WRF PBL SENSITIVITIES AND VERIFICATION IN FORECASTING LOW-LEVEL JET EVENTS.

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1. INTRODUCTION AND MOTIVATION

Nocturnal low-level jets (LLJs) are common features observed in the Great Plains region of the United States. LLJs play a key factor in initiating and sustaining mesoscale convective systems and other severe convective storm modes in the Great Plains. It has been previously shown that the LLJ is important source of water vapor over the Great Plains. The moisture convergence associated with LLJs has been shown to be linked to summer rainfall over the central United States. The widespread flooding in the central United States during the summer of 1993 has been linked to the strong southerly LLJ during this time (Arrit et al., 1997).

To forecast LLJs, accurate representation of the PBL is crucial, which is also important for being able to forecast many high impact events. Accurate representation of the LLJ can help forecasters predict where severe weather will initiate. At present, NWP models face a challenge in precise forecasting of the development, magnitude, and location of LLJs (Banta et al., 2002). This is due to the fact that LLJs are common during nighttime stable boundary layers, and there is a general consensus among researchers that our contemporary understanding and modeling capability of this boundary layer regime is quite poor.

In the present work, we investigate the potential of the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) in simulating an LLJ event and associated stably stratified boundary layer observed over the Southern High Plains of western Texas on June 2nd, 2004. During this night, over a period of 8 hours (from 04 to 12 UTC), two distinct low-level jet structures with wind maxima of greater than 16 ms^{-1} were observed. An extensive array of in-house monitoring systems is effectively utilized to study this event in great detail and assess the performance of the WRF model with different model configurations.

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2. DATA AND METHODS

To test the capabilities of the WRF in predicting an LLJ, a case well observed at Texas Tech University's Wind Science and Engineering (WISE) research center field site was used to compare the model results. The WISE research center field site includes an instrumented 200 meter tower, a boundary layer profiler, and the Reese mesonet station from the West Texas Mesonet network. Due to questions regarding the quality of the 200 meter tower data during June, 2004 (due to a lightning strike), these data were not rigorously compared to the model results and will not be presented in this paper.

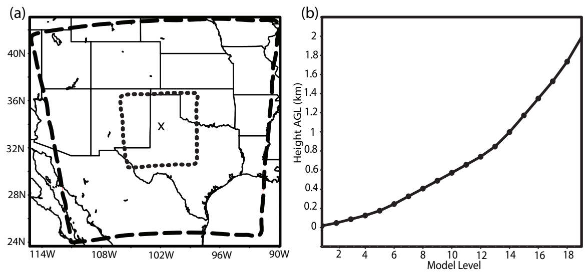

Figure 1: a) Domain coverage for 4 km grid (dashed line) and 1.33 km grid (dotted line). Wise field site location denoted by X. b) model levels and corresponding height AGL (km) at the WISE field site.

The Texas Tech boundary layer profiler, a Vaisala LAP-3000, 915 MHZ Doppler radar vertical profiler (Schroeder et al., 2005), has a vertical resolution of 60 meters, with an output of 30 minute averaged data. Data below 1 km AGL was mainly utilized due to loss of data above this level. Unfortunately, the RASS system, used to determine temperature profiles, was not functioning during the time of interest. This results in only wind profiles from the profiler being compared to the model output. Temperature and wind data from the Reese mesonet site were compared to the model output at the nearest grid point location. The temperature and wind data were also used to calculate upward heat flux, friction velocity, and Monin-Obukhov length based on similarity theory.

A pre-released version of the ARW (WRF version

Table 1: WRF parameters varying in model comparisons.

Model Run	PBL	Grid resolution	LW / SW radiation	Initialization Time (1 June 2004)	Initialization Source
YSU_rrtm	YSU	4km	RRTM/Dudhia	18 UTC	AWIP
MYJ_rrtm	MYJ	4km	RRTM/Dudhia	18 UTC	AWIP
MYJ_gfdl	MYJ	4km	GFDL/GFDL	18 UTC	AWIP
YSU_gfdl	YSU	4km	GFDL/GFDL	18 UTC	AWIP
YSU_12z	YSU	4km	RRTM/Dudhia	12 UTC	NARR
YSU_nest	YSU	4/1.33km	RRTM/Dudhia	18 UTC	AWIP

2.2) (referred to as WRF from hereon) was evaluated. Two PBL schemes, YSU and MYJ, are available in WRF and were the foundation of this study. Various configurations were evaluated to determine if any one configuration showed a clear benefit over the others. A 500x500 horizontal grid with either 4 /1.33 km spacing (Fig. 1a) and 36 vertical levels (13 below 1 km AGL) were used (Fig 1b). The number of vertical levels in the lowest 1 km is greater (almost double) than what is used typically in operational models.

Other common features between the model runs presented in this report include: 30-second USGS land use and topographic height data interpolated onto the grids domain, NOAH land-surface model (Chen and Dudhia, 2001), Ferrier microphysics (Ferrier et al., 2002), no cumulus parameterization, and the turbulence and mixing option turned off. This means no additional turbulence or explicit numerical filters are performed in either the horizontal or vertical, therefore all of the vertical mixing and diffusion is being performed by the boundary layer scheme. Two combinations of long-wave and shortwave radiation schemes were used, the Dudhia (Dudhia, 1989) simple cloud interactive shortwave scheme along with the rapid radiative transfer model (RRTM) long-wave radiation (Mlawer et al., 1997) scheme, and the Geophysical Fluid Dynamics Laboratory (GFDL) shortwave and long-wave schemes (Fels and Schwarztkopf, 1975; Lacis and Hansen, 1974) (Table 1). The PBL schemes, grid size resolution, initialization time, and initialization source were varied and shown in Table 1. All of the grids had the WISE field site in the center of the domain.

3. RESULTS

1) Wind Speed and Direction Profiles

Wind speed and wind direction profiles from the WRF grid point that corresponds to the WISE field site were compared to the wind speed and direction profiles from the Texas Tech profiler (Fig. 2 and Fig. 3). Since no distinct difference between the MYJ_rrtm and MYJ_gfdl runs as well as the YSU_rrtm and MYJ_gfdl runs were found, only model solutions using the RRTM radiation schemes are presented.

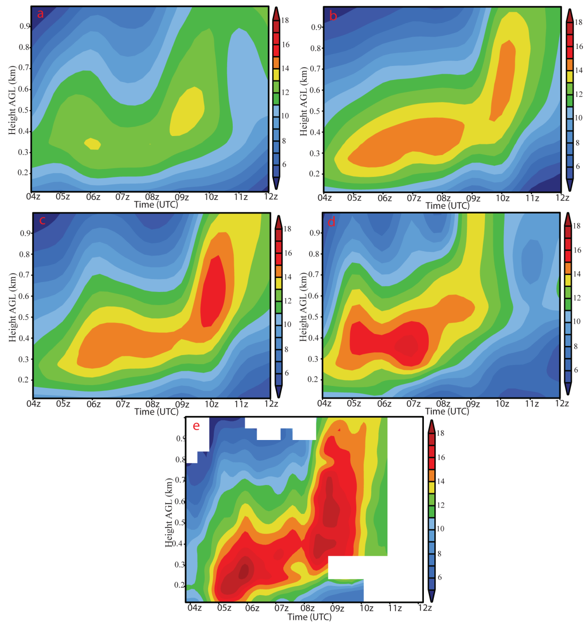

Figure 2: (a) - (d) hourly outputted WRF wind speed profiles (ms^{-1}) for grid point corresponding to WISE field site for YSU_12z, YSU_nested, YSU_rrtm, MYJ_rrtm respectively from 0400 UTC – 1200 UTC, 02 June 2004. (e) Texas Tech boundary layer profiler wind speed (ms^{-1}) from 2 June 2004 04 UTC – 12 UTC.

As seen in Fig. 2e, two jet maximums with wind speeds greater than 16 ms^{-1} were observed on 2 June 2004. The first occurred between 0530 - 0630 UTC, spanning from just above the ground to around 0.5 km AGL. The second maximum occurred between 0830 – 0930 UTC, spanning from around 0.3 – 0.9 km AGL. The first jet had a predominantly easterly direction, while the second maximum had a more southerly direction (Fig. 3e). At first we believed that the two maximums were the result of the first jet evolving and turning due to the inertial oscillation, but it was found that these two maxima are possibly from two separate LLJs. The forcing mechanism of these jets is not clear at this time.

According to Fig. 2 and Fig. 3, most of the simulations fairly well represented the spatial and temporal

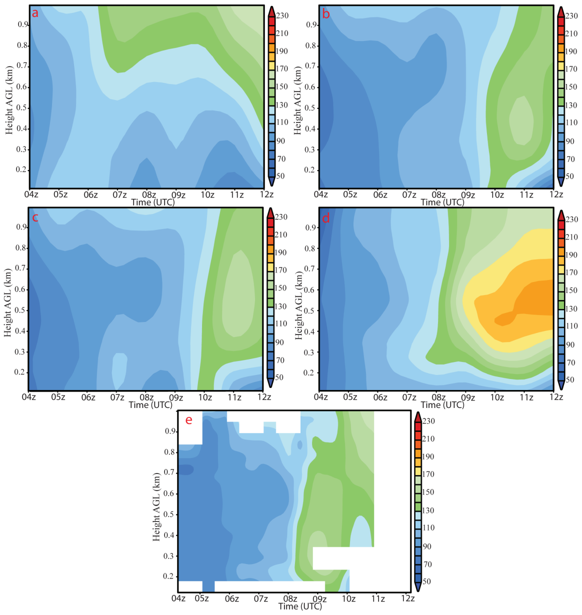

Figure 3: Same as Fig. 2 except for wind direction (degrees).

characteristics of the two LLJs observed. The YSU_12z (Fig. 2a and Fig. 3a) had significantly weaker wind speeds and different wind directions than the observed and other YSU simulations. The differences in the wind speed and direction from the YSU_12z compared to the YSU_rrtm (Fig. 2a,c and Fig. 3a,c), indicate the initialization time and input can have a significant impact on the solution. Similar results between the YSU_nest and YSU_rrtm were found. First indications imply that increasing the horizontal resolution does not give an inherent benefit on forecasting the structure and wind speed of this LLJ when the grid spacing is within the kilometer range. The MYJ_rrtm model has stronger wind speeds for the LLJ occurring at 0600 UTC than the YSU runs at this given grid point, and were closer to what was observed (Fig. 2). Significant differences between the MYJ_rrtm and profiler wind direction were also observed, while the YSU_rrtm and YSU_nest represented the wind direction accurately with a slight time displacement (Fig. 3b,c,d,e).

We would like to stress that these results are based on one grid point from WRF outputted every hour. Increasing the time resolution and changing the location of the grid point just slightly can make a significant difference in the results. For example, the YSU_rrtm had stronger winds roughly 35 km south (33.3^o N) of the WISE field site (33.6^o N), and were closer to what was observed (Fig. 4a and Fig. 2e).

At the same location, MYJ_rrtm did not represent the structure of both LLJs as well (Fig 4b and Fig. 2e). This

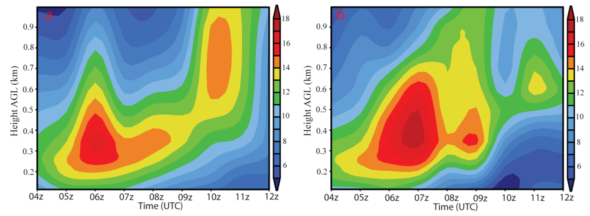

Figure 4: Hourly outputted WRF wind speed time-height plots (ms^{-1}) for grid point 35 km south of WISE field site from 0400 UTC – 1200 UTC, 02 June 2004, (a) YSU_rrtm, (b) MYJ_rrtm.

indicates that the spatial variability in the LLJ being represented by WRF is large, and may be of concern. It is not clear whether or not such large variability in the structure of the LLJ is observed in the real world since most studies of LLJs use single point observations (e.g. Bonner, 1968; Whiteman et al., 1997; Song et al., 2005). The WISE research center along with the Texas Tech atmospheric department is currently constructing two mobile Ka-band radars, which would be able to give large spatial coverage of the 3-D wind field, and consequently LLJ properties.

3.1 *Surface Parameters*

To further evaluate the various model runs, comparisons to surface parameters related to the wind power industry were done (10 m wind speed, and u_*) . Evaluation of the 10 meter wind (Fig. 5) shows that most of the WRF configurations evaluated represented the 10 meter wind within 1-3 ms^{-1}. Small differences were noted between the RRTM and GFDL simulations, but are not shown since the differences were not significant. Also, only small differences between YSU_nest and YSU_rrtm were observed (not shown). Increasing the horizontal resolution in this case did not show a significant improvement of the forecast. In areas with complex topography and land use, fine grid spacing maybe necessary. The YSU_12z simulation did not represent the peak wind speed observed around 0600 UTC as accurately as the simulations started at 1800 UTC (Fig. 5). This again shows the impact of the initialization time and input data for accurate model simulations. All of the simulations also had difficulty on predicting the wind speed after 0800 UTC.

When comparing the friction velocity (u_*) from WRF to that observed, small differences are present (Fig. 6a). Friction velocity is given as:

$$u_* = \frac{k * U}{ln(z/z_o) + \psi_m} \quad (1)$$

where k is the von Karman constant (0.4), U is the wind

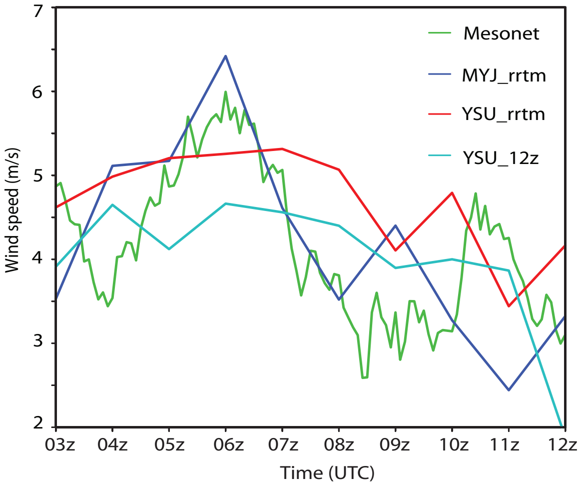

Figure 5: Observed (5 min. resolution) 10 meter wind speed (ms^{-1}) from WISE mesonet station (solid) and WRF corresponding grid point 10 meter wind speed (ms^{-1}) outputted every hour, valid through 0300 UTC - 1200 UTC, 02 June 2004.

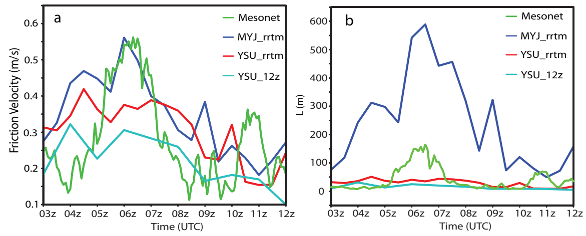

Figure 6: (a) Calculated (5 min. resolution) friction velocity (ms^{-1}) and (b) Monin-Obukhov length (L), from WISE mesonet station (solid) and WRF corresponding grid point friction velocity (ms^{-1}) outputted every 30 minutes. Valid through 0300 UTC - 1200 UTC, 02 June 2004.

speed, z is the height of U, z_o is the roughness length (assumed to be a constant 0.12 m in WRF at the grid point corresponding to the WISE field site and in calculations), and ψ_m is the stability function. The largest difference between the WRF u_* to that observed is from the YSU_12z run. This larger difference is partially due to the fact that the wind speed from the YSU_12z run is weaker than what was observed (Fig 5). Another possible source of error in which could account for the differences between u_* in the WRF and that observed, are errors in the stability function (Eq. 1).

The MYJ had a larger Monin-Obukhov length (L) than was observed for most the whole time period (Fig. 6b), while YSU underrepresented L between 0500 - 0700 and 1030 - 1130 UTC. Reasons for the misrepresentation at this time is not clear. This indicates though that the stability between the two models are different, with the YSU being more stable than the MYJ, and the MYJ being less stable than what was observed. However, the YSU was found to have very little variation in L, and being smaller than what was observed.

The differences in the stability parameters can also be explained in the potential temperature (θ) profiles aloft. Negative upward heat fluxes were observed and found in the model output, therefore the boundary layer would be classified as stable. However, potential temperature profiles (not shown) indicate that between 0600 - 0900 UTC that both the MYJ and YSU runs made the atmosphere less statically stable in the lowest 300 meters. The MYJ was even slightly statically unstable at 0600 UTC around 100 - 300 m AGL. Unfortunately no observed temperature data aloft is available for comparison due to the radio acoustic sounding system (RASS) feature on the profiler malfunctioning during this time. Reasons for why the temperature profiles varied between MYJ and YSU is not exactly known at this time as mentioned before. The NOAH land surface layer scheme alters the upward heat flux. This alteration may have negative impacts on the representation of L and other consequent parameters during stable night time hours, and should be further investigated.

4. CONCLUSIONS AND FUTURE WORK

Various WRF configurations were investigated to determine if the WRF model could forecast a LLJ from 2 June 2004, and if any clear biases or benefits were evident. Overall, both the YSU and MYJ configurations initialized at 1800 UTC 1 June 2004 represented the LLJ (Fig. 2 and Fig. 3). The YSU configurations portrayed the structure and direction of the LLJ better than MYJ, but had weaker wind speeds than the MYJ. Since WRF attempts to represent the timing, location, and in some way the magnitude of the LLJ, it is believed the parameterizations in the PBL schemes are performing well, but room for improvement is obvious for stable conditions.

Other factors, such as horizontal grid resolution were investigated. No large benefit was found using a 1.33 km two-way nest inside the 4 km domain (Fig. 2b,c and Fig. 3b,c). Since the 1.33 km nest is more computationally expensive, and did not show any benefit over the 4 km grid, it is possible the 4 km grid would be sufficient for representing LLJs.

It is not clear at this time how sensitive LLJ prediction is to vertical resolution. Vertical resolution may play a larger factor than horizontal resolution, and will be investigated in the future. The current configuration has 13 levels below 1 km with a spacing ranging from around 30 - 80 m. Current operational mesoscale NWP models have fewer vertical levels representing the boundary layer, typically around 5-7 levels. Representation of the boundary layer may be influenced with the amount of vertical levels used.

Initialization time and input source were also investigated. The NARR input was used instead of the AWIP input for the 1200 UTC initialization because of errors in the AWIP input at 1200 UTC 1 June 2004. A comparable input source was used instead, the NARR (some believe due to the higher grid and time resolution that the NARR is a better input). It was found that the YSU_12z did not predict the strength or direction of the jet accurately (Fig. 2 and Fig. 3). This single test indicates that accurately predicting LLJs more than 12 hours before hand may be difficult to do. Future work on determining the model predictability of LLJs will help in determining the current time constraints.

To determine the validity of the WRF forecasts, surface variables were also investigated. The 10 m wind speed in all the models, except for YSU_12z, were fairly accurate. Similar results were found when evaluating the friction velocity. Differences between the temperature profiles and stability were found. This difference may account for some of the variability in the friction velocity. The differences in the mixing length as well as the temperature profiles and friction velocity can help explain the differences in the magnitude of wind observed between the YSU_rrtm and MYJ_rrtm.

It is important to point out that all of these conclusions are based on one given example. In the future more cases will be investigated to determine if similar results are found. It is hope of the authors that this work will help lead to determining the predictability of LLJs.

5. ACKNOWLEDGMENTS

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