Simulation of Nocturnal LLJs with a WRF PBL Scheme Ensemble and Comparison to Observations from the ARM Project

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1. Introduction

Affecting everything from mesoscale convective systems to wind power production, low level jets (LLJs) play a pivotal role in weather over the Midwest. As areas of relatively fast-moving winds, LLJs have been most frequently studied because of their important role in transporting moisture to convective systems in the Central United States. LLJs are found in the lower troposphere and occur most often in the Great Plains of the United States. There are two types of LLJs: nocturnal and mid-latitude cyclone induced. Of these two types, the nocturnal LLJs are the most common and the type used in this research.

Several causes of nocturnal LLJs have been identified (see Stensrud 1996 for review). Perhaps one of the best known is the inertial oscillation by A. K. Blackadar. In 1957, Blackadar proposed a well-regarded theory on the formation of LLJs saying that frictional decoupling causes inertial oscillations in the early evening (Blackadar, 1957). During these early evening hours, a temperature inversion occurs and inhibits mixing, making the friction on the surface unable to affect the wind speeds aloft. This causes the wind speed to accelerate and a LLJ forms for there is no friction to stop it or slow it down.

Along with formation, the classification of LLJs based on intensity and duration has been another area of interest for many years. As a result, multiple studies about the climatology of LLJs have been completed. One of the most notable studies was Bonner (1968). In his study, Bonner established criteria for the classifications of wind speed and intensity during a LLJ event. Bonner's study and LLJ criterion remains the basis for many later LLJ studies. Whiteman (1997) looked at two years of LLJs in northern Oklahoma and found that LLJs occur 47% of the time during the warm season and 45% of the time during the cold season. Whiteman also noted that approximately 50% of the peak winds in LLJs occur below 500m.

Because of the very low elevation of LLJs, the best way currently to measure them is through the National Oceanic and Atmospheric Association (NOAA) Wind Profiler Network 404-mHZ radar profilers (Arritt, 1997). These profilers measure wind speed between 500m and 19km, unfortunately excluding the lowest 500 m where Whiteman found many jets may peak. There is little other observational data below 500 m (apart from surface data), and thus studying LLJs with 50% of the peak winds below 500 m has proven to be a daunting task. The task, though, is increasing in importance as taller wind turbines are being used to generate wind power, placing the blades closer to the strong winds within the LLJ. Thus, additional research is needed to understand the vertical profiles of winds beneath LLJs, and to improve forecasts of LLJs. The goal of the present study

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is to use wind profiler data from Lamont, OK, a site with data available much closer to the ground, to construct a climatology of winds in LLJ events and compare it with forecasts from an ensemble of numerical weather prediction models.

2. Data and Methodology

For this project, observed data was obtained from the U. S. Department of Energy's Atmospheric Radiation Measurement (ARM) project's Lamont, OK site. The Lamont, OK site (Fig. 1) is located just southeast of the city of Lamont on 160 acres of cattle pastures and wheat fields. The site is the central facility for the Southern Great Plains (SGP) research site, the first field site established for the ARM project, and the largest field site in the world.

Figure 1

Fig. 1: Location of Lamont site (Image from Google Earth)

The Lamont site is equipped with a 915-mHZ wind profiler. This type of profiler, unlike the 404-mHZ profilers, can measure wind speeds below 500 m. The Lamont, OK site was chosen based on the 915-mHZ profiler and the availability of data below 500 m. Using data below 2462 m, with a vertical resolution of 60 m, thirty cases were chosen between June 2008 and May 2010. Dates were selected for inclusion based on the presence of a nocturnal LLJ at the site with a mix of strong and weak LLJ cases chosen. Dates from November 14, 2008 to December 7, 2008 and from April 9, 2009 to August 13, 2009 were not used due to bad or missing data. In an attempt to have a complete year of data to work with, cases were analyzed when available between June 2008 and August 2009 and then selected from November 2009 and April and May 2010. Using the visual software program called Ferret, analysis took place and the thirty dates were selected. The thirty dates selected are as follows:

- June 26, 2008
- July 13, 2008
- August 4, 2008
- September 2, 3, 8, 30, 2008
- October 5, 19, 21, 2008
- December 14, 26, 2008
- February 7, 27, 2009
- March 5, 6, 19, 24, 27, 2009
- August 26, 28, 2009
- November 6, 7, 8, 9, 13, 14, 2009
- April 10, 22, 2010
- May 6, 2010

After selecting the thirty cases, we compared observations from these events to model output. Low Level Jets were simulated using an ensemble of 10 km grid spacing versions of the Weather Research and Forecasting (WRF) model and six different Planetary Boundary Layer (PBL) schemes. The PBL schemes used include the Mellor Yamada Janjic (MYJ), Yonsei University Scheme (YSU), Quasi Normal Scale Elimination (QNSE), Pleim or Asymmetric Convective Model (ACM2), and the Mellor Yamada Nakanishi Nino 2.5 and 3.0 (MYNN 2.5 and MYNN3.0). The Global Forecast System (GFS) numerical weather prediction model provided the initial and lateral boundary conditions. All model simulations were initialized at 00 UTC and ran for 54 hours; only the first 30 hours of the forecast were used in evaluation.

Comparisons between model output from the six different PBL scheme runs, an ensemble mean, and the observed data were looked at for peak wind speed, height of the LLJ max and duration. Duration was determined from a graphical display of the LLJ event. The duration starting hour was marked by the beginning of the LLJ event. The duration end hour was marked by either the end of the LLJ event or the hour in which the LLJ was one half the peak wind speed. LLJ strength and intensity was also determined and compared using the Bonner classification system as follows:

- Criteria 1 – Peak wind speed must equal or exceed 12 m/s and must decrease by at least 6 m/s by 3 km
- Criteria 2 – Peak wind speed must equal or exceed 16 m/s and must decrease by at least 8 m/s by 3 km.
- Criteria 3 – Peak wind speed must equal or exceed 20 m/s and must decrease by at least 10 m/s by 3 km

3. Results

A graphical representation showing an example of a strong LLJ with model forecasts can be seen in Fig. 2. The plot is from the June 26, 2008 case and represents one hour of the time during which the LLJ event occurred.

Figure2

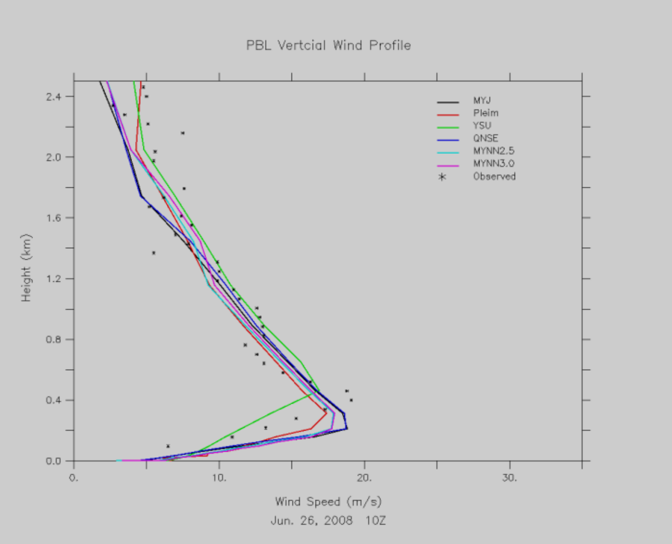

Fig. 2: Comparison of observed data from the Lamont, OK site to WRF runs with six PBL schemes at 10Z (4am CDT) June 26, 2008

In this case, it appears most of the PBL schemes led to a LLJ whose peak elevation was too low compared to observations. The one exception was the run using the YSU scheme.

Using all cases, averages were determined for peak wind speed, elevation of peak wind, and duration. Table 1 shows the comparison of the six schemes to observations for peak wind speed. All six PBL schemes and the ensemble mean under-predict the observed data with the QNSE scheme producing the best results: a mean under-prediction of 3.6 m/s. The YSU scheme leads to the largest underestimate of peak speed, 6.4 m/s.

Table 1: Average Peak Wind Speed

MYJ	Pleim	YSU	QNSE	MYNN 2.5	MYNN 3.0	Ensemble	OBS
19.0m/s	18.2m/s	16.3m/s	19.1m/s	18.2m/s	17.9m/s	18.1m/s	22.7m/s

Table 1: Average peak wind speed for each PBL scheme, the ensemble mean, and the observed data from all 30 cases

Table 2 shows results for the average height of the LLJ maximum. All six PBL schemes and the ensemble mean under-predicted the observed data with the YSU scheme producing the best results: an under-prediction of only 15 m. The QNSE and MYNN predicted the lowest height of the maximum, an underestimate exceeding 200 m.

Table 2: Average Height of LLJ Max

MYJ	Pleim	YSU	QNSE	MYNN 2.5	MYNN 3.0	Ensemble	OBS
371.2m	427.0m	538.3m	344.5m	365.3m	340.3m	397.8m	553.0m

Table 2: Average height of low level jet maximum for each PBL scheme, the ensemble mean, and the observed data from all 30 cases

Table 3 compares the average duration of the LLJ events in the models to observations. The duration of the simulated LLJ events was roughly 11 hours, a value matching results from the observed data well.

Table 3: Average Duration

MYJ	Pleim	YSU	QNSE	MYNN 2.5	MYNN 3.0	Ensemble	OBS
10.6hrs	10.4hrs	10.3hrs	10.6hrs	10.6hrs	10.6hrs	10.5hrs	11.1hrs

Table 3: Average duration of the LLJ event for each PBL scheme, the ensemble mean, and the observed data from all 30 cases

The observed data and model output was also broken down into the Bonner classification criteria (shown earlier). After being classified, the cases that satisfied each criterion were compared to one another for all three calculations: average peak wind speed, average height of the LLJ maximum, and average duration. First, for Bonner Criteria 1, all schemes except YSU over-predicted the average peak wind speed, although amounts were less than 2 m/s, and all schemes except MYJ over-predicted the average height of the LLJ maximum (Table 4). The average duration was under-predicted by the schemes for this criterion by as much as 6 hours for Pleim.

Table 4: Bonner Criteria 1

	Avg Peak Wind Spd	Avg Height of LLJ Max	Avg Duration
MYJ	15.2m/s	270.0m	7.7hrs
Pleim	14.5m/s	490.0m	5.3hrs
YSU	13.7m/s	583.3m	5.7hrs
QNSE	15.8m/s	463.3m	8.0hrs
MYNN2.5	15.1m/s	436.7m	8.0hrs
MYNN3.0	14.3m/s	403.3m	8.0hrs
Ensemble	14.6m/s	441.1m	7.1hrs
OBS	13.9m/s	366.7m	11.3hrs

Table 4: Results for all cases classified as Bonner Criteria 1

For Bonner Criteria 2 (Table 5), the schemes performed opposite to that of Bonner Criteria 1, under-predicting the average peak wind speed by roughly 2-4 m/s, and average height of LLJ maximum by 50-250 m. The duration, however, was over-predicted by the schemes, often by around 2 hours.

Table 5: Bonner Criteria 2

	Avg Peak Wind Spd	Avg Height of LLJ Max	Avg Duration
MYJ	19.4m/s	365.0m	12.0hrs
Pleim	18.1m/s	414.0m	11.9hrs
YSU	17.7m/s	538.0m	11.6hrs
QNSE	19.0m/s	352.0m	12.0hrs
MYNN2.5	18.3m/s	373.0m	12.0hrs
MYNN3.0	17.8m/s	373.0m	11.9hrs
Ensemble	18.4m/s	402.5m	11.9hrs
OBS	21.7m/s	592.0m	10.2hrs

Table 5: Results for all cases classified as Bonner Criteria 2

Bonner Criteria 3 results (Table 6) showed the schemes under-predicting all three calculations: average peak wind speed, average height of LLJ maximum, and average duration. Wind speeds were typically underestimated by 6 m/s, except for YSU, which was closer to 9 m/s.

Table 6: Bonner Criteria 3

	Avg Peak Wind Spd	Avg Height of LLJ Max	Avg Duration
MYJ	20.2m/s	410.9m	10.5hrs
Pleim	19.7m/s	441.3m	10.4hrs
YSU	16.7m/s	548.1m	10.4hrs
QNSE	20.5m/s	369.1m	10.4hrs
MYNN2.5	19.7m/s	400.0m	10.5hrs
MYNN3.0	19.3m/s	358.1m	10.5hrs
Ensemble	19.4m/s	421.3m	10.5hrs
OBS	25.8m/s	575.0m	12.0hrs

Table 6: Results for all cases classified as Bonner Criteria 3

Finally, the frequency of the hour in which the peak wind speed occured from the nocturnal LLJ event was also examined (Fig. 3).

Figure 3

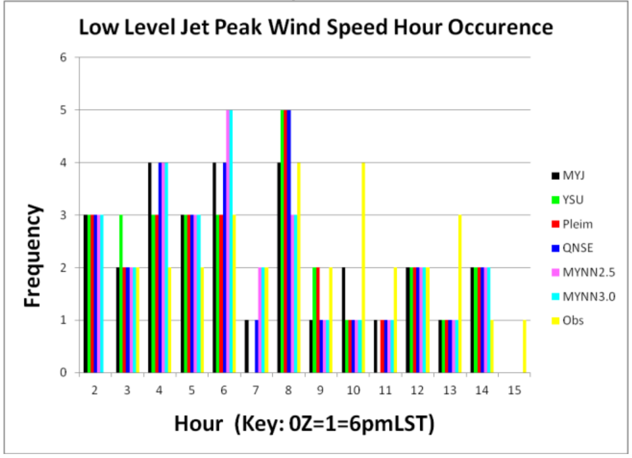

Fig. 3: Frequency of hour in which the peak wind speed took place for both the simulations and observed data

All schemes showed the peak wind speeds likely occurring in the late night hours up until around 1 am LST, while the observations showed the peak wind speed more likely to occur a little later, with twin peaks at 1 and 3 am LST. The peak wind speed never occurred more than five times at any one hour showing a pretty even spread during the night.

4. Summary and Conclusions

By comparing six different configurations of the WRF model, each using a different PBL scheme, and the ensemble mean, made up of those members, to observations from the Lamont, OK wind profiler, it was shown that average peak wind speeds are under-predicted by all ensemble members. In addition, and of potentially more importance to wind energy interests, with the exception of the YSU scheme, all of the schemes under-predicted the average height of the LLJ maximum by more than 150 m. Thus, it appears substantial improvements are still needed in numerical weather prediction codes to improve accuracy of forecasts for peak LLJ winds and elevation of the jet. However, duration of the modeled LLJ events agreed rather well with observed data.

Application of the Bonner Classification revealed some differences in behavior based on the type of event. Peak wind speed and height of LLJ maximum were over-predicted by most models for Bonner Criteria 1. Duration was under-predicted by almost 4 hours. This is definitely a substantial difference considering nocturnal LLJs usually only last for around 13 hours. For Bonner Criteria 2, the models under-predicted peak wind speed and average height of LLJ maximum whereas they over-predicted the duration. For Bonner Criteria 3 cases, the models under-predicted both average height of the LLJ maximum and average duration. For the average peak wind speed, the models of those cases classified as a Bonner Criteria 3 under-predicted the average wind speed with a larger difference than Bonner Criteria 1 or 2. Finally, examining temporal trends of jet peak, we found the models had peak wind speeds occurring during the late night, typically a few hours before observed jets peaked.

Overall, the results suggest substantial differences in the simulation of LLJs depending on which PBL scheme is used. No one scheme performs considerably better than any other and all show some serious errors. These differences will result in higher wind forecast uncertainty as taller turbines are created and used for wind power generation.

5. Acknowledgments

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6. References

ARM Climate Research Facility, U.S. Department of Energy, Office of Science, [Available online at http://www.arm.gov/.]

Arritt, R. W., T. D. Rink, M. Segal, D. P. Todey, C. A. Clark, M. J. Mitchell, and K. M. Labas, 1997: The Great Plains low-level jet during the warm season of 1993. Mon. Wea. Rev.,125, 2176–2192.

Blackadar, A. K. 1957. Boundary layer wind maximum and their significance for the growth of nocturnal inversions, Bull. Amer. Met. Soc., 38, 283-290.

Bonner, W.D., 1968: Climatology of the Low Level Jet. Mon. Wea. Rev, 96, 833–850.

Daniel, C. J., R. W. Arritt, and C. J. Anderson, 1999: Accuracy of 404-MHz radar profilers for detection of low-level jets over the central United States. J. Appl. Meteor, 38:1391–1399.

Stensrud, D. J., 1996: Importance of low-level jets to climate: A review. *J. Climate*, **9**, 1698-1711.

Whiteman, C. D., X. Bian, and S. Zhong, 1997: Low-level jet climatology from enhanced rawinsonde observations at a site in the Southern Great Plains. J. Appl. Meteor., **36**:1363–1376.