HIGH RESOLUTION NUMERICAL SIMULATION OF A NOCTURNAL MESOSCALE CONVECTIVE SYSTEM: COMPARISON WITH PECAN OBSERVATIONS

BY

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THESIS

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Nighttime convective storms produce a significant portion of warm season precipitation across the Great Plains region of the United States. The PECAN (Plains Elevated Convection at Night) project was designed to improve our understanding of how these storms can develop and maintain themselves in the absence of traditional sources of CAPE (Convective Available Potential Energy). This thesis focuses on the 20 June 2015 MCS (Mesoscale Convective System) event, in which airborne in-situ microphysical and radar data were collected using the NOAA P3 research aircraft. In terms of elevated MCS structure, this was the most ideal case observed during the campaign and produced numerous severe wind and hail reports, as well as at least one tornadic supercell. In order to expand upon the impact of microphysical processes on the kinematic evolution of the storm sampled by the P3, the WRF-ARW model was used to run high-resolution numerical simulations which would help highlight in detail the mechanisms that allowed this storm to maintain itself through the night and into the next morning. This thesis will address the benefits and limitations of data collection in field projects such as PECAN by directly comparing the data collected by the P-3 with analogous datasets extracted from the numerical simulation, and show that the simulation is sufficiently robust to carry out a detailed dynamical analysis of nocturnal MCSs’ mechanisms for propagation and maintenance.
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CHAPTER 1: INTRODUCTION

For over a century, it has been observed that a nocturnal maximum in warm season precipitation exists over the United States Great Plains region (Kincer 1916, Wallace 1975). More recent studies have shown that approximately 50% of the warm season precipitation can be attributed to Mesoscale Convective Systems (MCSs) and that nearly three quarters of it occurs at night (Fritsch et al. 1986, Heideman and Fritsch 1988). Since these systems occur at night, the environment is typically characterized by minimal surface-based Convective Available Potential Energy (CAPE) as a nocturnal inversion forms due to nocturnal radiative cooling, creating a stable boundary layer below these storms (Colman 1990). Instead there is a strong source of elevated CAPE in a southerly low-level jet that brings potentially buoyant air northward from the Gulf of Mexico (Blackadar 1957, Bonner 1968, Higgins 1997). As such, conventional reasoning for MCS propagation (Rotunno et al. 1988) does not apply, so another explanation is needed for why MCSs can potentially cross a third of the United States, intensifying through the night and into the next morning. This issue is worsened by the fact that nocturnal MCSs are poorly forecasted and not often well replicated in numerical weather prediction models (Davis et al. 2003, Jirak and Cotton 2007).

In order to better understand how nocturnal MCSs can propagate, and to devise a theory for the mechanisms behind the initiation and propagation of these MCSs, the Plains Elevated Convection At Night (PECAN) Project was designed and subsequently carried out in the Summer of 2015, from June 1 to July 15 (Geerts et al. 2017). Over 300 people participated in this multi-agency field campaign, in which 31 Intensive Operational Periods (IOPs) and 12 Unofficial Field Operations (UFOs) were run during the one and a half month period. A vast
array of instrumentation was deployed to observe these events, including 11 fixed and mobile vertical profiling units, 9 mobile ground-based Doppler radars, and three research aircraft, including the NOAA P-3, whose data will be of focus in this paper. Based on the previously mentioned climatological studies, as well as an additional 6-year climatology of the area, the study area chosen for the project encompassed most of Kansas and parts of Nebraska and Oklahoma (Fig. 1). This was where most of the instrumentation was based. The instrumentation used during the campaign was intended to observe three main phenomena in relation to MCS maintenance: the stable boundary layer, the low-level jet, and atmospheric bores.

It was hypothesized that a process exists in which the evaporatively generated downdraft in the rear of the MCS can descend and impinge on the nocturnal stable boundary layer, which in turn could initiate atmospheric waves and/or bores that would propagate ahead of the convective line and cause elevated parcels to be lifted to their level of free convection, allowing for new convective cells to form and the MCS to propagate. Based on this hypothesis, it was reasonable to make observations of atmospheric bores and the stable boundary layer, since they would be the best evidence that this process does take place in MCSs. In addition, it was also important to observe the downdraft region of the storm in order to understand the microphysical processes that contribute to the development of the downdraft. This paper will focus on observations made in this region using the NOAA-P3 aircraft. Figure 2, a schematic, details the hypothesized process, as well as the general location in the storm where the P3 targeted its collection of data.

There have been a few past field campaigns that have focused on observing MCSs: The Oklahoma-Kansas Preliminary Regional Experiment for STORM-Central (PRE-STORM; Cunning 1986), The Bow Echo and MCV Experiment (BAMEX; Davis et al. 2004), and the Midlatitude Continental Convective Clouds Experiment (MC3E; Jensen et al. 2016). All three of
these projects employed a similar methodology in which research aircraft would fly vertical spiral ascents/descents (illustrated in Fig. 2) to collect in situ data through a certain depth of the MCSs. The main difference between PECAN and these three field campaigns is that the previous campaigns focused on observing daytime MCSs—PECAN was the first large-scale field campaign solely designed to observe nocturnal MCSs.

One of the goals associated with PECAN’s data collection was to combine the analysis of field observations with numerical simulations, which would help put the rich observational datasets into a dynamic context. The numerical simulations would then be used to analyze the dynamics of the system relating to downdraft development and gravity wave propagation. This paper presents a numerical simulation developed for the purpose of making such an analysis for the PECAN case that most represented the conceptual model of an elevated MCS (Stechman et al. 2020).

Typically, when using numerical simulations to put field observations into context of the actual storms, it is customary to compare certain aspects of the simulation with the available observations to confirm that it is sufficiently representative of the observed system. This paper presents a highly detailed comparison between in situ data collected by the NOAA P-3 aircraft from the nocturnal MCS on 20 June 2015 and a high-resolution simulation of that system. A comparison at this level of detail provides unique insight into the nature of field observations in relation to numerical simulations.
CHAPTER 2: EVENT SUMMARY

At around 2200 UTC on 19 June 2015 (5:00 p.m. LT), a cluster of storms formed over north central Montana. During the day they produced numerous severe wind and hail reports as well as one tornadic supercell (Fig. 3). As the system propagated eastward into western South Dakota during the evening and into the night, the severe weather reports reduced as the cluster organized into a nocturnal MCS. Strong surface winds remained, however, throughout the system’s lifetime, with peak winds reaching approximately 80 mph, resulting in one death. From a synoptic perspective, the region in which this organization occurred was characterized by environmental conditions favorable for nocturnal elevated convection. Figure 4 illustrates these conditions, including the presence of a nocturnal low-level jet and low-level moisture advection, and strong upper level winds at 500 hPa in the South Dakota region where the storm occurred. Considering these factors, operational forecasts anticipated that this system would grow upscale and become elevated as it crossed the states of North and South Dakota during the nocturnal hours.

The PECAN operation times for this case were 0100-0900 UTC (8 p.m. to 4 a.m. LT), with the primary focus being between 0500 and 0800 UTC, when most of the in-situ data were collected. During this period, the system took on a classic MCS structure, conforming to the Houze (1989) trailing stratiform, leading convective line model. Of the MCS cases that occurred during PECAN, the 20 June case conformed most closely to the Houze (1989) model, and was the case with the strongest rear inflow jet (RIJ) and surface winds.

During the 20 June event, the only instrumentation that was utilized was that aboard the NOAA P-3 Research Aircraft, which flew a total of 7 spiral ascents/descents in the anvil and
stratiform regions of the MCS. The remaining PECAN assets were not deployed because the location of the MCS was too far north of the base. Stechman et al. (2020) summarizes the observations from this event. Figure 6 outlines the locations and times of these spirals relative to the system at the time they were flown. Spirals 1-3 were taken in the anvil region, and Spirals 4-7 in the stratiform region. Since some of these spirals were taken in similar locations (one ascent and one descent), only three key spirals, spirals 2, 5, and 7 will be analyzed for this paper and compared to the model simulation. These three spirals were taken in distinctly separate areas of the MCS, with Spiral 2 in the anvil region, Spiral 5 in the rear stratiform region, and Spiral 7 in the front part of the stratiform region, close to the transition zone. By separating by region, and also by the time elapsed between each spiral, a stronger perspective of the structural and temporal evolution of the system in relation to the model simulation can be obtained.

The data collected by the P-3 during these spirals included radar reflectivity and radial velocity scans from the NOAA Tail Doppler Radar, thermodynamic sounding data, and microphysical particle observations. This paper will examine the radar and sounding data, comparing directly with analogous plots created from the model simulation data. Stechman et al. (2020) details the microphysical observations from the P-3 as well as the specific instrumentation used for the three types of data that were collected.

The nature of the instrumentation used and the vertical extent through which the P-3 flew constrain and scale how we choose to compare the model simulation to the observations. With respect to the Tail Doppler Radar, as described by Stechman et al. (2020), there were two beams, one fore and one aft of the radar. These created vertical cross sections of reflectivity and radial velocity, with a new scan being made approximately every 10 seconds. The plots these scans produced cover about 40 km horizontally, but because of attenuation of the X-band radar, any
reflectivity data beyond approximately a 10 km radius becomes difficult to compare quantitatively to the model. This strongly limits the horizontal range of reflectivity data that is available for comparison. In addition to the short effective range of the radar for reflectivity, the P-3 only flew through a depth of about 5 km within the storm, typically from 2 km to 7 km MSL, for each spiral. While the radar data extend to the top of the system, the sounding data was limited to altitudes where the P-3 flew. Because of this, sounding comparisons with the model are confined to a 5 km deep layer within the MCS.
3.1 MODEL DESCRIPTION

For this study, the WRF-ARW model (v3.9.1.1) was used to carry out the simulations. Three domains were used, with their spatial extent indicated in Fig. 6. The outermost grid, with a horizontal grid-spacing of 5 km, was initialized at 0000 UTC 19 June, a full 24 hours before the 20 June MCS had developed. The model was initialized with archive North American Model (NAM) analysis data, updated every six hours for boundary conditions. The second domain was initialized at 0000 UTC 20 June with 1 km horizontal grid spacing. The innermost domain was then initialized at 0230 UTC 20 June with 200 m grid spacing, approximately 30 minutes before the desired time window for analysis would begin. All three domains used 80 vertical levels, with increasing concentration closer to the surface. Considering the scale of the phenomena, the data for the innermost domain was saved every minute for the duration of the model run, which ended at approximately 0630 UTC, allowing for about 4 hours of model data collection on the 200 m scale.

The physical parameterizations and options chosen are included in Table 1. Concerning the microphysical parameterization, multiple schemes were tested early in the study with the outermost domain to determine which would best reproduce the MCS evolution and structural features. The desired characteristics were mainly timing and geographical accuracy. Considering these two criteria, the Morrison microphysics scheme (Morrison et al. 2009) produced an MCS that evolved most closely compared to observations, so the Morrison scheme was used for the more detailed simulations.
3.2 COMPARISONS BETWEEN OBSERVATIONS AND MODEL SIMULATION

The goal of this paper is to develop a detailed comparison between the simulated and observed mesoscale convective system. The horizontal scale of the 20 June MCS was approximately 150-200 km from front to rear. The P-3 radar cross sections have a maximum width of approximately 40 km; however, due to attenuating effects on reflectivity, this is limited even further to 10-20 km. Consequently, each of the spirals capture about 10% of the width of the storm. Additionally, because the P-3 only flew between 2 and 7 km MSL, it captured a third of the vertical extent of the storm in the case of the microphysical and thermodynamic observations. Because of these limitations, it became important that the comparisons be as exact as possible relative to the time evolution and location of the MCS convective line.

As mentioned before, the data retrieved from the P-3 radar came in the format of radial cross sections of reflectivity and velocity. It would make sense to compare these data with analogous cross sections of the model output so that the two datasets could be compared directly. Due to the nature of the P-3 dataset, this posed multiple difficulties that needed to be overcome to ensure that these comparisons held weight. The greatest challenge was deciding when and where to choose the model cross sections, so that the location of the cross sections could be considered at the same relative location and time of evolution as that observed. There were two factors that were considered in placing the cross sections. The first was correct timing. The simulated MCS developed much quicker than the observed storm. Because our research questions are related more to the structure/dynamics of the MCS, it was decided that the comparisons should be made at similar time periods in each respective storm’s development, instead of at the same geographical location or time. By comparing convective features, it was determined that a 2-hour offset was most appropriate for the comparisons, i.e., since the first P-3
spiral was made at approximately 0500 UTC, this would be analogous to 0300 UTC in the model simulation.

Once the optimal timing was determined, the second factor to be considered was the relative location of the P-3 within the storm. It was decided that the best way to do so was to calculate the approximate distance of the P-3 from specific features that were represented in both the model and the observations and place the cross section at the same relative distance from those features in the model. In the following section, more detail regarding this method for each specific spiral will be presented. Overall, since the modeled MCS was almost exactly the same horizontal scale as was observed, this method proved most effective.

Because the P-3 was flying in a spiral pattern during operations, the orientation of the radar cross sections was constantly changing. In this work, cross sections that were approximately perpendicular to the convective line are used (west-east oriented), since these are most relevant to storm propagation. This choice limited the temporal resolution of the P-3 data to about every 5-10 minutes.

Concerning the P-3 sounding data, an analogous sounding was obtained from the model simulation, at the exact center of each model cross section. This posed potential issues as the P-3 covered a horizontal distance of about 20 km during its spirals, so a point sounding may not be entirely representative of the spirals. The impacts of this issue will be discussed more in the next section.
CHAPTER 4: RESULTS

In this section, three spirals chosen from three different regions in the MCS will be compared with the model solution, Spiral 2, taken in the anvil region, Spiral 5, in the rear stratiform region, and Spiral 7, in the front of the stratiform region, near the transition zone. Figure 7 depicts the locations of these spirals in the observed system. The comparisons will be grouped into five subsections based on the type of data analyzed: 1-km reflectivity plan view, vertical reflectivity cross sections, vertical cross sections of cross-section parallel wind speed, vertical cross sections of relative humidity, soundings, and contoured frequency by altitude diagrams (CFADs) of reflectivity and wind speeds. Each section will feature all three spirals to convey the development of the system.

4.1 LOW-LEVEL REFLECTIVITY

Figure 7 shows plan views of observed 1-km reflectivity and 1-km simulated reflectivity. Figs. 7a,d depict the location of the P-3 aircraft during Spiral 2, and the analogous location in the simulated MCS. At this time, the P-3 was located at the northern side of the rear inflow jet entrance region, as evidenced by the apparent reflectivity notch. This feature was clearly replicated in the simulation, so placing the cross section for Spiral 2 was straightforward. Figures 7b,e depict the placement of Spiral 5 in the model in relation to the P-3 position. In this case, the P-3 was located approximately 110 km from the leading convective line, calculated perpendicular from the apex of the bow echo. This position was used to place the model cross section in a similar location. The location of Spiral 7 is shown in Figs. 7c,f. Here it was decided to use the distance from the apex of the convective line, which was approximately 60 km, as well
as the distance from the southern terminus of the line, which was about 40 km to place the cross section within the simulation. Although it is difficult to create an exact analogue between the two systems, these estimates were the best choices, given the available data.

Comparing the two systems at 0506 UTC, during Spiral 2 (Figs. 7a,b), the first notable difference is the location of the MCS. The observed system had progressed farther east, towards central South Dakota, while the simulated system was located near the western border of South Dakota. The timing and location of the simulated MCS was similar to the observed storm early, but the maturation of the simulated system lagged behind geographically by about two hours by the end of the simulation. Aside from geographic position, similarities between the observed and simulated system are evident. The spatial scales of the convective line and stratiform region were roughly equal, measuring approximately 150-200 km front to back, and 200-300 km left to right. The orientation of the convective line, however, was somewhat different, with the observed convective line having a more NE-SW orientation, while the simulated convective line was generally more N-S.

Spiral 5 was flown at 0610 UTC (Figs. 7c,d). By this point, the observed system had begun to take on a leading convective line/trailing stratiform structure that was evident earlier in the simulation, so the similarities between the model and observations are more pronounced. The observed MCS convective line bowed out by this time, implying that surface winds increased as the system matured. The observed line also aligned in a more N-S orientation, akin to the simulation. Additionally, some minor convective features, such as the protrusion of enhanced convection directly east of the P-3 (Fig. 7c), as well as the additional convective line extending eastward ahead of the MCS, were replicated in the model.
At 0749 UTC, Spiral 7 (Figs. 7e,f) was flown near the transition zone of the system. At this period in the MCS’s development, the similarities between the observations and the simulation were at their most pronounced. The observed system fully conformed to the leading line/trailing stratiform model, with both the observations and model maintaining similar spatial scales. The bow echo in the observation was well developed and now directed towards the east completely, as opposed to its earlier NE-SW orientation. The previously mentioned additional convective features were well reproduced in the simulation, particularly the secondary convective line extending eastward, although it had southeastward-directed orientation in the observations, compared to the eastward direction in the simulation. While the innermost model domain does not extend further northward than depicted, the lobe of moderate reflectivity values extending north of the convective line had a similar spatial extent in the 1-km model grid (not shown). Overall, the similarities between the observed and modeled MCSs were sufficient to advance forward in analysis of other aspects of the structure.

4.2 VERTICAL REFLECTIVITY STRUCTURE

Figures 8a,d,g depict vertical cross sections of observed and simulated reflectivity during Spiral 2. As mentioned before, this spiral was flown in the anvil region, so the observations captured the rear part of the MCS. Figure 8a gives context to the spiral data by showing a cross section through the entire system (see Fig. 7 for location). This early in the simulation (0306 UTC simulation time), the storm already conformed to the Houze (1989) MCS model. The MCS dimension normal to the convective line was 200 km, with the cloud top near 15 km MSL. Figure 8d depicts the cross section in the black box region of Fig. 8a, analogous to the P-3 radar scan for Spiral 2. Here, the precipitation in the anvil region of the simulation reaches about 4.5
km MSL, with reflectivity values peaking around 30 dBZ in the western portion and almost 40 dBZ towards the east. Comparing this to the P-3 radar scan (Fig. 8g), a few differences are evident. First, the precipitation does not extend as far toward the ground as the simulation, stopping at about 5-5.5 km MSL. Second, it appears from the simulated reflectivity that reflectivity aloft is more intense in the simulation. This was difficult to compare quantitatively with the observations, due to attenuation of the P-3 radar signal. Closer to the center of the cross section, where attenuation was minimal, there were indications that the simulation still exhibited values approximately 10-15 dBZ greater than what was observed.

During Spiral 5, the P-3 had moved into the central stratiform region of the system. Figure 8b indicates the structure of the simulated MCS at this time. There was a well-defined radar bright band extending through the length of the stratiform region, with a region of weaker reflectivity between the eastern terminus of the bright band and the convective line. Figure 8e depicts the cross section from the model simulation analogous to the region observed by the P3. In the simulation, the melting level was located at 4.5 km MSL, with maximum reflectivity values reaching nearly 60 dBZ at that level. The cloud top ranged from about 11.0 km MSL toward the rear of the cross section to 14.0 km in the front. Comparing this to the P-3 radar scan in Fig. 8h, there are some strong similarities, as well as differences. The melting level is located at the same elevation. The cloud tops are more consistently at a higher elevation. The most notable difference, however, is the intensity of the reflectivity. Maximum reflectivity in the observations reached about 40 dBZ at the melting level, almost 20 dBZ less than in the simulation. Additionally, outside of the melting level, reflectivity was generally weaker in the observation than in the simulation. Attenuation of the radar signal was more evident, as the
bright band largely disappears about 10 km away from the P-3. This made the comparison more difficult, but close to the aircraft, large differences were still evident.

Moving to Spiral 7, at around 0549 UTC in the simulation and 0749 UTC in the observations, the MCS reached full maturity, as indicated by Fig. 8c. The bright band, transition zone, and melting level were fully evident. The simulated reflectivity has also increased in intensity overall, with the melting level consistently over 60 dBZ and the convective line over 65 dBZ, with other areas in the 40+ dBZ ranges. It is clear these values are not realistic, regardless of the context of the observed MCS. Focusing on the cross section (Fig. 8f), this area was still located in the trailing stratiform region, but much closer to the transition zone and convective line. In the simulation, the melting level was still located around 4.0-4.5 km MSL, the cloud tops at 14.5-15.0 km MSL, and reflectivity values in the bright band still exceeded 60 dBZ. The P-3 radar scan (Fig. 8i) better elucidates the similarities and differences between the two systems. While a similarly well-defined bright band was sampled by the P-3, the difference in reflectivity intensity is much more apparent, even with attenuation taken into account. The bright band reflectivity in the observations peaked at about 45-50 dBZ, with reflectivities closer to 35-40 dBZ in the rain region below it. Reflectivity in the observations above the bright band was markedly reduced to about 20 dBZ, while the simulation maintains the reflectivity intensity upwards to around 11km MSL, still averaging around 45-50 dBZ. The simulated reflectivity was typically 15-20 dBZ greater than what was observed by the P-3. The values of simulated vs observed reflectivity were the largest discrepancy found between the simulation and observations. Aside from the intensity of the reflectivity, structurally the two MCSs were quite similar. The bright band was again still located around 4-4.5 km; the cloud tops were about 1 km lower, around 13-14 km MSL, but constant throughout the cross section.
4.3 WIND SPEED

Analyzing wind speeds is another key to understanding structural similarities between the modeled and observed MCSs. In this section, cross sections similar to the previous section are presented, except using wind speed parallel to the cross sections, to understand the front-to-back structure of the MCS wind field. This will permit comparisons of features such as the RIJ and cold pool development. These features are particularly important since sources of dry air are of interest in the context of this study.

Beginning with Spiral 2, Fig. 9a depicts the vertical cross section of parallel wind speeds taken at the same location as 8a. The rear inflow jet is apparent, as well as the location of the convective line. Using the same location analogous to the P-3 scan, Fig. 9d depicts the parallel winds in a vertical cross section of dimension similar to the P-3 scan. In this plot, the rear inflow is located around 5.5-6.0 km MSL, and is about 4-5 km deep. Peak wind speeds are about 35 m/s. Comparing this to the P-3 scan in Fig. 9g, the elevation of the rear inflow is approximately the same as that of the simulation, but not quite as deep, about 2-3 km. It is important to note that because the radar only retrieves velocities of the hydrometeors, and this Spiral was located in the anvil region, it is difficult to discern the bottom of the RIJ, since there may be no scattering elements. It is quite possible due to the lack of particles below 4.5 km MSL, that the P-3 was just not capturing the full downward extent of the rear inflow. Wind speed values were roughly equivalent, peaking around 35 m/s, possibly slightly higher in some small regions.

In Spiral 5, the P-3 was positioned in the descending section of the RIJ, indicated by the window in Fig. 9b. Focusing on the windowed section (Fig. 9e), it is evident that this location is just at the point where the RIJ was beginning to descend. Across this 40 km wide section, the
axis of the RIJ descends from about 6 km MSL, to 4 km, a 2 km descent. Wind speeds intensified toward the eastern edge, reaching nearly 40 m/s. In the P-3 radar scan for this spiral (Fig. 9h), the descent is also evident, from about 5.5 km MSL to 3.5 km MSL, slightly lower in the observations. Wind speeds were weaker in the observations by about 5 m/s.

Moving forward to Spiral 7 (Fig. 9c), the RIJ had intensified substantially, with peak wind speeds of almost 60 m/s near the front of the MCS. The cross section for the spiral is depicted in Fig. 9f. It appears that through this 40 km section, the RIJ made its full descent, leveling out before reaching the ground, possibly at 100-200 meters above ground. In the western portion of the cross section, the RIJ was still descending, so this 40 km portion of the storm is likely where the RIJ reached its lowest elevation. In the radial velocity scan from the P-3 (Fig. 9i), the descent is also apparent, likely reaching the ground in the eastern portion of the cross section. The main difference is where the descent occurs. In the simulation, the descent occurs much closer to the western edge, while in the radar scan, it’s more centered. Comparing this to Spiral 5, where it appeared that the P-3 was closer to the convective line, it seems that the RIJ might have a slightly steeper descent in the observations than in the simulation. Quantitatively, the RIJ in the observations descended from about 3.5-4.0 km MSL to the ground (1.5-2 km MSL) over a 15-20 km long section, while in the simulation, the descent was only from about 3.0-3.5 km to 2.0-2.5 km. Considering wind velocities in this region, the simulation was roughly 5-10 m/s greater throughout, supporting the idea that the MCS was stronger in the simulation.

4.4 AIRCRAFT VS MODEL SOUNDINGS

In addition to the tail Doppler radar scans, the P-3 also collected in-situ thermodynamic data during its flights. By comparing the in situ sounding during the spirals with grid point
soundings from the model simulation, one can understand the thermodynamic similarities and differences between the simulation and observations. In this section, a cross section of the entire simulated MCS, at the same location as the reflectivity and velocity plots from the previous sections, will be presented for each of the three spiral times, depicting relative humidity with respect to water. The sounding data collected by the P-3 was collected along a spiral path. A grid point sounding at the center of the analogous cross section in previous figures was used for comparison. This presents potential complications, since MCSs are horizontally heterogeneous. Variations across 10 or 20 km, which was approximately the diameter of the spirals, may be significant, and it would be difficult to reflect those variations with a single grid point sounding.

Figure 10a depicts the vertical cross section of relative humidity for the entire storm at the same location and time as Figs. 8a and 9a. There are two apparent sources of dry air behind the convective line, the dry subcloud layer at about 2 km MSL, and within the RIJ at 6 km MSL on the western side of the cross section. Figure 10d shows a sounding taken at the center of the cross sections in Figs. 8d and 9d. Dry layers were centered at 450 hPa and 750 hPa (Fig. 10a). Comparing this to the P-3 sounding in Fig. 10g, the difficulty with comparing the two types of soundings becomes apparent. Most notably, the 450 mb dry layer is not present in the observations. If that dry layer were directly a result of transport of dry air from the west within the RIJ, then both soundings should exhibit that feature, since the velocity analyses earlier confirmed the existence of the RIJ at that location. However, referring back to Fig. 10a, there is high variability in relative humidity throughout the entirety of the RIJ. It could be that the P-3 did not descend through any significant dry regions during the spiral, but it is difficult to confirm this from the data available. On the other hand, if the model sounding was placed just 5 or 10 km east or west of where it was, the dry layer might not have been evident, and the two soundings
could be considerably more similar. In addition to this major difference, the model sounding also exhibits a lower cloud base, at about 650 mb, compared to 550 mb in the observation. This is consistent with Figs. 8d,g, in which the simulated reflectivity extended approximately 1 km lower than the observations. Below the cloud base in the observation, there is a 150 mb thick dry adiabatic layer. In the simulated sounding, there appears to be a slight dry adiabatic layer from 700 mb to 650 mb. Below 700 mb, the two soundings cannot be compared, since the P-3 spirals began at about 700 mb. This presents the second problem with comparing these two types of soundings. Since the P-3 only flew between 700 mb and 400 mb, any data in the simulation outside of this range has no analogue and cannot be included in the comparison. This means that the low levels cannot be interpreted in the context of the observed system, so features such as the dry layer at 750 mb in the simulation may or may not be present in the observed MCS.

In the model, the dry air associated with that RIJ was more homogeneous; however, the spiral was located closer to the front of the storm, so this homogeneous region was not sampled during Spiral 5 by the P-3 at this time. In the simulation, it appears that there was not yet a continuous stream of dry air connecting the back of the MCS to its front along the RIJ axis, but there was evidence of this beginning to occur from 90-130 km in Fig. 10b, at around 3 km MSL. Analyzing the model sounding at this time (Fig. 10b), it appears that no layer is completely saturated, at least with respect to water. In the relative humidity plot from Fig. 10b, the sounding does pass through a large portion of the rear inflow jet, which may contribute to dry air in that region. Comparing it to the P-3 sounding (Fig. 10h), there is a difference in relative humidity through the entire layer sampled by the P-3. The top of the dry subcloud layer in the model sounding was still about 100 hPa lower than in the observations. One similarity between the two
soundings is that they exhibit similar temperature profiles throughout the 750 – 450 hPa layer, decreasing with altitude from 15°C to -15°C.

At the time of Spiral 7, the RIJ was much more evident in the relative humidity fields (Fig. 10c), with a continuous stream of dry air being brought to the surface. The model sounding (Fig. 10f) was positioned ahead of where the RIJ finished its descent, which should be consistent with the P-3 sounding (Fig. 10i). Comparing the two soundings, the cloud base was located at the same pressure level, and the temperature profiles were still similar, decreasing with altitude from about 12°C to -12°C in the 750 – 450 hPa layer. The dry layer at 750 hPa appears similar, although the simulation exhibits about a 10°C dewpoint depression, while in the P-3 sounding it was only 5°C. Overall, as time progressed, and as each spiral was positioned progressively toward the front of the trailing stratiform region, the observations became more consistent structurally with the model simulation.

4.5 CONTOURED FREQUENCY BY ALTITUDE DIAGRAMS

To obtain a more quantitative understanding of the differences between the observations and the simulation, contoured frequency by altitude diagrams (CFADs) were used to compare both reflectivity as well as wind speeds. By calculating the frequency at which certain values of reflectivity and wind speed occurred at each height level across the entire MCS, it could be determined whether the specific cross sections chosen earlier are characteristic of the entire system or not. Considering the regular gridded structure of the model data, these diagrams were easily created for the simulation. To obtain a similar dataset from the observational data collected by the P-3, additional information was needed to supplement the P-3 scans. Stechman et al. (2020) utilized the Spline Analysis at Mesoscale Utilizing Aircraft and Radar
Instrumentation (SAMURAI; Bell et al. 2012) software, which synthesized a 3-dimensional field of radar observations by performing a multiple Doppler analysis using the P-3 tail radar scans and NWS WSR-88D radar data. Using this 3-dimensional dataset, a comparison could be made between the simulated MCS and the observed MCS.

Beginning with the CFADs of reflectivity (Fig. 11) for the three spirals, the quantitative differences become clearer. The most notable aspect is the definition of the melting level, at approximately 4 km MSL in the simulation (Fig. 11 d,e,f). In the SAMURAI runs (Fig. 11a,b,c), it is not as well-defined in any of the three spirals, and the maximum values peak at approximately 45 dBZ. In the simulation, the melting layer reflectivity at the second spiral time exceeded 50 dBZ, while at the first and third spiral time, 60 dBZ. This contrast wasn’t only present in the melting level, however. In the mid to upper levels, the difference in reflectivities still exists, often exceeding at least a 10 dBZ difference. Beyond this 4-10 km MSL layer, it is difficult to compare the SAMURAI runs with the simulation, since the lowest and highest levels did not have sufficient data coverage between the P-3 data and the WSR 88-D data. Because of this discrepancy, data outside of this 4-10 km layer for the SAMURAI runs for reflectivity (Fig. 11a,b,c) and wind speed (Fig. 12 a,b,c) have not been included, so as to illustrate the difference in sufficient spatial coverage.

Considering the line-normal west-east component of wind speeds (Fig. 12), the differences are not quite as distinct. Both the SAMURAI data and the simulation exhibit a similar bow-like vertical profile in horizontal wind speed, in which velocities peak in the mid-levels at the elevation of the RIJ, and velocities become negative in the upper levels, characteristic of MCSs conforming to the Houze 1989 conceptual model. The strongest difference between the observations and the simulation, however, is the wind speed values
themselves. In the observations (Fig. 12a,b,c), each of the three spirals exhibit maximum wind speeds of about 35 m/s. In the simulation, the maximum ranges from about 35 m/s during the comparison time of Spiral 2 (Fig. 12d) to over 50 m/s during the comparison time of Spiral 7 (Fig. 12f). This difference in wind speeds is consistent with the findings from the vertical cross sections of wind speed, suggesting that the peak wind speeds in the simulation increased as the storm evolved.
CHAPTER 5: DISCUSSION AND CONCLUSIONS

In this paper, a detailed comparison was carried out between field observations from the 20 June 2015 PECAN MCS and a high-resolution numerical simulation using the WRF-ARW model. This MCS was the one of the strongest observed during the PECAN field campaign, producing winds over 80 mph, severe hail reports, and one reported death. In addition, this system most closely conformed to the leading line/trailing stratiform model described by Houze (1989). During the operation, the NOAA P-3 flew seven vertical spirals in different locations within the trailing stratiform region of the storm, collecting Doppler radar reflectivity and velocity data, in situ sounding data, and cloud/precipitation particle observations. In order to add context to these data, and confirm that the model reasonably simulated the MCS structure, the radar and sounding observations were directly compared to the numerical simulation for three of the seven spirals by creating analyses from the simulation analogous to those produced from the observations, accounting for temporal and spatial differences between the two systems.

Considering the observations and the model, some general conclusions could be made about the MCS development and structure. Beginning with the low-level radar reflectivity analysis, it was clear that both systems maintained a similar structure throughout their lifetime, conforming well to the leading line/trailing stratiform paradigm for MCSs. Additionally, specific convective features were well replicated in the simulation, such that the observed and simulated storms were structurally similar in scale, with both having similar major features, and orientation of the convective line. Similarity was also apparent in the vertical cross sections, where features such as the bright band were located at similar elevations in both the observations and model. While they did maintain similar structure based on the reflectivity cross sections, the main
difference between the observations and model was that the simulation had higher reflectivities than what was observed at every time period analyzed. This is believed to be a direct result of how the microphysics parameterization scheme in the model calculates reflectivity. A difference of 15-20 dBZ was clearly not realistic, and further analysis of the reflectivity calculation within the model will be needed to understand what caused this difference. Testing additional parametrization schemes might be useful; however, they may present other discrepancies with the observed system.

The elevation, strength, and position of the rear inflow jet were then compared. It was concluded that the front-to-rear position of the RIJ, as well as its elevation, were approximately the same throughout the lifetime of the MCS in both the model and observations. The location of the descent of the RIJ was several km closer to the convective line in the observations than in the simulation. This might have been due to the difficulty in choosing analogous cross sections to compare the simulation to the observations. The magnitude of the cross-section parallel wind speeds was about 10 m/s greater in the simulation compared to the observations.

Considering the sounding observations, the comparisons highlighted additional differences between the two systems. For Spiral 2, there was a dry pocket in the simulated sounding that was not replicated in the observations. While this was only noted in one spiral, it does highlight a complexity in the methodology of comparing the P3 sounding to a grid point sounding from the simulation. The relative humidity cross section from the simulation suggests that, at least at this point in the MCSs life cycle, that the dry air being supplied by the RIJ was not homogenous, and that depending on where in the storm a sounding is selected, one might be observing significantly different results within a distance of 10-20 km.
Another difference between the two soundings, which was most evident with Spiral 2, was the elevation of the cloud layer, which was lower in the simulation than what was observed. This is consistent with the reflectivity at the same location, which showed that precipitation was reaching closer to the ground in the anvil region in the simulation. While the reflectivity analyses for Spiral 5 cannot address this difference, since the precipitation reaches the ground in both, they were consistent with the cloud layer continuing to be located at a lower elevation in the simulation. Spiral 7 did not feature any significant differences between simulation and observations. The soundings were nearly identical for the 750-450 mb layer that the P3 was sampled. This implies that as the MCS matured, the simulation structurally approached more closely what was observed. The reflectivity analyses reinforce this conclusion. Nevertheless, it is difficult to make a strong conclusion based on the soundings, since they cover such a small vertical portion of the atmosphere. There was no way to accurately compare near-surface conditions within the storm since the P3 did not collect data at those elevations.

CFADs were used to better quantify the results found from the radar reflectivity and velocity observations by accounting for the MCS as a whole, instead of a single vertical cross section. In both reflectivity and wind speed CFADs, the results were consistent with the vertical cross sections, such that the simulation produced overall higher reflectivities and wind speeds compared to the observations. It was also evident that as the MCS evolved, the differences grew larger, suggesting that the simulation strengthened much more rapidly than what was observed. One concern with the SAMURAI data used for these comparisons is that the method used to obtain the 3D fields leaves areas without data, which results in less spatial coverage than what the simulation can provide. However, there was still a clear consistency in the differences
between the observations and the simulation, compared to other techniques used for the comparisons.

Overall, considering the radar analyses and sounding data, the simulation showed strong similarities with the observations from the June 20, 2015 MCS event, with the most notable difference being that the simulation had higher reflectivity and somewhat stronger winds. Considering that future work is mostly concerned with the evolving structure of the MCS, and with a caveat that the microphysics scheme used in the model be tested or adjusted to account for the unusually high values of reflectivity, these results are considered sufficient to move forward with a detailed dynamical and microphysical analysis of the simulated MCS.
Figure 1. Frequency of nocturnal MCSs (number per week): (a) 6-yr Jun–Aug climatology (2010–15); (b) PECAN period (1 Jun–15 Jul 2015) (Geerts et al. 2017).
Figure 2. Cross section through an elevated MCS coupled with a mesoscale gravity wave on a stable layer capped by an inversion. The dark wavy region denotes the stable layer, and the burgundy color, dry air to the rear of the MCS. The symbols *, •, and / denote snow, graupel, and rain. Straight white arrows within the stable layer denote wave-relative flow. White arrows above the boundary layer denote the primary flows within the MCS. The yellow spirals show the proposed P-3 spiral locations, and the ⊙, the location of horizontal flight legs. The blue arrows denote the scan limits of the P-3 dual Doppler recovery regions for each horizontal flight leg.
Figure 3. Storm Prediction Center storm reports from 1200 UTC 6/19/15 to 1200 UTC 6/20/15. The red oval highlights the storm reports associated with the 20 June MCS that were made during the night.
Figure 4. 20 June 2015 0600 UTC Storm Prediction Center mesoanalysis maps showing (Left) 850 hPa composite geopotential heights (black contour), wind vectors, dewpoint (red dashed contour), and wind speeds (green shaded). (Right) 500 hPa geopotential height (black contour), wind vectors, and wind speed (blue shaded).
Figure 5. 1.0 km AGL composite of WSR 88-D radar reflectivity at 0758 UTC on 20 June 2015. Overlaid is the flight path of the NOAA P-3 between 0400 UTC and 0800 UTC during the June 20 operation with the seven spiral descents/ascents labeled.
Figure 6. Map showing the location of the three domains used in the model simulation.
<table>
<thead>
<tr>
<th>Physics</th>
<th>Option</th>
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<tr>
<td>Microphysics</td>
<td>Morrison (2009)</td>
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<tr>
<td>Land Surface</td>
<td>Noah LSM (2004)</td>
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<td>Surface Physics</td>
<td>Revised MM5 (2012)</td>
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<tr>
<td>Cumulus Physics (outer domain only)</td>
<td>Grell-Freitas (2014)</td>
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<tr>
<td>LW and SW Radiation</td>
<td>RRTMG (2008)</td>
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Table 1. Physics options used for the model simulation.
Figure 7. Comparison of 1.0 km AGL horizontal cross sections of reflectivity from (left) the observed WSR 88-D composites and (right) the model simulation for Spiral 2 (a,b), Spiral 5 (c,d) and Spiral 7 (e,f). The P-3 flight path is on the 88-D composites to indicate the location of each of the three spirals at the time being compared. The short blue bar on the panels on the right indicate the location and extent of the analogous cross sections being used to compare with the P-3 observations, while the long black bar indicates the cross section through the whole storm, used for context in Figs. 8, 9, and 10.
Figure 8. Vertical cross sections of simulated reflectivity (shaded) for Spiral 2 (left), Spiral 5 (middle) and Spiral 7 (right) at the locations indicated in Fig. 7(b,d,f). The top row (a,b,c) indicates the West-East vertical cross section of the entire MCS that passes through the location of the P-3 spiral. The black box indicates the relative spatial extent of the shortened cross sections (middle row). The middle row (d,e,f) details the shortened cross sections considered to be analogous to the P-3 radar scans, which are shown in the bottom row (g,h,i). Potential temperature is contoured every 2 K in panels a-f.
Figure 9. Same as Fig. 8, but for cross-section parallel wind speeds. Wind vectors (w exaggerated) are included in panels a-f instead of potential temperature.
Figure 10. (Top row) West-East vertical cross sections of relative humidity (shaded) for Spiral 2 (left), Spiral 5 (middle), and Spiral 7 (right) through the length of the MCS, passing through the location of each spiral with potential temperature contoured every 2 K. (Middle row) Sounding from the simulation taken at the location indicated by a vertical line in panels a, b, and c, which is at the center of the respective short cross sections from Fig. 7 (b, d, f). (Bottom row) Sounding data sampled by the P-3 during the three spirals.
Figure 11. Contoured frequency by altitude diagrams (CFADs) of reflectivities for Spiral 2 (left), Spiral 5 (middle), and Spiral 7 (right). (Top row) CFADs for the SAMURAI data. (Bottom row) CFADs for the simulation. Shaded is the frequency of occurrence of each reflectivity value for each height level (MSL) as a fraction of the total number of data points in each height level.
Figure 12. Same as in Fig. 11, except for the U (East-West) component of wind speed.
REFERENCES


