Discrimination of Mesoscale Convective System Environments Using Sounding Observations

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ABSTRACT

The prediction of the strength of mesoscale convective systems (MCSs) is a major concern to operational meteorologists and the public. To address this forecast problem, this study examines meteorological variables derived from sounding observations taken in the environment of quasi-linear MCSs. A set of 186 soundings that sampled the beginning and mature stages of the MCSs are categorized by their production of severe surface winds into weak, severe, and derecho-producing MCSs. Differences in the variables among these three MCS categories are identified and discussed. Mean low- to upper-level wind speeds and deeplayer vertical wind shear, especially the component perpendicular to the convective line, are excellent discriminators among all three categories. Low-level inflow relative to the system is found to be an excellent discriminator, largely because of the strong relationship of system severity to system speed. Examination of the mean wind and shear vectors relative to MCS motion suggests that cell propagation along the direction of cell advection is a trait that separates severe, long-lived MCSs from the slower-moving, nonsevere variety and that this is favored when both the deep-layer shear vector and the mean deep-layer wind are large and nearly parallel. Midlevel environmental lapse rates are found to be very good discriminators among all three MCS categories, while vertical differences in equivalent potential temperature and CAPE only discriminate well between weak and severe/derecho MCS environments. Knowledge of these variables and their distribution among the different categories of MCS intensity can be used to improve forecasts and convective watches for organized convective wind events.

1. Introduction

Organized clusters of thunderstorms meeting particular spatial and temporal requirements have been termed mesoscale convective systems (MCSs; e.g., Zipser 1982; Hilgendorf and Johnson 1998; Parker and Johnson 2000). Knowledge of the environments that support the intensity of MCSs is essential in operational meteorology. This is especially true of MCSs that are long lived and produce damaging surface winds. The

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most intense end of this spectrum includes a class of systems known as derechos, which can be as destructive to life and property as tornadoes and hurricanes (Miller and Johns 2000; Ashley and Mote 2005). Synoptic patterns that support derechos and MCSs in general have been examined in numerous studies (Johns and Hirt 1987; Johns 1993; Coniglio et al. 2004; Maddox 1983; Maddox et al. 1986; Anderson and Arritt 1998; Laing and Fritsch 1997; Parker and Johnson 2000).

Because of their propensity to produce a disproportionate amount of damage and number of fatalities associated with convective windstorms (Ashley and Mote 2005), derechos have received much attention recently in the literature. Johns and Hirt (1987) studied 70 warm season (May–August) derechos and found that large

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convective instability and the presence of dry air at midlevels above moist air in the low levels were characteristics common to many derecho environments. It is recognized that the dry-over-moist moisture profiles allow for the development of air parcels with large negative buoyancy in lower levels, which fosters the development of organized very cold downdrafts (the "cold pool") and severe winds at the earth's surface (Wakimoto 2001). Derecho environments were also examined by Evans and Doswell (2001), who suggested that strong system-relative winds in low levels that supply the potentially unstable air and weak systemrelative winds at midlevels may be important to derecho development through their effects on the formation of the cold pool and the speed of the MCS. Additionally, they emphasized that convective available potential energy (CAPE) and vertical wind shear vary widely in their dataset, which likely reflects the large spectrum of forcing mechanisms that can produce derechos. Coniglio et al. (2004) used proximity soundings to support these findings and to add that the environmental shear often extends through a large depth as derechos mature and that this deep-layer shear weakens as derechos decay.

Although the above-mentioned studies shed light on the environments of severe MCSs, there has not been a specific investigation into the differences in the MCS environments among a wide spectrum of intensities, in terms of more than two degrees of severe wind production. It is well known that the potential for an MCS to produce an organized severe windstorm is enhanced as the convection organizes into a quasi-continuous collection of cells along the leading edge of the system ("quasi linear"), which is a reflection of the organization of the downdrafts and the cold convective outflows. It is also well known that certain modes of convective organization, such as bow echoes, and certain kinematic features, such as line-end and leading-line mesoscale vortices and rear-inflow jets, are especially associated with the production of severe surface winds (Schultz et al. 2000; Weisman 2001; Klimowski et al. 2003; Wheatley et al. 2006). Although the real-time identification of these features of MCSs by operational Doppler radars has increased the skill of very shortterm forecasts of convective windstorms, the anticipation of MCS severity on longer time scales remains a difficult forecast problem. Therefore, the focus of this work is to identify environmental variables that may help to determine if a given quasi-linear MCS will produce widespread severe surface winds on 3-12-h time scales.

To build on the past work on MCS environments, we present a study on the environmental variables that discriminate among quasi-linear MCSs of different intensities, focusing on the details of the kinematic environment and how the wind profiles may impact the strength and motion of the systems. This will hopefully provide forecasters with information that can be used to improve the short-term prediction of MCSs. Section 2 describes the MCSs considered, the scheme used to rate the MCSs, and the statistical methods. Section 3 describes the ability of selected kinematic variables to discriminate the MCS environments and discusses some ideas on the motion of MCSs in the context of past studies and the current results. Section 4 briefly discusses some findings on the differences in thermodynamic variables, such as downdraft convective available potential energy (DCAPE), among the MCS environments. Finally, the results are summarized and briefly discussed in section 5.

2. Methodology

a. Data collection and classification

Using radar images archived by the University Corporation for Atmospheric Research (UCAR) and the Storm Prediction Center (SPC) (information available online at http://locust.mmm.ucar.edu/case-selection/ and http://www.spc.noaa.gov/exper/archive/events), 269 MCSs were selected between the years of 1998 and 2004 for this study. To focus on the types of MCSs that are usually associated with severe wind potential, each MCS in the dataset exhibited a nearly contiguous line of convection at least 100 km in length for at least five continuous hours. Although these types of systems can occur year round anywhere in the United States, we restricted our search to the region east of the Rocky Mountains between May and early September. In addition, the MCSs were selected only if a 50-dBZ radar reflectivity echo within the main convective line was no more than 200 km and 3 h removed from an observed sounding. As part of the process of selecting the MCSs, skew T-logp diagrams were examined for each sounding and surface charts and radar data were examined in order to verify that the sounding was not contaminated by convection.

Each system was then categorized as a weak MCS (WCS), a severe but non-derecho-producing MCS (SCS), or a derecho-producing MCS (DCS) based on their production of severe surface winds (wind gusts $\geq 26 \text{ m s}^{-1}$ or, in some cases, wind damage). Reports from both digitized versions of the National Climatic Data Center (NCDC) publication *Storm Data* and the SPC online database were used to categorize the events using the *SeverePlot* program (Hart and Janish 2006). For the benefit of the severe thunderstorm forecasters

at the SPC, an MCS was classified as severe if it produced at least six severe wind reports, which reflects the guidelines for the issuance of severe thunderstorm watches by the SPC. Composite radar images from the aforementioned UCAR archive and in some cases, National Weather Service (NWS) Weather Surveillance Radar-1988 Doppler level II data were used to verify that the severe wind reports emanated from the MCS in question. Because 2004 data were not yet available to *SeverePlot* at the time of classification, preliminary storm reports archived by the SPC (available online at http://www.spc.noaa.gov/climo/) were used to perform the classification for 2004 events.

Following Coniglio and Stensrud (2004), three criteria were used to define a DCS: 1) there were at least six severe wind reports produced by the MCS, 2) successive severe wind reports occurred within 3 h or 250 km of each other in a chronological progression and in a concentrated area, and 3) the major axis of the line connecting the initial and final severe wind reports was at least 400 km long. If either the second or third criterion was not met, the system was classified as an SCS. We did not include the requirement of at least three reports of 33 m s⁻¹ to define a DCS, which was used in Johns and Hirt (1987). Therefore, some of the systems that are defined as derechos in the present study may not have been considered derechos in Johns and Hirt (1987) [we refer the interested reader to Coniglio and Stensrud (2004) for a discussion on the effects of not including this criterion on derecho climatology].

We recognize that some of the MCSs may be underor overestimated in intensity because of population biases, inaccurate reporting, and/or a lack of *measured* severe wind events in the severe weather database [see Weiss et al. (2002) and Trapp (2006) for discussion of this topic]. However, the NCDC database provides the only means for examining sample sizes large enough to make statistically meaningful conclusions in a timely manner. The underlying assumption in this study is that there is enough fidelity in this data to separate the weaker, shorter-lived MCSs from the intense, longlived MCSs without an overreliance on the accuracy of any given report.

At the time of the proximity sounding, the appearance and trends of the radar reflectivity data were used to assess the mean motion of the MCS convective line around the sounding time, as well as the stage of the MCS in its life cycle. The stage of the MCS in its life cycle is important to know because the environments associated with weakening MCSs are quite different than the environments during their earlier stages (Gale et al. 2002; Coniglio et al. 2006). The three life cycle stages defined in this study are 1) initial cells prior to MCS development, 2) a mature MCS with strengthening or quasi-steady high reflectivity echoes (50 dBZ or higher), or 3) a decaying MCS with significantly weakened or shrinking areas of high reflectivity or a loss of system organization without any later reintensification. MCSs that were decaying around the time of the sounding were removed from the dataset to focus on systems that were in their more intense stages. The quantities calculated from the proximity soundings thus represent the collective conditions during MCS development and maturity. The criteria discussed above result in a dataset of 57 WCSs, 78 SCSs, and 51 DCSs, each of which has an associated proximity sounding. This dataset allows considerable confidence in the statistical comparison of WCS, SCS, and DCS environments, the method for which is described next.

b. Statistical method

Several hundred kinematic and thermodynamic variables are calculated for each of the 57 WCS, 78 SCS, and 51 DCS soundings. The goal is to find the variables that best discriminate between the MCS categories in a "brute force" manner; that is, we let the statistical procedure reveal the best discriminators instead of restricting the examination to a small number of variables to verify preconceived hypotheses. Therefore, the results focus on the variables that are found to have the most statistically significant differences among the MCS categories from a large number of potential variables. However, we also discuss those variables that have been examined in previous studies for comparative purposes regardless of their discriminatory ability.

Box-and-whiskers plots are displayed to help the reader gauge the relative magnitudes and the differences of the distributions between the three MCS categories. The reader can also gauge the significance of these differences as well as the discriminatory ability of a particular variable by displays of the absolute values of the Z scores resulting from the statistical testing for the select variables. The Mann-Whitney nonparametric test statistic (Wilks 1995) is used to calculate the Zscores. Nonparametric tests are appropriate in applications with relatively small sample sizes, because there is no requirement to assume a distribution to the data sample as is required in the widely used Student's t test. Another benefit of using the Mann-Whitney test statistic is that it can be interpreted as a standard Gaussian variable, and thus, probabilities can be ascribed easily with the symmetry of the Gaussian distribution. For reference to the Z-score figures discussed next, |Z| >1.645 (2.575) corresponds to a probability of less than 10% (1%) that the two distributions were drawn from the same population, and therefore, the differences are more significant for a higher Z score.

3. Kinematic variables

The first examination into the differences in MCS environments is performed on a variety of kinematic variables, but we focus on characteristics of the vertical wind shear and the mean winds.¹ Although many methods of calculating wind shear are performed (bulk shear, total shear, shear components), only the magnitude of the vector difference between the wind vectors at two levels (with units of meters per second) and its component perpendicular to the convective line is highlighted next, because the largest Z scores are associated with this metric and because this is a widely used measure of wind shear employed by forecasters (hereafter, shear will refer to this measure with units of meters per second, unless otherwise noted).

a. Vertical wind shear

The strength of quasi-linear MCSs has been examined through the relationship between the environmental vertical wind shear and the strength of the convectively induced cold pool for many decades. Model simulations by Rotunno et al. (1988) and Weisman and Rotunno (2004) and many others indicate that as the component of low-level shear perpendicular to the convective line increases relative to the system-generated cold pool, the initial cells become stronger and the generation of upright convective cells is favored for longer time periods. Furthermore, Fovell and Dailey (1995), Parker and Johnson (2004), and Coniglio et al. (2006) show that mid- and upper-level shear can also be important for initiating and maintaining stronger convection along the leading edge of the cold pool. Note that the most direct application of these kinematic concepts is on the strength, structure, and longevity of convection along the leading edge of the MCS, and therefore, these concepts do not necessarily apply to the potential for an MCS to produce severe surface winds.

Nonetheless, the shear over most layers tends to be largest in DCS environments (Fig. 1a). However, when examining the ability of the shear to discriminate between the MCS categories, which is the primary goal of this study, it appears that the utility is highest when the layer through which the shear is calculated is deep (e.g., 0-6 and 0-10 km) (Fig. 1b). Among the entire set of shear variables, the 0-10-km shear is found to discriminate the best with a median shear of only 22 m s⁻¹ in WCS environments, but over 32 m s⁻¹ in DCS environments. The shear in shallower layers (especially 0-2 km) is not found to be as good a discriminator as the 0-6- and 0-10-km shears (Fig. 1b).

Once the orientation of the convective line can be diagnosed, results suggest that the shear component perpendicular to the line provides even more discriminatory ability between weak and strong MCSs (Fig. 2a), with the very deep layer shear values again providing the largest *Z* scores, although the utility of the low-level shear values improves quite a bit when looking at the line-perpendicular component (Fig. 2b). Most striking is the large separation in the 0–10-km line-perpendicular shear between the WCS and DCSs, with the median value being only 10 m s⁻¹ for the WCSs, but 25 m s⁻¹ for the DCSs (Fig. 2a).

These results are consistent with the idea that a moderately sheared environment increases the potential for an MCS to produce severe surface winds through a stronger, more organized convective structure, as expected from many years of diagnosing model simulations and observed environments. However, the better discriminatory ability of the very deep layer shears compared with the lower-level shears is noteworthy. As shown in the observational studies of Gale et al. (2002), Burke and Schultz (2004), Coniglio et al. (2004), Stensrud et al. (2005), and in this study (Fig. 1a), shear exists in a much deeper portion of the real atmosphere in MCS environments compared with the more confined layers used in many past idealized modeling studies of quasi-linear MCSs (Rotunno et al. 1988; Weisman et al. 1988; Weisman 1993; Trapp and Weisman 2003) upon which the shear-cold pool relationships were founded. Some later studies (Weisman and Rotunno 2004; Bryan and Weisman 2006) examine the effects of upper-level shear in modeling studies and conclude that low-level shear contributes much more to system strength and structure than does upper-level shear, while others (Fovell and Dailey 1995; Parker and Johnson 2004; Coniglio et al. 2006) emphasize that this mid- and upper-level shear in the environment, although weaker in magnitude, can be important for system structure and especially its longevity.

Although we cannot gauge the relative importance of the low-level versus upper-level shear in this study, we do find that the 4–8-km shear values are well above zero and may be as useful as the 0–4-km shear values in discriminating between weak MCSs and derechos prior

¹ Mean winds are determined by taking the square root of the sum of the average squared u and squared v components of the wind at each interpolated level (every 500 m) within the layer under consideration.



FIG. 1. (a) Box-and-whiskers plots for the 0–2-, 0–4-, 0–6-, 0–10-, 4–8-, and 6–10-km shears. Each set of three categories indicates the results for the WCSs, SCSs, and DCSs, from left to right. The whiskers stretch to the 10th and 90th percentiles and the boxes enclose the 25th and 75th percentiles. The lines connect the medians (asterisks) for the distributions for each variable. (b) Absolute values of Z scores resulting from the Mann–Whitney test between WCSs and SCSs, SCSs and DCSs, and WCSs and DCSs for the 0–2-, 0–4-, 0–6-, 0–10-, 4–8-, and 6–10-km shears.

to knowledge of the convective line orientation (Fig. 1b). Again, the benefits of the low-level shear *perpendicular to the line* relative to the upper-level shear on the strength of the system become apparent once the orientation of the line can be diagnosed (Fig. 2b). This is apparent especially in the discrimination of the DCSs

with the other two categories (Fig. 2). However, the smaller Z scores for the 4–8- and 6–10-km shears and the 0–2- and 0–4-km shears compared with the 0–6- and 0–10-km shears suggest that low-level and upper-level shear *alone* are not as useful for determining the ability of a system to produce severe surface winds as are the



FIG. 2. Same as in Fig. 1 but for the component of the bulk wind shear perpendicular to the convective line.

very deep shear values (Figs. 1 and 2). Thus, the important point here is that a measure of shear over a much deeper layer, such as the 0–10-km shear, which takes into account the benefits of low-level and upperlevel shear, appears to be a better indicator of overall MCS intensity than either the low-level shear or upperlevel shear alone. Interestingly, this is also found when discriminating between mature and dissipating quasilinear MCSs (Coniglio et al. 2007), although the benefits of the very deep shear versus the low-level shear are not quite as apparent in the present study.

b. Mean wind vectors and MCS motion

One of the most important aspects of MCS forecasting is the anticipation of MCS motion. Based on ideas rooted in many years of studying the motion of MCSs (Newton and Katz 1958; Merritt and Fritsch 1984; Chappell 1986) and forecasting MCSs, Corfidi (2003) hypothesizes that the strength and orientation of the mean winds in the cloud layer can affect the motion of the cold pool in such a way as to change the distribution of convergence along the cold pool and the propagation



FIG. 3. Same as in Fig. 1 but for the MCS speed.

of the system as a whole [in fact, this is the determining factor for using the upwind- versus downwindpropagating technique for forecasting MCS motion presented in Corfidi (2003)]. This is an important point in the current context because it has been recognized for some time that the production of severe surface winds by an MCS is strongly related to its forward speed. Indeed, it is found in this study that almost 90% of the DCSs move faster than 18 m s⁻¹ while almost 75% of the SCSs and over 90% of the WCSs move slower than 18 m s⁻¹ (Fig. 3). Therefore, it is clear that a potentially useful way to forecast MCS severity is the anticipation of the forward speed of the MCS itself from observable features in the environment.

1) GROUND-RELATIVE MEAN WINDS

Among the ground-relative mean wind speeds, it is found that layers that include upper-level winds are the best discriminators between SCS and DCS environments and between WCS and DCS environments (Fig. 4). It is interesting that the Z scores for the mean winds *in upper levels alone* are especially high (Fig. 4b); 75% of the 6–10-km mean wind speeds for the DCSs are above 20 m s⁻¹ while 75% of the wind speeds for the WCSs are below 20 m s⁻¹. The physical importance of the upper-level wind speeds compared with the lowerlevel wind speeds is not obvious but may be tied to enhanced baroclinicity and the larger values of deeplayer wind shear observed for the stronger MCS events.

Regarding the use of a "cloud layer" mean wind, an important point here is that it is critical to include upper-level winds (6-10 km) in any estimation of a cloudlayer wind, perhaps more so than the low-level winds, if one is to use it to forecast the motion and severity of MCSs. This is interesting because it has been shown in idealized settings that the motion of cold pools, which is driven largely by the hydrostatic pressure variations between the cold pool and the environment, can be enhanced significantly by the mean winds over the depth of the cold pool (Seitter 1986; Rotunno et al. 1988). Furthermore, the relationship between the mean wind speeds at lower levels and the MCS speeds is found to be weak in this study, with correlation coefficients generally in the 0.05–0.25 range (not shown). Some of this poor relationship may be because the observations are of the mean speed of the convective line and not necessarily of the cold pool itself. But, this suggests further that the speeds of the ground-relative mean winds in lower levels are not very useful in determining the overall strength of the convectively generated surface winds or in determining the overall speed of the MCS. This result does not, however, translate into a lack of utility for the winds in a storm-relative framework, as shown next.

2) MCS-RELATIVE MEAN WINDS

As discussed previously, past studies have suggested that the inflow of potentially unstable air in low levels relative to the system is a characteristic of severe MCSs (Evans and Doswell 2001; Gale et al. 2002; Coniglio et al. 2004), and therefore, prediction of the motion and propagation characteristics of the cold pool and the system itself is crucial. Indeed, the storm-relative inflow is found to be an excellent discriminator, as the median 0-1-km system-relative wind speeds drop from 22 m s⁻¹ for DCSs to 14 m s⁻¹ for WCSs. Figure 5a suggests that a quasi-linear MCS is likely to be a derecho if the mean system-relative inflow is $>20 \text{ m s}^{-1}$ and is very likely to be weak or nonsevere if these winds drop below 10 m s^{-1} . It is also interesting that the midlevel system-relative winds (e.g., 4-6 km in Fig. 5) are relatively weak and are not significantly different between all three categories, especially between the WCSs and DCSs, which was also found by Evans and Doswell (2001). We echo their suggestion that weak system-relative winds in



FIG. 4. Same as in Fig. 1 but for ground-relative mean wind speeds in the 0–2-, 0–4-, 0–6-, 0-10-, 4–8-, and 6–10-km layers.

midlevels, which facilitate cold pool development and strong outflows (Brooks et al. 1994), are not sufficient for discriminating the potential for WCSs versus DCSs by themselves. This shows that once MCS motion is known, low-level system-relative flow can be very useful for nowcasting and strengthens the idea that methods for predicting MCS motion accurately from environmental clues would be most beneficial.

To assess the potential relationships between mean winds and MCS motion, the angle between the MCS

motion vector and the mean wind vector (α) over various layers² is calculated next. A consistent difference between the SCSs and the other MCS categories is found for this measure with Z scores above 2.0 for all of the layers examined and is largest for the 4–8-km mean wind (Fig. 6). An interesting aspect of this relationship

² A positive angle indicates MCS motion to the right (in natural coordinates) of the reference vector in question.



FIG. 5. Same as in Fig. 1 but for the system-relative mean wind speeds in the 0–1-, 0–4-, 2–4-, and 4–6-km layers.

is that the angles are relatively small and not very different between the WCSs and DCSs. This shows that the overall direction of motion for the WCSs and DCSs is consistently more aligned with the mean wind vectors than is the overall direction of motion for the SCSs; that is, the largest component of MCS motion away from the mean wind vector is found for the SCSs. The physical reasons for this are not clear, but one possibility may be inferred from the concept of cell advection and propagation in determining the overall MCS motion (Chappell 1986; Corfidi et al. 1996; Corfidi 2003). The small angles, in combination with the much slower speeds for the WCSs (Fig. 3) that are similar in magnitude to the mean deep-layer wind speeds (Fig. 4), suggest that cell advection tends to dominate for the weaker events, but is less influential compared with downwind cell propagation for the SCSs and DCSs. The influence of cell propagation for the SCSs is supported by mean wind directions that are not significantly different between the WCSs and SCSs (not shown), yet α between the



FIG. 6. Same as in Fig. 1 but for the angle between the MCS motion vector and the 0–2-, 0-4-, 0-6-, 0-10-, 4-8-, and 6-10-km mean wind vectors.

WCSs and SCSs tends to be quite different (Fig. 6). Large cell propagation is also suggested for the DCSs, albeit in a different manner. The angles tend to be small for the DCSs, as they are for the WCSs, yet many DCSs are observed to move faster than the mean wind speeds over any layer. In fact, 75% (38 out of 51) of the DCSs move faster than the 2–10-km mean wind speed, while only 33% (26 out of 78) of the SCSs and 30% (17 out of 51) of the WCSs move faster than this speed, which suggests that propagation in the same direction as cell advection is a trait that separates the shorter-lived and longer-lived severe MCSs.

Regarding the DCSs, the mean flow tends to be stronger and the axis of instability tends to be aligned with the mean wind directions for DCSs (Johns and Hirt 1987; Johns 1993; Coniglio et al. 2004). As suggested by Corfidi (2003) and others, this is a configuration that can further encourage system propagation in a similar direction as cell advection, because the most rapid and intense cell development is favored in the



FIG. 7. Same as in Fig. 1 but for the angle between the MCS motion vector and the 0–4-, $0-6-, \, 0-10-, \, and \, 4-8-km$ shear vectors.

regions of enhanced instability. Elongated regions of enhanced instability can therefore promote long-lived systems if the addition of cell advection and propagation persists into this region. This result may be useful for nowcasting in that examining the MCS motion vector and how it relates to the mean cloud layer wind vector (and the axis of favorable instability) can provide a good assessment of MCS severity and potential longevity.

To further investigate the role of advection versus propagation, we examine the shear vector over various layers (which has commonly been used as a guide for the direction of MCS motion and has been shown to greatly affect the favored region of convective regeneration and propagation in numerical studies) and its angle relative to the MCS motion vector. It is not surprising that the angle between the shear vector in several surface-based layers and the direction of motion of the MCS (β) is generally <30° among all MCS environments (Fig. 7), which provides quantitative evidence that the orientation of the surface-based deep-layer shear vector does indeed provide a good first-order estimation of the overall MCS direction of motion, as shown by Merritt and Fritsch (1984). In terms of the differences in β among the MCSs, β for the 0–4- and 0-6-km mean winds is an excellent discriminator between the WCSs and SCSs, with β being largest for the SCSs. Again, it is interesting that β between the WCSs and the DCSs is not very different, as was found for the mean winds. Again, it is likely that β is often nonzero and positive for the SCSs because of a disproportionate degree of cell propagation away from the shear direction; that is, SCSs tend to move to the right of the shear vector more than the WCSs and DCSs. It is also interesting that the variability of β is found to be smallest for DCSs with a median angle close to zero when using the 0-6-km shear (Fig. 7), indicating that DCSs tend to follow the mean low- to upper-level shear vector more closely than do SCSs and WCSs. This provides more quantitative evidence that the propagation component tends to be aligned more with advection for DCSs than it is for less severe MCSs [new cell development is favored on the downshear side of the cold pool for unidirectional shear profiles; Rotunno et al. (1988)].

Finally, the moderate to high correlation between the shear and mean winds prevents an assessment of the relative physical importance of the mean winds versus the wind shear in determining the propagation and overall motion of the MCS.³ Our focus on mean winds is not to diminish the importance of the wellestablished physical effects of line-perpendicular wind shear on cell regeneration and system propagation (Weisman and Rotunno 2004; Parker and Johnson 2004; Coniglio et al. 2006). Rather, our results suggest that the mean deep-layer shear is useful for determining the direction of the MCS, but the orientation and magnitude of the mean winds are important parts for determining the overall MCS motion, including its speed. When viewing the results in the context of forecasting, these results support the idea that forecasters should be aware for the potential for severe, long-lived MCSs where both the deep-layer wind shear and the deep-layer mean winds are large and in a similar direction, which, not incidentally, occurs with largely unidirectional wind profiles above the boundary layer. Indeed, Corfidi (2003) and others emphasize that cold pools that align perpendicular to strong unidirectional wind (and shear) profiles tend to support fast forwardpropagating systems. Furthermore, even though the

physical processes associated with system propagation are likely influenced by the line-perpendicular shearcold pool interactions, these results suggest that the use of mean winds in conjunction with wind shear can be useful on 3–12-h time scales, and may be even more useful once the steady orientation of the convective line within an MCS becomes established and the lineperpendicular shear and mean winds can be assessed.

4. Thermodynamic variables

Several thermodynamic variables exhibit considerable skill in discriminating among the MCS environments (Figs. 8–10), including CAPE, midlevel lapse rates, and vertical differences in equivalent potential temperature (θ_e). CAPE is calculated in three ways: by lifting the surface parcel (SBCAPE), the most unstable single parcel (MUCAPE), and the most unstable parcel resulting from mixing any 100-hPa layer in the lowest 400 hPa (MLCAPE). The energy available for downdraft parcels is measured by the vertical difference in θ_e ($\Delta \theta_e$) and DCAPE (Gilmore and Wicker 1998), which is calculated using a parcel that descends from the larger of two values: the height level of minimum θ_e , and the wet-bulb zero height.

a. CAPE and lapse rates

None of the CAPE variables discriminate well between SCS and DCS environments, but all of the CAPE variables discriminate at very high levels between the WCSs and the other two categories (Fig. 8), suggesting that single values of CAPE can provide some useful information on whether or not an MCS will produce severe winds, regardless of its longevity. The differences between WCS and SCS/DCS environments is largest for MLCAPE; median MLCAPES range from around 1400 J $\rm kg^{-1}$ for WCSs to around 2400 J $\rm kg^{-1}$ for SCSs and 2100 J kg⁻¹ for DCSs. The lack of a large difference in the CAPE variables between the SCS and DCS environments may reflect the inability of a sounding to detect differences in the spatial distribution of CAPE. It may be that the higher CAPE values are more elongated along fronts for the DCS events, much as previous studies have shown that higher low-level dewpoint air tends to "pool" along boundaries ahead of derechos (Johns 1993; Coniglio et al. 2004). This may be the deciding factor for the longevity of a severe MCS in many cases and obviously cannot be diagnosed directly from a single sounding, although a unidirectional wind profile in which the mean wind and mean shear are large and in the same direction, a feature of DCS environments, may be a reflection of the larger-scale

³ Assessing the *physical* effects of mean winds in an idealized setting requires a realistic treatment of the surface boundary effects and perhaps changes in mean wind direction with height, which historically has not been examined in idealized numerical model experiments.



FIG. 8. Same as in Fig. 1 but for SBCAPE, MUCAPE, MLCAPE, and DCAPE.

processes that develop strong, elongated frontal features with zones of enhanced instability and wind shear.

Despite the fact that CAPE was found to be greater for SCSs than for DCSs and WCSs (Fig. 8), the midlevel environmental lapse rates are found to be greatest for DCSs (Fig. 9). In addition, the 2–6- and 3–8-km lapse rates discriminate very well among all three MCS environments, despite the fact that CAPE could not discriminate between SCSs and DCSs. Median values of the 2–6-km lapse rate range from 6.5° C km⁻¹ for WCSs to 7.3° C km⁻¹ for DCSs. The distributions of the 2–6km lapse rate suggest that an MCS is likely to be severe for values $>7^{\circ}C$ km⁻¹ (Fig. 9a) and that this could be a way to use the environmental instability to discriminate

between weak and longer-lived severe MCSs, although its practical utility could be questioned because of the relatively small differences in the mean values among the MCS categories, as discussed later in section 5.

It is interesting that the utility of the lapse rates as a discriminator diminishes with the surface-based layers. One of the factors thought to be important for wet microbursts (Atkins and Wakimoto 1991) is a large lapse rate below the melting level that extends to the surface (Proctor 1989; McCann 1994). Our results indicate that this does not appear to be true for organized systems as the 0–2- and 0–3-km (not shown) lapse rates do not discriminate very well among the MCS categories and are highly variable (see Fig. 9a for the 0-2-km



FIG. 9. Same as in Fig. 1 but for the 0-2-, 0-4-, 2-4-, 2-6-, and 3-8-km lapse rates (K km⁻¹).

results) because of diurnal effects and the frequent placement of soundings on the cool side of stationary or warm fronts. This suggests that the processes responsible for the organization of mesoscale cold pools and deeper overturning tied to instability over deeper layers appear to be more important in determining the severity of a system than its potential to produce localized downdrafts. In other words, larger, faster-moving cold pools associated with severe MCSs likely are not as dependent on large 0–2-km lapse rates as more isolated "pulse" type storms that occur more typically in weaker shear/mean flow environments and often produce their severe surface winds without an organized cold pool (Atkins and Wakimoto 1991).

b. DCAPE and θ_e

The physical processes that affect the coolness of convective downdrafts, including phase changes of precipitation and drag effects associated with precipitation loading, are well understood and are favored by the availability of relatively dry air in the precipitation source region. The DCAPE and $\Delta \theta_e$ between low and midlevels are two measures used to assess the potential for organized cold downdrafts in this study. Indeed, we



FIG. 10. Same as in Fig. 1 but for the vertical difference in θ_e between 0–3, 0–5, and 0–7 km, and the levels of the maximum and minimum θ_e ($\theta_{\text{emax}} - \theta_{\text{emin}}$).

find that DCAPE increases with increasing MCS intensity (Fig. 8a), as found by Evans and Doswell (2001). The Z scores of 1.5–3.5 among the three MCS categories suggest that DCAPE can be a good discriminator. Figure 8a also suggests that DCAPE may be useful in an exclusionary sense; if a warm season MCS develops in an environment with DCAPE <900–1000 J kg⁻¹, it is likely to be weak or nonsevere. However, as with the lapse rates, we caution the reader on the use of DCAPE in practical applications for reasons discussed later in section 5. Regarding the examination of $\Delta \theta_{e_i}$ we reiterate from past studies that relatively dry conditions below cloud base can be supportive of downdrafts through the continued initiation of negatively buoyant parcels, but strong downdrafts already under way can be enhanced by a very *moist* low-level environment as the parcels will encounter relatively high *virtual* potential temperatures at low levels (Proctor 1989; Wakimoto 2001). Indeed, $\Delta \theta_e$ between the surface and midlevels (0–3, 0–5, and 0–7 km) is found to be an excellent discriminator between WCS and both SCS and DCS environments (Fig. 10). It is apparent that the large correlation between $\Delta \theta_e$ and CAPE (not shown) is a reflection of similar physical processes that are represented by $\Delta \theta_e$ and CAPE. It is also assumed that $\Delta \theta_e$ and DCAPE represent similar processes. However, it is interesting to note that the 0–7-km $\Delta \theta_e$ and the $\Delta \theta_e$ between the maximum and minimum θ_e between low and midlevels $(\theta_{emin} - \theta_{emax})$ do a much better job discriminating between WCS and SCS environments than does DCAPE (Fig. 10). The median of $\theta_{emin} - \theta_{emax}$ ranges from around -23 K for the WCSs to around -30 K for the SCSs. Although the physical reasons for this are not clear, this suggests that the use of $\Delta \theta_e$ may be a more robust predictor of severe wind potential than DCAPE, especially when considering the practical difficulties of using DCAPE as a forecast parameter (Gilmore and Wicker 1998).

5. Summary and discussion

This study presents an analysis of meteorological variables and their ability to discriminate among the environments of MCSs of different intensities. Three MCS categories are defined from a set of warm season, quasi-linear MCSs based on their production of severe wind reports: weak MCSs, severe but non-derecho-producing MCSs, and derecho-producing MCSs. The variables are calculated from a set of 186 observed soundings that were taken in proximity to the MCSs during the beginning and mature stages of the system.

Much of the discussion of the differences in the kinematic variables centers on the vertical bulk wind shear and the vertical mean winds. It is shown that the deep-layer wind shear (0–6 to 0–10 km) is a better discriminator than the low-level shear (0–2 and 0–4 km), although the discriminatory ability of both the low-level-only and deep-layer shear is very good once the orientation of the convective line is known and the line-perpendicular shear component can be used. These results suggest that a shear variable that includes the physical benefits of low- and upper-level shear together, such as the 0–10-km bulk shear, may be the best way to use the environmental shear to assess the potential for a quasi-linear MCS to produce severe winds.

Regarding the mean winds and the overall motion of the MCSs, an interesting result is that WCSs and DCSs tend to move in a direction more parallel to the mean mid- and upper-level winds (and wind shear) than SCSs. However, the fact that DCSs move much faster than the WCSs suggests that the propagation component of the system motion and the advective component are both large and additive for the long-lived severe MCSs, as suggested by Corfidi (2003). This shows that environmental relationships that can forecast MCS motion would be very useful in forecasting the intensity of MCSs. The present results support the notion presented in Corfidi (2003) that a configuration in which the deep-layer shear is large and in the same direction as the deep-layer mean wind (as is usually the case for a unidirectional shear profile) greatly favors a fast forward-propagating and severe MCS.

Many thermodynamic variables are found to be good discriminators of MCS environments. The most discriminating variables include the midlevel lapse rates, the low- to midlevel difference in θ_e , and the most unstable 100-hPa mixed-layer CAPE. Similar to the CAPE variables, the vertical differences in θ_e discriminate well between the weak and severe MCSs, but not between the severe/nonderecho and derecho MCSs. The results suggest that the midlevel lapse rates and the vertical difference in θ_e may be helpful in discriminating between the severe/nonderecho and derecho MCSs as a supplement to the CAPE and DCAPE.

This study provided a description of the environments associated with severe wind-producing MCSs based on the analysis of numerous variables derived from observed sounding data. With an understanding of these variables and their climatological distributions, the intention of this study is to provide forecasters with improved guidance on forecasting MCS severity. It is important, however, to recognize the disconnect that is sometimes present between the statistical and the practical significance of the results from studies of this type. The analysis was performed on observations taken near MCSs to obtain the best possible estimate of the surrounding environment. The disadvantage of this method is that forecasters usually have to rely on estimates of the environment from other sources because the placement of an MCS in close proximity to an observed sounding is uncommon on a day-to-day basis. Objective analyses or short-term numerical forecasts of the environment are likely to be less accurate than direct observations from a sounding and can have biases that may decrease one's confidence in the accuracy and utility of a particular forecast parameter. This may be especially true for DCAPE and the lapse rates, in which the statistical differences are relatively large but the differences in the median values between the MCS categories likely are not very large relative to the observational and analysis error. Future studies should attempt to examine DCAPE, lapse rates, and the other forecast parameters from other data sources to determine the robustness and the practical utility of the results, similar to the studies of Kuchera and Parker (2006) and Coniglio et al. (2007). When combined with an understanding of the practical utility of these results and how the horizontal distribution of these variables affects MCS development and evolution, such as the distribution of CAPE and shear along fronts, this study can contribute to a more complete understanding of the factors contributing to MCS severity and will serve to supplement the growing body of work describing the forecasting of MCS environments.

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