the mountain, not over (if the mountain is too wide, the flow will be blocked). When the Froude number is critical (Fr = 1), the oscillation frequency triggered by the flow over the range equals N, or the air's natural oscillation frequency. In this case, the wave shape mimics the shape of the terrain it intersected. If the Froude number is slightly greater than 1 (between roughly 1 and 1.8), wave patterns will setup downstream of the terrain, although the wave shape will be different that the terrain shape. If however Fr >> 1, the air readily flows over the mountain with very little lateral displacement. (Linacre and Geerts, 1998)

Clearly, topography has an effect on the NLLJ. Decreasing the grid spacing of the WRF to better resolve the topography would increase computational requirements. However, understanding some of the other meteorological factors that influence how the NLLJ and terrain interactions can be useful in helping with the improvement of wind forecasts.

2. METHODOLOGY

2.1 Criteria for case studies

Three nights were chosen to study where the NLLJ was the dominating factor in the wind that Blue Canyon experienced. The studies ran from 0000 UTC through 1100 UTC. The first two nights had shallow, ground-based stable layers of varying strength form while the third night did not. The purpose for this was to see how the stability profile of the lowest part of the atmosphere leads to changes in the flow over the terrain at and near Blue Canyon. Table 1 summarizes the stability of the lowest part of the atmosphere by quantifying the stable layer (if it was present) and the lapse rate in the lowest 1 km AGL. A Stable Layer is defined here as a portion of the atmosphere with a lapse rate less than that of the Moist Adiabatic Lapse Rate (5 K km^{-1}).

Date	**Stable Layer Height (m AGL)**	**S.L. Lapse Rate (-K km^{-1})**	**SFC → 1000m Lapse Rate (-K km^{-1})**
17 June	400 m	-4	6
22 June	400 m	2	4
4 July	N/A	N/A	4

Table 1. Forecasts from the WDT WRF 3-km model were examined to classify the stability of the lowest part of the atmosphere during NLLJ events. Values are for 0500 UTC, based on forecast hour 8 from WRF.

To assess stability and NLLJ characteristics without other meteorological influences, cases had to meet these criteria in order to be considered

- Low pressure gradient, no greater than 2 Pa km^{-1}
- No thunderstorm outflow or gust fronts in the vicinity
- No frontal boundaries in the vicinity
- Little or no convective activity in the region
- Evidence of the NLLJ in soundings
- Sustained winds at 8 m s^{-1} or greater at tower height at Blue Canyon

The pressure gradients analyzed with archived surface maps generally ranged between 1 and 1.5 Pa km^{-1}. To check that no thunderstorm outflow or gust fronts occurred, surface maps and METAR data from stations surrounding Blue Canyon were analyzed.

Figure 3. Locations where METAR was obtained from. There was no close METAR available to the north of Blue Canyon.

All three nights had strong southerly wind components from 300 to 600 m AGL, which is typical for the NLLJ. CAPE was analyzed from the WRF to check that that there was little convection.

All of the cases were studied between 0000 to 1100 UTC, (approximately 2 hour before sunset until 1 hour before sunrise) since the NLLJ usually initializes shortly after sunset and dissipates around sunrise with surface heating.

2.2 17 June 2010

The first case study done of the NLLJ occurred on 17 June 2010.

On 17 June, overnight conditions were clear with the closest thunderstorms located east of the trough in eastern New Mexico and western Texas (Figure 4). The 500 hPa map from 17 June 0000 UTC shows a trough located over Nevada and ridging over Minnesota. Flow is primarily zonal over the southern Great Plains.

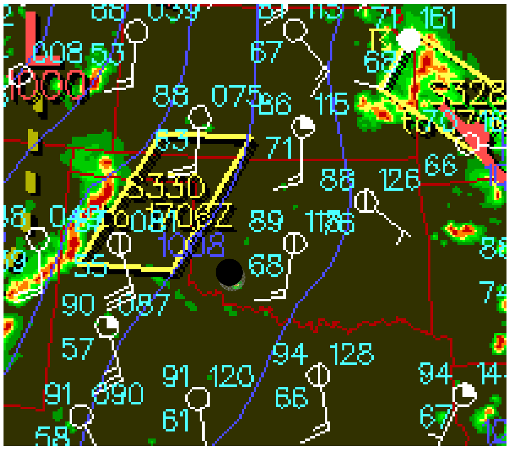


Figure 4. Surface map from 0500Z on 17 June 2010. The thunderstorms present in the Texas panhandle dissipated well before reaching Blue Canyon, hence thunderstorm outflow did not occur at Blue Canyon (Black Dot). Figure from Unisys Weather Surface Map Archive.

The wind meteogram from Blue Canyon Wind Tower (Figure 5) shows that overnight winds were sustained at about 10 m s $^{-1}$. The WRF 3 km under forecasted the wind speed by about 1 to 2 m s^{-1} for the majority of the night.

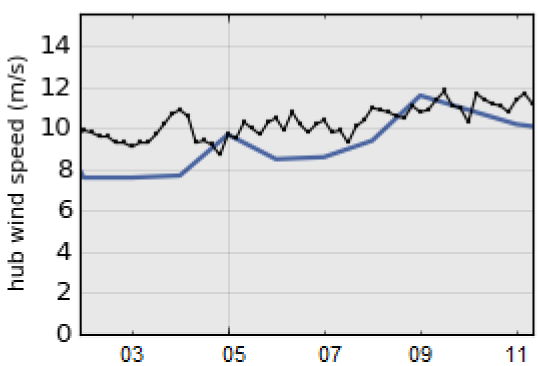
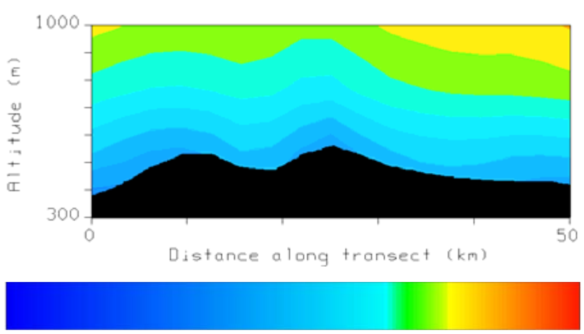
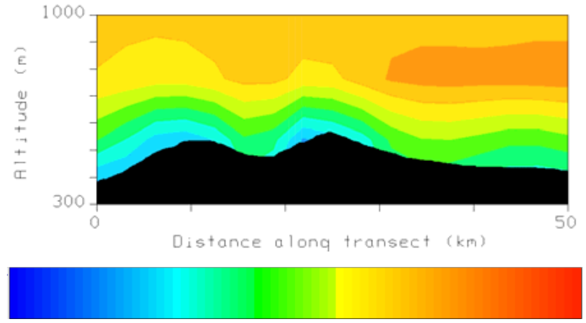


Figure 5. Observed (black) and WRF 3-km forecast (blue) of wind speed at 60 m for 17 June 2010 at Blue Canyon.



295K **310K**



0ms^{-1} **25ms^{-1}**

Figure 6. Images from IDV during the NLLJ case on 17 June showing a south-north cross-section through the Blue Canyon wind farm, as shown in Figure 2. (Top) Potential temperature (shading at 1 K intervals). (Bottom) Wind speed (shaded at 2 m s^{-1} intervals). The WRF terrain is shown in black. The first elevation maximum on the left side shows the Wichita Mountains while the second elevation maximum in the middle shows Blue Canyon and the Slick Hills. Both images are from the 16 June 2100 UTC run for forecast hour 8.

Potential Temperature can be used to understand the motions of unsaturated air parcels. The isentropes in Figure 6 are representative of the flow over the Wichita Mountains and Slick Hills. They can be useful in determining areas of high winds within the first few hundred meters off the surface.

Areas where isentropes are vertically slanted downwards represent areas of strong near-surface winds (COMET 2004). With the flow going from south to north, we can see that the lee sides of both the Wichita Mountains and the Slick Hills represents areas where the highest winds for turbines might be available (Figure 6). The model shows that on the lee side if the Slick Hills is where the highest winds would occur at hub height, or about 70 m AGL (Figure 6).

2.3 22 June, 2010

The mesoscale meteorology scenario on 22 June was very similar to that seen on 17 June. This can be seen by comparing the surface map from 0000 UTC on 22 June (Figure 7) with the surface map from 0000 UTC on 17 June. The 22 June 0000 UTC 500 hPa map shows zonal flow, with a slight trough in the west.

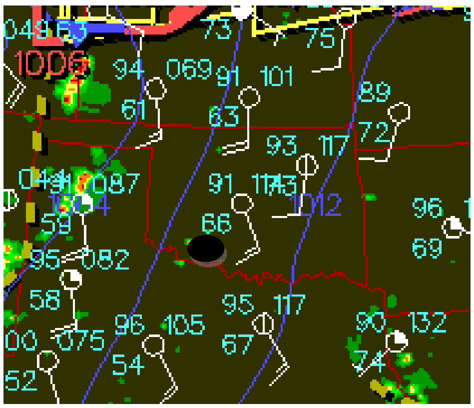


Figure 7. Shows the surface map for 0500 UTC on 22 June. Blue Canyon is located with the Black Dot

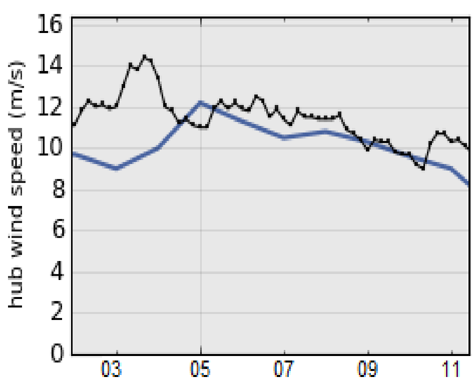


Figure 8. As in Figure 5, except for 22 June.

Even with synoptic and mesoscale meteorological conditions very similar on both days, there are distinct differences in the Blue Canyon meteograms.

IDV images from 22 June show similar features to 17 June, with down sloping isentropes and maximum near ground wind speeds located on the lee side of the Slick Hills. It can be seen that the isotachs are closer together while isentropes are farther apart when compared to the 17 June.

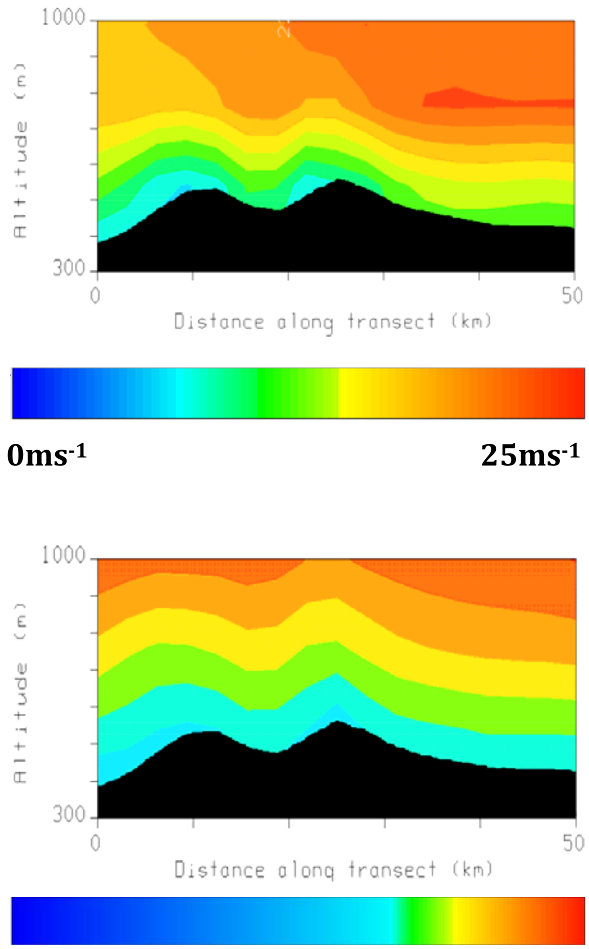


Figure 9. As in Figure 6, except for 0500 UTC 22 June.

2.4 4 July 2010

July 4th differed from the previous two nights. On this night, the air was near or at saturation for the entire boundary layer. The air was conditionally stable. Rain showers were present in the vicinity. Although there were thunderstorms on the surface map near the southern Oklahoma Texas border. The 500 hPa map shows a trough in Nevada and a ridge over the Great Lakes. Flow was more meridional compared to previous two dates.

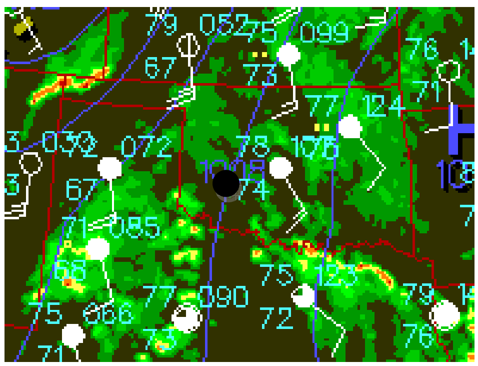


Figure 10. Shows the surface map for 0500 UTC on 4 July.

4 July was chosen to study to understand how stability affects the flow over terrain near Blue Canyon when the atmosphere is not stable. Like the previous two nights, there was sustained southerly flow from the NLLJ the whole night. The meteogram shows wind speeds never under 10 m s^{-1} the entire time.

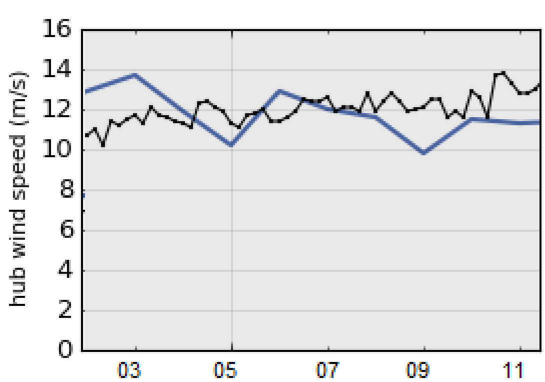


Figure 11. As in Figure 5, except for 4 July

The cross sections made on the night of 4 July show a different scenario than what is seen on either of the two previous nights. First, on the potential temperature cross section, we see more variation in the projection of the isentropes. The isentrope closest to the mountain and closest to the 1000 m level seem to be affected by the terrain, while the one in the middle seems unaffected. Isentropes above 1000 m level showed no mountain wave activity. The atmosphere was less stable on this night. It can be seen on the cross section for wind speeds that there is a less of a wave like appearance when compared to the previous two nights.

The change in stability appears to have an effect on how the model shows flow over the terrain. Therefore, it is important to understand how the terrain, stability, and NLLJ interact to produce the wind patterns at Blue Canyon. Specifically, will a change in atmospheric stability from absolutely stable to conditionally stable lead to a different flow scenario at Blue Canyon?

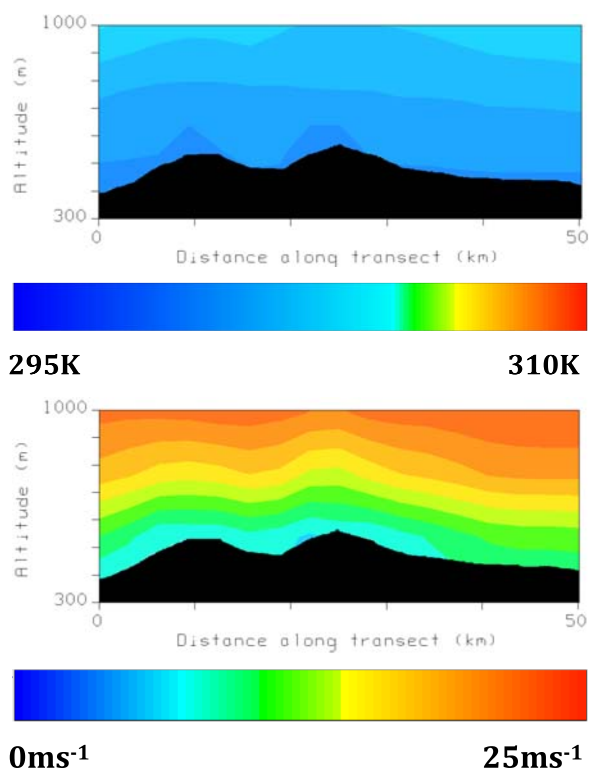


Figure 12. Cross Sections for 4 July, 2010. See figure 6 for further explanation.

3. RESULTS

3.1 Occurrence of Mountain Waves

It appears that when the lowest part of the atmosphere has different stabilities, flow over the terrain at Blue Canyon will behave differently. To confirm this finding, the Froude number and Brunt Väisälä frequency were analyzed (Table 2). A terrain height of 190 m was used, which is the average base to summit height of the Slick Hills and Wichita Mountains.

Date	Wind Speed ($m\ s^{-1}$)	T_v (K)	$\frac{\partial \theta v}{\partial z}$ ($K\ m^{-1}$)	Fr
17 June	10	302.4	.010	2.91
22 June	12	302.8	.008	3.91
4 July	10	297.0	.002	6.58

Table 2. Calculation of Froude numbers based on RUC 13-km analysis. Analysis for each data at 0500 UTC.

As seen in Table 2, there is a large difference in the Froude numbers between 17 June and 4 July. As the Froude number gets much larger than 1 (critical value), mountain waves become much less likely. A Froude number over 2 signifies mountain waves will not occur (COMET, 2004). With the Froude number on 4 July being over six times greater than the critical value, it is expected that mountain waves will not form. The Froude number on 17 June is less than three times the critical value. Although this value is not conductive to mountain wave activity, occurrences can still potentially occur from flow passing over the higher peaks in the Wichita Mountains. When comparing Figures 6 and 12, it is apparent that mountain waves are present on 17 June but not on 4 July.

On 22 June, calculations indicate mountain wave activity did not occur. However, in Figure 9, it appears that mountain waves occurred. This difference in the calculations based on the RUC and Figure 9, from the WRF, could be due to how the two models portray stability. In this case, the WRF would have to have higher stability than the RUC since mountain waves form in stable environments. This would disagree with a previous study that found the wind profiles and boundary layer structures simulated by the WRF is often neutrally stratified at night, even when the observed boundary layer is stable (Draxl et al., 2010).

The differences in the findings could be due to the terrain features of the Wichita Mountains and Blue Canyon. In Figures 6 and 9, it appears that the wave structure in the isentropes experiences amplification as they pass first over the Wichita Mountains and then the Slick Hills. This amplification process has been observed with other mountains where there is a series of ridges (COMET, 2004).

Draxl et al. also found that winds below 30-100 meters are often overpredicted. From Figures 5, 8, and 11, it appears that the winds are underestimated at Blue Canyon the majority of the time. However, conclusions about this bias are hard to make since the wind data comes from only one wind tower at Blue Canyon.

4. CONCLUSIONS

Several conclusions can be made from this work. First, it appears that regardless of the stability, during NLLJ events the strongest turbine hub height winds are located about 5 to 10 km downstream from Blue Canyon and the Slick Hills. This, however, does not necessarily indicate that Blue Canyon should have been relocated since this study only looked at summer time NLLJ events and not the year long wind climatology.

Secondly, accurate modeling of the stability in the lowest part of the atmosphere is important for accurate wind forecasts during NLLJ events due to the way the terrain influences the flow. A slight error in stability forecasting could mean the difference between wave or no wave activity. When there is wave activity, stability forecast errors will lead to error in wavelength and amplitude of the wave flow, leading to wind forecast errors. This error is expected knowing that the WRF neutralizes the stability (Draxl et al., 2010).

5. ACKNOWLEDGEMENTS

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