Beatty, K., E. N. Rasmussen, and J. M. Straka, 2008: The supercell spectrum. Part I: A review of research related to supercell precipitation morphology. *Electronic J. Severe Storms Meteor.*, **3** (4), 1-21.

Electronic Journal of
SEVERE STORMS METEOROLOGY

The Supercell Spectrum. Part I: A Review of Research Related to Supercell Precipitation Morphology

KYLE BEATTY
Willis Re Inc.
Minneapolis, Minnesota

ERIK N. RASMUSSEN
Rasmussen Systems LLC
Mesa, Colorado

JERRY M. STRAKA
School of Meteorology, University of Oklahoma
Norman, Oklahoma

(Submitted 03 March 2008; in final form 15 December 2008)

ABSTRACT

This paper reviews the history of nomenclature used to describe the supercell spectrum. Studies are reviewed that attempt to explain the physical processes associated with variations in supercell morphology. The observational evidence for disparate risks associated with variations in morphology is examined.

1. Introduction

The first of a two-part paper concerning the supercell spectrum, Part I summarizes prior research on the supercell spectrum as a review article. The evolution of the terminology describing these variations in precipitation morphology is documented in Section 2. The work of Browning and his coauthors is used throughout this section to describe some of the key features of a “classic” supercell. The reader is referred to the AMS Meteorological Monograph series (specifically, #27, 36, 38, and 50) for a more comprehensive discussion. Once it became obvious that a variety of precipitation structures were associated with storms having persistent mesocyclones, researchers began examining the possible environmental influences on supercell structure. These studies are summarized in Section 3. There is some evidence, summarized in Section 4, that the variations in morphology are associated with variations in severe weather hazards. This evidence of disparate hazards, coupled with the need for an objective basis for characterizing supercell morphology, is the motive for the research presented in part two of this study.

In the second part of this paper, the authors develop and perform initial testing on a semi-objective, radar-based technique for discriminating within the supercell spectrum. It is hoped that the technique can be improved and used as a basis for supercell classification. If this proves effective, it will become much easier to perform studies that evaluate the influences of the larger scale environment on the supercell spectrum. It also may be possible to use radar identification of supercell type to gain better real-time assessments of supercell hazards.

2. Observations of archetypical supercell thunderstorms

a. Early observations and the "classic" supercell

Byers and Braham (1949) were perhaps the first to suggest that a thunderstorm's rainfall distribution and intensity indicated the gross

---

Corresponding author address:
E. N. Rasmussen, P.O. Box 267, Mesa, CO
81643. Email: rasm1@rasmsys.com

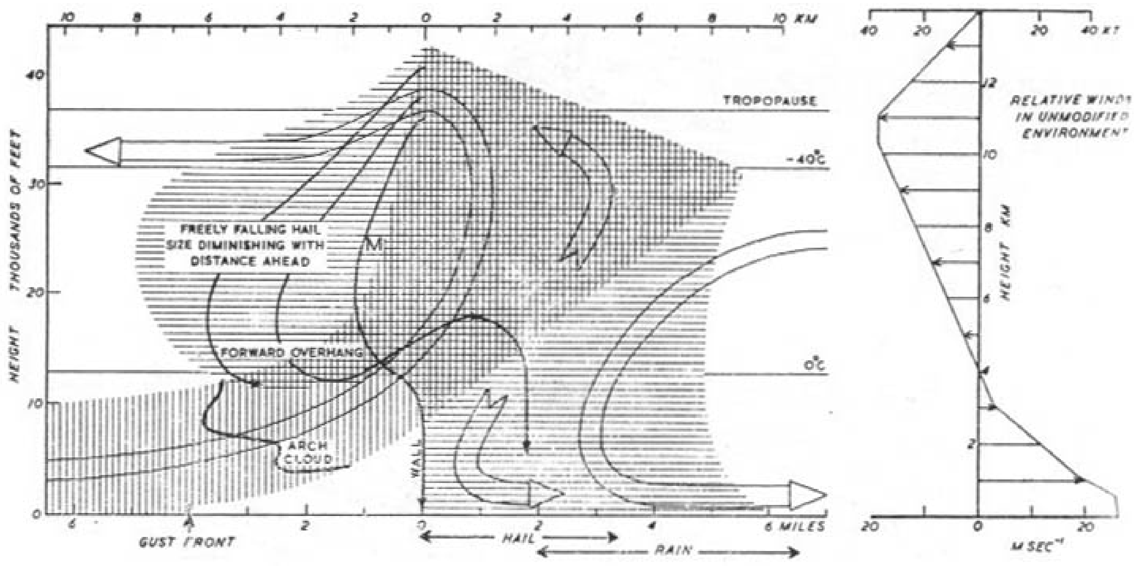


Figure 1. Vertical section along the direction of motion through the center of the Wokingham, England hailstorm of 9 July 1959. The reflectivity-inferred updraft is denoted by vertical hatching. The area of equivalent radar reflectivity in excess of 10^3 mm^6 m^{-3} is denoted by horizontal hatching. Hailstone trajectories were inferred from proximity sounding and radar reflectivity data. (After Browning and Ludlam 1962).

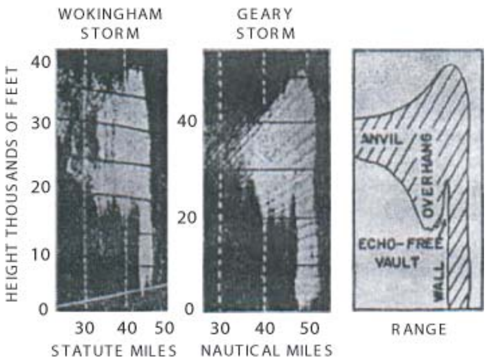


Figure 2. RHI radar reflectivity presentations illustrating the similarity between the Wokingham and Geary storms during their most intense phases. Note that the term "forward overhang" was not used to describe the reflectivity structure of the Geary storm as the orientation of the storm relative winds were such that the overhang was largely located on the storm's right flank. (After Browning and Donaldson 1963).

nature and intensity of the thunderstorm. Byers and Braham classified convective phenomena based on common stages of development characterized by the draft(s) observed through instrumented aircraft penetrations. The life cycle of a thunderstorm cell was divided into three stages: the Cumulus Stage (updraft), the Mature Stage (updraft and downdraft), and the Dissipation Stage (downdraft). It was hypothesized that the downdraft portions of these thunderstorm cells were driven by the drag of descending hydrometeors.

Byers and Braham noted that the mature stage of a cell could be prolonged when strong environmental wind shear was present. They described a tilted updraft in which precipitation would descend outside of the cloud boundary, allowing the updraft to persist until its energy source was exhausted. Browning and Ludlam (1962) derived a similar model of the airflow in the Wokingham, England hailstorm of 9 July 1959 (Fig. 1) from multiple-wavelength radar, sounding, and surface weather observations. Range-height indicator (RHI) displays of the Wokingham storm during its intense phase revealed three prominent radar reflectivity features termed the "wall," the "forward overhang," and the "echo-free vault."

The forward overhang (see also Fig. 2) was identified as an area of reflectivity extending downshear from the primary updraft by up to 3 mi (4.8 km) or more, over an area void of any echo[1]. The majority of this elevated reflectivity region extended well below the lower cloud boundary of the anvil. The reflectivity of the forward overhang, and thus inferred hydrometeor size, decreased with increasing distance ahead of the primary updraft. Browning and Ludlam inferred that hydrometeors within the forward overhang were advected toward the region of primary updraft as they descended, with the largest hailstones reaching the surface first. Within the lowest ~3 km these large hailstones formed a sharply defined, upright plane of reflectivity referred to as the wall. The primary updraft was inferred to be located at the plane of intersection between the lower boundary of the forward overhang and the wall. At this location the base of the forward overhang rose approximately 900 m forming an echo-free vault.

The vault has also been referred to as a bounded weak echo region (BWER; Marwitz 1972a). Browning (1964) used the term *supercell* to describe such single large cells within severe local storms that exhibited these characteristic radar reflectivity structures and which propagated continuously, as opposed to discretely[2]. The observations of Byers and Braham and Browning were later supported by theoretical studies that described the relationship between environmental shear and updraft maintenance. The storm-relative low-level inflow has been shown to limit the advancement of the storm's outflow (e.g., Wilhelmson and Klemp 1978; Thorpe and Miller 1978). In addition, the presence of an updraft in a sheared environment yields tilting of horizontal vorticity into the vertical and subsequently, the development of lifting pressure gradients that reinforce existing or facilitate new updraft growth (e.g., Schlesinger 1980; Rotunno and Klemp 1982).

The RHI presentation of the Geary, OK storm analyzed by Browning and Donaldson (1963) had qualitative similarities to the Wokingham storm (Fig. 2). The primary difference between these storms was the orientation of the storm-relative winds. The circulation of the Wokingham storm was primarily two- dimensional, oriented parallel to the storm motion vector, while the circulation of the Geary storm was highly three-dimensional. The warm, moist inflow approached the Geary storm from the right flank approximately normal to the storm motion vector. Inflow parcels were thought to have turned cyclonically (~270°) as they ascended within the primary updraft before diverging at the echo summit, with the thunderstorm anvil extending downstream to the right of the storm motion vector. Severe local storms containing this particular airflow structure and movement later were generalized by Browning (1964) as severe right (SR) storms, where right is in reference to a supercell's continuous propagation to the right of the lower- and mid-tropospheric winds. Browning (1965) modified Byers and Braham's model of thunderstorm evolution for the case of supercells included a SR Mature Stage, prior to the onset of the Dissipation Stage. Using linear theory, Rotunno and Klemp (1982) showed that Browning's observation of deviant motion to the right of the environmental winds was related to the vertical wind shear profile. Lifting pressure gradients that favor updraft development on the supercell's right flank are produced when the environmental shear vector veers with increasing height. While SR storms were observed to contain the characteristic radar features of Browning's supercell (i.e., the overhang, wall, echo-free vault, and hook echo), the location of these features relative to the direction of storm propagation was different than in the Wokingham storm (Fig 3). The presence of a strong updraft in an environment of strong storm-relative wind that veered with increasing height led to the development of an expansive echo overhang in the storm's forward, right, and

---

[1] This area void of echo is not the same as the "weak echo region" (WER; Chisholm 1970). Chisholm's WER referred to areas of strong updraft associated with newly developed cumulus towers, presumably containing cloud droplets with diameters below the detectable range of conventional radar systems. The area void of echo beneath Browning's "overhang" was largely the result of hydrometeors descending in a highly sheared environment. This area does not necessarily comprise updraft.

[2] The discrimination between continuous and discrete propagation of cells via radar may not be feasible at long ranges. Both regimes can coexist within the supercell system. The definition of a supercell has been refined since the early work of Browning with more detailed observations and the advancements of Doppler radar and numerical models. Most recent supercell definitions emphasize a persistent correlation between vertical velocity and vertical vorticity (e.g., Weisman and Klemp 1984; Doswell and Burgess 1993).

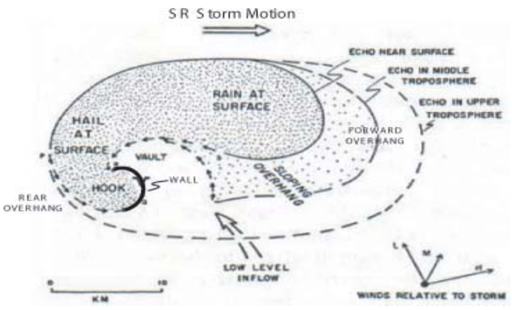


Figure 3. Generalized schematic of the severe right (SR) storm's radar reflectivity field at three elevations. Note that echo overhang is present in the front, right, and rear flanks of the storm. (After Browning 1964).

rear flanks. Detailed radar analyses indicated that the descending overhang echo was advected by the environmental flow, with the forward- and right-flank overhangs lowering to the ground toward the SR storm's left flank. The overhang in the storm's rear flank was attributed to strong divergence at the updraft summit and later was related to the hook echo (e.g., Lemon and Doswell 1979).

Although not described for the Geary storm, Browning (1965) described the evolution of the wall in a case study of the SR storms of 26 May 1963. The wall of "storm E" initially bounded the left side (relative to the storm motion vector) of the echo-free vault. Over a 30-min period, the wall was observed to develop successively outward and rearward to form the leading edge of a hook echo (similar to the location of the wall in Fig. 3). Browning referred to the hook echo of storm E as "…the most obvious feature of the supercell structure." Browning (1964) suggested that this hook echo might be the result of the continuous ejection of hailstones from preferred generation regions within the cyclonically turning updraft. Lemon and Doswell (1979) interpreted the pendant echo development as the downward forcing of hydrometeors from the rear echo overhang by the rear flank downdraft (RFD) at a rate in excess of their individual terminal velocities (Fig. 4).

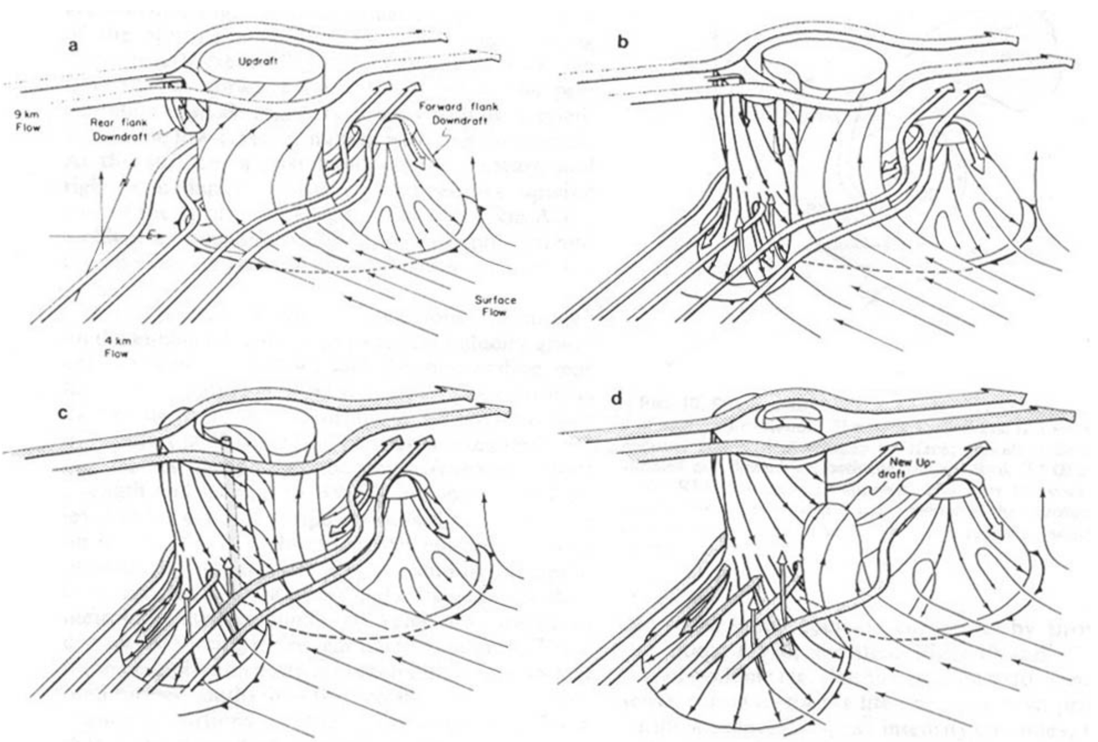
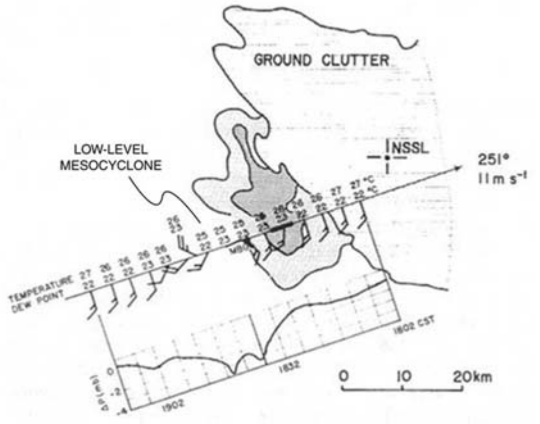


Figure 4. Schematic depiction of the evolution of the drafts of an evolving supercell storm. The evolution of the rear flank downdraft and its associated rotation is of particular relevance to pendant echo development. (After Lemon and Doswell 1979).

Recognizing that the SR storm Browning had described was a member of a larger class of supercells, Lemon (1976) referred to the Geary storm as a "classic supercell." While the reflectivity features initially described by Browning are frequently present, the defining characteristic of the classic supercell as the term is most often used, is the presence of a deep, persistent mesocyclone containing some visible precipitation [e.g., Doswell and Burgess 1993; Rasmussen and Straka 1998 (hereafter RS98)]. This precipitation often is described as a curtain around the left and rear sides of the updraft within the rear flank downdraft, and may be manifested on radar as a hook echo, provided it is sampled at a detectable range and resolution. During the Collapse Stage or Dissipation Stage, the classic supercell's mesocyclone may fill with precipitation.

b. Low precipitation (LP) supercells

Davies-Jones et al. (1976) described an atypical severe storm producing hail of at least 4 cm in diameter but very little accumulating rain. The low-level rotating updraft was found to be to the rear of and outside the low-level radar echo (Fig. 5). This updraft was capped at 6 km AGL (all heights hereafter AGL unless specified otherwise) by a reflectivity overhang with reflectivity in excess of 40 dBZ, extending to the surface downstream from the low-level updraft. The authors stated that "Storm A appeared benign on the WSR-57 radar, satisfying none of the criteria for severe weather warnings," such as cyclonic curvature in low-level reflectivity field, a BWER, a large and intense echo core, etc. This observation was particularly striking given that a sounding observation immediately in advance of the storm indicated storm-relative winds veered with increasing height similar to Browning's observations of SR storms. A peak wind gust of 25 m s^{-1} was observed behind the low-level reflectivity region, within the low-level mesocyclone, but temperature and dewpoint observations indicated that no cold air outflow was present. The relative absence of variation in the temperature and dewpoint traces as the storm passed over the observing station is surprising given the observation of a locally lowered cloud base or wall cloud. Burgess and Davies-Jones (1979) documented similar tornadic hailstorms that had little precipitation falling from the cloud base and that did not meet severe warning criteria when judged solely on their radar appearance. Burgess and Davies-Jones used the terminology "dryline storms" to distinguish the tornadic storms in proximity to the dryline from the towering cumuli that were present in central Kansas along a frontal boundary on 5 December 1975. Thus, contrary to some references, it does not appear that the authors intended for this term to apply in a general sense.



<u>Figure 5.</u> 0° elevation radar reflectivity field of an LP supercell at 0032 UTC, 4 June 1973. Areas of ground clutter are hatched. 20 and 40 dBZ reflectivity areas appear in light and dark gray, respectively. The black dot marks the position of the Middleburg, OK (MBG) NSSL surface network observing station. The MBG time series observations are plotted relative to 0032 UTC, using a storm motion of 251° at 11 m s^{-1} for the space to time conversion. The dark line on the temporal axis denotes the period of measured rainfall. The whole and half wind barbs represent 5 and 2.5 m s^{-1}, respectively. (After Davies-Jones et al. 1976).

Bluestein and Parks (1983) and Bluestein (1984) observed 13 additional severe storms termed LP that exhibited the following distinguishing features: little to no visible precipitation around the cloud base; no evidence of a strong precipitation-driven downdraft at the surface; and large hail falling outside the main cumuliform tower. Bluestein and Parks also added that LP severe storms "always form as isolated cells" and noted that some LP severe storms exhibited a tilted updraft structure, as compared to the upright, bell-shaped cumulonimbus described by Davies-Jones et al. (1976) and Burgess and Davies-Jones (1979). Bluestein and Woodall (1990) documented a tornadic hailstorm that exhibited LP-storm characteristics for the first 1.5-2 h of its existence, including a relative translucence beneath cloud base and the absence of strong precipitation-driven outflow. However, a spatially small cold pool may have been present as the stations capable of measuring thermodynamic variables were located in the storm's extreme forward flank, outside of and in advance of the low-level radar echo boundary. The storm's primary updrafts were imbedded in low reflectivity and capped by higher reflectivity overhangs on both the storm's northern and southern flanks (Fig. 6), differing from the echo configuration described by Davies-Jones et al. (1976). In addition, the storm's core reflectivity at 1 km exceeded 50 dBZ, much greater than that observed by Davies-Jones et al. (1976). Bluestein and Woodall hypothesized that a relatively low concentration of large precipitation particles might be responsible for the high radar reflectivity and lack of significant light attenuation under cloud base. Dual-Doppler analyses of the vertical velocity and vertical vorticity fields verified that this LP storm was a supercell.

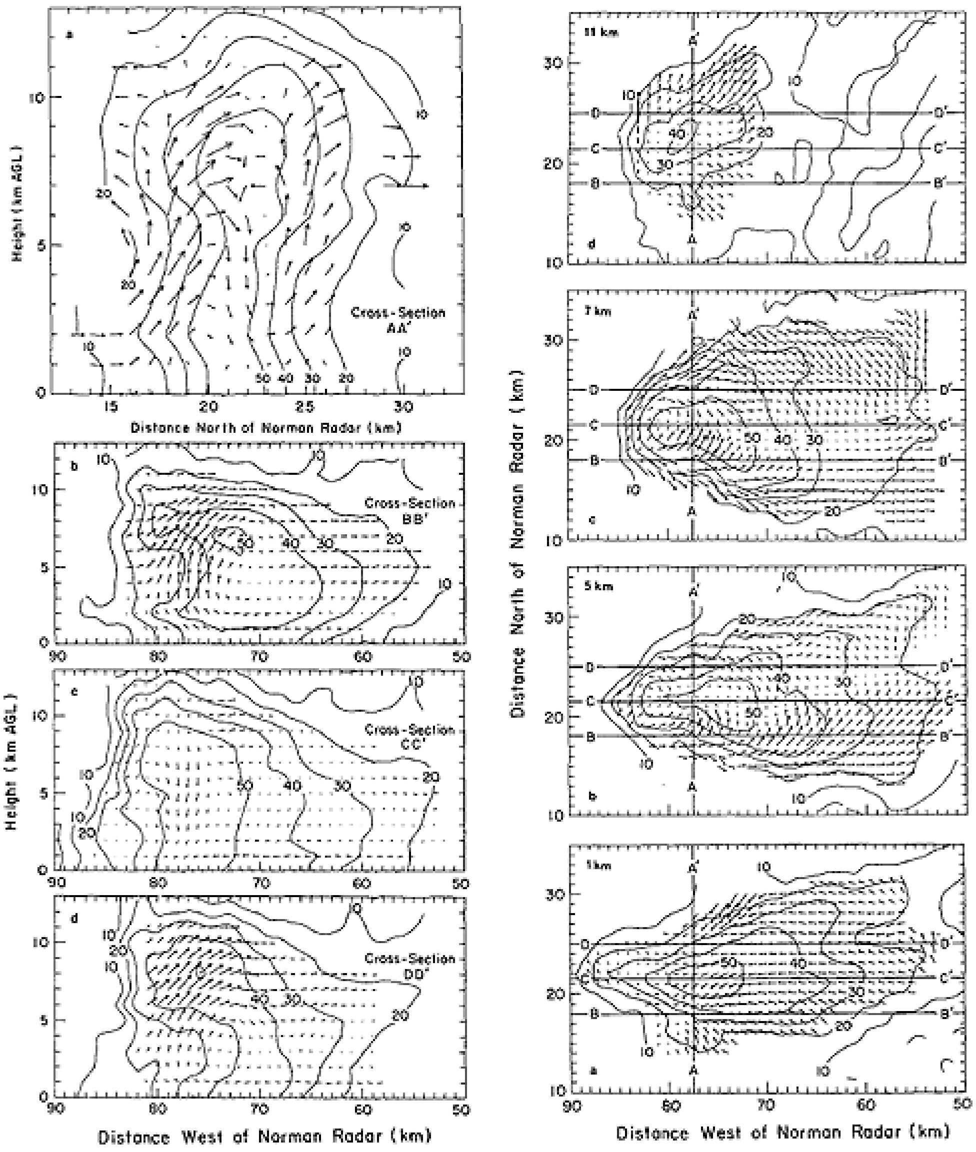


Figure 6. a) Dual-Doppler storm-relative, horizontal wind field and reflectivity analysis of the LP phase of a supercell at 2236 UTC on 26 April 1984. b) Vertical sections of dual-Doppler-derived storm-relative wind and reflectivity along the lines AA', BB', CC' and DD' depicted in Fig. 8a. (After Bluestein and Woodall 1990).

Adopting the criteria of a deep, persistent mesocyclone as the single distinguishing characteristic of a supercell, Doswell and Burgess (1993) noted that the visual signs of rotation observed by Davies-Jones et al., Burgess and Davies-Jones and Bluestein and Parks were sufficient to label these storms supercells. Doswell and Burgess added that radar reflectivity might not adequately (if at all) reveal the circulation within LP supercells. They advocated that since radar measurements are range and resolution dependent, purely radar-based identification processes might not be appropriate. Rather, they stressed the visual observation of little to no precipitation within the LP supercell's mesocyclone. RS98 also advocated that LP supercells should not have low-level hook echoes, provided they are sampled at adequate range and resolution.

c. High precipitation (HP) supercells

Nelson and Knight (1987) described the radar-derived reflectivity and flow structure of a "hybrid" hailstorm from 17 May 1980 that contained features common to both supercells and multicell storms. This storm maintained concave curvature along the leading edge of the low-level radar reflectivity field (wall) that was overlaid by an expansive forward overhang. This hailstorm resembled the Wokingham storm described by Browning and Ludlam (1962). The hailstorm was long lived, having a sustained vault approximately coincident with the storm's leading gust front. Significant convection was noted along this gust front, with considerable reflectivity in the storm's right rear flank. Reflectivity and dual-Doppler analyses indicated that multiple updraft maxima were coexistent within this broad vault. The periodic development of these drafts was consistent with discrete propagation (as opposed to the continuous propagation Browning included in his definition of a supercell), while the gross or background storm structure evolved much more slowly.

Nelson (1987) proposed that the "hybrid" nature of the 17 May 1980 hailstorm might be closely related to the presence of an intense downdraft and the accompanying strong gust front. The author speculated that an intense gust front might intensify the updrafts, increasing their horizontal extent, thereby making their boundaries less distinct.

Lemon and Burgess (1993) and Lemon and Parker (1996) described the gust front and associated drafts of two similar supercells in detail. An intense RFD was inferred to develop aloft, behind an established updraft. Potentially cold, mid-level air was believed to descend to the surface and form an intense rear flank gust front. The storm's low-level inflow would encounter that gust front and be forced upward, presumably to its level of free convection, where an intense updraft was maintained. An extraordinarily deep zone of convergence of Doppler velocity, referred to as the Deep Convergence Zone (DCZ), was found along the updraft/downdraft interface. Lemon and Parker likened the DCZ to a "fluid wall" that shielded the updraft from mixing with environmental air. The authors hypothesized that a region of negative perturbation pressure within the DCZ enhanced the mass convergence over its depth, thereby amplifying the RFD and associated low-level outflow. This enhanced RFD also would minimize the hailstone's residence times beneath the melting level.

Nelson and Knight's hybrid hailstorm and those described by Lemon and his collaborators are members of a larger class of storms termed "High-precipitation (HP) supercells." HP supercells are distinguished by the presence of considerable visible precipitation on the trailing (and perhaps leading) side of the mesocyclone. Using a sample of approximately 50 similar storms, Moller et al. (1990) presented two composite radar reflectivity life cycles for HP storms (Fig. 7). HP supercells commonly evolved from classic supercells following the formation of an intense RFD and the accompanying rear flank gust front (2-4 in Fig. 7). A more detailed example of stage 4 in this evolution is shown in Figure 8. With the forward acceleration of this outflow (5-8b in Fig. 7), these supercells often evolved into bow echoes (e.g., Fujita 1978; Johns and Hirt 1987). An alternative evolution of the HP supercell was the northeastward progression of the mesocyclone relative to the radar reflectivity pattern (5-7a in Fig. 7).

Common to each life cycle phase was the presence of abundant visible precipitation within and near the storm's mesocyclone during the storm's mature phase. In each example, a persistent forward overhang overlaid a WER that was bounded by a concave wall of reflectivity.

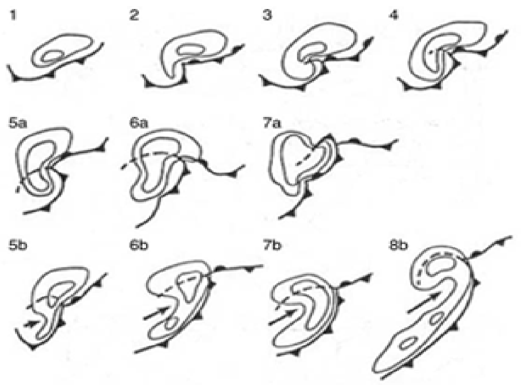


Figure 7. Composite life cycles of an HP supercell in radar plan view. Boundary and gust front positions are depicted with frontal symbology. (After Moller et al. 1990).

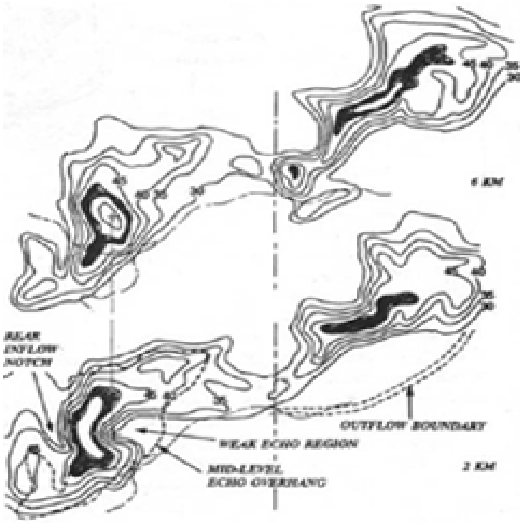


Figure 8. Contoured radar reflectivity fields (dBZ) at 2 and 6 km AGL of a warm season HP Supercell. Values in excess of 50 dBZ are shaded. (After Przybylinski et al. 1993).

A vault (often notably expansive) was observed often along the plane of intersection between overhang and the wall. These features are strikingly similar to those observed by Browning and Ludlam (1962) with the Wokingham hailstorm. As proposed by Nelson (1987), Moller et al. (1990) also found that HP supercells typically move along pre-existing thermal boundaries. The authors hypothesized that the rotational character of the HP supercell might be enhanced by locally backed surface winds (thereby increasing the low-level shear) and/or enhanced horizontal vorticity owing to gradients in buoyancy along the boundary.

d. Summary of supercell precipitation archetypes

A few key points in the reviewed literature warrant emphasis regarding the classification of supercells. First, the methods used by an individual to characterize a supercell's precipitation distribution often vary. The most common tools are weather radar (reflectivity in particular) and visual observation. Distinguishing between which method is used to characterize a storm's precipitation distribution is critical. Large raindrops of low concentration often do not attenuate light significantly and therefore may not be visible to the eye, but would have substantial reflectivity on radar due to the large dependence of reflectivity on hydrometeor diameter. Therefore an LP storm that may appear to have no precipitation in its left or rear flanks actually may have highly reflective hydrometeors in its rear flank downdraft that give it a classical radar appearance. At long ranges, a storm may also appear to have substantial precipitation in its left and rear flanks because the storm is being sampled at middle levels. In actuality, it is possible that no hydrometeors reside in this region below the radar horizon.

Second, it is clear that a storm might be characterized by more than one archetype during its existence. Browning's storm B near Oklahoma City on 26 May 1963 is such an example, where little accumulating rain was initially observed, but the storm evolved to exhibit a classical radar appearance (e.g., a hook echo). The storm documented by Bluestein and Woodall (1990) is another such example that had little visible precipitation around its updraft, but quickly evolved to a clear classical or HP radar presentation. Only a few cases of a "true" LP supercell, as characterized from both the visual and radar perspectives (e.g., Davies-Jones et al. 1976), have been described in the formal literature, though storm chasers and scientists have photographed many storms that appeared to be LP supercells.

3. Hypothesized forcing mechanisms of supercell archetypes

a. Storm-relative wind considerations

Building off the work of Marwitz (1972b) and Foote and Fankhauser (1973), Browning (1977) showed evidence of an inverse relationship

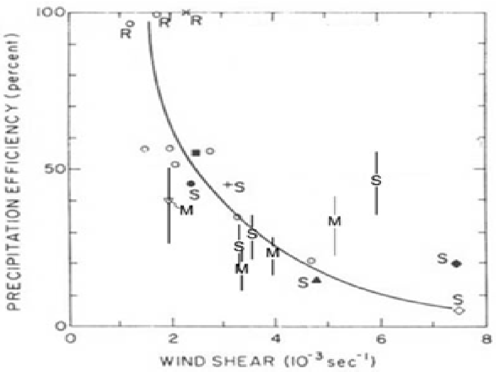


Figure 9. Precipitation efficiency for High Plains storms as a function of vertical wind shear within the cloud bearing layer. Storms that produced rain only are labeled R, multicell storms are labeled M and supercell storms are labeled S. Error bounds are indicated with vertical lines on some estimates. (After Browning 1977; Fankhauser 1988).

between the precipitation efficiency[3] of a High Plains convective storm and the environmental wind shear in the cloud-bearing layer (Fig. 9). Consequently, supercell thunderstorms, which largely depend on environmental shear as a source of mid-level rotation, are among the least efficient precipitation producers. The mechanism(s) controlling these efficiencies is not well understood. Brooks et al. (1994) used a three-dimensional numerical model to investigate the effects of varied 3-7 km environmental wind shear on the precipitation distribution of simulated storms. In their simulations, the initial environment was constrained so no environmental wind shear existed above the 7-km level, with the wind constant above this level. Brooks et al. (1994) noted that one of the effects of the strong storm-relative winds in the high-shear case (0.015 s^{-1} in the 3-7 km layer) was to advect rainwater[4] away from the updraft. This led to a separation of the rainwater and updraft at the lowest model level. Thus, although the magnitude of the mid-level shear was varied in the simulations, the magnitude and orientation of the storm-relative wind resulted in the varied precipitation characteristics.

Heavy precipitation in the vicinity of the updraft was found to begin earlier and descend closer to the updraft in the low-shear case (0.005 s^{-1} in the 3-7 km layer). In this case, the rain was drawn around the rear flank of the updraft as it descended through the mesocyclone. Brooks et al. (1994) concluded that the strength of the mesocyclone, which is a function of the low-level environmental wind shear, also influenced the simulated storm's precipitation distribution. This conclusion is consistent with the findings of Bluestein and Parks (1983) of greater subcloud shear for supercell storms (presumably classic) as compared to LP storms; however, Bluestein and Parks' finding only may represent differences in the environments of supercells and "ordinary cells." RS98 had similar findings of LP supercells occurring in environments with relatively low storm-relative environmental helicity (SREH), with SREH increasing as storms tended toward the HP portion of the supercell spectrum, in general. Brooks et al. (1994) noted that as the low-shear case evolved, large amounts of rainwater developed around the updraft, similar to observations of HP supercells. The weaker storm-relative, mid-level winds in the low-shear case are consistent with the observations of Moller et al. (1990) and Lemon and Parker (1996) for HP supercells.

RS98 utilized soundings representative[5] of the LP, classic, and HP supercell environments to compute numerous parameters, including the variation of storm-relative wind with height. Two features were most distinct between the supercell environments when expressed as composite hodographs. In general, the magnitude of the storm-relative wind in the 8-10 km layer was greatest in LP supercell environments, with decreasing magnitude as supercells tended

---

[3] Precipitation efficiency is defined as the ratio of the surface precipitation rate to the water vapor flux (Browning 1977).

[4] The Kessler microphysical parameterization used in the simulations of Brooks et al. (1994) excludes ice-phase processes. The authors noted that since frozen hydrometeors may have different fall speeds, the location of precipitation in actual storms might vary from those found in their simulations. RS98 added that precipitation formation occurs too quickly in Kessler microphysical parameterizations, biasing the precipitation toward the updraft.

[5] The challenges regarding the definition of a proximity sounding have been documented well by Brooks et al. (1994). These include judgments regarding the spatial and temporal variability of the "environment" as well as judgment of when data should be retained or discarded.

toward the HP portion of the spectrum (Fig. 10; cf decreasing mean storm relative winds from the top to the bottom panel). However, there was substantial variance and overlap between the proximity soundings in each archetype. In addition, the wind in the composite LP environment was found to back relatively strongly with height above 6 km, while the direction of the wind in the classic environment varied little above 6 km and the storm-relative wind in the HP environment veered slightly aloft (Fig. 11). Although these results are statistically significant, notable exceptions still exist in the reviewed literature. The sounding-derived hodographs presented by Bluestein and Woodall (1990) for a supercell that transitioned from the LP toward the HP portion of the spectrum revealed relatively weak storm-relative flow (~20 m s^{-1}) in the 8-10 km layer and a slightly veered wind profile aloft during its LP phase. While the amount of veering in the wind profile increased with time, so did the magnitude of the storm-relative flow in this layer, reaching approximately 30 m s^{-1} during the supercell's HP phase.

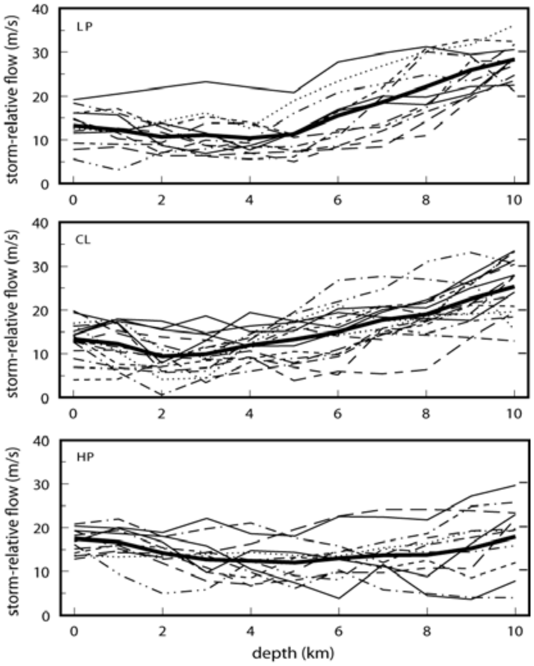


Figure 10. Storm-relative wind speed for each of the LP, classic, and HP supercells reviewed in the study. The single bold line in each panel depicts the mean wind speed of all the cases displayed in the panel. (from RS98).

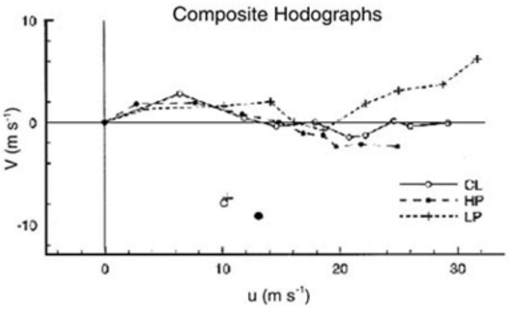


Figure 11. Composite hodographs for the LP, classic, and HP classes. All hodographs have been rotated so the boundary layer to 4-km shear vector is oriented toward the east and the boundary layer mean wind is at the origin (after RS98).

RS98 argued that with parcels residing in the updraft for 10 min or less, there is insufficient time for precipitation to form in a supersaturated parcel. They reasoned that hailstone embryos from outside the updraft likely were ingested and grew at the expense of supercooled water until they reached sizes sufficient to descend through the updraft. They noted that this mechanism would not necessarily be required along the fringes of the updraft, where parcel residence times are likely greater. They proposed that the magnitude and direction of the storm relative flow in the LP environments transported hydrometeors relatively far distances and directed them away from the storm's low-level inflow. This effect was considered to be less prominent as storms approached the HP portion of the supercell spectrum. This hypothesis was similar to that proposed by Marwitz (1972b), who suggested that strong winds and dry air aloft act to erode cloud water and to transport hydrometeors downwind in the thunderstorm anvil. It is important to note that the observations of Burgess and Davies-Jones (1979) did not support this hypothesis, as prominent anvils were absent in the LP supercells of 5 December 1975. Weisman and Bluestein (1985) and Bluestein and Woodall (1990) speculated that a supercell's precipitation efficiency might be influenced by its drop size spectra. They speculated that the relative inefficiency of the coalescence process in a strong, narrow, isolated updraft such as an LP supercell might promote a narrow drop size spectra more readily as compared to storms with multicell characteristics.

The results of RS98 and Brooks et al. (1994) are not considered contradictory, but rather complementary. The results of each study relate to the structure of the echo overhang and the eventual deposition of hydrometeors at the surface. Ignoring parcel entrainment, if in general an LP supercell is characterized by relatively low convective available potential energy (CAPE; as indicated by RS98) and updraft of relatively small horizontal scale (e.g., Bluestein and Woodall 1990), then it also likely would have reduced summit divergence. This coupled with relatively high-speed flow impinging on the LP supercell's rear flank would reduce the upstream extent of the rear overhang. Moreover, the orientation of the flow aloft from the storm's right-rear to left-forward flank would tend to reduce the horizontal scale of the right-flank overhang. If RS98's composite hodographs are robust, then the precipitation descending within the overhang would be advected further downstream and to the left of the storm's path. This would result in the displacement of hydrometeors away from the low-level inflow, reducing their potential for reingestion and yielding a separation between the low-level updraft and the precipitation area. Enhanced mid-level storm-relative flow as considered by Brooks et al. (1994) would tend to increase this result.

In the case of the classic supercell, relatively larger CAPE and horizontal updraft scale would yield greater summit divergence. This combined with the lower magnitude and different orientation of the storm-relative flow aloft would tend to increase the horizontal scale of the rear and right-flank overhangs. As the hydrometeors within the overhang descend, the slightly weaker mid-level storm-relative flow and its orientation toward the storm's rear right flank at low levels would increase the likelihood of ingestion into the updraft and decrease the separation between updraft and precipitation area. This effect would be even more pronounced in the HP case. The low-level storm-relative inflow of the HP composite hodograph is in an almost front-to-back orientation similar to that described by Browning and Ludlam (1962) and Lemon and Parker (1996).

b. Vertical distribution of water vapor

Bluestein and Parks (1983) found the low-level environment of LP severe storms to be statistically significantly drier in the mean than that of other supercells. This difference was most evident when considering the mean water vapor mixing ratio in the lowest kilometer, but also was manifested as a significantly higher lifting condensation level (LCL) for LP storms. Given that nearly all 13 LP cases included in their study formed near the dryline, Bluestein and Parks noted that this result might be the difference between the near dryline and the far dryline environments rather than a characteristic difference between LP and supercell storms. The results of RS98 indicate that this may well have been the case as no significant differences in mean relative humidity or source parcel mixing ratio was present in their study. Although not directly assessed in their study, RS98 did remark how low relative humidity beneath the anvil might prolong a supercell's LP phase. In such a case, it would take additional time for the overhang to grow to a depth sufficient for the ingestion of descending hydrometeors into the updraft. They note that this might be especially true near the dryline where the depth of the moist layer can be low. This scenario may not be the most common, however, as Bluestein and Parks (1983) found the subjectively identified moist layer to be 1.4 km deep in the mean for both LP storms and supercells. Moreover, RS98 found the mid-level environment of HP storms the driest, in the mean. Finally, while not described at length, RS98 found the precipitable water of HP supercell environments to be significantly larger than that of LP and classic environments.

From the foregoing analysis of past literature, it is apparent that the physical processes responsible for the variations in precipitation morphology have yet to be determined. Future work involving high resolution numerical models with sophisticated microphysical parameterizations, as well as future observations using dual-polarization radar, should advance the understanding of the supercell spectrum significantly.

4. Motivation for further investigation of supercell precipitation characteristics

a. Evidence for disparate hazards

Several refereed and non-refereed papers (e.g., Doswell and Burgess 1993; Doswell and Przybylinski 1990; Moller et al. 1994; RS98) have described characteristics of LP, classic, and HP supercells. Each of the aforementioned publications provided anecdotal evidence that storm severity relates to the quantity and spatial distribution of its precipitation. These phenomena, such as tornadoes, large hail, strong winds, flash flooding, and lightning can cause substantial financial and human losses.

LP supercells most often have been observed to be nontornadic (Doswell and Burgess 1993; RS98), although tornadic LP supercells have been documented (e.g., Burgess and Davies-Jones 1979). Those tornadoes that have been observed were often weak, with no violent tornadoes (F4 and F5 damage ratings) observed according to Moller et al. (1994) and the subsequent literature. Despite having little to no visible rainfall, large hail often has been observed descending from the LP supercell's anvil (Moller et al. 1994; RS98). However, this hail may be smaller in diameter than that common with classic supercells (Doswell and Przybylinski 1990). The absence of significant rain precludes the production of damaging, hydrometeor-driven outflow winds and flash flooding (Moller et al. 1994).

Classic supercells have been observed to produce all types of severe weather including tornadoes, hail in excess of 1.91 cm in diameter, or winds in excess of 26 m s^{-1}. Although they are rare, violent tornadoes are most often associated with classic supercells (Doswell and Burgess 1993; Moller et al. 1994). In addition, classic supercells are the dominant contributor to major tornadic outbreaks (Doswell and Burgess 1993). The classic supercell has also been described as the "most prolific producer of large hail" (RS98), as compared to LP and HP supercells. This supercell archetype is rarely associated with flash flooding (Doswell and Burgess 1993) despite its readily visible precipitation shield downshear of the updraft (RS98).

As described by Moller et al. (1994), some of the greatest financial losses due to severe weather have been attributed to HP supercells (e.g., Dallas/Ft. Worth, TX on 8 May 1981; Denver, CO on 11 July 1990; and Dallas/Fort Worth “Mayfest” supercell on 5 May 1995). HP supercells have been observed to produce severe weather of all types and can occur over large areas, often imbedded in or near heavy precipitation (Doswell and Burgess 1993). Moller et al. (1993) suggested that strong and violent tornadoes are less common with HP supercells as compared to classic supercells. The authors also noted that HP supercells are often observed in tornado outbreaks. HP supercells, with substantial precipitation within their mesocyclones and also often beneath their forward anvil, are capable of producing flash floods.

Of course, the foregoing associations of weather phenomena are made in reference to subjectively, often visually, classified storms. This subjectivity is perhaps one reason why there is a dearth of information in the *formal* literature regarding these associations.

b. Potential influences of precipitation character on hazards

1) Tornadogenesis and tornado maintenance

Through analysis of the vorticity equation in the context of the severe storm environment, Davies-Jones (1982) concluded that "large" tornadoes were the result of the reorientation of ambient horizontal vorticity. The author suggested that internal processes [as used by Doswell and Przybylinski (1990) in reference to processes that arise solely from the storm's presence], such as a downdraft, transport vertical vorticity downward to develop low-level rotation. Once reaching the surface, it was hypothesized that at least a portion of the vorticity-rich outflow would enter the updraft and be stretched vertically. This outward propagation of the downdraft outflow would also act to enhance convergence beneath the updraft, further enhancing low-level vertical vorticity.

Klemp and Rotunno (1983) and Rotunno and Klemp (1985) suggested that negatively buoyant, rain-cooled air in the supercell's forward flank might also contribute to the origin of low-level rotation. In their simulations, divergent air in the storm's forward flank obtained baroclinic horizontal vorticity as parcels were drawn toward the updraft, traveling along and parallel to the gust front, perpendicular to the low-level temperature gradient. As these parcels were ingested into the updraft, their vorticity was reoriented into the vertical and enhanced through stretching. Davies-Jones and Brooks (1993) concluded that the tilting of horizontal vorticity into the vertical by an updraft cannot produce rotation very near the ground and thus cannot be instrumental in the genesis of tornadoes. In their simulations, significant positive vertical vorticity at the 100 m level formed through the simultaneous tilting of quasi-streamwise vorticity and baroclinic vorticity generation by an evaporative cooled downdraft. The production of a tornado-like vortex was considered possible if the downdraft air became entrained into the primary updraft and underwent considerable vertical stretching. Based largely on the above conclusions, Davies-Jones (2000) suggested, "the hook echo (i.e., a precipitation curtain located in the rear flank of a supercell) may be more than just an indicator of a tornado; it may be the instigator of one."

The baroclinic mechanism of vorticity generation proposed by Davies-Jones and Brooks (1993) has not been supported by fine-scale surface measurements in proximity to tornadoes. The results of Markowski (2000) indicate that surface baroclinity is not a necessary condition for tornadogenesis. Markowski hypothesized that tornadogenesis "failure" occurs when RFD air at the surface is characterized by substantial convective inhibition (CIN) and insufficient CAPE to permit ample vortex stretching when parcels are entrained into the primary updraft. Mobile mesonet observations indicated that tornado-genesis "success" is characterized by minimal CIN and substantial CAPE for significant vortex stretching. However, it is important to note that Markowski's conclusions were based on adjusting warm inflow soundings with RFD surface measurements. It is uncertain if these inflow soundings are representative of the near-storm environment. Through axisymmetric simulations, Davies-Jones (2000) proposed that an annular curtain of rain descending to the surface near the updraft/downdraft interface could transport high angular-momentum air to the surface, near the base of the updraft where substantial vortex stretching could occur. The production of a tornado-like vortex could be entirely the result of tilting and stretching of barotropic vorticity, consistent with the observations of Markowski (2000).

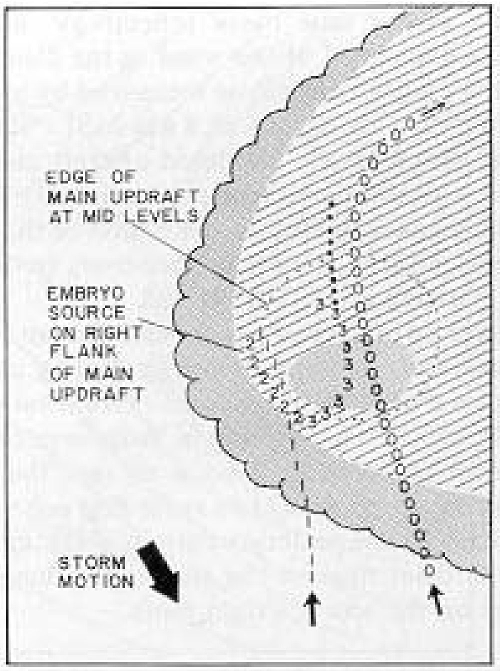


Figure 12. Plan view schematic model of hailstone growth trajectories within a supercell. Trajectories 1, 2, and 3 represent the three stages in the growth of large hailstones. Cloud particles with initial growth in the updraft are rapidly carried up and out of the anvil along trajectory 0. (From Browning 1977; adapted from Browning and Foote 1976)

Common to each of the aforementioned theories of tornadogenesis is the dependence on downdrafts driven by the drag and evaporation of precipitation. Thus, the presence, physical state, size, and spatial distribution of hydrometeors in the rear and forward flanks of a thunderstorm could play an instrumental role in the development of tornadoes. The recognition of supercells with varied, radar-based precipitation characteristics similar to those described for LP, classic, and HP supercells, coupled with knowledge of the near-storm thermodynamic structure could have important implications in the understanding and anticipation of tornadoes.

2) Hail production

Although many hailstone growth models have been proposed, the Browning-Ludlam model is perhaps the most widely accepted and will be the focus of the following review. As described by Browning (1977), Browning and Foote (1976) inferred a three-stage process of hail growth (illustrated in Figs. 12 and 13). During the first stage, small particles grow into hailstone embryos (as graupel or frozen raindrops) in an area of weak updraft on the right edge of the radar vault or primary updraft. As some of these particles grow, their terminal fall speeds may exceed the updraft velocity, yielding ground-relative particle descent. These particles continue to grow as they descend through weak updrafts, transversing the forward edge of the main updraft. Near the base of the overhang (or embryo curtain), these hailstone embryos may have terminal fall speeds very near the vertical velocity of the main updraft in this region. Thus, these particles can grow through the accretion of supercooled water droplets during their relatively long residence time in this growth region. These hailstones tend to remain on the lower boundary of the overhang and eventually ascend along the lower vault edge as

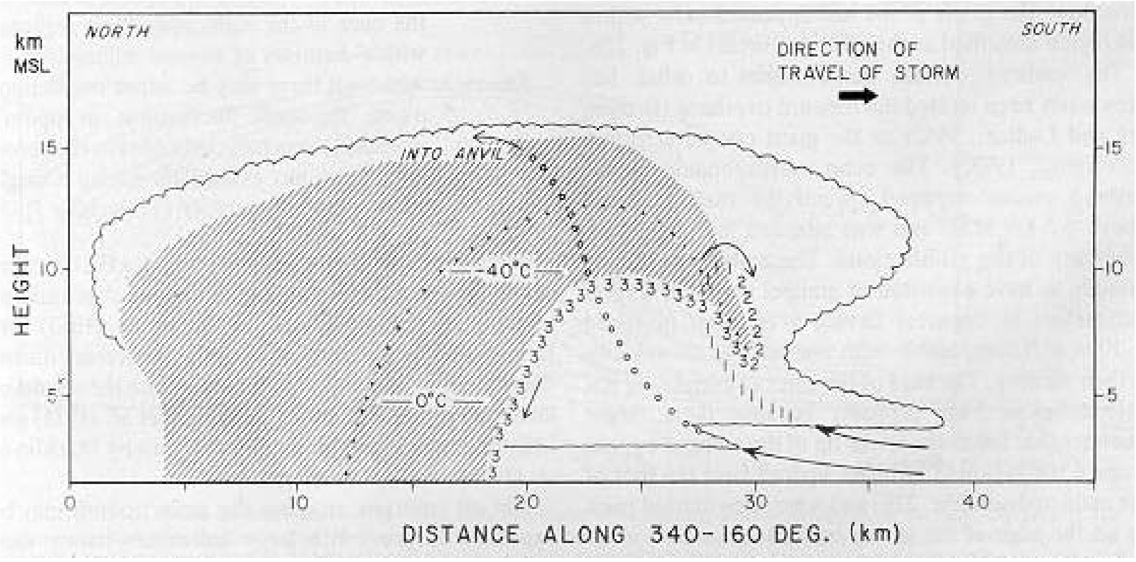


Figure 13. Schematic model of hailstone growth trajectories within a supercell in a vertical section (see Fig. 12). Trajectories 1, 2, and 3 represent the three stages in the growth of large hailstones. Cloud particles with initial growth in the updraft are rapidly carried up and out of the anvil along trajectory 0. (From Browning 1977; adapted from Browning and Foote 1976)

they continue to penetrate the updraft. At the summit of the vault, these hailstones may reach a balance level where substantial accretion of supercooled cloud droplets can take place. Their growth continues as they descend along the vault edge or hail cascade forming what Browning has referred to as the wall.

A key to the growth of large hail in the above model is particle residence time in the growth regions. The observations of Davies-Jones et al. (1976) indicate that the base of the echo overhang for an LP supercell was higher than those described by Browning and Foote (1976). If the observations of Davies-Jones et al. (1976) are representative of other LP supercells, then hailstone size may be limited in this class of storms by shorter particle residence times. This hypothesis is consistent with the anecdotal observation of smaller diameter hailstones observed with LP supercells as compared to classic and HP supercells.

3) Downdrafts and Severe Winds

It long has been recognized that the existence and magnitude of downdrafts are dependent in part on the precipitation characteristics of a given storm (e.g., Kamburova and Ludlam 1966). Kamburova and Ludlam proposed that strong downdrafts were most likely when environmental lapse rates approached dry adiabatic and rainfall dominated by small radii drops fell at a relatively high rate. The one-dimensional simulations of Srivastava (1985) supported these conclusions and found that when the lapse rate is near dry adiabatic, microbursts could occur at almost any rainwater concentration. As lapse rates become more stable, higher rainwater concentrations are required to produce intense downdrafts.Other factors contributing to the simulated downdraft intensity included entrainment, the environmental relative humidity profile, and the physical state of the hydrometeors. The entrainment of environmental air could reduce the simulated downdraft velocity substantially if the downdraft radius was less than 1 km. Greater environmental relative humidities were found to support more intense downdrafts due to the virtual temperature effect. Srivastava (1985) suggested that the evaporation of light precipitation prior to downdraft formation could condition the atmosphere for more intense downdrafts by increasing the environmental virtual temperature. With the inclusion of ice processes into one-dimensional simulations, Srivastava (1987) found that the contribution of melting to negative buoyancy supported more intense downdrafts for relatively stable environmental lapse rates. This effect became more pronounced with increasing ice content, similar to the rainwater cases. In addition, Srivastava suggested that the presence of larger drop sizes within the precipitation distribution might play an important role in downdraft formation by spreading the evaporative cooling over a greater depth.

The results summarized above indicate that the phase, concentration, and size of hydrometeors play an important role in the development and maintenance of intense downdrafts, particularly when the lapse rate is less than dry adiabatic. In addition to the aforementioned possible influence on tornadogenesis, intense outflows can result as a consequence of a downdraft interacting with the ground. Moreover, the ground-relative speed of this outflow can be enhanced by storm motion, which may be large in the highly-sheared supercell environment [e.g., the traveling, outflow, radial, and twisting microburst (Fujita 1985)]. Thus, continued investigation of supercell precipitation characteristics might provide insight into the development of these phenomena that ultimately could influence the warning decision process.

4) Flash flooding

The probability that a given local storm will yield a flash flood situation is dependent not only on meteorological factors, but also on the hydrologic situation [e.g., antecedent rainfall, drainage basin characteristics, etc. (Doswell et al. 1996)]. Doswell et al. described a long duration of high precipitation rates as the result of slow storm movement and/or a large area of high rainfall rates along the storm motion vector. The presence of downdrafts and their associated cold pools are also relevant to flash flooding, as they can produce and/or sustain boundaries that can focus the initiation of new convection. Thus, the updraft-relative location of a storm's precipitation cascade can have a significant impact on surface boundary location, storm propagation, and the associated flash flood potential.

While supercells have relatively low precipitation efficiencies, some are still capable of high rainfall rates due to the large flux of water vapor into a spatially large and/or high vertical velocity updraft. Among the aforementioned supercell archetypes, the HP supercell is considered to have the most significant flash flood potential (Moller et al. 1994; Doswell et al. 1996). Some examples of flash flood producing HP supercells include those in northeast Missouri on 30 June 1993 (Moore et al. 1993) and that of 16 May 1989 near Amarillo, Texas (Moller et al. 1994).

5) Lightning

Although numerous theories exist on the electrification of thunderstorms, as MacGorman and Rust (1998; pp. 56) describe, all theories involve the charging of hydrometeors and their movement to create regions of net charge. With respect to the charging of hydrometeors, laboratory and numerical modeling studies indicate that the graupel-ice mechanism is the most likely means for sufficient charge to support lightning (MacGorman and Rust 1998; pp. 65). MacGorman et al. (1989) suggested that the number of particle interactions might increase as the mesocyclone develops a divided structure, comprised of both updraft and downdraft. As indicated earlier, the transition of the mesocyclone to this divided structure is likely to depend on the storm's precipitation characteristics.

The cloud-to-ground (CG) lightning polarity characteristics of the 13 March 1990 tornado outbreak in the Central Plains was investigated by Branick and Doswell (1992). The authors found those storms in the LP end of the supercell spectrum to be dominated by high rates of positive CG flashes, while storms with HP characteristics were dominated by negative CG flashes. Similar observations were found by Curran and Rust (1992) for the LP thunderstorms in Oklahoma on 26 April 1984 (the same LP storms described by Bluestein and Woodall (1990) and summarized in section 1.2).

MacGorman and Burgess (1994) also observed LP supercells dominated by positive flashes, but this characteristic was not unique to the LP archetype. Some classic supercells and non-supercellular storms were found to exhibit dominantly positive flash polarity. No study to date has found a dominant positive flash polarity in HP supercell storms. MacGorman and Nielsen (1991) suggested that positive ground flashes in supercells might be the result of a tilted dipolar charge distribution, where the precipitation at middle to low levels is displaced horizontally from the updraft core. Branick and Doswell (1992) extended this hypothesis as a possible explanation for the observations of dominantly positive flashes associated with LP supercells. They suggested that high positive CG flash rates might be favored when the positively charged ice crystals in the anvil are displaced from the negatively charged precipitation core, exposing the upper positive charge to the ground. In addition, Branick and Doswell (1992) suggested that the lack of low- to middle-level precipitation in LP storms might interfere with the formation of a large region of negative charge.

5. Summary

This paper has provided a review of the historical evolution of the nomenclature describing the spectrum of precipitation morphologies associated with supercells. From an analysis of the literature, it is apparent that significant subjectivity exists in the classification of supercells, with some authors using visual indicators and others using radar descriptions. And within these two approaches, there is significant disparity in opinions. One observer's LP storm is often another observer's classic supercell.

When considering the forcing mechanisms for various supercell precipitation structures, there is perhaps less clarity than in the classification nomenclature. Various explanations have been posited, ranging from mid-level to upper-level storm-relative flow, mesocyclone strength, hydrometeor distributions, and the quantity of lower tropospheric water vapor. There exists considerable evidence, summarized herein, that supercell morphology is related to variations in the accompanying severe weather phenomena.

In light of the current understanding of the supercell spectrum, and the obvious need for better definitions and more objectivity, the second part of this paper will propose a radar-based classification scheme. If such a scheme could be advanced to the point of operational utility, it then would be possible to conduct more systematic evaluations of supercell hazards and analyses of the environmental influences on supercell morphology.

ACKNOWLEDGMENTS

The NSF grants ATM-0733531 (Rasmussen Systems) and ATM-0733539 (University of Oklahoma) are acknowledged. This work was also conducted with the support of an American Meteorological Society Industry/Government Graduate Fellowship.

REFERENCES

Bluestein, H. B., 1984: Further examples of low precipitation severe thunderstorms. *Mon. Wea. Rev.*, **112**, 1885-1888.

____, and C. R. Parks, 1983: A synoptic and photographic climatology of low precipitation thunderstorms in the Southern Plains. *Mon. Wea. Rev.*, **111**, 2034-2046.

____, and G. R. Woodall, 1990: Doppler-radar analysis of a low-precipitation severe storm. *Mon. Wea. Rev.*, **118**, 1640-1664.

Branick, M. L., and C. A. Doswell III, 1992: An observation of the relationship between supercell structure and lightning ground strike polarity, *Wea. Forecasting*, **7**, 143-149.

Brooks, H. E., C. A. Doswell III, and R. B Wilhelmson, 1994: The role of midtropospheric winds in the evolution and maintenance of low-level mesocyclones. *Mon. Wea. Rev.*, **122**, 126-136.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. *J. Atmos. Sci.*, **21**, 634-639.

____, 1965: The evolution of tornadic storms. *J. Atmos. Sci.*, **22**, 664-668.

____, 1977: The structure and mechanisms of hailstorms. *Hail: A Review of Hail Science and Suppression*, G. Foote and C. Knight, Eds., *Meteor. Monogr.*, No. 38, Amer. Meteor. Soc., 1-43.

____, and F. H. Ludlam, 1962: Airflow in convective storms. *Quart. J. Roy. Meteor. Soc.*, **88**, 117-135.

____, and R. J. Donaldson Jr., 1963: Airflow and structure of a tornadic storm. *J. Atmos. Sci.*, **20**, 533-545.

____, and G. B. Foote, 1976: Airflow and hail growth in supercell storms and some implications for hail suppression. *Quart. J. Roy. Meteor. Soc.*, **102**, 499-533.

Burgess, D. W., and R. P. Davies-Jones, 1979: Unusual tornadic storms in eastern Oklahoma on 5 December 1975. *Mon. Wea. Rev.*, **107**, 451-457.

Byers, H. R., and R. R. Braham, Jr., 1949: *The thunderstorm*. U. S. Govt. Printing Off., Washington, D. C., 287 pp.

Chisholm, A. J., 1970: Alberta hailstorms: A radar study and model. Ph.D. dissertation, McGill University, 287 pp. [Available from McGill Univeristy, Montreal, Quebec, Canada.].

Curran, E. B., and W. D. Rust, 1992: Positive ground flashes produced by low-precipitation thunderstorms in Oklahoma on 26 April 1984, *Mon. Wea. Rev.*, **120**, 544-553.

Davies-Jones, R. P., 1982: A new look at the vorticity equation with application to tornadogenesis. Preprints, *12th Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 249-252.

____, 2000: Can the hook echo instigate tornadogenesis barotropically? Preprints, *20th Conf. on Severe Local Storms*, Orlando, FL, Amer. Meteor. Soc., 269-272.

____, and H. E. Brooks, 1993: Mesocyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards*, Geophys. Monogr. No. 76, Amer. Geophys. Union, 105-114.

____, D. W. Burgess, and L. R. Lemon, 1976: An atypical tornado-producing cumulonimbus. *Weather*, **31**, 336-347.

Doswell, C. A. III, and D. W. Burgess, 1993: Tornadoes and tornadic storms: A review of conceptual models. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards*, Geophys. Monogr. No. 76, Amer. Geophys. Union, 161-172.

____, A. R. Moller, and R. Przybylinski, 1990: A unified set of conceptual models for variations on the supercell theme. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Amer. Meteor. Soc., 40-45.

____, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560-581.

Fankhauser, J. C., 1988: Estimates of thunderstorm precipitation efficiency from field measurements in CCOPE. *Mon. Wea. Rev.*, **116**, 663-684.

Foote, G. B., and J. C. Fankhauser, 1973: Airflow and moisture budget beneath a northeast Colorado hailstorm. *J. Appl. Meteor.*, **12**, 1330-1353.

Fujita, T. T., 1978: *Manual of downburst identification for Project Nimrod*. Satellite and Mesometeorology Research Project, Research Paper 156, Univ. of Chicago, 42 pp.

____, 1985: The *downburst, microburst and macroburst*. Satellite and Mesometeorology Research Project, Research Paper 210, Univ. of Chicago, 122 pp.

Johns, R. H., and W. D. Hirt, 1987: Derechoes: Widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32-49.

Kamburova, P. L., and F. H. Ludlam, 1966: Rainfall evaporation in thunderstorm downdraughts. *Quart. J. Roy. Meteor. Soc.*, **92**, 510-518.

Klemp, J. B., and R. Rotunno, 1983: A study of the tornadic region within a supercell thunderstorm. *J. Atmos. Sci.*, **40**, 359-377.

Lemon, L. R., 1976: The flanking line, a severe thunderstorm intensification source. *J. Atmos. Sci.*, **33**, 686-694.

____, and C. A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.*, **107**, 1184-1197.

____, and D. W. Burgess, 1993: Supercell associated deep convergence zone revealed by a WSR-88D. Preprints, *26th International Conf. on Radar Meteorology*, Norman, OK, Amer. Meteor. Soc., 206-208.

____, and S. Parker, 1996: The Lahoma storm deep convergence zone: Its characteristics and role in storm dynamics and severity. Preprints, *18th Conf. on Severe Local Storms*, San Francisco, CA, Amer. Meteor. Soc., 70-75.

MacGorman, D. R., and W. D. Rust, 1998: *The Electrical Nature of Storms*. Oxford University Press, New York, New York, 422 pp.

____, and K. E. Nielsen, 1991: Cloud-to-ground lightning in a tornadic storm on 8 May 1986, *Mon. Wea. Rev.*, **119**, 1557-1574.

____, and D. W. Burgess, 1994: Positive cloud-to-ground lightning in tornadic storms and hailstorms. *Mon. Wea. Rev.*, **122**, 1671-1697.

____, D. W. Burgess, V. Mazur, W. D. Rust, W. L. Taylor, and B. C. Johnson, 1989: Lightning rates relative to tornadic storm evolution on 22 May 1981. *J. Atmos. Sci.*, **46**, 221-250.

Markowski, P. M., 2000: Surface thermodynamic characteristics of hook echoes and rear-flank downdrafts, with implications for tornado genesis and maintenance. Ph.D. dissertation, University of Oklahoma, 217 pp. [Available from the University of Oklahoma, Norman, OK, 73072.]

Marwitz, J. D., 1972a: The structure and motion of severe hailstorms. Part III: Severely sheared storms. *J. Appl. Meteor.*, **11**, 189-201.

____, 1972b: Precipitation efficiency of thunderstorms on the High Plains. *J. Rech. Atmos.*, **6**, 367-370.

Moller, A. R., C. A. Doswell III, and R. W. Przybylinski, 1990: High-precipitation supercells: A conceptual model and documentation. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Amer. Meteor. Soc., 52-57.

____, ____, M. P. Foster, and G. R. Woodall, 1994: The operational recognition of supercell thunderstorm environments and storm structures. *Wea. Forecasting*, **9**, 327-347.

Moore, J. T., S. M. Nolan, F. H. Glass, D. L. Ferry, and S. M. Rochette, 1993: Flash flood-producing high precipitation supercells in Missouri. Preprints, *17th Conf. on Severe Local Storms*, St. Louis. MO, Amer. Meteor. Soc., (J4) 7-12.

Nelson, S. P., 1987: The hybrid multicellular-supercellular storm—an efficient hail producer. Part II: General characteristics and implications for hail growth. *J. Atmos. Sci.*, **44**, 2060-2073.

____, and N. C. Knight, 1987: The hybrid multicellular-supercellular storm—an efficient hail producer. Part I: An archetypal example. *J. Atmos. Sci.*, **44**, 2042-2059.

Przybylinski, R. W., T. J. Shea, D. L. Ferry, E. H. Goetsch, R. R. Czys, and N. E. Wescott, 1993: Doppler radar observations of high-precipitation supercells over the mid Mississippi Valley region. Preprints, *17th Conf. on Severe Local Storms*, St. Louis, MO, Amer. Meteor. Soc., 158-163.

Rasmussen, E. N., and J. M. Straka, 1998: Variations in supercell morphology. Part I: Observations of the role of upper-level storm-relative flow. *Mon. Wea. Rev.*, **126**, 2406-2421.

Rotunno, R., and J. B. Klemp, 1982: The influence of the shear-induced pressure gradient on thunderstorm motion. *Mon. Wea. Rev.*, **110**, 136-151.

____, and ____, 1985: On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.*, **42**, 271-292.

Schlesinger, R. E., 1980: A three-dimensional numerical model of an isolated deep thunderstorm. Part II: Dynamics of updraft splitting and mesovortex couplet evolution. *J. Atmos. Sci.*, **37**, 395-420.

Srivastava, R. C., 1985: A simple model of evaporatively driven downdraft: Application to microburst downdraft. *J. Atmos. Sci.*, **42**, 1004-1023.

____, 1987: A model of intense downdrafts driven by the melting and evaporation of precipitation. *J. Atmos. Sci.*, **44**, 1752-1773.

Thorpe, A. J., and M. J. Miller, 1978: Numerical simulations showing the role of the downdraught in cumulonimbus motion and splitting. *Quart. J. Roy. Meteor. Soc.*, **104**, 873-893.

Weisman, M. L., and J. B. Klemp, 1984: The structure and classification of numerically simulated convective storms in directionally varying wind shears. *Mon. Wea. Rev.*, **112**, 2479-2498.

____, and H. B. Bluestein, 1985: Dynamics of numerically simulated LP storms. Preprints,*15th Conf. on Severe Local Storms*, Indianapolis, IN, Amer. Meteor. Soc., 167-171.

Wilhelmson, R. B., and J. B. Klemp, 1978: A three dimensional numerical simulation of splitting that leads to long-lived storms. *J. Atmos. Sci.*, **35**, 1037-106.

REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Donald W. Burgess):

Initial Review:

Recommendation: Accept with minor revisions

General Comments:

I find only a small amount of fault with this manuscript…listed below under Major Comments. … To its favor, this manuscript does add some amount of interpretation to the previously published results. Does EJSSM want review articles that restate/interpret previous research results? If so, then this paper is acceptable after consideration of Major Comments. However, I will offer my opinion (based on EJSSM guidelines about manuscript length and content) that the current manuscript could be considerably shortened if it did not try to review all research concerning the whole supercell spectrum, but instead focused on specific issues associated with the companion Part II (A semi-objective method for radar classification of supercell type). As such, the current manuscript (appropriately shortened) could be used as the introduction to a single manuscript (combination of #45 and #44) that could still be fit within the EJSSM 32-page text limit.

I see two major issues: 1) omissions from the supercell review, and 2) poor quality of the figures. Concerning omissions, I take my guide from the EJSSM Reviewer Guidelines that say: "the use of principle source references (e.g., the original source of information) is encouraged whenever possible." I list the following as supercell review omissions (in order of importance):

1. AMS *Meteorological Monograph* Vol. 5, #27 (1963): Severe Local Storms. This is an important original source of information with airflow discussion by Ludlam that pre-dates Browning and Ludlam, and radar discussion of precipitation by Atlas that pre-dates all current manuscript radar/precipitation references.
2. AMS *Meteorological Monograph* Vol. 28, #50 (2001): Severe Local Storms. This is an important update to (1) (just above). Considerable new information on supercell types, supercell airflow, specific supercell phenomena (tornado, hail, wind, and flash flooding), and supercell microphysics are provided.
3. AMS *Meteorological Monograph* Vol. 14, #36 (1973): Alberta Hailstorms. No mention is made in the current manuscript of the pioneering work of Hitschfeld, Chisholm, Renick, English, and their co-authors. Their work on supercell airflow, radar structure, and hail analysis is on par with and contemporary to Browning and Ludlam. Their foundation greatly influenced Marwitz and other authors who are referenced in the current manuscript. Most currently-used diagrams of supercell airflow and radar structure have their origin in the original diagrams of Chisholm and Renick.
4. AMS *Meteorological Monograph* Vol. 16, #38 (1977): Hail Science and Hail Suppression. No mention is made of the National Hail Research Experiment and its important supercell science. Much original knowledge of supercells, their airflow, their microphysics, and their hail production came from this body of work. Browning's last and most comprehensive discussion of supercells is a part of this work as is the High-Plains-class evolving multicell/supercell storm type (Foote and Frank and others).

We greatly appreciate the reviewer's comments regarding these references. We recognize that there is a wealth of historical research that has been conducted on the supercell that warrants acknowledgment. We have chosen to focus on the work of Browning and his co-authors to describe some of the key features of a supercell to achieve our goal of surveying the phenomena, rather than providing a complete survey of the research history. We have added the following statement to the introduction to make this clear to the reader: "The work of Browning and his coauthors is used throughout this section to describe some of the *key features of a “classic” supercell. The reader is referred to the AMS Meteorological Monograph series for a more comprehensive discussion.”*

The original scanned figures have been re-imported in attempt to improve figure quality. These figures are of higher resolution than what is available via electronic journals on the AMS website. Since this is a review article, we feel that optimal clarity is less critical in this case than in their first publication. The reader is referred to the physical journals for a more detailed inspection of the content.

[Editor’s Note: For any version of original figures that still may be poorly legible at single-column width, but which can be improved simply through enlargement, we have two options:

- *The authors run the figure across two columns, and/or*
- *In the layout stage we work with authorship to provide a hyperlink from within the document to a larger version stored with the manuscript on the EJSSM site.]*

[Minor comments omitted...]

Second review:

Concerning figures, I think they are somewhat better. In the Version 2 PDF, I can now read most of the letters/numbers and make out most of the detail...at least enough to get the content...except for one figure...Fig 6...the figure has 8 panels/each panel shows only as a "postage stamp"; content cannot be discerned. I recommend that Fig 6 be made into a 2-column figure.

Concerning re-review, I do not think a re-review is necessary. For almost all of my small comments, the authors made absolutely the minimum change necessary to improve, but the changes are just that...minimally acceptable. The one point that is left is my #6 (wordy paragraph with apparent contradiction that I found confusing). The authors' response is "we disagree." I still think the paper would be better with the paragraph rewritten, but it is a small point with respect to the theme of the paper. I don't think it's worth a re-review just for that one small point, so, on that point, I guess we just agree to disagree.

REVIEWER B (Richard L. Thompson):

Initial Review:

Reviewer recommendation: Accept with minor revisions

General Comments: This paper is a literature review of previous work related to precipitation distribution in supercell thunderstorms, and serves as the ground work for a second paper that proposes a new methodology for categorizing supercells. In its current form, this paper is a reasonable thorough summary of the previous work. The only element lacking is a clearer focus on the purpose of this paper.

[Minor comments omitted...]

REVIEWER C (Alan R. Moller):

Initial Review:

Recommendation: Accept with minor revisions

General Comments: The paper is very well written from what I see, upon the first couple of reads.

There are a few things that need to be rectified, but not much. I can only assume that the past publishing excellence from the co-authors is the reason. This is the "cleanest" paper, upon an initial, close look, that I have seen to date.

Suggested changes [Editor’s note: The only arguably “major” comment among a list of minor ones is highlighted below.]:

A possible addition to the paper, in passing, would be commentary of the May 5, 1995, "Mayfest" HP supercell in the DFW, Texas area. The storm resulted in 1.2 billion dollars of damage, from mainly hail and intense rainfall. The hail pounded Tarrant County and extreme western Dallas County, then ended abruptly in western Dallas County, where the storm next unleashed an intense rainfall, that resulted in 16 drownings in northeast Dallas County -- mainly people trapped in their cars hiding under or near underpasses, where they were trying to dodge the hail. Two other fatalities occurred from lightning. The dollar damage was later exceeded in the same year, in Sydney, Australia.

Reference added to Section 4 as: "(e.g., Dallas/Ft. Worth, TX on 8 May 1981; Denver, CO on 11 July 1990; and Dallas/Fort Worth "Mayfest" supercell on May 5, 1995)."

NOTE:

Corrections: References corrections 11 March 2009. EE.