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WRF Forecasts of Great Plains Nocturnal Low-Level Jet-Driven MCSs. Part II: Differences between Strongly and Weakly Forced Low-Level Jet Environments

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Keywords
Circulation/ Dynamics, Convective storms/systems, Atm/Ocean Structure/ Phenomena, Jets, Forecasting, Mesoscale forecasting, Models and modeling, Mesoscale models, Model errors

Disciplines
Atmospheric Sciences | Climate | Meteorology

Comments
WRF Forecasts of Great Plains Nocturnal Low-Level Jet-Driven MCSs. Part II: Differences between Strongly and Weakly Forced Low-Level Jet Environments

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ABSTRACT

The classic Great Plains southerly low-level jet (LLJ) is a primary factor in sustaining nocturnal convection. This study compares convection-allowing WRF forecasts of LLJ events associated with MCSs in strongly and weakly forced synoptic environments. The depth of the LLJs and magnitude, altitude, and times of the LLJ peak wind were evaluated in observations and WRF forecasts for 31 cases as well as for case subsets of strongly and weakly forced synoptic regimes. LLJs in strongly forced regimes were stronger, deeper, and peaked at higher altitudes and at earlier times compared to weakly forced cases. Mean error MCS-centered composites of WRF forecasts versus RUC analyses were derived at MCS initiation time for the LLJ atmospheric water vapor mixing ratio, LLJ total wind magnitude, convergence, most unstable convective available potential energy (MUCAPE), and most unstable convective inhibition (MUCIN). In most configurations, simulated MCSs in strongly and weakly forced regimes initiated to the north and east of observations, generally in a region where LLJ moisture, MUCAPE, and MUCIN fields were forecast well, with larger errors outside this region. However, WSM6 simulations for strongly forced cases showed a southward displacement in MCS initiation, where a combination of ambient environmental factors and microphysics impacts may simultaneously play a role in the location of forecast MCS initiation. Strongly forced observed and simulated MCSs initiated west of the LLJ axis and moved eastward into the LLJ, while observed and simulated MCSs in weakly forced environments traversed the termini of the LLJ. A northward bias existed for simulated MCS initiation and LLJ termini for weakly forced regimes.

1. Introduction

The Great Plains nocturnal low-level jet (LLJ) has been found to be an important ingredient for fueling nocturnal convective events (Means 1952; Bonner 1966; Augustine and Caracena 1994; Stensrud 1996; Schumacher and Johnson 2009). Understanding the Great Plains LLJ climatology and being able to differentiate between strongly and weakly forced LLJ environments is important since the LLJ and its supporting synoptic environment influences the amount of moisture, low-level convergence, and lift needed to support nocturnal convection (Chen and Kpaegeh 1993; Augustine and Caracena 1994; Mitchell et al. 1995; Higgins et al. 1997). Blackadar (1957) was among the first to attribute LLJ development to the inertial oscillation of the ageostrophic wind field and lift needed to support nocturnal convection (Chen and Kpaegeh 1993; Augustine and Caracena 1994; Mitchell et al. 1995; Higgins et al. 1997). Blackadar (1957) was among the first to attribute LLJ development to the inertial oscillation of the ageostrophic wind field as well as to identify the importance of the LLJ on deep moist convection. Bonner and Paegle (1970) found that differences in diurnal terrain heating had major impacts on LLJ development. These studies were further supported by Parish and Oolman (2010), who found that a maximum southerly geostrophic wind profile was induced across the Great Plains as a result of the heating of sloped terrain, providing a background flow for the LLJ to build upon, as noted in Augustine and Caracena (1994) via the inertial oscillation.

Bonner (1968) was among the first to create a nocturnal warm season LLJ climatology in the Great Plains, finding that strong southerly flow prevailed from the Gulf of Mexico as a result of the Bermuda high. This finding was further supported by Chen and Kpaegeh (1993) via an air mass and moisture budget analysis. Higgins et al. (1997) also noted a relationship between summer Great Plains nocturnal convection and LLJs. With the implementation of the Lamont, Oklahoma, high vertical resolution vertical profiler, Whiteman et al. (1997) and Song et al. (2005) were able to detect many LLJs within a few hundred meters above the ground that were often missed in 0000 and 1200 UTC NWS radiosondes and previous studies, supporting the notion that the nocturnal
LLJ is a frequent warm season phenomena likely responsible for many extreme rainfall events.

Kumjian et al. (2006) investigated the LLJ climatology and its relation to warm season central plains MCS behavior and found that many LLJ peak wind magnitudes were associated with the Bonner III criteria devised in Bonner (1968). The majority of the LLJs in Kumjian et al.’s study exhibited an anticyclonic curvature to the jet, with MCS development highly favored along the left exit region of the LLJ core. MCS development was also more favored along the sloping terrain of the high plains during the later summer months (July and August) versus earlier in June, hinting that differences between synoptic environments supporting LLJs and MCS activity exist.

Following up on Great Plains LLJ connections to broader climatological features (Chen and Kpaeveh 1993), Weaver et al. (2009) conducted a study of LLJs in the central United States from 1949 to 2002 using the Community Climate Model (CCM3) for simulated behavior of long-term LLJ trends. The goal was to see if LLJ development and associated warm season precipitation were associated with global sea surface temperature variability. It was determined through idealized CCM3 simulations that a strong association existed between sea surface temperatures and LLJ seasonal development, where cooler Atlantic or warmer Pacific temperatures led to the optimal development of LLJs and associated precipitation during the summer months across the Great Plains.

Squitieri and Gallus (2016, hereafter referred to as Part I) noted correlations between the forecast accuracy of the LLJ and forecast skill of MCS precipitation. Specifically, mean absolute error (MAE) of multiple LLJ parameters correlated significantly with equitable threat scores (ETSs) for MCS quantitative precipitation forecasts (QPFs) for strongly forced cases, while little to no correlation between LLJ variables and MCS QPF ETSs was noted for weakly forced cases. It was also suggested in Part I that distinguishing differences between both regimes was vital to understanding the forecasting challenges associated with the relationship between the LLJ and MCSs.

In Part I, LLJs in strongly forced synoptic environments often accompanied by strong cyclonic and resultant isallobaric flow with lower- and upper-jet coupling (Uccellini and Johnson 1979), also known as low-level jet streams (Markowski and Richardson 2010), were classified as type-C (for cyclonic) LLJs, and nocturnal low-level wind maxima (Markowski and Richardson 2010) in anticyclonic upper-level ridge environments with weak forcing and jet coupling, often induced by the inertial oscillation, terrain sloping, and heating effects were classified as type-A (for anticyclonic) LLJs. Uccellini and Johnson’s findings lend credibility to the idea that type-C LLJs would have more associated lift than inertial-oscillation-driven low-level wind maxima (type-A LLJs), which could have a substantial impact on MCS evolution. Uccellini (1980) was one of the first to distinguish the differences between type-C and type-A LLJ environments, though no mention was made regarding how environmental differences impacted nocturnal convective precipitation evolution. While Uccellini and Johnson explored the relationship of deep moist convection in type-C environments, Schumacher and Johnson (2009) noted that MCSs often occurred in weakly forced (type A) environments, where initiation and sustainment mechanisms for MCSs were more ambiguous and posed a challenge for forecasters. In a broader sense, Peters and Roebber (2014) noted that uncertainty in synoptic environment forecasts led to larger errors in simulated precipitation accumulations, thus quantifying a relationship between synoptic environmental forecast accuracy and simulated precipitation forecast skill.

One motivation for this study was to evaluate LLJ climatology similar to Bonner (1968), Whiteman et al. (1997), Song et al. (2005), and Kumjian et al. (2006) in both observations and forecasts to see if there were notable differences between type-C and -A simulated LLJs. A second motivation was to examine how differences between type-C and -A LLJ environment forecast errors would influence forecast MCS displacement errors within multiple WRF configurations.

2. Data and methodology

This research builds on the results shown in Part I of this study and uses the same 31 cases (16 type C and 15 type A). With in situ LLJ observations lacking, 13-km 0-h RUC analyses (NCDC 2015b) were again used to represent the observed atmosphere. The same ARW (Skamarock et al. 2008) forecasts initialized with 12-km NAM forecast output (NCDC 2015a) on the same domain and Stage IV data (NCAR/UCAR/EOL 2015) used in Part I were also used in the present study, with the same classification system for LLJs. Archived mosaic composite radar data, passed through quality control algorithms, was obtained from NCEP’s data archive (Liu et al. 2016). As in Part I, 4-km WRF data were placed through a Gaussian filter to smooth wavelengths finer than 26 km (2Δx), and interpolated to the 13-km grid in order to fairly compare forecasts to the RUC analyses. Given limited resources, WRF output was generated at 3-hourly intervals, hence, the comparison to 3-hourly RUC analyses, observed composite radar, and Stage IV data despite hourly RUC/radar/precipitation data being available.

Observed and simulated LLJ peaks were evaluated for each case using Bonner’s (1968) criteria, based on
the magnitude of the peak wind (criterion I for a peak magnitude of at least 12 m s$^{-1}$, decreasing to 6 m s$^{-1}$ at the next minimum or before 3 km; criterion II for 16 m s$^{-1}$, decreasing to 8 m s$^{-1}$ in the same fashion as criterion I; and criterion III for 20 m s$^{-1}$, decreasing to 10 m s$^{-1}$). Subdomains were selected at 0300, 0600, 0900, and 1200 UTC in the RUC analyses and WRF output for all cases to minimize the influences of convective contamination and filter out other features of data that may falsely mimic the Great Plains LLJ. An argument could be made against defining peak LLJ magnitudes and times based on a single grid point of data. As such, the 95th percentile of the 250–2000 m AGL (at 250-m intervals) wind magnitudes was calculated and all points with values exceeding this threshold were averaged to a single value at each 3-h period (between 0000 and 1200 UTC) for each case, representing the area of the LLJ core and replacing a single grid point of data. When the averaged 95th percentile wind magnitude had its highest value, that time period was recorded as the time of the peak LLJ. Within a gridded framework (such as the RUC analysis and ARW), the peak LLJ wind was defined as the gridpoint value within the 95th percentile of the LLJ wind magnitudes (at the time of the peak LLJ core) that had the highest wind magnitude within the 250–2000 m AGL layer (at 250-m intervals) with the appropriate wind magnitude decrease noted between the altitude of the maximum and 3000 m AGL, as defined in Bonner (1968). The height (AGL) of the peak wind was recorded as the LLJ altitude. Finally, the depth of the LLJ was recorded. Since the RUC analysis was only available at 250-m intervals, with subjective analysis revealing that wind magnitudes at 250 m AGL were well within the Bonner I criteria in most observed and simulated cases, the bottom of the LLJ was determined to be 250 m AGL. The top of the LLJ was defined for all vertical profiles (from the bottom to the top) in both the RUC analyses and WRF runs as the height AGL at which the appropriate wind magnitude decrease was first met after the associated Bonner I, II, or III criterion wind maximum was achieved. For example, if a gridpoint wind magnitude in a column of data reached a value within the Bonner II criteria, the top of the LLJ was defined as the altitude AGL where the winds first decreased by 8 m s$^{-1}$ from the maximum value in the column. At the time of the peak LLJ core, the height for the top of the LLJ in all vertical profiles of data in the RUC and WRF which met Bonner I, II or III criteria, was defined. The LLJ bottom height (250 m) was subtracted from the LLJ top height, with differences for all vertical profiles meeting Bonner criteria averaged to a single value representative of the LLJ depth. Each peak point of magnitude/altitude was manually inspected in the RUC analyses and all WRF configurations to assure that the values realistically represented the LLJ and were not influenced by convective contamination. The observed LLJ peak wind times, magnitudes, altitudes, and depth were evaluated for all cases along with type-C and type-A LLJs separately to differentiate LLJ characteristics between strongly and weakly forced synoptic regimes.

Mean error composites of LLJ environments were created for type-C and -A cases using averaged values at every 250-m interval in the 250–2000-m layer (LLJ bearing layer) of atmospheric water vapor mixing ratio, total wind magnitude, and mass convergence, along with most unstable convective available potential energy (MUCAPE) and the associated most unstable convective inhibition (MUCIN). RUC analyses were used for observed quantities for all atmospheric variables for the composites, and compared to output from all six WRF configurations after filtering and regridding (mentioned earlier). The MCS-centered compositing methods used in Coniglio et al. (2010) were employed. Data were composited at MCS initiation times for RUC analyses and all WRF configurations, with data collected within a 350 km $\times$ 350 km box surrounding the MCS initiation point. The size of the box was the largest that could be used for compositing given that a few MCSs initiated approximately 175 km from the western bounds of the project domain. As such, westward data collection out to 175 km at most from the MCS initiation point was possible, allowing for equal-sized boxes with a perimeter no greater than 350 km $\times$ 350 km. While WRF output was composited at the time when the simulated MCSs initiated, these data were compared with RUC analyses at the time of the observed initiation using the RUC-selected box, allowing for the evaluation of forecast errors present in the initiation environment. WRF output was subtracted from RUC analyses for each case, leading to the generation of the mean error fields. These error fields were then averaged, with the average observed MCS initiation point (henceforth referred to as the MCS initiation centroid) placed in the center of the composite. The average forecast MCS initiation point was calculated and plotted on the composite to allow comparison of spatial displacements from the observed MCS initiation centroid.

After applying the Blanchard (1990) definitions of identifying MCSs (Table 1), MCS initiation criteria were subjectively defined for each case in the observations and all WRF configurations. In the cases chosen for the present study, observed MCSs had to be sustained for at least 6 h (Table 1) from initiation to dissipation such that there were at least three 3-h periods for which MCS initiation, maturity, and dissipation could be defined in both the observations and 3-hourly WRF runs. MCS initiation was determined to be the first 3-h interval at
which the Blanchard (1990) criteria could be subjectively applied to the convective feature of interest. For linear or occluded MCSs, the initiation location was selected at the leading edge of the convection, along the midpoint of a solid or semidiscrete, but highly organized, linear system. For chaotic structures, the leading edge of the MCS with the point of highest reflectivity was chosen as the MCS initiation point.

While environmental mean error composites were generated at MCS initiation time, average MCS maturity and dissipation times also were calculated in order to understand how models handled MCS evolution in comparison to observations between type-C and -A regimes. Like initiation, MCS maturity was also subjectively defined. For observations and all model simulations, mature linear or occluded MCSs were defined at the time in which reflectivity values (specifically, with magnitudes above 45 dBZ) were most prevalent, expansive, and continuous within the leading line, with a maximum of the trailing stratiform precipitation field in both areal coverage and intensity (relatively higher reflectivity values compared to other times). For chaotic structures, MCS maturity was noted when the areal coverage of the most intense convective cells (i.e., reflectivity values of 45+ dBZ) was at a relative maximum. The point for chaotic MCS maturity for each case was assigned with the strongest convective core along the leading edge of the convection. MCS dissipation was defined as the point at which an MCS collapsed before or during 1200 UTC. For linear and occluded MCSs, dissipation was noted at the last 3-h interval with reflectivity greater than 40 dBZ across much of the line. The point for MCS dissipation was delineated as being at the leading edge of the convective remnants, along the midpoint of the line. For chaotic MCSs, dissipation was noted at the last 3-h interval before all heavier cores (40+ dBZ) ceased altogether, with the leading edge of the remnant cluster noted for the specific dissipation location. If the MCS persisted past 1200 UTC, the location of the MCS at 1200 UTC was noted for dissipation, where enduring convection would begin to be affected by daytime processes, which are not the focus of the present study. An example of MCS

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initiation, maturity, and dissipation classification for a linear MCS (a type-C event) and a chaotic structure MCS (a type-A event) is provided in Fig. 1. It should be noted that the 19 June 2010 case was excluded from section 3b of the results given that the simulated MCSs initiated around 0900 UTC and matured near 1200 UTC, thus failing to meet the time requirements previously mentioned. As such, MCS initiation composites for type-A environments were derived using only 14 cases instead of 15.

Finally, maps showing MCS initiation points with respect to their associated LLJ axes were plotted for type-C and -A case subsets in order to demonstrate the influence that each LLJ had on MCS initiation. LLJ axes were subjectively defined starting from the south, where total wind magnitudes first reached 10 m s$^{-1}$, and ending northward, where total wind magnitudes either decreased to 10 m s$^{-1}$, or where the LLJ intercepted the MCS. For each case, the level (m AGL) for the LLJ was chosen for each case the same way altitudes were determined for the LLJ climatology.

3. Results

a. LLJ climatology during MCS events in strongly and weakly forced environments

The majority of observed and simulated LLJs in all WRF configurations peaked at 0600 or 0900 UTC for the whole set of cases studied (Fig. 2), as well as the type-C and -A subsets, concurring with Bonner and Paegle (1970), Mitchell et al. (1995), and Whiteman et al. (1997). Keep in mind that the 3-hourly resolution of the data used in the present study prevents detailed quantitative analysis of timing differences. Observed and simulated type-A LLJs peaked later in the evening compared to type-C cases, as type-A LLJs reached their peak intensities more slowly, driven primarily by the inertial oscillation (not shown). Many simulated LLJs also peaked later compared to the observations. In type-C cases, nearly 80% of observed LLJs peaked at 0600 UTC, while several model configurations had a near even split between LLJs peaking at 0600 and at 0900 UTC, with a majority of cases peaking at 0600 UTC in the Thompson MYJ and WSM6 Yonsei University (YSU) schemes. Roughly 70% of observed type-A LLJs peaked at 0900 UTC, with multiple WRF configurations noting roughly half of the weakly forced LLJs peaking at 0900 UTC and nearly all the remaining cases peaking at 0600 or 1200 UTC (roughly 25%–35% for each time period).

Simulated MCSs were often displaced from the observations, frequently passing through the core of simulated LLJs during times when the RUC analysis delineated a convection-free environment in the LLJ region. In some cases, this led to the time of the simulated peak LLJ intensity being temporally displaced by one 3-h time period. While simulated LLJs were sometimes forecast to peak earlier than observed, most temporal displacements were
on the late side. Convective interference in simulations was more prevalent in type-C cases, as large-scale ascent aided larger, more progressive forecast MCSs, which progressed too quickly into the warm sector, altering the LLJ wind field considerably. The adverse impact of the forecast LLJ wind field can be seen, for example, by comparing the 65th percentile of the total wind fields at 750 m AGL (height at which many observed and simulated LLJs peaked) between the RUC analysis and WSM6 YSU simulation for the 15 June 2012 case (Fig. 3). An expansive, southward-propagating MCS formed along a large-scale cold front (evident via the wind shift noted in the 0000 UTC plot), which acted as the LLJ terminus, providing large-scale low-level convergence. Fronts were mainly observed in type-C LLJ regimes, but the event shown in Fig. 3 was a type-A case, where the MCS initiating from a cold front sustained itself from the convergence of opposing southerly flow induced by the LLJ. This scenario is similar to the southward burst MCS events described in Stensrud and Fritsch (1993). This particular WRF configuration also resulted in a secondary region of intense convection forming in central Oklahoma, not otherwise noted in observations or WRF runs with different microphysics (MP) or planetary boundary layer (PBL) schemes. Reasons for this are unclear and more research is needed to understand the spurious convection. Still, timing displacements of MCSs were common overall and

![Fig. 2](image2.png)

**Fig. 2.** Frequency of occurrence (%) of time of LLJ peak winds for the whole sample of LLJ cases, as well as type-C and type-A LLJ subsets.

![Fig. 3](image3.png)

**Fig. 3.** (top) Observed composite mosaic reflectivity and (bottom) simulated reflectivity using the WRF WSM6 YSU scheme (in dBZ) overlaid with the 750 m AGL total wind (barbs, m s$^{-1}$) and the 65th percentile of the 750 m AGL total wind field (blue contours, m s$^{-1}$) from the 0-h 13-km RUC analysis in the top panel and WRF WSM6 YSU in the bottom panel for 0000, 0300, 0600, and 0900 UTC for the 15 Jun 2012 case.
likely contributed to the high precipitation biases noted in Part I of this study.

Most observed and simulated LLJs matched the Bonner III criterion, with average peak wind magnitudes around 25 and 26 m s\(^{-1}\), respectively, for all observed and simulated cases (Fig. 4). Mitchell et al. (1995) and Kumjian et al. (2006) also found that most LLJs in their studies fit the Bonner III criteria. Observed and simulated type-C LLJ peak wind magnitudes were significantly stronger (26–28 m s\(^{-1}\)) compared to type-A cases (22–24 m s\(^{-1}\)). Differences in magnitudes between LLJ regimes are likely due to the influences of large-scale dynamic features such as jet coupling or cyclogenesis induced isallobaric flow, as explained in Uccellini and Johnson (1979). Averages and quartiles for all cases for peak simulated LLJ magnitudes agreed fairly well with the observations, and even more so among the WRF configurations. Observed LLJ peak magnitudes were somewhat greater compared to simulated LLJs though. For type-C and -A LLJ subsets, strongly forced cases exhibited the greatest disagreement between observations and forecasts, likely because of the convective contamination in the WRF simulations mentioned earlier.

The peak wind altitudes for all observed and simulated cases (Fig. 5) were mainly between 500 and 750 m AGL, similar to those in Bonner (1968) and Mitchell et al. (1995), but higher in some cases compared to Whiteman et al. (1997) and Song et al. (2005). Type-C LLJ peak wind altitudes in both the observations (around 45%) and all but the Thompson Mellor–Yamada–Nakanishi–Niino (MYNN) WRF simulations were often 250 m AGL higher (between 50% and 75%) compared to type-A cases, which mainly peaked at 500 m AGL in the observations (nearly 45%) and all but the WSM6 YSU WRF simulations (45%–60%). While type-A LLJ cases (40%–60%) peaked at lower altitudes overall in the observations and simulations compared to type-C cases, the type-A subset had more outlier cases with higher LLJ altitude peaks. All but the Thompson YSU WRF runs fairly simulated the LLJ peak wind altitude distribution. Why type-A LLJs had more outlier cases with peak wind LLJ altitudes (1000–1250 m) is unclear and more research is needed to

![Fig. 4. Box-and-whisker plots showing the maximum, minimum, median, 25th percentile, 75th percentile, and average (indicated by a red line) of the LLJ peak wind magnitude (m s\(^{-1}\)) in the RUC analyses and all WRF configurations for the entire set of cases, as well as type-C and type-A case subsets.](image-url)
gain deeper insight regarding the three-dimensional structure and evolution of weakly forced LLJs. It is possible that some of these higher altitudes for type-A LLJ peaks may be an artifact of the specific cases chosen.

For all 31 cases, the average LLJ depths were mainly 1700–1800 m, with the lower and upper quartiles of 1500–1600 and roughly 1800–1900 m (respectively) noted for both observations and all WRF configurations (Fig. 6). Type-A jets were shallower by 100–200 m compared to type-C events. Despite the larger span of LLJ depths among type-A cases, observations and all WRF configurations showed reasonable agreement in LLJ depths among the averages and quartiles, as opposed to type-C cases, where more variance existed between the observed and simulated depth averages and quartiles. Similar to the reasoning for greater peak LLJ magnitudes in type-C versus type-A events, large-scale mass adjustment in strongly forced dynamic events is likely the cause.
of the more intense low-level jet streams, as noted in Uccellini and Johnson (1979) and Markowski and Richardson (2010). Type-A LLJs were shallower, likely as a result of less forcing, with the inertial oscillation (driven by sloping and heating effects of the Great Plains terrain) promoting more limited forcing and mass adjustment compared to strongly forced regimes.

While the RUC analyses are coarser in their vertical resolution compared to the in situ observations used in past studies, the gridded output in the RUC analyses and WRF simulations allowed statistical quantification of observed and forecast LLJs within a three-dimensional framework. Despite the issues with somewhat coarse spatial and temporal resolutions, RUC biases, and small sample size, it is believed that the present research provides a basic idea of four-dimensional (space and time) LLJ evolution during MCS events in both strongly and weakly forced synoptic regimes.

b. Differences in forecast errors between type-C and type-A environments

Type-C regimes often exhibited broader, stronger, and deeper LLJs associated with stronger isallobaric flow. Mean error magnitudes of LLJ atmospheric water vapor mixing ratio in all WRF configurations were positive ahead of the observed MCS initiation centroid for type-C cases (Fig. 7), with an overall weak dry bias noted in all WRF configurations for type-A cases (Fig. 8). The dry biases west of the observed and simulated MCS initiation centroids in type-C cases were caused mainly by displacements of frontal and terrain-driven moisture gradients, especially along the high plains, as can be seen in the observations and forecasts at MCS initiation time for the 4 June 2013 case (Fig. 9). Convective feedback may also play a role in the type-C LLJ moisture dry biases, especially in the WSM6 configurations, where the dry biases were greater in magnitude compared to the Thompson configurations. Referring back to Fig. 9, the 8 and 10 g kg\textsuperscript{-1} contours in the Thompson and WSM6 MYJ runs reveal that both model configurations have an eastward displacement of the LLJ moisture gradient compared to the observations, where the LLJ moisture gradient was located farthest to the west (an occurrence noted in multiple other cases). It should also be noted that especially for type-C cases, simulated MCSs initiated on average south of where observed MCSs began. Many MCSs in type-C cases were broad in their latitudinal extent, driven by large-scale forcing, and originated from semidiscrete, but widespread, convection off the higher terrain (as can be seen in the 7 June 2014 case from 0000 to 0300 UTC; Fig. 1). As such, it is possible that graupel overloading in pre-MCS convective cores and increased evaporation rates behind the cores (Morrison et al. 2009) might play a role in MCS initiation placement and alteration of the environment behind the MCS for WSM6 configurations. More research on pre-MCS convective cold pools is needed to understand the impact microphysics has on MCS evolution in comparison to influences from the forecast ambient environment. The temporal resolution for the model output would need to be hourly or finer for future microphysics research tasks and to determine if evolving convection prior to MCS development is at least partially responsible for postconvective dry biases. Finally, more detailed analyses of individual vertical levels (AGL) within the LLJ should be performed to better understand the behaviors of the model biases (i.e., are moisture gradient displacements more common closer to the surface versus higher aloft in low-level jet streams or low-level wind maxima).

MUCAPE and MUCIN mean error fields were also composited to show how stability might influence the placement of MCS initiation. For type-C cases, in all WRF configurations, MUCAPE was overforecast (Fig. 10), especially in the central and eastern portions of the composites. The MUCAPE results are likely influenced by the moist bias in the LLJ. MUCAPE was more over-forecast in Thompson schemes compared to WSM6 schemes (by as much as 200–400 J kg\textsuperscript{-1} in the central regions of the composites), likely because of the highest positive LLJ moisture biases being juxtaposed in these locations. MUCIN was overforecast (i.e., the environment was too inhibited in the model) in regions behind the MCS initiation and was weaker south and east of the observed MCS initiation centroid compared to what was observed. While WSM6 configurations show simulated MCS initiation centroids displaced to the southeast in regions of weaker MUCIN in comparison to forecasts, it is difficult to ascertain if these displacements are due to convection forming in forecast weaker CIN, the microphysics discrepancies mentioned earlier, or both. In type-A environments, based on the evaluation of multiple cases, microphysics had a weaker impact on the simulated MCS initiation location and forecast ambient environments. As seen in both Figs. 8 and 11, simulated MCSs often formed east and north of where observed MCSs began. Although mean LLJ moisture errors (Fig. 8) were very small (little to no moisture bias) at the simulated MCS initiation centroid locations, forecast MUCAPE and MUCIN either closely matched the observations, or MUCAPE was slightly higher with the associated CIN weaker than observed. These relatively accurate MUCAPE, MUCIN, and moisture forecasts and the associated northeast-displaced MCS initiation in the forecasts were indicated among all WRF configurations for type-A cases.
FIG. 7. Observed MCS-centered mean error composites of LLJ atmospheric water mixing ratio (filled contours, g kg$^{-1}$) and overlaid observed (black wind barbs) and forecast (blue wind barbs) winds, along with red line contours of convergence (10$^{-6}$ s$^{-1}$) for type-C cases at MCS initiation time. Dashed black and red lines denote negative values of total wind magnitudes and convergence, respectively. The black X denotes the observed MCS initiation centroid and the blue X denotes the displacement of the average simulated MCS initiation points with respect to what was observed.
FIG. 8. As in Fig. 7, but for type-A cases.
Mean errors of LLJ mass convergence (Figs. 7 and 8) were also examined to see if forecast errors in LLJ structure would impact the simulated MCS initiation locations. In several WRF configurations, for both type-C and -A cases, the simulated MCS initiation centroids were juxtaposed with regions of minimal errors in the convergence fields, while other configurations showed the simulated MCS initiation centroid in regions where maximum mean errors with both over- and underforecast convergence magnitudes existed. The evaluation of several individual cases showed that the convergence mean error fields were mainly influenced by convective feedback via pre-MCS convection, where individual MCS initiation displacements relative to the observed MCS initiation centroid produced many of the over- and underforecast errors observed. As such, a systematic relationship between the ambient environmental mass convergence mean error fields derived from weaker convergence values (observed or simulated) and the displacement of simulated MCS initiation points on such small scales cannot be discerned.

Type-C cases often occurred earlier in the year compared to type-A cases (Table 1). While seasonal changes in large-scale ascent, buoyancy, and LLJ moisture are already known, the trends in the forecast skill of these parameters and convective evolution in convection-allowing models are still not fully understood, especially for weakly forced regimes. In the present study, model errors seemed to worsen in magnitude with the progression of the warm season, where weakly forced synoptic regimes showed poorer model accuracy via greater spatial displacements and magnitudes of the errors for LLJ and non-LLJ variables (also noted in Part I). Jankov and Gallus (2004) noted that QPFs were better simulated in strongly forced environments than in weakly forced ones. Schumacher and Johnson (2009) found that weakly forced MCSs were difficult to simulate given that convective initiation and sustainment mechanisms were nebulous in nature. Finally, Part I of this study found that unlike type-C LLJ cases, MCS precipitation forecast skill and LLJ forecast accuracy showed little correlation for type-A events. Reasons for poorer forecasts of MCSs and their ambient environment in weakly forced synoptic regimes still remain unclear and additional research involving more detailed analyses of individual cases with higher temporal frequency output is needed.

c. Differences in MCS behavior between type-C and -A LLJ regimes

Observed and forecast individual MCS initiation points were plotted with respect to the axes of their associated developing LLJs. For type-C events, in both the observations and forecasts, most MCSs established themselves west of their developing LLJ axes (Fig. 12). Most MCSs likely developed farther west in type-C cases as a result of deep-layer ascent associated with the strong QG forcing commonly known to occur in type-C regimes. In type-A events, where synoptic forcing was mainly weaker, MCSs often formed near or slightly to the left of the developing LLJ terminus (Fig. 13), concurring with Kumjian et al. (2006). Compared to the observations, over half of the MCSs initiation points and LLJ axis termination points occurred farther to the
FIG. 10. As in Fig. 7, but for MUCAPE mean errors (black line contours, J kg$^{-1}$, where dashed contours denote negative values) and MUCIN mean errors (filled contours, J kg$^{-1}$) at MCS initiation time for type-C cases. Where MUCIN errors are positive, the model predicted the environment to be more inhibited than what was shown in the RUC analyses.
FIG. 11. As in Fig. 10, but for type-A cases.
north compared to what was observed for type-A cases, confirming the northward displacement of type-A simulated MCS initiation centroids for all WRF configurations in MCS-centered composites discussed earlier.

The timing of MCS evolution (initiation, maturity, and dissipation or longevity to 1200 UTC) was documented for the observations and forecasts for all WRF configurations for the full set of cases, and types C and A alone (Fig. 14), to determine if there were consistent biases in the model forecasts. Regardless of the synoptic environment, MCS initiation for all WRF configurations and WSM6 runs throughout the MCS evolution shows an overall earlier trend. For MCS initiation time, up to 15%–20% of type-C events under nearly all WRF configurations have MCSs initiating at 2100 UTC, with a slightly greater distribution of MCSs initiating in the 2100–0000 UTC time frame for WSM6 runs. Up to 10%–15% of the Thompson runs and 15%–20% of WSM6 runs initiate MCSs at 2100 UTC in type-A cases, where observations suggested MCS initiation at 0000 UTC or later. A greater number of MCSs did initiate later in type-A simulations compared to forecasts under all WRF configurations, with 0600 UTC initiation, for type-C cases. WSM6 runs have more MCSs peaking around 0300–0600 UTC compared to Thompson runs in type-A regimes, where more MCSs initiated at 0300 and 0900 UTC compared to the majority (nearly 60%) of the observed MCSs, which reached maturity at 0600 UTC. WSM6 runs for type-C events show a clearer trend of earlier MCS maturity. WSM6 runs have more MCSs peaking around 0300–0600 UTC compared to Thompson runs in type-A regimes, where more MCSs peaked during the 0600–0900 UTC time frame, suggesting that simulated MCSs in type-A regimes do not mature fast enough in Thompson runs. MCSs tend to decay faster in WSM6 runs for type-C and -A regimes, where up to 10%–20% more MCSs dissipated before 1200 UTC compared to observations for type-C cases, and up to 20%–40% more MCSs decayed before 1200 UTC in simulations for type-A regimes.

With only 3-hourly model output available, it is difficult to ascertain how much of an impact microphysics has on the simulated MCS evolution. Output with hourly (or finer) temporal resolution and perhaps finer horizontal grid spacing may reveal better key factors impacting MCS evolution. Specifically, the development and magnitudes of cold pools and their ability to enhance convergence for continuing convection or undercutting storms and shortening their life cycles should be investigated as a potential primary influence on the timing of MCS evolution. It would also be important to conduct separate microphysics and PBL sensitivity studies to determine which (hydrometeor or evolving PBL processes) has the biggest impact on MCS evolution.

4. Conclusions and discussion

An LLJ climatology was performed for type-C and -A environments for 31 total cases when LLJs were present over the Great Plains accompanied by nearby MCSs. LLJs in both weakly and strongly forced synoptic regimes peaked mainly during the 0600–0900 UTC period, concurring with the past literature. The majority of type-C LLJs peaked at 0600 UTC, with most of the remaining LLJs peaking at 0900 UTC. Roughly half of type-A LLJs peaked at 0900 UTC, with a majority of other cases peaking at 0600 UTC, but still a substantial number of cases peaking at 1200 UTC. Type-A LLJs may peak later with limited forcing provided mainly by the inertial oscillation. Observed and simulated type-C LLJs had stronger wind speeds at higher altitudes, and were deeper compared to type-A LLJs. Larger-scale mass adjustment and dynamic forcing in type-C events are likely responsible for these results. More disagreement existed for the magnitudes, altitudes, and depths of type-C LLJ forecasts compared to type-A cases given convective interference in the warm sector that otherwise was not observed.

To improve our understanding of observed and forecast LLJ behavior within gridded pseudo-observational networks (i.e., a reanalysis), research should be restricted to either type-A cases or type-C events alone, without widespread convection, to eliminate problems where MCSs disrupt the LLJ core. Interference from MCSs in type-C cases may have influenced our results. In future work, a larger sample of convection-free nocturnal LLJ events should be used to test the generalizability of the present findings.

Composites of forecast mean errors were generated for strongly and weakly forced case subsets. Overforecast LLJ moisture and associated MUCAPE were noted in type-C events. An overall dry LLJ moisture bias was noted for weakly forced regimes. While the total wind magnitude and mass convergence in near-storm environments did not offer a strong, consistent signal for explaining simulated MCS displacements, forecast MCS initiation appeared to be collocated with regions of underforecast MUCIN, or regions of minimum LLJ moisture and MUCIN and MUCAPE errors, especially for weakly forced synoptic LLJ regimes. As such, MCSs tended to be displaced farther to the north and east for strongly forced Thompson forecasts as well as all forecasts in weakly forced environments. A southward displacement in MCS initiation in strongly forced regimes in WSM6 forecasts was noted. It is currently believed that
FIG. 12. Type-C observed and simulated MCS initiation points transposed with associated LLJ axes at MCS initiation time. MCS initiation points are marked by an X and the LLJ axis is shown in blue. The terminus of the LLJ is demarcated by the case number assigned to the LLJ. The numbers associated with each MCS initiation point and LLJ axis streamline correspond to a particular case.
FIG. 13. As in Fig. 12, but for type-A cases.
too aggressive convection in strongly forced environments allows for progressive cold pooling from pre-MCS convection, causing MCSs to develop farther south and east from where the observed MCSs began. Much more research is needed for the evaluation of microphysics impacts on MCS evolution, and finer temporal model output would be required to perform this task.

In type-C environments, broader MCSs developed to the west of the LLJ axis and propagated eastward throughout the evening, while MCSs in weakly forced regimes were more confined to the nose of the LLJ axis. Forecast LLJ termini and MCS initiation and evolution exhibited a northward bias in weakly forced synoptic regimes for nearly half of all type-A cases. Simulated MCSs often initiated earlier than observed ones in both weakly and strongly forced regimes, especially in WSM6 simulations, but were delayed in reaching maturity in comparison to the observations, especially for Thompson runs. Simulated MCSs often dissipated earlier compared to the observations in both strongly and weakly forced regimes in WSM6 runs. More research is needed to determine if microphysics plays a greater or lesser role in influencing MCS evolution compared to atmospheric features at larger spatial and temporal scales. Simulations with more frequent output and perhaps finer grid spacing are needed to better understand how important model microphysics is to MCS evolution compared to ambient environmental factors such as PBL or LLJ evolution.

More research is needed to understand forecast errors associated with nocturnal MCSs, especially in weakly forced synoptic regimes. While the current work has focused on evaluating general forecast associations between LLJs and MCSs, future work should consider the associations using a more complex classification for MCSs, perhaps via radar data similar to Duda and Gallus (2010) or by cold pool characteristics as in Corfidi (2003). In addition, more focus should be placed on individual MCSs, with a more detailed look at LLJ structure near the

Fig. 14. Percent distributions of MCS initiation, maturity, and dissipation times (UTC) for observations and all WRF configurations categorized for the entire set of cases, as well as type-C and type-A case subsets.
terminus and associated thermodynamic characteristics of air parcels located within and immediately above the PBL.

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