Structure and Motion of Severe-Wind-Producing Mesoscale Convective Systems and Derechos in Relation to the Mean Wind

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ABSTRACT

The goal of this study is to document differences in the convective structure and motion of long-track, severe-wind-producing MCSs from short-track severe-wind-producing MCSs in relation to the mean wind. An ancillary goal is to determine if these differences are large enough that some criterion for MCS motion relative to the mean wind could be used in future definitions of ‘‘derechos.’’ Results confirm past investigations that well-organized MCSs, including those that produce derechos, tend to move faster than the mean wind, exhibiting a significantly larger degree of propagation (component of MCS motion in addition to the component contributed by the mean flow). Furthermore, well-organized systems that produce shorter-track swaths of damaging winds likewise tend to move faster than the mean wind with a significant propagation component along the mean wind. Therefore, propagation in the direction of the mean wind is not necessarily a characteristic that can be used to distinguish derechos from nonderechos. However, there is some indication that long-track damaging wind events that occur without large-scale or persistent bow echoes and mesoscale convective vortices (MCVs) require a strong propagation component along the mean wind direction to become long lived. Overall, however, there does not appear to be enough separation in the motion characteristics among the MCS types to warrant the inclusion of a mean-wind criterion into the definition of a derecho at this time.

1. Introduction

Thunderstorms that become organized as they grow upscale are known as mesoscale convective systems (MCSs; e.g., Maddox 1980; Parker and Johnson 2000). MCSs produce a large percentage of the annual summer rainfall in the central United States, and their associated precipitation may be accompanied by a wide range of hazardous weather, including flash floods, tornadoes, and damaging winds (Fritsch et al. 1986). Particularly damaging and widespread windstorms produced by MCSs are known as derechos (e.g., Johns and Hirt 1987; Ashley and Mote 2005; Corfidi et al. 2016). It is estimated that these storms are responsible for up to 40% of MCS-related wind casualties (Metz and Bosart 2010), despite composing only a small percentage of the total MCSs.

The present (Johns and Hirt 1987) widely accepted definition of ‘‘derecho’’ is based largely on observed wind and wind damage reports. The report criteria in the definition are based on reporting strategies of the mid-1980s that, compared to today, typically yielded very sparse coverage (e.g., Weiss et al. 2002; Smith et al. 2013). Although the number of observations has increased in recent years, nonhomogeneous population distribution, inconsistent reporting, and gaps in the surface observation network (e.g., Weiss et al. 2002; Trapp et al. 2006; Cohen et al. 2007) lessen the quality and reliability of the surface wind speed and wind damage observations. The increased number of reports also has resulted in an increase in the biases associated with the variable population distribution and vegetative cover (Smith et al. 2013), further lessening the ability to assess societal impact from individual storms. Recognizing these issues, Corfidi et al. (2016, hereafter C16) propose that the minimum severe-wind swath used to define a derecho be

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increased from 400 km [the value used by Johns and Hirt (1987)] to 650 km (~400 mi), along with introducing a width criterion, to better distinguish exceptional wind-producing convective systems from more common severe-wind events.

Along with modifying the length and width criteria of wind damage swaths, C16 suggest that because the physical structure of derecho-producing MCSs may now be discerned via WSR-88D data, such information should be incorporated into the definition of a derecho. The Johns and Hirt (1987) derecho criteria require that the damaging wind be produced by "an extratropical MCS," but this is based on pre-WSR-88D-era radar imagery and is rather vague considering the variety of convective entities that could be considered an MCS. This has led to the assignment of the term derecho to wind events of widely varying intensity and associated convective structures. In an attempt to place the definition of a derecho on a more firm physical foundation, C16 proffer a new definition based, in part, on the structure and behavior of the associated convective systems as viewed in composite radar imagery, requiring such features as bow echoes, rear-inflow jets, and mesoscale convective vortices (MCVs), referred to here as "mesoconvective" organization, following Weisman (1993).

The goal of the present study is to determine if the motion of severe-wind-producing MCSs with mesoconvective organization (including derechos, per the proposed definition in C16) move differently relative to the mean environmental wind than do other types of severe-wind-producing MCSs. An ancillary goal is to determine if these differences are large enough that some criterion for MCS motion relative to the mean wind could be used in the definition of a derecho. Past research suggests that a common characteristic of derecho-producing MCSs is their faster speed of motion relative to the mean wind (Johns and Hirt 1987). More specifically, Corfidi (2003) and Cohen et al. (2007) suggest that cell propagation in the direction of cell advection (i.e., by the mean wind) is a trait of long-track severe-wind-producing MCSs, but this is not quantified extensively in those works, and is not placed within the context of an MCS's structure. This paper provides a quantitative analysis of the motion of severe MCSs relative to the mean wind and cell propagation. It also relates MCS motion, mean wind, and propagation to MCS organization, intensity, and longevity. The goal of this paper is not to find causative links between MCS motion and the mean wind, but rather, for forecasting purposes, to determine if the mean wind (and other vector quantities related to it and the MCS motion) can help to discriminate between MCSs with different structures and lengths to the wind swath (although some causative links are hypothesized). This is meant to complement the many studies that have examined the relationship between MCS organization, intensity, and longevity as well as vertical wind shear (e.g., Rotunno et al. 1988; Weisman et al. 1988; Weisman 1993; Weisman and Davis 1998; Evans and Doswell 2001; Gale et al. 2002; Trapp and Weisman 2003; Weisman and Trapp 2003; Coniglio et al. 2004; Mahoney et al. 2009; Coniglio et al. 2010; Lombardo and Colle 2012). In particular, Weisman and Davis (1998) show that variations in observed MCS structures like those described later in this study can have a simple dependence on vertical wind shear in idealized simulations of quasi-linear convective systems. However, given the strong dependence on severe-wind production to MCS speed, it is hoped that the focus on MCS speed and motion in the work presented here (versus a focus on vertical wind shear) might stimulate future derecho definition refinements by identifying physical features or implied physical processes related to the mean wind that distinguish derecho-producing convective systems from other severe-wind-producing MCSs.

2. Methodology

a. MCS identification and dataset

To meet the goals of this study, all of the examined MCSs produced swaths of severe wind reports greater than 100 km in length during some part of their lifetime. A "swath" constitutes a nearly continuous progression of severe wind reports following the convective portion of an MCS (see Fig. 1 for three examples of wind swaths). The term nearly continuous is admittedly subjective, but given the report inconsistencies noted above, some gaps in the reports are allowed in both space and time. No set criteria for the size of these gaps in space and time were used, but generally no more than 1 h and 100 km separated successive wind reports, even in sparsely populated areas of the country (see Fig. 1c for an example of a gap that was allowed).

Using the Storm Prediction Center's (SPC) severe-wind report database, 356 severe-wind-producing warm-season (May–August) MCSs are identified for the years 2010–2014. These 356 systems are taken from the MCS dataset in C16. The National Climatic Data Center [NCDC, now known as the National Centers for Environmental Information (NCEI)] National Radar Reflectivity Mosaic (NCDC 2016) is examined to ensure that each severe wind swath identified using the severe-wind report database was produced by an MCS. Convection is considered to be an MCS if the leading line or arc of convection is ≥100 km long, lasts at least 3 h, shows spatial and temporal continuity/organization, and generates accompanying stratiform precipitation during

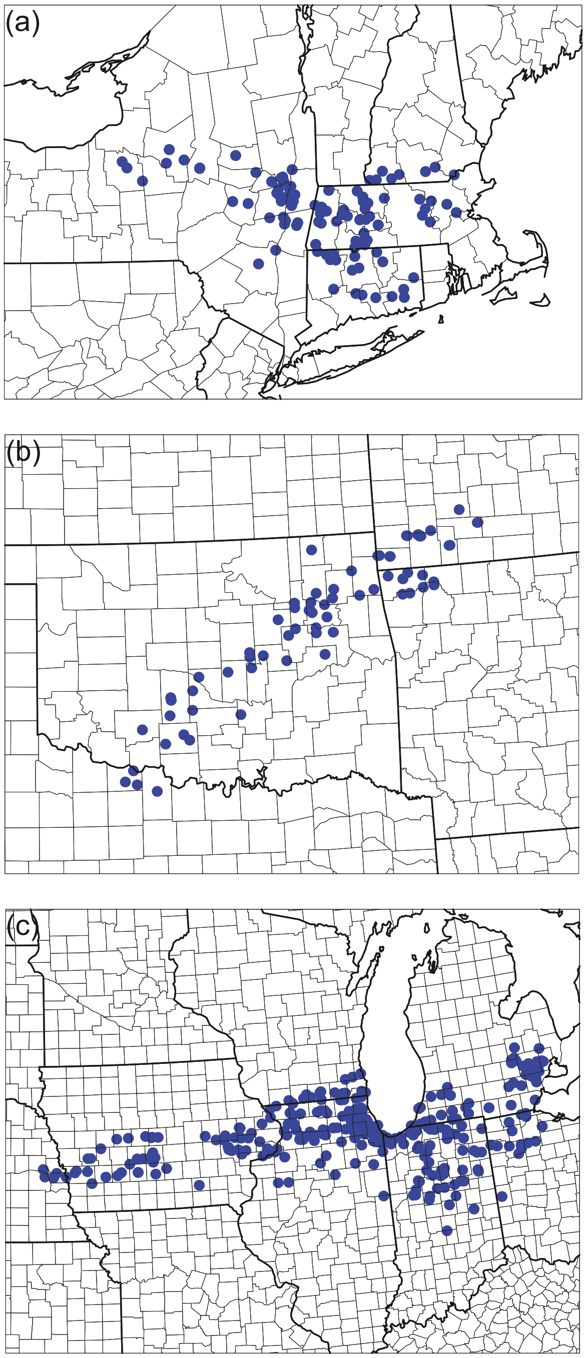


FIG. 1. Examples of severe wind and/or damage report swaths associated with MCSs for (a) 1600–2200 UTC 4 May, (b) 0700–1300 UTC 13 May, and (c) 1200 UTC 18 Jun–0300 UTC 19 Jun 2010. An example of a gap in the reports that was allowed is shown over south-central to southeastern IA in (c).

MCS maturity [generally following Zipser (1982) and Parker and Johnson (2000)]. Figure 2 provides an example of a typical MCS life cycle, showing three stages of development based on radar reflectivity. The mature stage of each MCS is used in our analysis, and all subsequent discussion of MCS motion and its components correspond to the mature phase of analyzed MCSs. The time of MCS maturity occurs when the system displays maximum-intensity reflectivity covering the greatest area in conjunction with peak continuity and mesoconvective organization of individual cells, in addition to a well-defined transition zone between the convective precipitation and the stratiform precipitation.

b. *MCS and mean wind characterization*

Various mesoscale processes that govern MCS structure and behavior frequently exist simultaneously within a given MCS on different spatial and temporal scales (McAnelly and Cotton 1989). These processes often are associated with distinctive organizational patterns in radar reflectivity data. In this study, both meso-α-scale (200–2000-km scale) and meso-β-scale (20–200 km) structural features (e.g., coherent quasi-linear segments) are often present within the MCS (see Fig. 3 for examples). Meso-α-scale features include large, nonlinear regions of high reflectivity; large-line segments; and single-arcing bows, all of which contain a contiguous area of 50+ dBZ reflectivity with a major axis longer than 200 km (Fig. 3). Meso-β-scale features include individual convective cells, embedded bow echoes within a larger quasi-linear convective system (QLCS), small single-arcing bows (<200 km), and small (<200 km) line segments. If an MCS were to contain both meso-α-scale and meso-β-scale features, the meso-α-scale feature is used to define the MCS motion to ensure that the motion of each MCS is represented on the largest scale possible. Start and end longitude and latitude points are recorded, along with a corresponding start time and end time, so that the direction of movement, distance traveled, and average speed could be obtained for each MCS specifically during the mature portion of the MCS's existence (as illustrated in Fig. 2). Specifically, during a ~30–90-min window representing MCS maturity, the approximate center of the leading edge of the feature of interest (bow echo or convective line) is used to define MCS motion. Only a single time interval and corresponding path within the mature phase of each MCS are treated as representative of the MCS's motion. It is recognized that MCS speeds and the background mean wind fields may change along the path, especially for the very long-lived systems. However, the MCS speeds and parameters used to define the environment are approximately time matched, as described below, so that the MCS motion during its maturity is represented.

The aforementioned MCS motion, as computed in the mature phase of the MCS, can be viewed as the aggregation of advection of convective cells by a representative

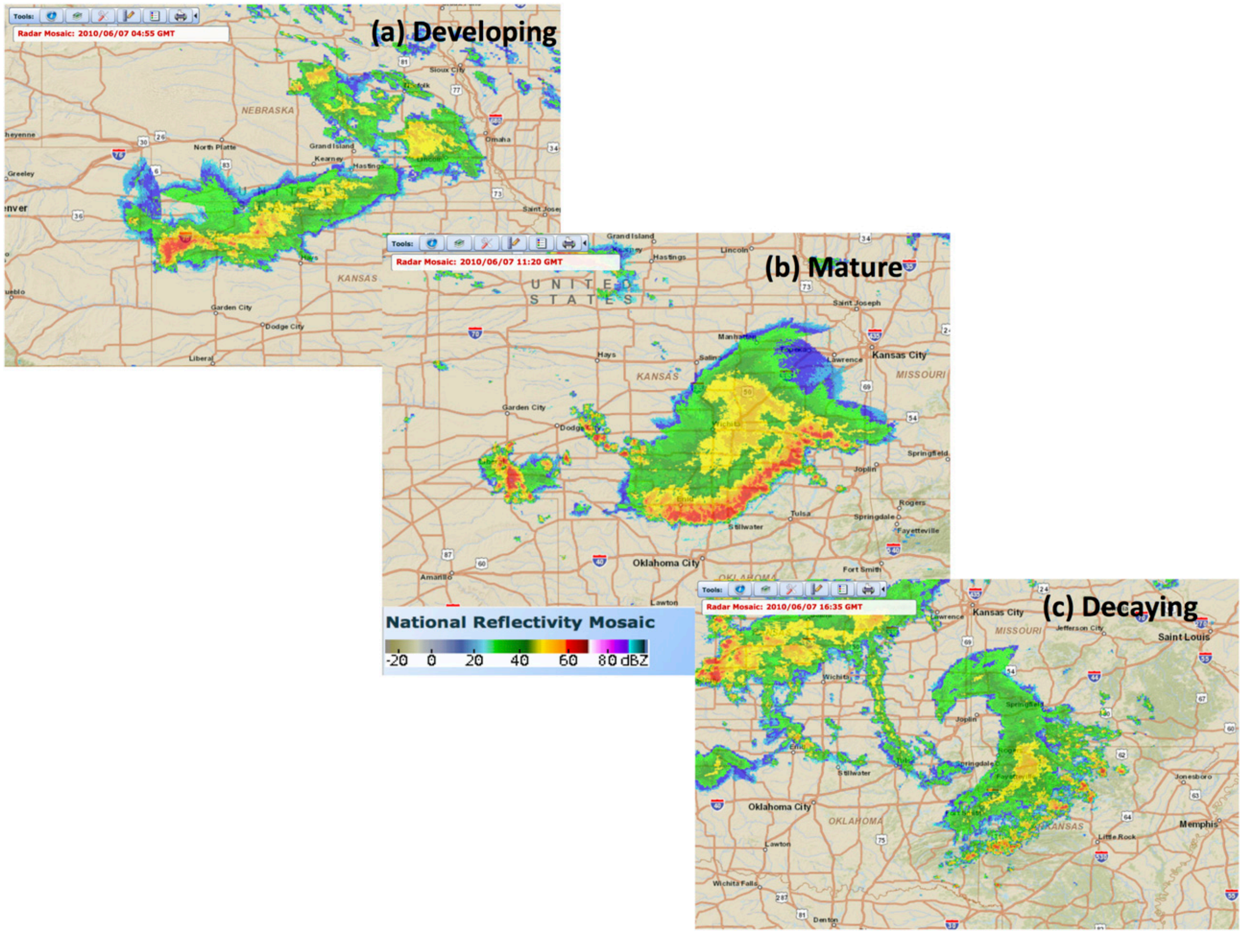


FIG. 2. Mosaic radar reflectivity example of (a) developing phase of an MCS, (b) mature phase of an MCS (focus of subsequent analysis), and (c) decaying phase of an MCS.

deep-layer mean wind and the development of new convective cells (propagation) relative to existing storms (e.g., Chappell 1986; Corfidi et al. 1996; Corfidi 2003). For the forward-propagating systems examined in this study, the propagation is usually forced along the downwind/downshear side of the advancing cold pool. Merritt and Fritsch (1984) and Corfidi et al. (1996) hypothesize that the advective component of the stronger convective elements in MCSs is proportional to the mean wind in the cloud layer, where the nonpressure weighted mean wind in the 850–300-hPa layer is used as a proxy. In this study, the advective component of MCS motion is estimated using the pressure-weighted mean wind between the lifting condensation level (LCL) and the equilibrium level (EL) for a mixed-layer parcel, representing the deep flow within a convective cloud layer. The propagation component of MCS motion is then defined to be any motion not accounted for by the mean wind. The mean wind in the LCL–EL layer (the proxy for the advective component of MCS motion) is determined at the beginning time and location of the tracking period (30–90-min period) for each mature MCS from the nearest SPC surface mesoscale objective analysis[1] (SFCOA; Bothwell et al. 2002) grid point. The SFCOA winds from the hour before the start of the tracking period are used since this best represents the near-storm environment prior to mesoscale convective overturning that may contaminate the SFCOA wind fields.

The angle between the MCS convective line orientation and the mean wind or vertical wind shear vector can help to provide insight into the severe weather threat (wind, flood, or both) associated with an MCS. When the convective line is oriented similarly to the vertical wind shear, trailing line/adjoining stratiform or backbuilding MCSs increase the flash flood threat (Maddox et al. 1979; Schumacher and Johnson 2005). Many studies

[1] More information on this analysis can be found online (http://www.spc.noaa.gov/exper/mesoanalysis/).

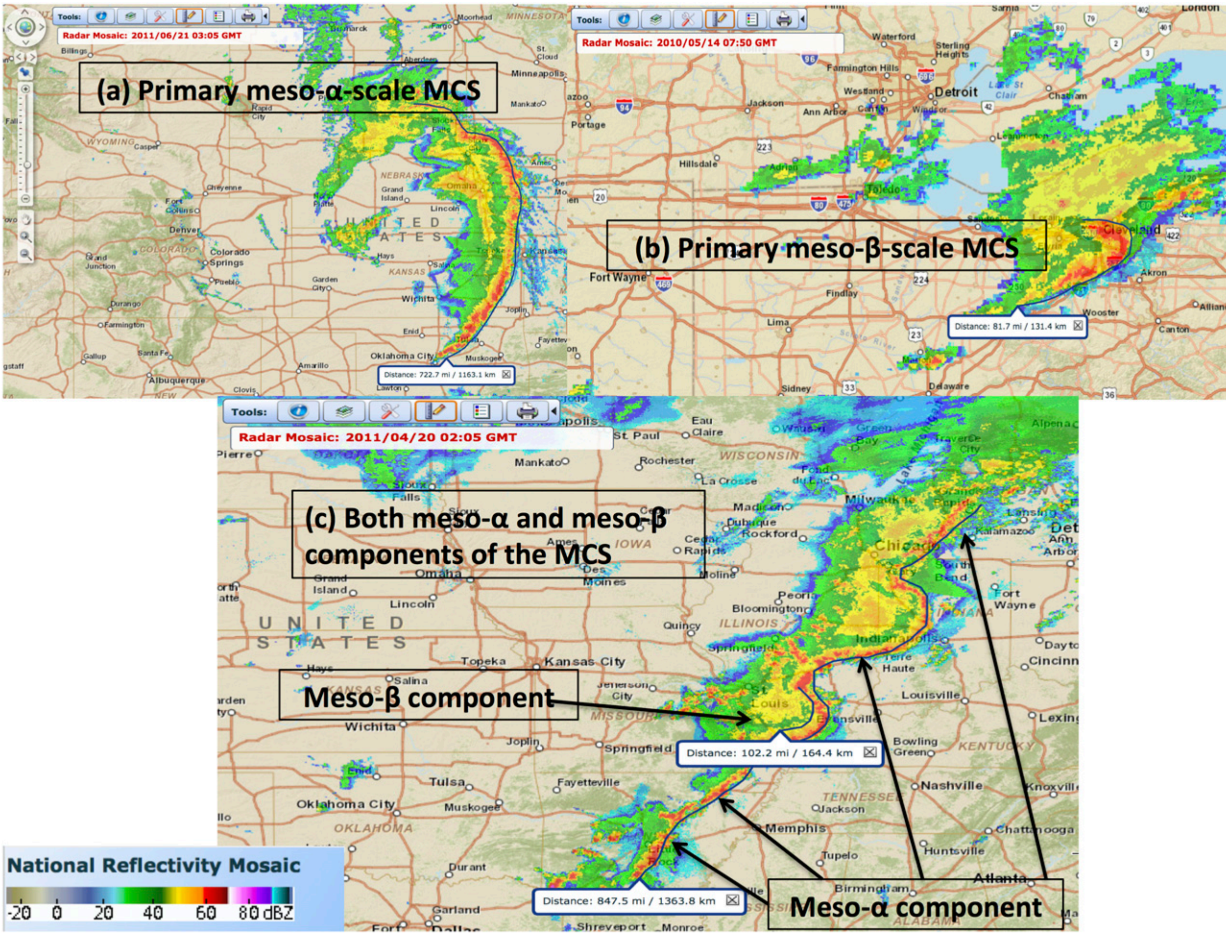


FIG. 3. Mosaic radar reflectivity example of (a) a meso-α-scale MCS element with a leading line of convection between 200 and 2000 km in length, (b) a meso-β- scale MCS element with a leading line of convection between 20 and 200 km in length, and (c) and a meso-α-scale MCS element with embedded meso-β-scale features. Distances measured along various MCS components highlighted by black curves are identified adjacent to the curves.

have established that a convective line oriented at a large angle to the low-to-midlevel vertical wind shear favors a severe wind threat (e.g., Cohen et al. 2007), but this implicitly assumes that the mean wind is substantial, allowing for a large advective component to MCS motion and the cold pool. The forward propagation of an MCS is controlled substantially by the strength of the cold pool and the hydrostatically induced motion based on density current theory (e.g., Benjamin 1968; Rotunno et al. 1988). However, in laboratory experiments and numerical model experiments, Simpson and Britter (1980) and Seitter (1986) show that an ambient wind oriented perpendicular to a density current augments its hydrostatically induced motion by a factor of $\sim 0.62\overline{U}$, where $\overline{U}$ is the mean ambient wind in the cold pool. The effect of the ambient wind on augmenting cold-pool motion within MCSs is hypothesized to affect MCS structure in Corfidi (2003) and Cohen et al. (2007). Mahoney et al. (2009) show that downward momentum transport associated with strong environmental winds aloft can be a significant driver of cold-pool-driven MCS motion and potentially severe surface winds. Since all of the cases considered here produce abundant severe winds at the surface, an assumption is made that the MCS is primarily cold-pool driven, following Bryan and Weisman (2006), who find that the production of severe winds at the surface in simulations depends on whether or not the system is able to produce a surface-based cold pool.

Line orientation is tracked for each MCS during the mature phase. This angle is measured by taking two latitude and longitude points along the line orientation and calculating the angle between the line generated by the two points and a meridian intersecting that line (Fig. 4). For single bowing convective lines, the two points form a line tangent to the apex of the bow. The two points form a line segment along the average orientation of the

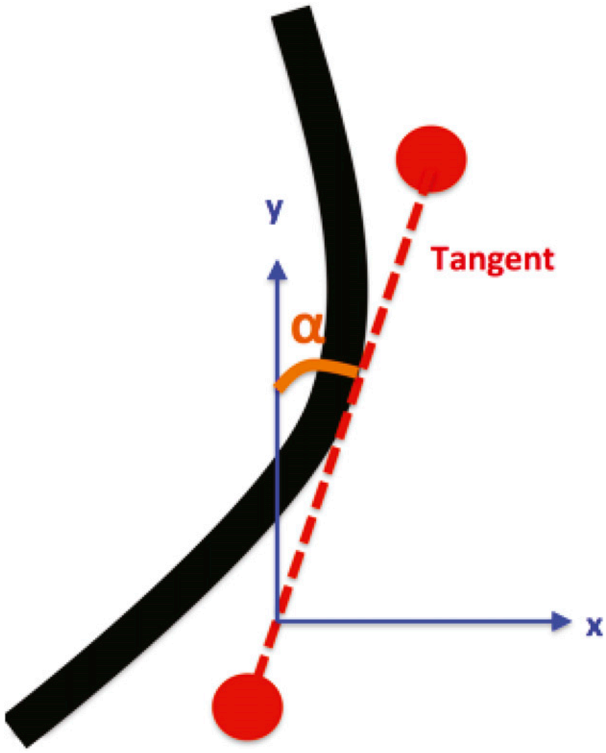


FIG. 4. Illustration of the process for determining the orientation of the leading convective line of an MCS (denoted by black arc), yielding angle α. Two points (in red) determine the line tangent to the black arc. The line determined by those points (in red) is compared to the meridian (y axis of the Cartesian coordinate system superimposed on the red tangent). The orientation, yielding angle α, is measured such that α is less than 90°. In this case, the red tangent is measured clockwise from the $+y$ axis such that α is approximately 20°.

convective line if there are multiple bowing segments within it. The orientation angle is always selected as the acute angle (never exceeding 90° in magnitude) formed by comparing the tangent line to the meridian, such that clockwise rotation from the meridian yields a positive angle and counterclockwise rotation yields a negative angle.

c. *MCS classification scheme*

A subjective, four-class scheme based on the degree of mesoconvective organization exhibited by each MCS is created to identify possible relationships between organizational structure and MCS motion. The MCSs are classified subjectively during the ~30–90-min window that encompasses their period of peak organization and the time of MCS maturity described earlier (typically a short time after the MCS reaches the mature stage). Each of the four classes is illustrated in Fig. 5.

"Class one" is composed of MCSs that are the most strongly organized, meaning they 1) contain a single-arcing bow, 2) have a well-defined line-end vortex or MCV behind the northern portion of the convective line identified by an area of reflectivity ≥ 50 dBZ that circulates at least 180° from the leading convection to the stratiform rain region, and 3) have a well-formed transition zone between the leading line of convection and the stratiform rain. Examination of composite reflectivity reveals that these vortices appear to begin as a northern line-end ("bookend") vortex (Weisman 1993) and quickly grow upscale into what appears to be a quasi-balanced circulation within the stratiform precipitation, resulting in a vortex similar to that described in Brandes and Ziegler (1993). The total number of class one systems identified is 15, averaging 3 per year.

"Class two" is composed of MCSs that contain a single arcing or bowing convective line but without a well-defined MCV. Since only composite reflectivity is examined here, it is possible that some class two systems contain line-end vortices that remain small and do not grow upscale and are not identified. Class two systems are, therefore, considered to be less organized than class one systems. The total number of class two systems is 88. The MCSs that compose classes one and two meet the part of the proposed C16 derecho criteria that requires the parent MCS to exhibit one or more *sustained* bow echoes with mesoscale vortices and/or rear inflow jets.

"Class three" is composed of MCSs that do not contain a single arcing or bowing convective line but may exhibit multiple broad arcs or transient bows and/or multiple line segments within the meso-α-scale system. Cases often classified as elongated QLCSs or squall lines with transient line-echo wave patterns (LEWPs) compose many of these systems. The total number of class three systems is 201. "Class four" is composed of MCSs that exhibit noncontinuous areas of reflectivity ≥ 50 dBZ along the leading edge of the convective system, do not show any evidence of bow echoes or LEWPs, and are the least organized of all MCSs. The total number of class four systems is 53. Class three and four systems include many severe MCSs, among them many that would likely be classified as serial derechos as defined in Johns and Hirt (1987), with geographically extensive lines of convection and embedded transient bows or lines of convection. While it is required that at least one wind swath be produced by the class three and class four MCSs, they are deemed to be insufficient to satisfy the proposed derecho criteria of C16 regardless of the length of the wind swath because of their lack of sustained mesoconvective organization (C16 propose that most serial-type severe-wind-producing systems should no longer be considered derechos).

In addition to classifying MCSs based on their structure as depicted by radar reflectivity, the MCSs in each class are binned based on the length of the major axis of

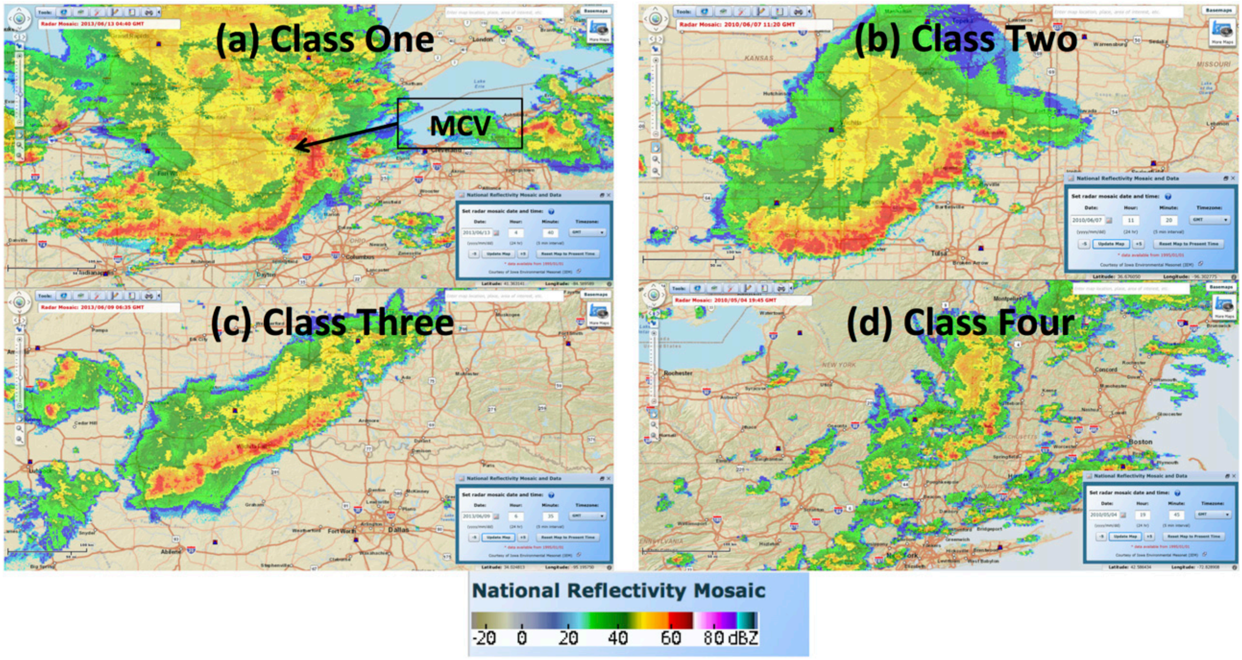


FIG. 5. Examples of the four MCS classes as seen by mosaic radar reflectivity: (a) class one MCSs contain a well-defined MCV, transition zone, and large arcing bow; (b) class two MCSs contain a single arcing bow but no well-defined MCV; (c) class three MCSs contain continuous nonarcing line segments (but can contain embedded transient bows/LEWPs); and (d) class four MCSs are less organized without evidence of bows or LEWPs.

severe wind reports (swath). The swaths are first separated into ''short'' and ''long'' categories using the 650-km criterion proposed by C16. It is noteworthy that, *by the proposed C16 definition* of derechos, use of the 650-km criterion results in large differences in the sample sizes of the two subsets. This is largely by design, as the increased length criterion of 650 km [relative to the 400 km of Johns and Hirt (1987)] is proposed to ensure that the term derecho be reserved for exceptional events; therefore, the sample size of cases with swath lengths ≥ 650 km is necessarily small (sample sizes ≤ 10 are not shown). However, to examine the robustness of differences in mean wind and MCS motion parameters versus longevity, subsets using a swath-length criterion of 400 km also are computed, which acts to increase the sample sizes in the long category (and increase the reliability of the statistics).

The statistical significance of the differences between the distributions corresponding to each class is assessed through the two-sample Kolmogrov–Smirnov (K–S) test (Wilks 2006). This scheme tests the null hypothesis that two independent samples are drawn from the same continuous distribution. This is a nonparameteric test that compares differences in the cumulative density functions of two samples. A benefit of the K–S test is its lack of assumption of an underlying statistical distribution. However, this test can be sensitive to sample size such that particularly small or large sample sizes may render statistical significance without practical significance. Alternatively, large differences in cumulative density function over small ranges of sample values could result in unrealistic determinations of statistical significance if the two distributions otherwise are very similar. We present the p value corresponding to incorrect rejection of the null hypothesis (lower p values indicate higher confidence that the two distributions are not drawn from the same population) as long as the sample size in each distribution is at least 15 cases (Tables 1 and 2).

3. Results

a. *MCS speed versus mean wind speed*

The results for MCS speed of motion and mean wind speed are first compared using all MCSs in each class, regardless of the length of the severe-wind swath (the darkest gray bars in the box-and-whisker plots, representing all MCSs in each class in Figs. 6–12). Class one systems tend to move faster (mean of 23.6 m s^{-1}) than any other class of MCS (Fig. 6a). Class two systems (mean of 20.4 m s^{-1}) move faster than class three (mean of 17.7 m s^{-1}) and class four systems (mean of 18.8 m s^{-1}), suggesting that severe-MCS organization is related to MCS speed. However, this relationship is not seen when

TABLE 1. The p values for the K–S test for the metrics between pairs of the four MCS classes. Statistically significant values (defined here as $p < 0.05$) are shown in boldface.

Metric	1 vs 2	1 vs 3	1 vs 4	2 vs 3	2 vs 4	3 vs 4
MCS total speed	0.126	**0.000**	**0.002**	**0.001**	0.061	0.335
Mean wind speed	0.767	0.415	0.394	0.518	0.702	0.932
Difference between MCS speed and mean wind speed	0.074	**0.004**	**0.008**	**0.032**	0.255	0.993
MCS propagation speed	0.562	0.068	**0.020**	**0.005**	**0.000**	0.134
Propagation speed projected onto the mean wind vector	0.535	0.158	0.194	0.146	0.355	0.801
Angle between line and MCS motion	0.233	0.056	**0.006**	0.194	**0.039**	0.164
Angle between line and mean wind	0.793	0.490	0.400	0.326	0.658	0.866

comparing the long-track systems in classes two and three and comparing the short-track systems in classes three and four (Fig. 6a). The most statistically significant differences are found between class one and class three/four systems with p values < 0.01, although the p value when comparing class two and class three systems, which have relatively large sample sizes, is also small ($p = 0.001$).

When viewing all systems in each class, there are no statistically significant differences in mean wind speed among the four MCS classes (Fig. 6b), suggesting that the magnitude of the mean cloud-layer winds alone is not the primary reason for the differences in MCS speed between the MCS classes (Fig. 6a). Note, however, that when all of the MCSs in every group are combined, the mean wind speed does have a strong relationship to MCS speed (Fig. 7; $p < 0.001$), which is likely a reflection of the advective effects or downward momentum transport on cold pool/MCS motion mentioned earlier. However, the result that the mean wind speeds do not differ significantly among the four MCS classes suggests that differences in MCS propagation, to be examined later, are important for distinguishing MCSs with varying structures.

Figure 6c shows the distributions of mean wind speeds subtracted from the MCS speed, and shows that systems in all four MCS classes tend to move faster than the mean wind (class one mean difference is $8.2\,\mathrm{m\,s^{-1}}$, class two mean difference is $5.2\,\mathrm{m\,s^{-1}}$, class three mean difference is $3.3\,\mathrm{m\,s^{-1}}$, and class four mean difference is $3.5\,\mathrm{m\,s^{-1}}$).[2] The differences in MCS speed and mean wind speed are largest for the class one systems, in which all 15 systems move faster than the mean wind speed. While the mean difference in MCS speed and mean wind speed is greater than zero for the other MCS classes, there are some cases in MCS classes two–four that moved slower than the mean wind speed (about 20%–25% in each class). Again, the most statistically significant differences are found between class one and class three/four systems, with p values < 0.01, although the differences between the class two and three systems are statistically substantial ($p = 0.03$).

b. *MCS propagation magnitude*

The previous section simply compares the differences in speeds between MCSs and the mean wind and showed that the better-organized systems tend to move significantly faster than the mean wind speed, although the mean difference in MCS speed and mean wind speed is above zero for all classes. Furthermore, no significant differences in mean wind speeds are found among the four classes, which suggest that the differences in MCS speeds and the differences in MCS organization are related to differences in MCS propagation. Therefore, this section compares MCS classes through characteristics of the propagation vector. Following Corfidi (2003), any MCS motion not equaling the mean wind can be attributed to a residual propagation vector defined to be the vector that needs to be added to the mean wind vector to equal the MCS motion vector.

As for the differences between MCS speed and mean wind speed, propagation magnitude is largest for class one MCSs followed, in sequence, by the other three classes (class one mean is $13.1\,\mathrm{m\,s^{-1}}$, class two mean is $11.5\,\mathrm{m\,s^{-1}}$, class three mean is $10.5\,\mathrm{m\,s^{-1}}$, and class four mean is $9.8\,\mathrm{m\,s^{-1}}$; Fig. 8a). In particular, the class four

TABLE 2. As in Table 1, but for p values for comparisons between the wind swaths shorter (longer) than 650 km in each MCS class. Comparisons including classes one and four are not shown since they include subsets of cases with ≤10 cases.

Metric	Class 2	Class 3
MCS total speed	0.582	0.903
Mean wind speed	0.211	**0.006**
Difference between MCS speed and mean wind speed	0.966	**0.020**
MCS propagation speed	**0.015**	0.515
Propagation speed projected onto the mean wind vector	0.856	**0.015**
Angle between line and MCS motion vector	0.195	0.675
Angle between line and mean wind	0.449	0.329

[2] Note that for the time being, no provision is made to account for differing directions; only the vector magnitude MCS speed and vector magnitude mean wind speed are being compared here.

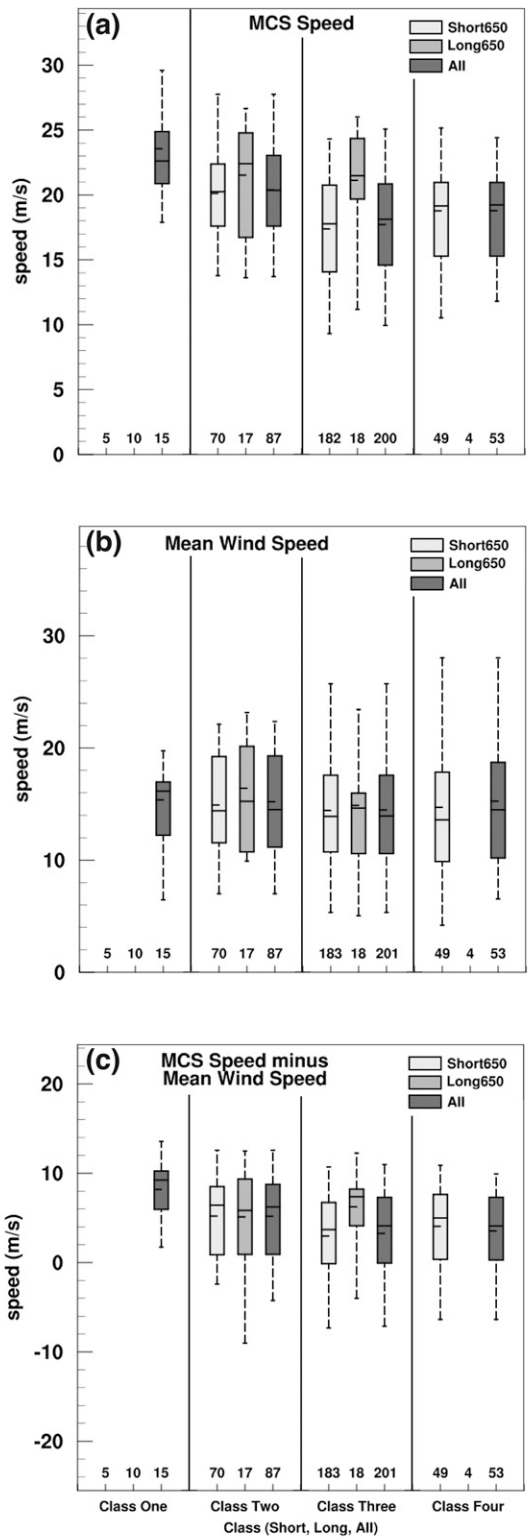


FIG. 6. Box-and-whiskers plots for (a) magnitude of MCS velocity (MCS speed in $m\,s^{-1}$), (b) magnitude of the mean wind (mean wind speed in $m\,s^{-1}$), and (c) the difference between the MCS speed and the mean wind speed ($m\,s^{-1}$), separated by MCS class and damage-swath length for a threshold of 650 km. Light-gray shading represents "short" damage swaths < 650 km, medium-gray shading represents "long" damage swaths ≥ 650 km, and dark-gray shading represents all MCSs of each class including both short and long damage swaths. Boxes represent the IQR of the distributions (25th–75th percentiles), with embedded, long horizontal dashes depicting the median of the distributions, and short horizontal dashes depicting the mean values. Whiskers extend to the 5th and 95th percentiles. Numbers below the class labels represent the sample size in each set. Distributions with sample sizes less than 15 are not shown.

systems have significantly smaller propagation magnitudes compared with class one ($p < 0.02$) and class two ($p < 0.001$) systems. This suggests that the level of organization and physical appearance of an MCS in composite radar imagery may be related to the magnitude of the propagation component of the system's overall motion. However, the long-track class two systems are exceptions here in showing significantly faster ($p < 0.02$) propagation magnitudes than their short-track counterparts (Fig. 8a). This suggests that the magnitude of the propagation might distinguish the short- and long-track wind swaths for the more organized MCSs with bowing structures. While the propagation magnitude distributions for all class two and three systems are more similar to one another, the class three systems have a wider distribution because of the presence of more systems with relatively small propagation magnitudes. This leads to high statistical significance that class two and three systems have different propagation magnitudes ($p < 0.01$) (since the K–S test assesses the shapes of the distributions in addition to location), but the large overlap of their interquartile range (IQR) results (Fig. 8a) brings into question the practical significance of this finding.

c. *MCS propagation along mean wind direction*

In this section, the component of the propagation vector along the mean wind vector $\mathbf{V}_p$ is summarized for the different MCS classes (Fig. 8) and for two groupings of MCSs with different speeds (Fig. 9). Figure 10 helps us to visualize the relationship between the propagation vector and the mean wind among the four classes of MCS organization. The sign of $\mathbf{V}_p$ is relevant because it may distinguish back-building heavy-rain-producing MCSs from fast-moving severe-wind-producing MCSs, especially when the magnitude of $\mathbf{V}_p$ is large (Chappell 1986; Corfidi et al. 1996; Schumacher and Johnson 2005). Physically, $\mathbf{V}_p$ represents how much the MCS motion is augmented by new cells developing along the periphery of the MCS. In the present dataset, the primary reason for the faster-moving systems when *all four* classes of the MCSs are grouped together (so that the MCS structure

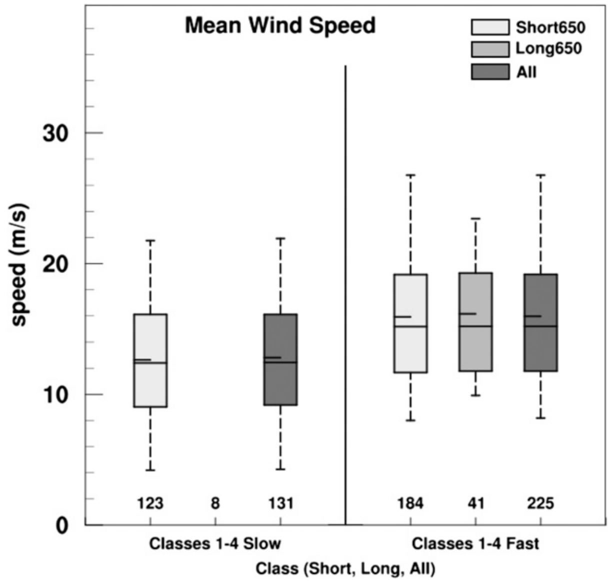


FIG. 7. As in Fig. 6b, but for a comparison of the magnitude of the mean wind vector for slow (MCS speed < 17.5 m s^{-1}) and fast (MCS speed ≥ 17.5 m s^{-1}) MCSs with all the MCS classes (1–4) grouped together.

is not considered) appears to be the large magnitudes of $\mathbf{V}_p$ (Fig. 9), which is highly statistically significant ($p < 0.0001$). This result is in agreement with the finding of Cohen et al. (2007), who did not consider the structure of the MCS. The median value of $\mathbf{V}_p$ for MCSs that move faster than 17.5 m s^{-1} (~35 kt) is about 5 m s^{-1} (~10 kt) whereas it is actually below zero (−2 m s^{-1} or −4 kt) for the systems that move slower than 17.5 m s^{-1} (Fig. 9). However, this difference for MCS speeds does not necessarily translate into differences in $\mathbf{V}_p$ for MCS structures, as shown next.

The highest mean positive $\mathbf{V}_p$ is found for the class one systems (Figs. 8b and 10), meaning that propagation tends to have a large component in the direction of the mean wind for the few highly organized systems with MCVs, although the differences are not statistically significant (p values range from 0.16 to 0.54 when compared with the other classes). This is because the majority of the MCSs in the other three categories also tend to have a large $\mathbf{V}_p$, and the mean and median values of $\mathbf{V}_p$ are all similar for classes two–four (Figs. 8b and 10). Yet, a significantly larger *overall* propagation magnitude is exhibited by class one systems (Fig. 8a), which is associated with the MCS speed always exceeding the mean wind speed for class one systems (Fig. 6c). The combination of these factors implies that *along-mean-flow propagation* in class one MCSs does not fully explain why systems in this class move more rapidly than those in any other class (Fig. 6a), but rather that the larger overall propagation magnitude itself, and a correspondingly larger component of propagation *normal* to the mean wind, also play a role.

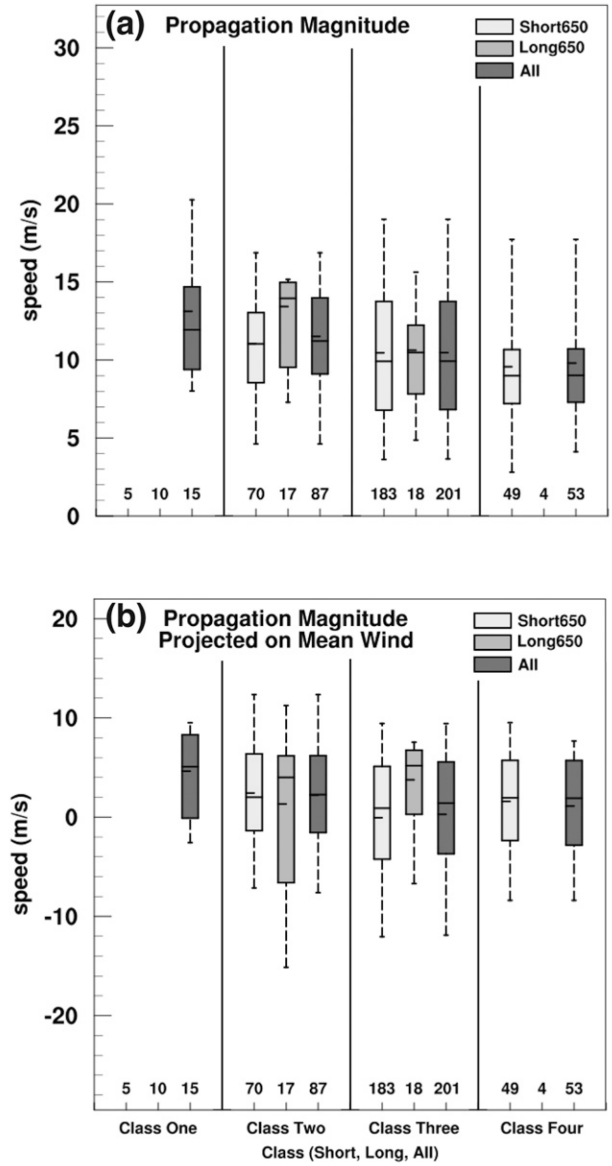


FIG. 8. As in Fig. 6, but for (a) the propagation magnitude and (b) the magnitude of the propagation projected onto the mean wind vector.

The physical factors contributing to a large propagation magnitude (and fastest overall speeds) for the class one systems are not clear. It is certainly possible that these systems have stronger cold pools and therefore have a stronger hydrostatically induced motion. Another factor could be the presence of well-defined line-end vortices or MCVs in this class, and their absence in the others, suggests that they may play a role in enhancing cell propagation. If the vortex is behaving like line-end vortices of the type described in Weisman (1993) and Trapp and Weisman (2003), then it is possible that the enhancement to the rear-inflow jet (RIJ) induced by a

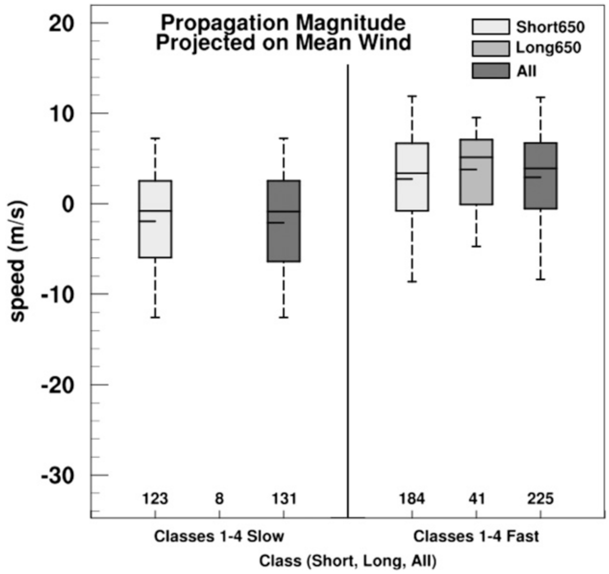


FIG. 9. As in Fig. 7, but for a comparison of the magnitude of the propagation projected onto the mean wind vector for slow (MCS speed < $17.5\,m\,s^{-1}$) and fast (MCS speed ≥ $17.5\,m\,s^{-1}$) MCSs with all the MCS classes (1–4) grouped together.

northern line-end vortex is playing a role in enhancing convergence near the leading edge of the system and/or opposing the negative effects of the cold-pool circulation (Weisman 1992). If the vortices are behaving more like a quasi-balanced version of the MCVs (Zhang and Fritsch 1988; Trier and Davis 2007), then mesoscale lifting on the downshear side of the MCV, often southeast of the MCV center, could play a role in facilitating the development of new convective cells on the downshear flank of the cold pool in a direction toward the southeast of the MCV. This latter effect could explain the large component of propagation *normal* to the mean wind pointed to the southeast (Fig. 10). MCVs also can locally enhance the vertical wind shear in this region (Trier and Davis 2007), which can promote the organization and sustenance of new convection forming on the downshear side of the cold pool (Rotunno et al. 1988; Parker and Johnson 2004; Coniglio et al. 2006). Figure 10 shows that the class two systems, those without well-defined MCVs but with well-defined bow echoes, also have a larger propagation component normal to the mean wind compared with the class three and class four systems, so the processes that contribute to the larger propagation are not limited to the presence of an MCV. Furthermore, if the MCV is enhancing the vertical-wind shear locally, then it is likely that the mean wind is being enhanced locally as well. Therefore, it is not clear how much of the increased speed of the class one systems can truly be attributed to larger propagation or if the enhancement to the mean wind speed (assuming that it went undetected in SFCOA mesoscale analyses) is playing a role. Finally, it is recognized that consideration of the thermodynamics [convective available potential energy (CAPE), lapse rates, etc.] is needed for a more complete physical explanation for the differences in MCS motion and propagation (e.g., Kirkpatrick et al. 2007), as systems that move along gradients in CAPE could tend to propagate toward larger CAPE [like the "southward burst" MCSs in Porter et al. (1955) and Stensrud and Fritsch (1993)]. Skamarock et al. (1994) find that southward propagation can also result from the impact of Coriolis forcing on the convectively generated cold pool. However, examination of thermodynamics is beyond the scope of the present study so that sufficient detail on the mean wind relationships can be provided.

The acute angle between the convective line and the MCS direction of motion, as well as the angle between the convective line and the mean wind vector, are computed (Fig. 11) to further examine if the structure of the MCS relates to the mean wind and the direction of MCS motion. It is recognized that these angles tend to be larger for progressive derechos than for the serial derechos as defined in Johns and Hirt (1987). Serial events are much more prevalent in classes three and four. Therefore, examining this quantity among the different classes could give some quantitative insight into typical values of these angles for progressive versus serial derechos. Furthermore, it is expected that faster-moving systems are aligned more perpendicular to the mean flow than are more slowly moving systems (Corfidi 2003). Fast-moving convective lines perpendicular to the mean flow indicate abundant wind-shear-induced convective regeneration along the downwind-advancing portion of the cold pool (Weisman et al. 1988, Cohen et al. 2007), or it could reflect the advective/momentum transport effects mentioned earlier. Statistically significant differences for the angle between the convective line and the MCS direction of motion (Fig. 11a) are seen for the comparisons between the class one and class three/four systems (Table 1). This is an indication of many strongly forced disorganized systems moving at a relatively small angle to the convective line in classes three and four, as well as the tendency for organized systems to have a convective line at a large angle to their direction of motion.

The angle between the convective line and the mean wind (Fig. 11b) tends to be largest for class one systems and smallest for the class three and four systems. However, the variability within each class is large, which prevents any statistically significant differences. This result suggests that physical factors other than the advective component to cold-pool motion or momentum transport effects on the MCS speed must be important for maintaining convective organization, including thermodynamic effects, vertical wind shear effects, and those related to spatial inhomogeneities

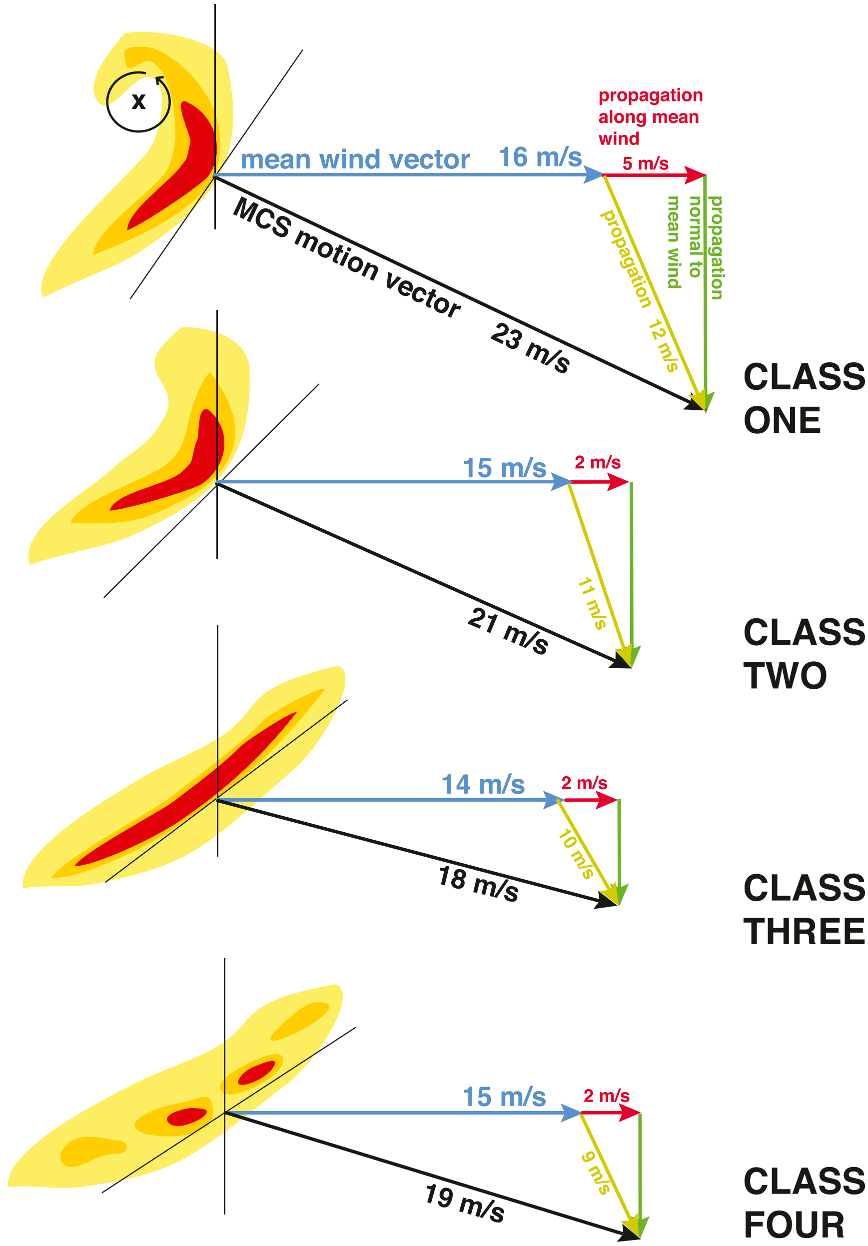


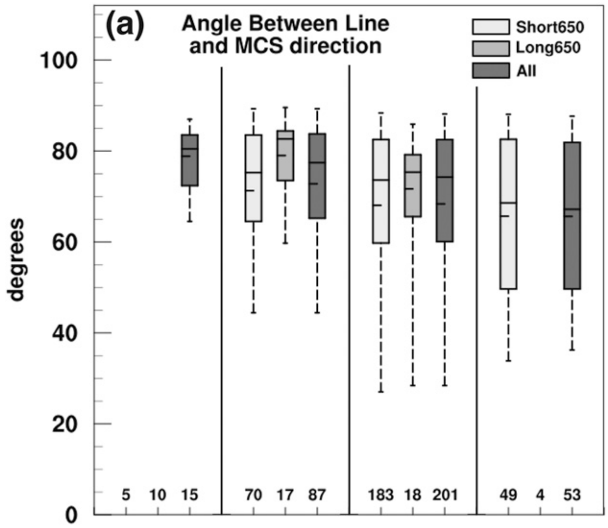
FIG. 10. Graphical representation of the relationships between the various median vector quantities in each MCS class described in section 3. The lengths of the vectors are approximately drawn to scale based on the median values of each calculated quantity (vector labels).

in the environment (e.g., French and Parker 2010), none of which are examined in this study.

d. Comparison of short- and long-track systems

The previous sections identify differences in MCS motion among different levels of MCS organization (i.e., classes one–four), but did not focus on the length of the associated severe wind swath. One of the motivations for this study is to examine past findings of differences in the motion of the parent MCS relative to the mean wind speed between derechos and shorter-lived severe MCSs. Johns and Hirt (1987) find that 56% of the 51 progressive derecho cases they examined moved faster than the mean wind.[3] Cohen

[3] Similar to the method employed here, Johns and Hirt (1987) defined the mean wind to be the layer between approximately 1500 m above ground level and the tropopause (or 200 hPa if tropopause data are not available).



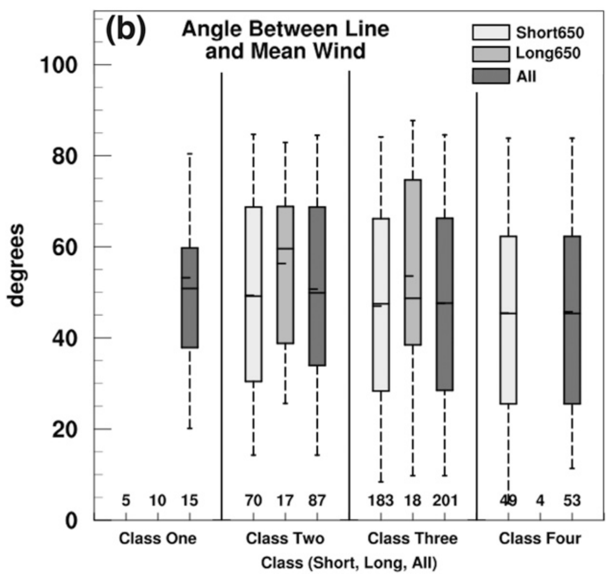


FIG. 11. As in Fig. 6, but for (a) the angle (°) between the MCS leading line and the MCS direction of motion and (b) the angle (°) between the MCS leading line and the mean wind direction.

et al. (2007) find that 75% (38 out of 51) of the derechos in their dataset moved faster than the mean 2–10-km wind speed, but only about 33% of severe-non-derecho MCSs and 30% of nonsevere MCSs exceed the 2–10-km wind. The above studies, however, do not examine the differences in severe-MCS structure as identified by radar reflectivity.

For the comparisons using a 650-km criterion to separate short- and long-track systems, sample sizes for both the short- and long-track systems in class one and for the long-track systems in class four are small (≤10) and are not shown or discussed. The long-track systems using a 650-km track criterion in classes two and three show a tendency to move faster than the short-track systems (especially for the class three systems) (Fig. 6a). While the mean wind speeds for class two and three systems are slightly larger for the long-track systems compared to the short-track systems (Fig. 6b), there are no significant differences in mean wind speeds between these two subsets.

The short- versus long-track systems in class two show little difference in their speeds relative to the mean wind speeds, but some separation is seen for class three systems (Fig. 6c). Almost all of the 18 long-track class three systems move faster than the mean wind speed (2 move slower), with a mean difference of about 7 m s^{-1}, but over 25% of the 183 class three short-track systems move slower than the mean wind, with a mean difference of about 3 m s^{-1}. This suggests that when the parent MCS does not contain an MCV or a well-defined single bow echo or arcing convective line, the presence of factors that contribute to MCS motion being faster than the mean wind is important if the system is to remain severe over long distances (≥650 km). An environment in which the deep-layer shear vector is substantial and aligned closely with the mean wind vector is such a scenario (e.g., Fovell and Dailey 1995; Parker and Johnson 2004; Coniglio et al. 2006; Cohen et al. 2007). Indeed, the component of propagation along the mean wind direction for class three long-track MCSs is larger compared with that for class three short-track MCSs (Fig. 8b). The relatively small sample size of the long-track class three systems (18), and the great disparity compared with the short-track subset (183), prevents a robust generalization. However, the results suggest that when well-organized features of severe MCSs (single well-defined bow echoes and MCVs) are not present, a distinguishing characteristic of long-track systems is propagation strongly in the direction of cell motion. Conversely, when well-defined bow echoes are present (class two systems), the addition of cell propagation along the direction of the mean wind (Fig. 8b) does not necessarily distinguish short- and long-track systems. In other words, an environment that supports cell propagation in the direction of cell advection [along with a long spatial extent to favorable environmental conditions; e.g., Coniglio et al. (2010)] is particularly important if an MCS that does not contain a well-defined bow echo, RIJ, or MCV (which can internally augment MCS speed as discussed previously) is to produce a long-track event.

Differences in MCS characteristics relative to the mean wind were also computed with a wind swath length criterion of 400 km [the criterion used by Johns and Hirt (1987) and many others] to examine if the results discussed above change when including shorter-track wind swaths in the long category. The relative differences in MCS speed and the lack of differences in the mean wind

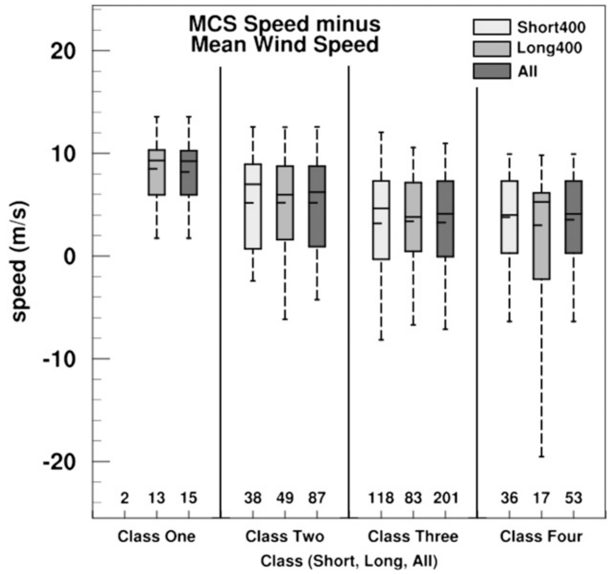


FIG. 12. As in Fig. 6c, but the short and long wind damage swaths are separated using a threshold of 400 km.

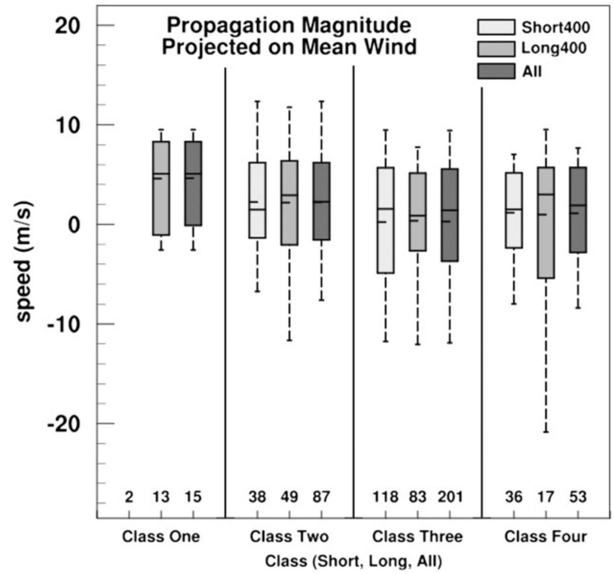


FIG. 13. As in Fig. 8b, but the short and long wind damage swaths are separated using a threshold of 400 km.

speed among the different classes for the 650-km criterion also hold for the 400-km criterion and are not shown. However, one change results when examining the differences in MCS speed relative to the mean wind speed. Whereas the short- and long-track class three systems using a 650-km criterion are significantly different, they are no longer so when using a 400-km criterion (cf. Figs. 6c and 12). Likewise, the propagation magnitude along the direction of the mean wind is no longer significantly larger for the long-track systems when a 400-km criterion is used (cf. Figs. 8b and 13). This supports the results stated above that the presence of factors that promote strong propagation along the direction mean wind are important (e.g., spatial distributions of instability or favorable wind shear normal to the convective line) if systems that do not contain well-defined bow echoes or MCVs are to remain severe over long distances (≥650 km).

4. Summary and conclusions

The relationship between the structure of MCSs and MCS motion relative to the mean environmental wind is investigated with a study of 356 warm-season, severe-wind-producing MCSs during the years 2010–14. The goal of this study is to determine if the motion of long-track, severe-wind-producing MCSs that contain specific physical characteristics move differently relative to the mean environmental wind than do other types of severe-wind producing MCSs. Given that derechos often move faster than the mean environmental wind speed, another goal is to determine if there exists a meaningful and quantitative way to include MCS motion relative to the mean wind in the recently proposed revision to the definition of a derecho by C16. It should be noted that it is beyond the scope of this study to examine the thermodynamic characteristics of the environments that certainly influence both MCS propagation and MCS cold-pool characteristics; any differences in cold-pool strength will surely impact the motion of the MCS. Rather, the focus herein is on determining any observed differences in MCS motion among MCSs of different organization without any consideration of specific physical processes driving the MCS propagation (beyond some hypothesizing as appropriate).

The 356 MCSs are categorized into four classes, each with progressively less organization following the most organized (class one). Within each class, they also are separated into two subsets according to the major-axis length of the severe-wind swath. The motion of each MCS is determined from sequences of mosaic radar reflectivity images made during the mature phase of the system. Following Corfidi et al. (1996), MCS motion is considered to be the sum of an advective component of motion (i.e., the component of MCS motion from the winds "moving" the convective cells) and a propagation component. The pressure-weighted mean wind in the layer between the lifted condensation level and the equilibrium level for a mixed-layer parcel using the SPC mesoanalysis system is used as an estimate of the advective component of MCS motion. The propagation component is then defined to be any MCS motion not attributed to the mean wind.

The results show that *highly organized MCSs with both line-end vortices/MCVs and well-defined single bow* *echoes (class one) move the most rapidly, have the greatest magnitude of propagation, and the largest component of propagation in the direction of the mean wind.* Along with mean wind speeds that do not much differ from those in the other MCS classes, these findings suggest that *the best-organized MCSs tend to move the most rapidly primarily because of the additive effects of propagation.* Since line-end vortices/MCVs are only present in class one systems, it is hypothesized that mesoscale lifting or localized enhancements of deep-layer shear and mean wind near the MCVs, and/or enhancements to the RIJ by the line-end vortex, could play a role in accelerating MCS motion by encouraging new cell development and sustenance. However, factors contributing to fast MCS motion for the more organized systems are of course not limited to those related to MCVs, and likely include downshear propagation related to cold-pool–vertical wind shear interactions (Parker and Johnson 2004; Weisman and Rotunno 2004; Coniglio et al. 2006) and other factors (including thermodynamic ones; e.g., Kirkpatrick et al. 2007) not considered here.

However, the additive effects of propagation in the direction of the mean wind are not a distinguishing characteristic of the classes of MCSs that do not show evidence of a well-defined line-end vortex/MCV (classes two–four). Differences in the component of propagation normal to the mean wind direction among these three MCS classes are larger than the differences in the component of propagation along the mean wind direction (see Fig. 10). This indicates that the majority of the propagation is not necessarily being added to the mean wind for severe MCSs, even with evidence of bow echoes and mesoscale organization (class two).

Contributions from the advective component of motion and propagation are compared among short- and long-track systems using a severe-wind swath length criterion of 650 km (a derecho, per the proposed definition of C16). It is found that propagation *along the direction of the mean wind* is significantly larger for the long-track class three systems compared to the short-track class three systems (those with contiguous convective lines but no bow echoes or MCVs) (Fig. 8b). However, this is not true for the other MCS classes, which is somewhat contrary to the interpretations of past results (Corfidi 2003; Cohen et al. 2007). The fact that the class three systems do not contain evidence of internal mesoscale organization suggests that factors external to the MCS are important for promoting cell propagation on the downwind/downshear portion of the cold pool if the system is to produce a long-track severe wind swath (≥650 km).

While some statistically significant differences are found among the difference MCS classes and swath lengths, the differences are not deemed great enough or consistent enough to recommend using any quantitative criterion for the motion of the MCS relative to the mean wind in any derecho definition at this time. However, the results of this study do suggest that the physical structure and environment may still be used as a general aid in determining the likelihood of a severe MCS becoming a derecho by examining the structural character of the MCS and its relation to the mean flow. Specifically, if a severe-wind-producing system contains signs of strong mesoconvective organization as it reaches maturity, and is moving significantly faster than the mean flow (implying a large propagation component as suggested here), regardless of whether or not the propagation is aligned with the mean wind, it is more likely to become a derecho. Previous work has suggested that propagation in the direction of the mean wind is a distinguishing characteristic of derechos versus shorter-lived severe MCSs (Corfidi 2003; Cohen et al. 2007), but the current study suggests that the large propagation component does not necessarily need to be aligned closely with the mean wind for the system to become a derecho if it contains significant internal features that could be affecting its motion. This is likely true as long as other factors [e.g., a loss of convective instability, a loss of supporting vertical wind shear, or increasing convective inhibition, per Evans and Doswell (2001), Gale et al. (2002), and Coniglio et al. (2010)] do not prevent the system from continuing its motion over long distances.

Finally, regarding the recent proposal to alter the derecho definition in C16, we note that only 22 out of 254 class three and class four MCSs satisfy the proposed 650-km length criterion of a derecho. Recall that class three and class four systems do not contain well-organized bow echoes or MCVs on any scale, and class four systems do not contain organized convective lines, which would eliminate them from consideration as derechos using the proposed C16 criterion of requiring evidence of sustained mesoconvective organization. This illustrates that placing the organizational requirements on an MCS, as well as a requirement that the severe-wind swath length is at least 650 km as in C16, would eliminate only 22 MCSs from the lesser-organized categories from being considered derechos. However, 100 out of the 254 class three and class four systems have a wind swath length greater than 400 km (not shown), the traditionally accepted length criteria for an MCS-produced damaging wind swath to be called a derecho. This means that the requirement for mesoconvective organization would eliminate many more events from being considered derechos if the 400-km length criterion were kept compared to using a 650-km criterion. In other words, under the proposed derecho definition of C16, the requirement for a longer damaging wind swath excludes many more candidate derechos events than the requirement of mesoconvective organization. While it is important, we believe, to consider the parent convective structure in deciding whether a given convective windstorm is or is not a derecho, requiring a longer wind swath lessens the impact of this requirement for mesoconvective organization.

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