P1.3 RADAR SURVEY OF MESOSCALE CONVECTIVE SYSTEM DEVELOPMENT

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1. INTRODUCTION

Mesoscale convective systems (MCSs) are significant rain-producing weather systems for the central United States during the warm season (Fritsch et al. 1986). Additionally, MCSs produce a broad range of severe weather events (Maddox et al. 1982 and Houze et al. 1990) that are potentially damaging and dangerous to society. Given the profound influence that MCSs have on the midlatitudes, continued study is essential in gaining a deeper insight of these systems.

One approach that has been used to study MCSs involves classifying the systems and analyzing the differences among the categories. For example, Bluestein and Jain (1985) used radar data to classify severe squall lines in Oklahoma by their development. Other types of classification include sorting systems by their convective/stratiform precipitation arrangement (Houze et al. 1990) and categorizing systems by their infrared (IR) satellite characteristics (Maddox 1980). These previous studies laid the foundation on which the classification schemes presented in this paper were based.

The objective of this study was to supplement prior studies on MCS classification by providing a more comprehensive MCS study in terms of number of systems, types of systems, length of study, and geographical area considered. The focus of the classification process was directed toward the developmental stages to better characterize common patterns by which convection becomes organized into mature MCSs. This paper describes the process used to select, analyze, and classify a sample of MCSs.

2. DATA AND METHODS OF ANALYSIS

In an attempt to obtain a large sample of MCSs, a relatively long time period and large geographical area were studied. The central United States during the warm seasons (April-August) of 1996-1998 was selected for the study to ensure an initial sample of several hundred systems. Both satellite data and radar data were used to observe and analyze the MCSs during this time period. Satellite data were used to initially identify and classify each MCS due to the extensive coverage and ease of identifying weather systems. Then, using radar data each system was reanalyzed at a higher temporal and spatial resolution and categorized by its developmental characteristics. Augustine's (1985) MCS documentation program was modified to work with both types of data to record lifecycle information for each system.

Information from the documentation program allowed for categorization of the systems by satellite characteristics, generation of time series plots of area and rainfall rate for each system, and calculation of average statistics for each MCS category. In addition, a representative sounding was selected for each system to provide some information on the environment in which the storms formed. Finally, severe weather reports were recorded for each system. This multitude of information was used to investigate any differences among the various categories.

3. SATELLITE CLASSIFICATION OF MCSs

Hourly infrared (IR) satellite images were reviewed to initially identify the MCS sample. Any system that exhibited persistent, coherent structure at the -52°C blackbody temperature threshold was recorded as a MCS. This subjective process resulted in an initial sample of 643 MCSs. The next step involved using the documentation program to obtain hourly information on the size, centroid, and eccentricity of the system to allow for classification by these characteristics.

The satellite classification scheme used in this paper is based on Maddox's (1980) definition of mesoscale convective complexes (MCCs). Essentially, the systems were classified according to their size, duration, and eccentricity of the -52°C cloud top temperature threshold. Four categories were compiled for this scheme to encompass MCSs of all sizes and shapes. The two large categories had previously been defined in the literature. MCCs are large, circular systems while persistent elongated convective systems (PECSs) (Anderson and Arritt 1998) are large, linear systems. Thus, it was natural to create two categories of smaller MCSs, so the scheme would be inclusive of a wide variety of systems.

The eccentricity criterion of the smaller systems remained the same as for the larger systems, so only the size and duration criteria of the -52°C cloud top temperature threshold needed to be set for these smaller systems. These minimum criteria were important because they basically set the definition of a MCS for this study. Following Parker and Johnson (2000), the appropriate MCS time scale is f^{-1}, which is approximately 3 hours for the midlatitudes. Thus, the duration criterion was set at ≥3 hours for the smaller systems. Choosing the minimum size of the smaller systems was somewhat more arbitrary, but after reviewing several of the systems, the most coherent systems persisted at an area of at least 30,000 km^2. Therefore, the size criterion for the smaller systems was set at ≥30,000 km^2 with the caveat that they must have a maximum size of at least 50,000 km^2 as a way of

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Table 1
MCS definitions based upon analysis of IR satellite data

MCS Category	*Size*	*Duration*	*Shape*
MCC	Cold cloud region ≤ -52°C with area ≥ 50,000 km^2	Size definition met for ≥6 hours	Eccentricity ≥ 0.7 at time of maximum extent
PECS	Cold cloud region ≤ -52°C with area ≥ 50,000 km^2	Size definition met for ≥6 hours	0.2 ≤ Eccentricity < 0.7 at time of maximum extent
MβMCC	Cold cloud region ≤ -52°C with area ≥ 30,000 km^2 & maximum size must be ≥ 50,000 km^2	Size definition met for ≥3 hours	Eccentricity ≥ 0.7 at time of maximum extent
MβPECS	Cold cloud region ≤ -52°C with area ≥ 30,000 km^2 & maximum size must be ≥ 50,000 km^2	Size definition met for ≥3 hours	0.2 ≤ Eccentricity < 0.7 at time of maximum extent

connecting the definition of the smaller systems to the larger systems. From Orlanski's (1975) definitions of meteorological scales, the smaller MCSs fit appropriately into the meso-β scale; thus, the smaller, circular systems were called meso-β MCCs (MβMCCs) while the smaller, linear systems were called meso-β PECSs (MβPECSs). Table 1 shows the definitions of the four classes of MCSs according to infrared satellite characteristics: *MCC, PECS, MβMCC, and MβPECS*.

After further screening and the classification process, a total of 465 MCSs fit into one of the four categories. Table 2 provides some satellite lifecycle statistics for each of the MCS categories. PECSs and MCCs were the most common types of MCSs with PECSs alone accounting for 40% of the sample total. April was by far the least likely month for a MCS to develop accounting for less than 10% of the total sample while May, June, and July were about equally the most common months for MCS occurrence. PECSs were also the largest systems on average having an average maximum area of over 200,000 km^2. Even though the average maximum size of the entire sample was around 160,000 km^2, about ⅔ of the systems were smaller than this due to a few large systems skewing the average. The larger systems (MCCs and PECSs) persisted longer than the smaller systems (MβMCC and MβPECS) with average durations of more than 10 hours compared to average durations of just over 6 hours for the smaller systems. Finally, the average eccentricities for the linear and circular systems fell approximately in the middle of their respective ranges.

Table 2
Average statistics for each satellite-defined MCS.

	#	Max Area (km^2)	Duration (hr)	Eccen.
MCC	111	193,282	10.9	0.83
PECS	187	213,473	10.6	0.50
MβMCC	71	74,696	6.1	0.84
MβPECS	96	85,195	6.7	0.53
All MCSs	465	160,980	9.2	0.64

4. RADAR CLASSIFICATION OF DEVELOPMENT

Following the satellite classification process, several more systems were removed from consideration due to a lack of radar coverage bringing the final total to 387 MCSs. The 15-minute radar images for the remaining systems were animated and analyzed to determine some common patterns of development.

4.1 *Definition of classes*

The goal of this stage was to develop a classification scheme that described the orientation and interaction of the system's convective components. Bluestein and Jain's (1985) study on the development of severe squall lines in Oklahoma provided the foundation of the classification scheme presented in this paper. They used four classes to describe squall line development: *broken line, back building, broken areal, and embedded areal*. However, their classification scheme needed to be expanded for this study to accommodate all types of MCSs over a larger geographical area. After thorough review of all MCSs in the sample, a few notable differences among the systems appeared including the presence of stratiform precipitation, the arrangement of convective cells, and the interaction between convective clusters. These factors led to a classification scheme of three *levels*. Each level is discussed in more detail in the next few sections with a depiction of the development classification scheme in Figure 1.

4.1.1 *Presence of stratiform precipitation*

The first level in the classification process involved determining whether or not the initial convection developed in an area of stratiform precipitation. This follows directly from the embedded areal category of Bluestein and Jain (1985) and was included due to anticipated differences between these systems and those that formed in non-precipitating areas. As seen in Fig. 1, a system that initiated in a region of stratiform precipitation was tagged with the term *embedded* while the other systems remained nameless for this level.

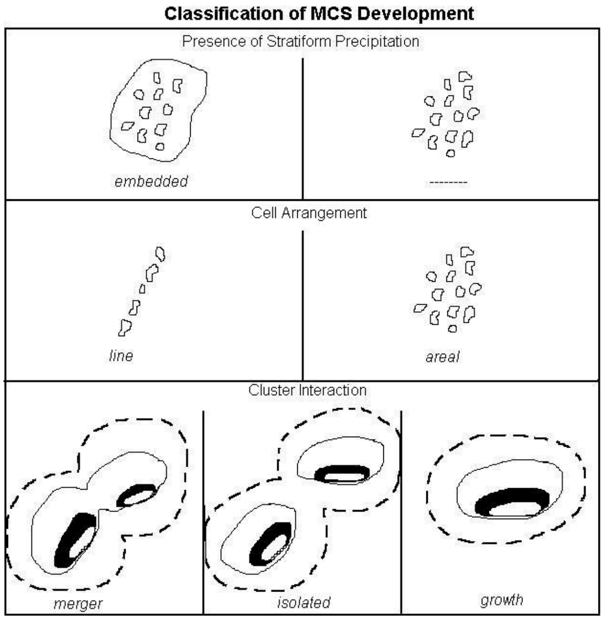

Figure 1. Idealized depiction of the three-level classification process used to categorize MCS development as seen by radar. The solid lines and contours represent relative reflectivity levels while the dashed lines represent the outline of the cold cloud shield.

4.1.2 *Arrangement of convective cells*

The next level in the classification process described the arrangement of the initial convection. Once again, this follows closely from Bluestein and Jain (1985) who basically broke the cellular arrangement into line and areal categories. Thus, systems with convection organized in a linear fashion received the term *line* while systems with convection scattered over an area received the term *areal* (see Fig. 1). If a system showed both types of cellular arrangement, it was given the name *combination*.

4.1.3 *Interaction of convective clusters*

The final level in the classification process involved observing the interactions of the convective clusters. Please note that this step occurred later in the lifecycle of the MCSs. The term *cluster* refers to a meso-β grouping of contiguous or nearly contiguous convective cells. Three major features of cluster interaction emerged when reviewing the systems. Systems in which the convective cells grew into a single convective cluster were called *growth* systems. Other systems had multiple convective clusters that merged, and these were called *merger* systems. Finally, systems that had convective clusters close enough to share a common cloud shield but did not physically merge as seen by radar were referred to as *isolated* systems (see Fig.1).

4.2 *Basic characteristics*

Including the *unclassifiable* category, there are a total of 17 development categories. The *areal merger* and *combination merger* categories together accounted for the development of more than half of the MCSs. The next most common types of development included the *areal growth* and *line merger* categories each accounting for about 10% of the entire sample. Another way to view the results involves breaking the data into the three levels of the development process. Table 3 provides frequency and satellite lifecycle statistics for each level of the classification process. Embedded systems were much less common than systems that were not embedded. About half of the systems were areal systems and more than 70% of the MCSs formed from the merger of multiple convective clusters. Embedded, areal, and growth systems were all statistically smaller than the other respective categories at the 95% level or greater. Areal systems were also shorter-lived than systems with other types of cellular arrangement. Additionally, line systems tended to develop into linearly shaped systems at maturity. These findings suggest that the arrangement of convection at initiation may provide relative information about the system's duration, shape, and size at maturity.

Table 3
Average statistics for each development level.

	#	Max Area (km^2)	Duration (hr)	Eccen.
Embedded	65	130,072	9.3	0.66
Not Embed	312	162,581	9.0	0.64
Line	63	191,393	9.3	0.54
Areal	200	129,768	8.4	0.69
Combination	114	185,688	10.2	0.63
Merger	275	162,819	9.3	0.64
Isolated	32	185,195	9.0	0.61
Growth	70	121,577	8.3	0.68
Unclassifiable	10	191,401	8.9	0.60

5. COMPOSITE RESULTS

When reviewing the environments for each MCS classification, a couple of systems showed a tendency to develop in more stable environments than the other types of MCSs. MβPECS and embedded systems had higher average lifted indices and lower average convective available potential energies than the other systems in their respective classifications. Inspection of severe weather reports for each system revealed that PECSs had the greatest propensity to be associated with severe weather. The smaller satellite classes (MβMCCs and MβPECSs) were much less likely to be associated with severe weather than the larger systems (MCCs and PECSs). In addition, embedded and areal systems were much less likely to produce severe weather than their counterparts.

The systems were also analyzed by compositing their lifecycles. The satellite lifecycles were composited by normalizing the MCS timescale according to the time a system first met its MCS definition, its time of maximum extent, and the time when it was no longer a MCS. This allowed the areas at the -52°C, -58°C, -64°C, and -70°C blackbody temperature thresholds to be summed together at each normalized MCS time. Figure 2 shows the composite IR satellite lifecycle for all 387 MCSs. This plot is representative of the satellite lifecycle plots for each MCS classification. One feature that can be seen in Fig. 2 is that the areas of the colder temperature thresholds reached a maximum before the warmer thresholds. For example, the -58°C area (2nd curve from top) peaked before the -52°C area reached a maximum (top curve). In addition, the composite shows that systems had longer growth periods than decay periods (as demarcated by vertical lines in Fig. 2).

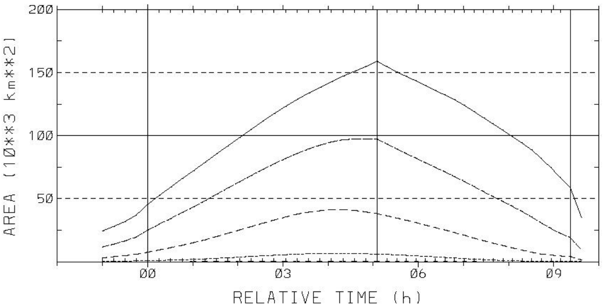

Figure 2. Infrared satellite lifecycle composite for entire MCS sample. Curves represent the areas of the -52°C, -58°C, -64°C, and -70°C blackbody temperature thresholds. Vertical lines represent start, max, and end times.

The radar lifecycle composite for the entire MCS sample (Figure 3) was created in a very similar manner to the satellite lifecycle composite. The volumetric rain rate, average rain rate, and area are plotted in Fig. 3. Notice that the average rain rate (thin, dashed line) peaked out very early in the lifecycle at about the time of MCS initiation (left vertical line). As the systems grew in area (thick, dashed line), the average rain rate diminished indicating an increase in stratiform precipitation. The volumetric rain rate (solid line) peaked at nearly the same time as the -52°C cloud shield area (middle vertical line), but about an hour before the precipitation area reached a maximum.

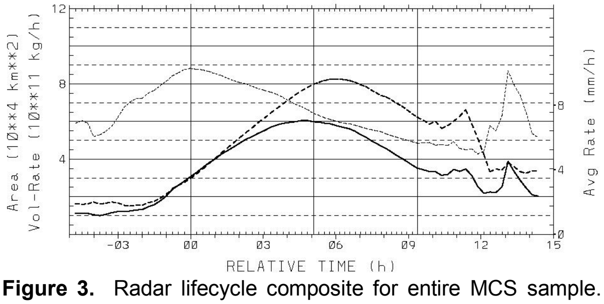

Figure 3. Radar lifecycle composite for entire MCS sample. Solid curve represents volumetric rain rate, thick, dashed curve represents area, and thin, dashed curve represents average rain rate. Vertical lines represent start, max, and end times of the *satellite* lifecycle.

6. SUMMARY AND CONCLUSIONS

A large sample of MCSs was analyzed with both satellite and radar data. The systems were initially examined and classified with satellite data into four categories: *MCC, PECS, MβMCC, and MβPECS*. Then, the systems were reanalyzed with 2-km national composite radar reflectivity data to evaluate the development of each system. A three-level classification process was devised to categorize MCS development. These levels involve looking at the presence of stratiform precipitation, the arrangement of convective cells, and the interaction of convective clusters. Finally, further analyses of each category's environment, production of severe weather, and lifecycles were carried out.

PECSs were the largest and most common type of MCS in this study. They were also the most likely to be associated with severe weather. MβPECSs had much different properties than their namesake, as they tended to form in the most stable environments, and along with MβMCCs were the least likely MCSs to be associated with severe weather.

Most systems in this study initiated in an area free of stratiform precipitation and developed from the merger of two or more convective clusters. Finally, it appears that there might be some valuable information hidden in the arrangement of the convective cells at initiation as areal systems were statistically smaller, shorter lived, and produced fewer severe weather reports than systems having convection arranged in a line.

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