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The Relationship of the Great Plains Low Level Jet to Nocturnal MCS Development

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1. INTRODUCTION

Mesoscale Convective Systems (MCSs) and Mesoscale Convective Complexes (MCCs) of the Great Plains create numerous hazards, including damaging winds, large hail, frequent lightning, flooding rains, and occasional tornadoes. Because of the numerous types of severe convective phenomena associated with these systems, accurate prediction of their initiation and development is important for operational forecasting in the warm season (Stensrud and Fritsch 1993). Oftentimes MCS initiation occurs after sunset, indicating that their occurrence is separate from diurnal convection, which is especially prevalent during the spring and summer months. Another prominent nocturnal feature of the Great Plains is the low-level jet (LLJ). Thus, it would be natural to assume a relationship between LLJs and MCS initiation. In fact, many studies have investigated the role of the LLJ in MCS initiation and development, including Walters and Winkler (2001a, and 2001b), Uccellini and Johnson (1979), and Higgins et al. (1997).

The nocturnal LLJ is characterized by a strong, near-surface southerly wind maximum that transports warm, moist air from the Gulf of Mexico northward. This moisture and temperature advection promotes instability and enhanced low-level convergence for vertical motion, leading to the release of this instability (Walters and Winkler 2001). Bonner (1968) defines three categories of LLJs based on intensity in an attempt to distinguish between them for climatological purposes. In criterion-1 LLJs, the maximum wind speed exceeds 12 ms^{-1}, with maximum winds exceeding 16 ms^{-1} and 20 ms^{-1} for criterion-2 and -3, respectively. Also, the LLJ must be a distinct, isolated low-level maximum, having winds decreasing to a minimum speed just above the jet maximum, but below 3 km AGL.

Whiteman et al. (1997) found that the peak frequency of the low-level wind maximum height is at or below 500 m AGL, and that over 80% of the cases had the jet maximum at or below 1 km AGL. Whereas earlier studies stressed the lower frequency of criterion-3 LLJs, Whiteman et al. (1997) found that the strongest jets occurred at a much higher frequency than expected.

This study investigates the role of the LLJ in the initiation and development of MCSs over the Great Plains during the 2005 warm season (June, July, and August).

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2. METHODOLOGY

The data set for this study was compiled using cases from the summer (June, July, August) of 2005 in the Great Plains. The domain (Fig. 1) was roughly defined by the area enclosed by 102°W longitude, 90°W longitude, 33°N latitude, and 49°N latitude (the United States – Canada border). The emphasis of this study is the relationship between the LLJ and MCS initiation, so nocturnal MCSs with initiation between 0300 UTC and 1200 UTC are preferred.

The initial data collection pass utilized archived 3-hour infrared satellite imagery. Storms that appeared to reach MCC cloud-top criteria (Maddox 1980) were documented for further investigation. The second pass through the list of potential cases used national mosaic base reflectivity data from the National Weather Service (NWS) WSR-88D network. Cases were included if the storms evolved into an organized squall line or organized cluster of cells, with a common cold cirrus canopy near MCC criteria. Also, only cases that significantly intensified or initiated after 0300 UTC were included. Significant intensification was determined using mosaic base reflectivity data, and was defined to be when there was a noticeable increase in the coverage and intensity of convective cells (>45 dBZ). Initiation was defined to occur when the first strong echoes (>45 dBZ) appeared. The date, time of initiation, dissipation, and location of each MCS event were documented. The initiation locations were plotted on the domain and climatology plots were constructed (Fig. 3). Severe storm reports (tornado, hail and wind) and flooding reports (both flash floods and floods) from each case were documented.

The next phase of the study investigated LLJs coinciding with the aforementioned MCS events. Archived wind profiler data from the National Climatic Data Center were utilized to detect the geographic location of the maxima, height, and time of the LLJ maximum wind speed for each case. Plots of the MCS and wind profiler data for each case were constructed to determine the location of the MCS initiation relative to the LLJ maximum (Fig. 4). Additionally, profiler data from several days in which no MCSs occurred were examined to determine any noticeable differences in LLJ characteristics (e.g., intensity, location, etc.) from days in which MCSs did occur. Point-forecast soundings from the RUC model at the time of the initiation, immediately downstream of the MCS, were also collected and many thermodynamic parameters calculated for each case.

3. RESULTS AND DISCUSSION

3.1 MCS Characteristics

A final data set of 45 MCS cases was compiled, and the positions of each MCS initiation location are plotted and shown in Figure 2. The point of initiation was taken to be at the center of the convective line or centroid of the convective cluster.

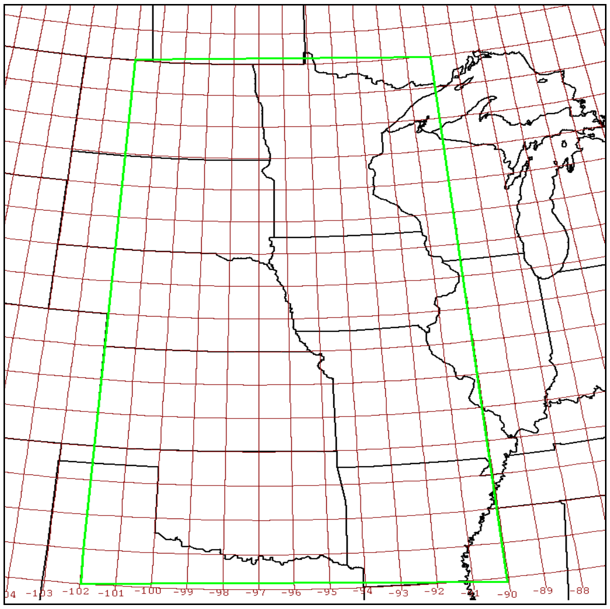

Fig. 1. *Domain used in the study is outlined in green*.

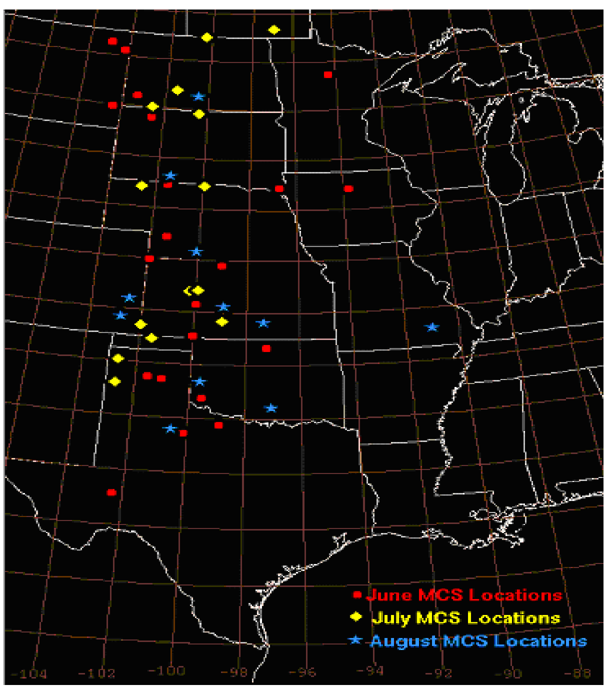

Fig. 2. *All MCS initiation locations from the summer of 2005 data set. Red markers represent June initiation locations, with yellow and blue representing July and August locations, respectively.*

It is evident from Fig. 2 that there are several discernable trends. In June, the MCS initiations almost exclusively occur west of 99°W longitude but extend from central Texas northward to the Canadian border. In July there are two distinct maxima in the concentration of MCS initiation, one centered on the Oklahoma/Texas panhandles and another spanning across the western half of the Dakotas. In August, the favored location for initiation is concentrated in the Central and Southern Plains.

3.2 LLJ Characteristics

The LLJs in the MCS cases can be classified using the criterion presented in Section 1 from Bonner (1968). Interestingly, the overwhelming majority of MCS cases were associated with criterion-3 (intense) LLJs, as shown in the histogram in Figure 3. Out of all the MCS cases, only one case had a very weak or negligible LLJ (the maximum wind speed was 10 ms^{-1}, shy of the Bonner criterion-1). Because the criterion-3 presented by Bonner (1968) only uses a threshold wind maximum of 20 ms^{-1}, and the fact that the authors have noted numerous cases both in this study and in operational forecasting observations when the LLJ intensity greatly exceeded the minimum threshold for criterion-3, the scale has been extended in increments of 4 ms^{-1}. Thus, criterion-4, -5, and -6 LLJs would have maximum winds exceeding 24 ms^{-1}, 28 ms^{-1}, and 32 ms^{-1}, respectively. The histogram showing the distribution of LLJ classes from the summer MCS cases is shown in Figure 4, and the results are quite interesting. The distribution is perfectly symmetrical, and almost normal.

It is important to note that of the non-MCS days that were examined for LLJs, several did have strong (criterion-3+) jets. Nevertheless, it appears that although LLJs do not cause the MCS itself, the presence of LLJs (particularly the strong ones) are necessary for MCS initiation a majority of the time.

The location of the maximum observed wind speed for each LLJ was recorded and these are shown in Figure 5. The highest concentration of LLJ maxima appear to be quite similar in June and July, though by August the frequency of LLJs and MCSs is smaller.

The vast majority of cases (21) had an anticyclonically curved LLJ axis, while 5 were straight and 6 had a cyclonically curved axis. The LLJ axis in each of the remaining 13 cases did not have a discernable shape. Note that just three categories of shapes are probably oversimplifying the true characteristics of the LLJ. For instance, Walters and Winkler (2001) describe 12 different LLJ shapes. However, the objectivity of their analysis is questionable because of the poor spatial resolution of the profiler and rawindsonde network. For this study, the three basic shapes of LLJs presented appear suitable to describe the observed LLJ configurations reasonably well.

The location of the MCS initiation relative to the LLJ is shown in Fig. 6, and a preponderance of points is clearly located at the exit region of the LLJ maximum, also appearing to favor the left terminus of the jet core. Using analogous arguments to upper level jets, the left exit region would be expected to have associated rising motion due to the secondary circulation, aiding in the development of MCSs. Perhaps more importantly, the nose of the LLJ focuses both low level Θ_e advection and mass convergence. Note that there were no MCS initiations in the right entrance region, though there were several in the left entrance.

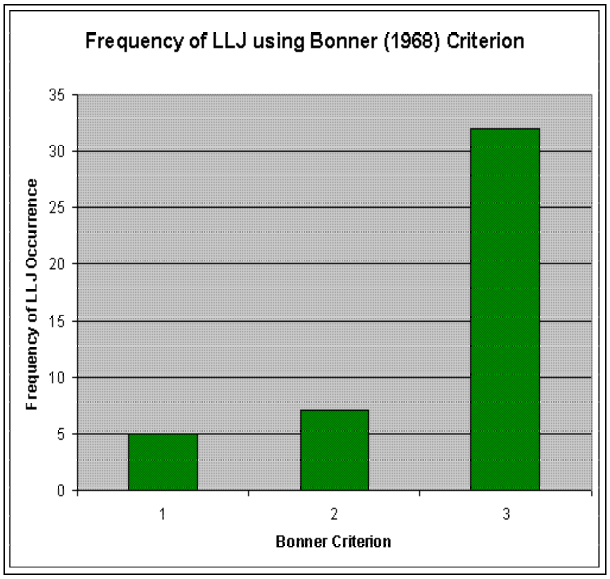

Fig. 3. *Histogram showing the Bonner (1968) criterion LLJs frequency of occurrence from the summer 2005 MCS data set. Note the overwhelming majority of criterion-3 LLJs.*

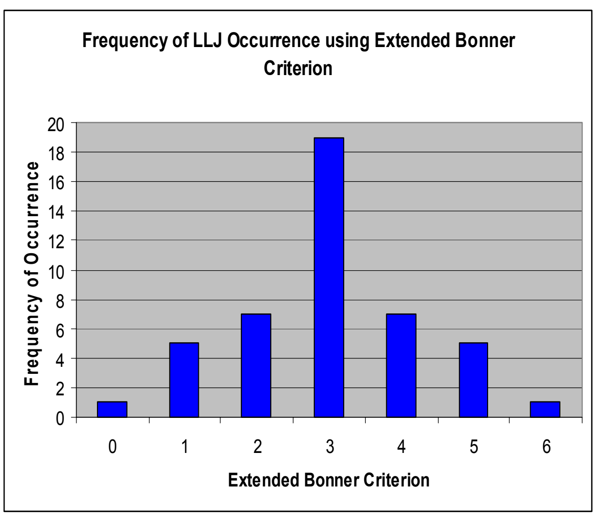

Fig 4. *Same as Figure 3, but using the extended criterion.*

3.3 Severe Storm Reports

Next, the severity of the MCS cases as related to the strength of the LLJ was investigated. Figure 7 shows the number of severe reports from each MCS case plotted against the Bonner (1968) criterion. There were no tornado reports associated with any of the MCS cases included in this case study. As the LLJ increases in intensity, or criterion number, the MCSs had more severe reports. However, lower-end severe events (with 20 reports or less) tended to be equally as likely with all three criterion LLJs.

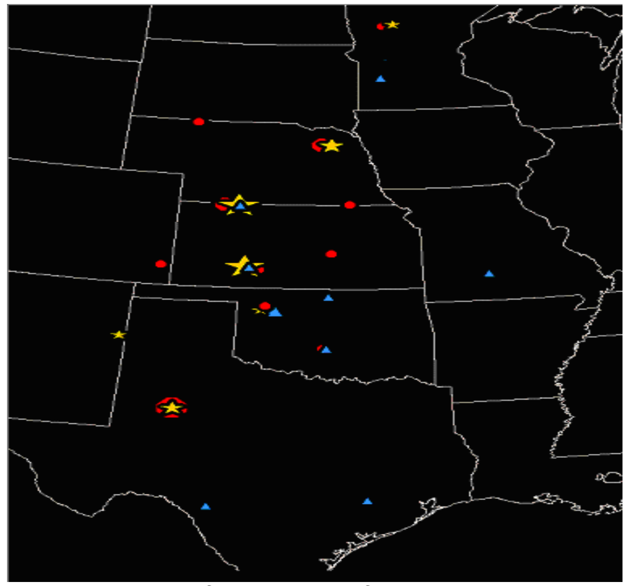

Fig. 5. *Location of LLJ maxima for the entire data set. Red circles correspond to June, yellow stars to July, and blue triangles to August. The size of the marker reflects the frequency of occurrence (small = 1, medium = 2, large = 3).*

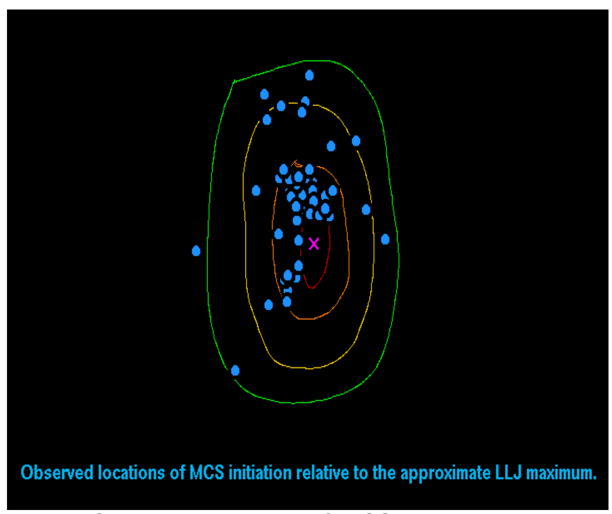

Fig. 6. *Observed locations of MCS initiation relative to the LLJ core. This is a schematic and the distances are not to scale, though the relative locations are accurate.*

A similar trend is evident for the flood reports associated with each MCS case (not shown). The flood reports included both floods and flash floods. However, when comparing flood reports to reports of large hail and damaging winds for the entire data set, there is no clear trend. The number of severe reports generally decreased with time during the life of the MCS, with most occurring at the beginning of its organizational stage. This is especially true for specifically hail reports, when the convection was transitioning between discrete and linear modes. There were no large hail reports (>2.00 in) once the storm transitioned to a linear mode. This decrease in storm reports over the lifetime of the MCS could be due to the MCS weakening with time, or that the number of people observing the storms decreased with time (since these events occurred overnight and in the early morning hours).

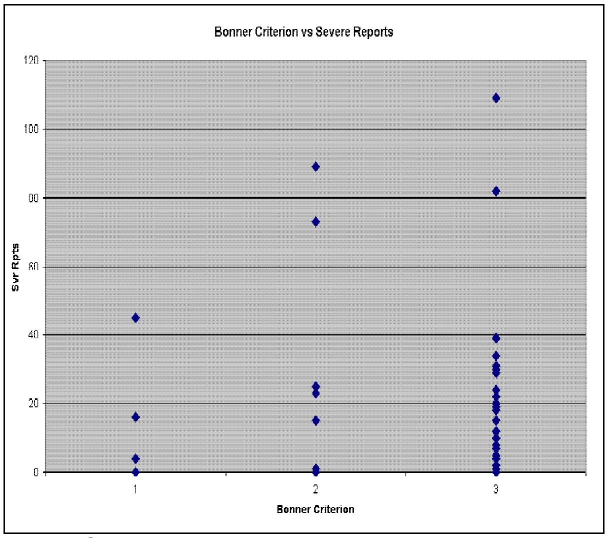

Fig. 7. *Severe reports (hail and wind only) compared to intensity of the LLJ, given by the Bonner (1968) criterion. The single case where the LLJ failed to meet any of the Bonner criteria was omitted.*

3.4 RUC Environmental Parameter Correlations

The RUC point-forecast soundings were collected just downstream and near the time of the initiating MCS in an attempt to sample the environment feeding the system. Many thermodynamic and kinematic parameters were calculated based on these soundings. These data, plus the LLJ data from the profilers and the MCS data, were used to construct a matrix, which was filled with the calculated linear correlation coefficients between parameters (not shown). None of the correlations were strong (roughly > ± 0.6), though some were weak to moderate (between ± 0.25 and ± 0.4).

The correlation between the maximum LLJ wind speed and the 0 – 1 km AGL helicity is 0.325, which is a better correlation than maximum LLJ wind speed and 0 – 3 km AGL helicity. Thus, the LLJ enhances the lowest 1 km of the hodograph, which would lead to a favorable environment for tornadoes, should storms be rooted in the lowest 1 km AGL. The correlation between severe reports (wind and hail) and 0 – 1 km AGL helicity is quite low. However, of the severe wind reports, the correlation between the maximum reported severe wind gust and 0 – 1 km AGL helicity is 0.260. Flood reports and helicity were negatively correlated (-0.279). Flood reports and maximum LLJ wind speed are weakly correlated, showing no significant relationship.

It turns out that the downdraft CAPE (DCAPE) had the highest correlation to severe reports associated with MCSs, although the correlation was still weak (0.353). The next highest correlation was the most-unstable CAPE (MUCAPE), with r = 0.225. MUCIN (most unstable parcel convective inhibition) has the best negative correlation with severe reports, with r = -0.301. This indicates that as the MUCIN decreases, the number of severe reports generally increases. Using just severe wind reports, which accounted for 61% of the total severe reports in this data set, the correlations all improve, though are still weak (Table 1). The DCAPE and MUCIN have the best positive and negative correlations, respectively.

Thermodynamic Parameter	Correlation to Number of Severe Wind Reports
SBCAPE	0.198
SBCIN	-.175
MLCAPE	.246
MLCIN	-.239
MUCAPE	.261
MUCIN	-.426
DCAPE	.378

Table 1. *Correlation of various thermodynamic parameters to number of severe wind reports. The abbreviations refer to the parcel used to determine the CAPE or CIN; SB is surface based, ML is mixed layer, MU is most unstable, and D is downdraft.*

Lapse Rate Layer	Correlation to Number of Severe Reports (Hail and Wind)
0 – 2 km	-0.294
2 – 4 km	0.104
0 – 3 km	-0.341
3 – 6 km	0.377
3 – 8 km	0.332

Table 2. *Lapse rates from various layers and number of storm reports correlation coefficients.*

As far as variables correlated to the maximum severe wind gust report, the Bulk- Richardson Number (BRN) shear was best, with r = 0.331. The maximum LLJ winds and the 0 – 1 km AGL bulk shear were moderately correlated (0.515), though with the 0 – 2 km bulk shear the correlation was much lower (0.132). Again, this emphasizes that the LLJ enhances the shear in the lowest 1 km of the atmosphere.

Interestingly enough, the 0 – 6 km AGL bulk shear was moderately-correlated with the maximum hail size from the severe hail reports (r = 0.409). When maximum hail size (from the severe reports) is compared to the height of the LLJ max, one finds a moderate negative correlation (r = -0.342). Thus, lower altitude LLJs appear to be associated with larger hail size.

The environmental lapse rates through certain layers of the atmosphere, when compared to the severe reports, exhibit moderate correlation coefficients (Table 2). From Table 2, the strongest correlation between lapse rate and number of severe reports comes from using the 3 – 6 km AGL layer. The worst-correlated lapse rate to severe reports is the 2 – 4 km AGL layer. Layers starting at the surface show negative correlations. This is most likely due to the surface-based radiation inversion in place because of nocturnal cooling. The 3 – 6 km AGL lapse rate, despite having a positive moderate correlation to number of severe reports, has a negative moderate correlation (r = -0.317) with flood reports. The lifting condensation level (LCL) had no correlation (r < |0.01) to the LLJ height, regardless of whether SBCAPE or MLCAPE was used to determine the LCL.

3.5 Summer Climatology

Examining summer climatologies, we see that the maximum LLJ wind speed decreases with increasing Julian day. In other words, as the summer goes by (June to August), the maximum LLJ wind speed generally decreases. The correlation coefficient for maximum LLJ wind speed and "summer day" is r = -0.357, where summer day is defined as 1 for June 1, with 92 for August 31. Also decreasing with increasing summer day is the time of MCS initiation, with r = -0.339. The height of the LLJ maximum and summer day show a weak positive correlation, indicating that on average the LLJ height increases slightly throughout the summer. Additionally, the MCSs that form later in the summer are less severe based on severe reports, especially with hail reports (correlation to summer day = -0.398) and maximum hail size (correlation to summer day = -0.483). This could be due to warmer temperatures aloft, and/or a higher welt-bulb zero (WBZ). The maximum wind gust and number of severe wind reports correlated to summer day also show negative values, though less significant.

There are several notable cases of an MCS intensifying coincident with the intensification of the LLJ. The MCSs of 6/19, 6/25, 7/3, 7/4, 7/20 and 7/21 exhibit rapid intensification as they interact with the exit region of the LLJ, which is also intensifying. These cases do not show thermodynamic environments more conducive to storm development, so it appears as if the LLJ was instrumental in the intensification of these MCSs. However, since this only happened in 6 of the 45 cases, it suggests that a strengthening LLJ is not critical to MCS development. These cases should be further explored to determine exactly to what capacity the LLJ intensification affected the strengthening of the MCS.

4. CONCLUSIONS

This study has shown that the Great Plains low level jet is an integral part of the occurrence of nocturnal mesoscale convective systems. While not the only phenomenon involved in the initiation of nocturnal MCSs, virtually every case from the summer of 2005 was associated with a southerly LLJ. Of these LLJs, a majority (71.1%) of them satisfied the Bonner criterion-3 classification, showing that intense LLJs are frequently related to MCSs. The study also found that an extended Bonner criterion scale could be applied for MCS climatologies, since 40.6% of the LLJs exceed the criterion-3 definition and could be classified as criterion-4 or greater. The LLJ is most frequently oriented along the western Great Plains, roughly along 100° longitude. Additionally, the LLJs are most commonly anticyclonically curved.

Compared to the LLJ maximum, the terminus of the jet max tends to be a preferred location for MCS initiation. A majority of the MCSs in this study initiated in the western regions of the Great Plains and propagated generally southeastward or eastward across the Plains.

Statistical relationships from the RUC forecast soundings indicate that there are no strong correlations between any thermodynamic or kinematic parameters and the severity of the MCS. However, several weak-to-moderate correlations exist. The best indicators of MCS severity appear to be downdraft CAPE (DCAPE), convective inhibition for the most unstable parcel (MUCIN), and the 3 – 6 km lapse rate.

For operational meteorologists, forecasting MCS initiation and development can be difficult. This study has indicated from a climatological view that locations at the nose of the LLJ maximum or just to the left (west) in an unstable environment are likely areas for MCS initiation. The mid-level lapse rates, DCAPE, and MUCIN should be utilized to give a sense of the potential severity of the MCS. However, it should be stressed that these relationships on average are weak, and no one parameter alone will provide sufficient information about the likelihood of severe reports with nocturnal MCSs. Additionally, classifying the LLJ into the Bonner criterion scale eliminates inter-criterion variability of wind speed maxima and can also give an indication as to the potential for high-end severe MCSs (or derechos). However, LLJ maximum wind speed itself does not show any correlation to number of severe reports (it is near zero). Further research should be conducted to increase the MCS/LLJ data set and to better analyze the effect of LLJs and the thermodynamic environments on the initiation, development, and severity of nocturnal MCSs over the Great Plains.

5. ACKNOWLEDGEMENTS

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