3.3 USE OF PROXIMITY SOUNDING PARAMETERS TO IMPROVE THE PREDICTION OF MESOSCALE CONVECTIVE SYSTEM (MCS) SPEED AND DISSIPATION

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1. INTRODUCTION

The speed and longevity of mesoscale convective systems (MCSs) continues to be a difficult forecasting problem. Part of this problem stems from incomplete knowledge of the processes that lead to organized cold pool development and forward-propagating systems, as well as factors that lead to the weakening and dissipation of MCSs after they are established. Through analyses of proximity soundings, Evans and Doswell (2001) show that a wide range of convective available potential energy (CAPE) and vertical wind shear is found in the environments of long-lived forward-propagating MCSs that produce damaging surface winds (derechos). They also show that the strength of the mean wind (0-6 km) and its effects on cold pool development and MCS motion may play a significant role in sustaining derechos through modifying the relative inflow of unstable air. The analysis of proximity soundings in Coniglio et al. (2004) also shows that CAPE and low-level wind shear varies considerably in derecho environments and that significant wind shear often exists in mid and upper levels in the pre-convective environment. Through the use of wind profiler observations and numerical model output, Gale et al. (2002) examine nocturnal MCSs in Iowa to determine predictors of their dissipation. Similar to Evans and Doswell (2001), they find that changes in MCS speed may control its dissipation through changes in low-level storm-relative inflow. However, despite some indications that a decreasing low-level-jet intensity and low-level equivalent potential temperature (θe, and it's advection, can be useful in some cases, they did not find robust predictors of MCS dissipation.

The speed of MCSs appears to play a significant role in both the production of damaging surface winds and its longevity, but accurate estimates of MCS motion prior to MCS initiation are difficult, at best. MCS motion has been estimated as the vector sum of the advection and the propagation of the convective cells. Useful estimates of the advective component can be provided by the mean cloud-layer wind, but forecasting the propagation component is more problematic since the cold pool of air that results from the evaporation/melting of precipitation always interacts with the environment. The ensuing regions of convergence along the cold pool can greatly influence the propagation of the parent MCS (Corfidi 2003).

The goals of this work are to examine a large data set of proximity soundings to identify predictors of MCS speed and dissipation and to develop forecast tools based on these predictors. The approach is to use statistical techniques on the predictors to develop equations for the probability of MCS maintenance and the probability of MCS speed above a certain threshold. Although a wide variety of convective clusters and precipitation systems can be included under the general category of MCSs (Zipser 1982), we focus our attention on the more robust systems that obtain a quasi-linear leading line and tend to produce severe weather.

2. METHOD

We identified MCSs by examining composites of base radar reflectivity for the months of May-August during the seven-year period of 1998-2004. We focus our attention on the MCSs that had a quasi-linear or bowed leading edge at least 100 km in length for at least 5 continuous hours. From a set of over 600 MCSs of this type, we identified 269 soundings that were taken within about 200 km and 3 h of the linear portion of the MCS and displayed no obvious signs of contamination from convection. We added 79 derecho proximity soundings used in Coniglio et al. (2004) for a total of 348 warm-season (May-August) MCS proximity soundings.

Although the prediction of the dissipation of *quasi-stationary* MCSs is an important problem to address, we focus our attention on the prediction of *forward-propagating* MCSs in this study. Therefore, we removed those soundings that sampled the environment ahead of a system in which the leading line was moving < 10 m s^{-1} near the sounding time. This results in 287 soundings to be used in developing the MCS dissipation predictors. These soundings were then stratified into 76 "initiation", 96 "mature", and 115 "dissipation" soundings based on the appearance and trends of the radar reflectivity at the time of the sounding.

To derive predictors for the speed of MCSs, we removed the dissipation soundings and stratified the remaining 228 soundings according to the speed of the leading line during the organizing and mature stages of the MCSs. These soundings were classified into two

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groups; the 98 soundings associated with MCS speeds ≥ 18 m s^{-1} and the 130 soundings associated with MCS speeds < 18 m s^{-1}. We used a speed of 18 m s^{-1} as the break point because operational experience suggests that systems moving faster than this speed have an increased likelihood of producing damaging wind gusts (as long as the storms are rooted in the boundary layer).

Hundreds of convective parameters were then calculated for each sounding. Using various statistical significance tests (Wilks 1995), we identified parameters that gave the lowest probabilities that the sample means among the two groups were the same. Discriminant analyses (Wilks 1995) were then used to find the combination of these parameters that created the best separation of the two groups. Once these parameters were identified, we used logistic regression (Wilks 1995) to develop probability equations for MCS maintenance and for MCS speed ≥ 18 m s^{-1} (35 kts). Logistic regression is a method of producing probability forecasts on a set of binary data (or data within two groups) by fitting parameters to the equation

$$y = \frac{1}{1 + \exp[b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_k x_k]} \quad (1)$$

where y is the fractional probability of one of the groups occurring, k is the number of predictors, x_k refers to the k^{th} predictor, and b_k refers to the k^{th} regression coefficient for each predictor (see Wilks 1995 for more information). Logistic regression is attractive in this context because the predictand is a probability, i.e., it allows for the direct computation of probabilities between two possible outcomes in a set of data. In developing the MCS maintenance probabilities, the two possible outcomes are a mature MCS or a dissipating MCS. For example, y=0.9 should be interpreted as a 90% chance that an MCS will, at least, be maintained at its peak intensity. In developing the MCS speed probabilities, the two possible outcomes are a speed < 18 m s^{-1} or a speed ≥ 18 m s^{-1}. In this case; y=0.9 means that the MCS has a 90% chance of having a forward-propagating leading edge that moves at speeds ≥ 18 m s^{-1}.

3. RESULTS

a. MCS maintenance probabilities

Guided by previous studies that find parameters related to the environmental wind shear profile (Weisman and Rotunno 2004, Coniglio et al. 2004, Parker and Johnson 2004), the mean winds speeds (Evans and Doswell 2001), and the instability to be important for the development and maintenance of robust, quasi-linear MCSs, we seek to quantify the differences among these parameters between the mature and dissipation soundings. We examine many wind shear parameters (bulk shear, total shear, positive versus negative shear) over many different layers of the atmosphere and identify the particular wind shear parameter and layer that best separated the mature and dissipation soundings. Although many of the differences in the wind shear parameters are statistically significant, the greatest differences are found among the shear vector magnitudes (bulk shear) over very deep layers (Fig. 1). The differences are relatively small for the low-level shear magnitudes, suggesting that these values, alone, have limited utility and that an integrated measure of shear over a very deep layer will have the most utility in forecasting the weakening of MCSs (calculations of the total shear, or the hodograph length, support this claim). This measure is perhaps the most promising since mid-upper-level wind shear can have significant influences on the maintenance of MCSs (Coniglio et al. 2004, Parker and Johnson 2004), along with the positive influences of the low-level shear on the strength of the system (Weisman and Rotunno 2004). To account for the possibility of variable heights of the low-level or upper-level jets that often control the effective magnitude of shear, we use the maximum bulk shear between 0-1 km and 6-10 km as our shear parameter for all of the calculations discussed later in this section; this is hereafter referred to as the "maximum shear".

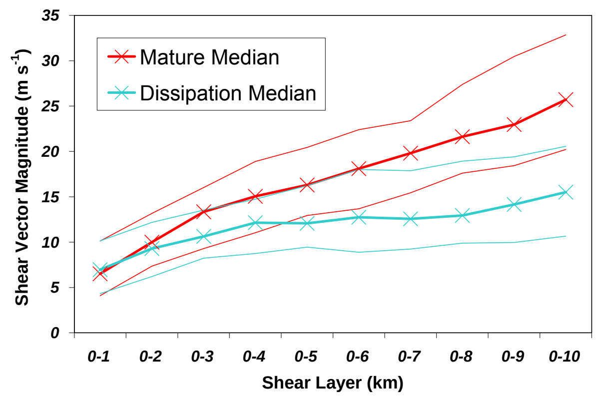

Fig. 1. Median shear vector magnitudes (lines marked X) calculated over various depths among the mature (red) and dissipation (blue) sounding groups. The thin lines enclose the 25th and 75th percentiles of each distribution.

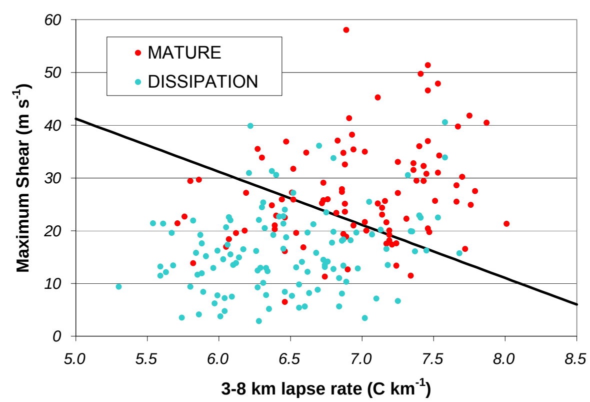

Fig. 2. Scatterplot of the maximum shear (m s^{-1}) versus the 3-8 km lapse rate (C km^{-1}) for the mature and dissipation soundings. The linear discrimination line separates 75% of the soundings correctly.

For the instability measures, lapse rates that represent the lower half of the convective cloud layer were found to be the most significantly different among the mature and dissipation soundings. As illustrated in Fig. 2, A discriminant analysis between the two groups shows that the 3-8 km lapse rate along with the maximum shear separate correctly 75% of the soundings. This indicates that these two parameters alone could be used to forecast the weakening and dissipation of MCSs effectively, but there is no limitation to the number of parameters that can be used in a discriminant analysis, or in logistic regression leaving room for improvement. We found that the most unstable parcel CAPE (MUCAPE) was very different between the mature and dissipation soundings and, interestingly, was only weakly correlated with the 3-8 km lapse rates. In addition, the 3-12 km mean wind speeds were significantly different between the mature and dissipation soundings. Despite the correlation with the maximum shear values, the mean winds were used because they provided an increased ability to discriminate between the mature and dissipation soundings when included with the other three parameters. These four parameters collectively can separate over 80% of the soundings correctly when input into a discriminant analysis. Because of the mutual correlations among the hundreds of variables, any additional parameters provided negligible benefit to discriminate among the two groups, thus, the maximum shear (maxshear), 3-8 km lapse rate (3-8 lr), MUCAPE, and 3-12 km mean wind (3-12 mw) were used as predictors in eq. (1) to develop the following equation for the MCS maintenance probability (MMP):

$\underline{\underline{For\ MUCAPE \geq 100\ J\ Kg^{-1}}}$:

$$MMP = \frac{1}{\left[1 + EXP\left(a_0 + (a_1 * \{\max shear\}) + (a_2 * \{3-8\ lr\}) + (a_3 * \{MUCAPE\}) + (a_4 * \{3-12\ mw\})\right)\right]}$$

$\underline{\underline{For\ MUCAPE < 100\ J\ Kg^{-1}}}$:

$MMP = 0,$

where the regression coefficients are $a_0 = 13.0$, $a_1 = -4.59 \times 10^{-2}$, $a_2 = -1.16$, $a_3 = -6.17 \times 10^{-4}$, and $a_4 = -0.17$ and the predictors are described above. By design, the application of these probabilities is conditional upon the development of an MCS. Fig. 3 shows a plot of the equation for MMP for the four predictors that are normalized by their respective minimum and maximum values in the data set. The steepness of the curve for MMP suggests substantial skill in discriminating mature and dissipating MCSs. We envision the best real-time application of the MMP would use observational data or short-term model output at a time close to convective initiation. For example, gridded fields from the hourly Rapid Update Cycle (RUC) (Benjamin et al 2003) can be used to calculate these probabilities and give guidance to the regions most likely to sustain MCSs that do develop. This could benefit Day 1 Severe Weather Outlooks, Mesoscale Discussion products, and the issuance of Severe Weather Watches at the Storm Prediction Center (SPC) and short-term forecasts issued by local forecast offices. Although the MMP was designed to discriminate between mature and dissipating MCSs, it may also be used with mesoscale model output well before convective initiation to give a general idea of where mature MCSs may be favored on longer time scales (assuming convection in the model doesn't remove instability erroneously).

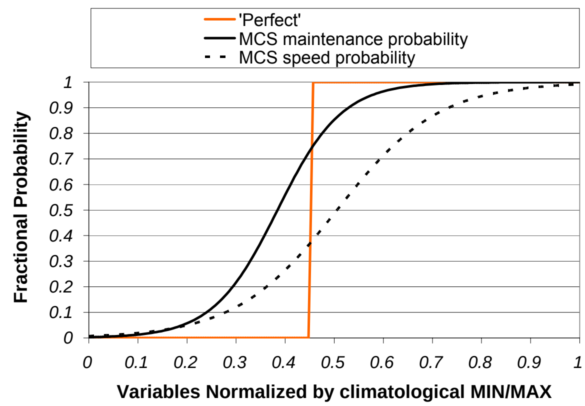

Fig. 3. Probability of MCS maintenance (MMP, solid line) and MCS speed ≥ 18 m s^{-1} (MSP, dashed line) based on logistic regression. A "perfect" regression (orange line) is shown for reference. The ordinate represents the predictors normalized by their minimum and maximum values in the data set. For example, if all four of the predictors for the equation for MCS maintenance are exactly half way between their min and max values (0.5), then the regression equation predicts a ~90% chance that the MCS will be maintained at its peak intensity. In general, a steeper curve means a better ability of the parameters to discriminate between the two groups.

b. MCS speed probabilities (MSP)

A similar procedure was followed using the C < 18 m s^{-1} and C ≥ 18 m s^{-1} soundings to identify the parameters that best discriminate between the two groups. Through significance testing and discriminant analysis, it was found that the low- to upper-level mean wind speed discriminated between the two groups very well. However, it was found that the geographical signal in the data hindered the general use of the thermodynamic parameters. For example, a specific value for θ_e that discriminates well over Louisiana doesn't discriminate well over North Dakota. To better isolate the physical signal for general use, the thermodynamic parameters were then converted to non-dimensional standard normal variables (z-scores) (Wilks 1995) based on their 7-year (1998-04) mean and standard deviation derived from radiosonde data. Among the parameters converted to z-scores, the maximum low- to mid-level difference in θ_e and the lapse rate in the lower half of the cloud layer were found to discriminate between the two groups very well. Based on these findings, z-scores of the maximum vertical difference in θ_e between low and mid levels (zmaxthediff), the 2-12 km mean wind speed (m s^{-1}) (2-12 mw), and z-scores of the 2-6 km lapse rate (2-6 zlr) were used as predictors in eq. (1) to generate an MCS speed equation. This equation can be used with observational data and numerical model output to generate the conditional probability that an MCS will move with speeds ≥ 18 m s^{-1} at maturity, and is given by,

$$\underline{\underline{For\ MUCAPE \geq 100\ J\ Kg^{-1}:}}$$

$$MSP = \frac{1}{[1 + EXP(a_0 + (a_1 * \{z\max thediff\}) + (a_2 * \{2-12\ mw\}) + (a_3 * \{2-6\ zlr\}))]}$$

$$\underline{\underline{For\ MUCAPE < 100\ J\ Kg^{-1}:}}$$

$$MSP = 0$$

where the regression coefficients are a_0 = -3.46, a_1 = 0.447, a_2 = 0.119, and a_3 = 0.79 and the predictors are described above. Although the regression curve for MSP is not as steep as the curve for MMP (Fig. 3), indicating a lesser degree of statistical difference between the two groups, the slope of the curve still suggests the ability to discriminate between "slow" and "fast" MCSs, and, thus, give an indication of the likelihood for the occurrence of a severe-wind producing MCS.

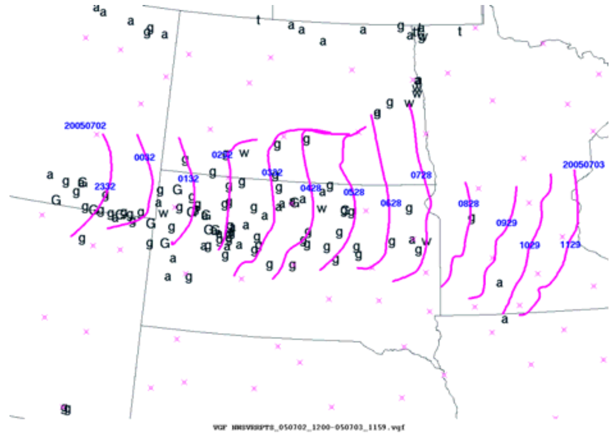

Fig. 4. Hourly traces of the leading edge of the nearly contiguous area of 35+ dBZ echoes associated with the MCS on 2-3 July 2005 (pink lines). Times (UTC) of the traces are labeled in blue and the dates (YYYYMMDD) are shown for the first and last trace. The letters represent severe weather reports from 1200 UTC on 2 July 2005 to 1159 UTC on 3 July 2005 (g – severe wind gust, w- severe wind, a – severe hail, t – tornado). Capital letters represent "significant" reports (65+ kt wind or 2+ in hail).

4. APPLICATION AND DISCUSSION

As part of the NOAA Hazardous Weather Testbed, a small collaborative program is currently taking place at the SPC and the National Severe Storms Laboratory (NSSL) to test the ability of these conditional probability forecasts to provide useful guidance on the speed of forward-propagating MCSs and their eventual dissipation (see http://www.spc.noaa.gov/exper/Summer_2005 for more information). To meet the goals of this program, daily activities include the documentation of MCSs using national mosaic radar reflectivity and the evaluation of the probabilities calculated using the SPC mesoscale objective analysis method (Bothwell et al. 2002) and using the hourly RUC forecasts. Fig. 5 shows an example of the MMP and MSP generated from operational RUC model output during a derecho MCS that occurred on 2-3 July 2005 (Fig. 4). The MCS developed a broad bowing signature in its early stages and was composed of smaller-scale bow echoes that were responsible for several reports of wind gusts > 65 kts in western South Dakota. The wind reports became less frequent as the MCS expanded in size and the leading line exhibited less bowing characteristics after 0700 UTC. During its lifetime, the MCS moved at speeds of 40-45 kts (20-22 m s^{-1}), but slowed to around 30-35 kts in the last few hours of its existence, which coincided with a general weakening of the 50+ dBZ echoes within the leading line.

The RUC forecasts generated MMPs over 90% in the region of the MCS for much of its lifecycle (Fig. 5a). The area of the MMP contours changed little throughout the 12 h forecast cycle so that the 3 h forecasts of MMP provide a good representation of the fields at the other forecast hours. The MMP appeared to indicate that the northern half of the MCS would begin to weaken after 0800 UTC as the probabilities decreased to 30-40% in western and north-central Minnesota; it also indicated that the MCS would dissipate altogether in southeastern Minnesota as a large east-west gradient in the probabilities was found in this area. The MSPs also suggested the persistence of a favorable environment for the system to attain speeds > 35 kts as the MSPs were 60-70% in much of the area that the MCS traversed (Fig. 5b). In addition, the MSPs dropped to 20-30% where the system slowed to speeds < 35 kts over southern Minnesota toward the end of its lifecycle.

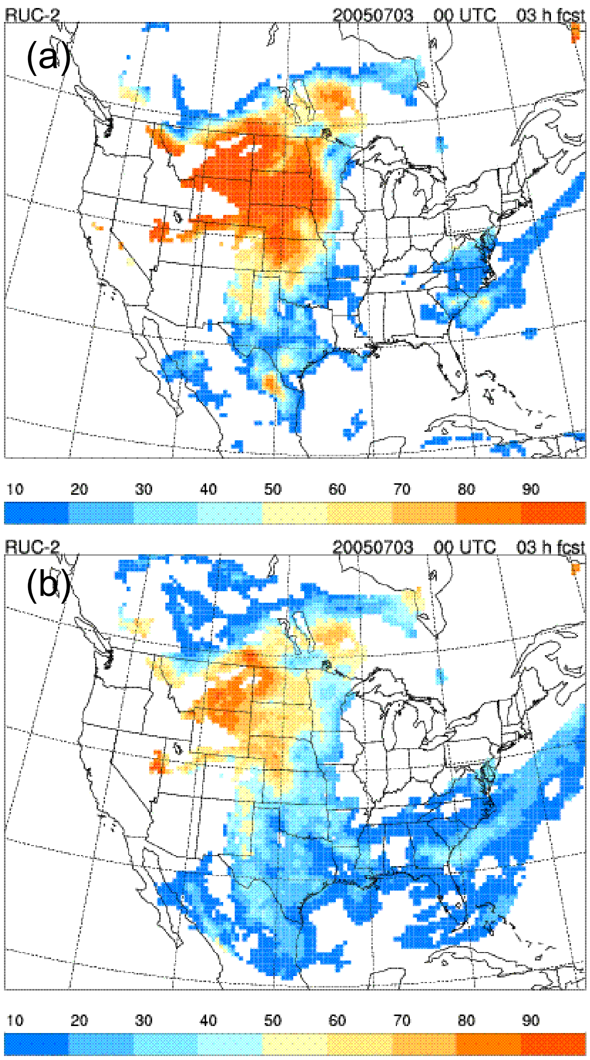

Fig. 5. (a) A 3 h forecast of the MCS maintenance probability equation (%) valid at 0300 UTC 3 July 2005 generated from the 0000 UTC RUC. (b) As in (a), except for the MCS speed probability equation (%).

The above example illustrates a successful application of the MMP and MSP probabilities with short-term numerical model output. By design, the probabilities can be applied to MCSs east of the Rocky Mountains, since the 600+ MCSs collected for the data set occurred in this region. However, the MMP and MSP may apply best to the Plains and Midwestern U.S., since this is where MCSs in the developmental data base occur most frequently. Thus, the climatological values of the shear, instability, and mean winds may be biased to these areas (this will be examined in the SPC/NSSL program).

We are also examining other possible limitations of the probability equations. For example, the probabilities will likely work best on MCSs that develop and continually generate and sustain convection through cold pool/shear/mean wind interactions when the shear and mean winds are substantial. However, MCSs can also maintain coherence through discrete propagation of the stronger cells along a surging outflow. The shear in these cases tends to be very weak, and if the other fields that comprise the MMP do not have unusually large values, the MMP will likely generate low probability values (one such case occurred in the upper Midwest and Ohio Valley region on 30 June 2005). This may also be true in cases with a spreading deep cold pool in weak shear and mean wind, but with very low levels of free convection and little convective inhibition, in which the quasi-linear convection can be continually maintained along the leading edge of the outflow. With this in mind, we will explore if there are certain types of MCSs (trailing, parallel, or leading stratiform) that tend to be handled better than others and if there are certain values or trends in the MMP or MSP fields that signal changes in character of the MCS (e.g., the type and/or amount of severe weather that it produces and/or transitions among MCS archetypes and the mode of the individual cells).

5. ACKNOWLEDGMENTS

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