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A UNIFIED SET OF CONCEPTUAL MODELS FOR VARIATIONS ON THE SUPERCELL THEME

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1. INTRODUCTION

The notion of supercell storms, introduced mainly by Browning (1964), has survived with only minor modifications and clarifications since it was proposed. That such storms are relatively rare in any given location is fortunate since they account for a disproportionate share of thunderstorm-associated damage and casualties. As our experience base with supercell thunderstorms has broadened, it is clear that while such storms are more common in some places than in others, the same basic storm processes are shared by all supercell storms. As noted by Weisman and Klemp (1984), the most scientifically supportable definition of a supercell is <u>a convective storm which shows a persistent correlation between vertical vorticity and vertical motion</u>. That is, it is a storm which has a persistent, rotating updraft. Such a storm scale vertical vorticity center historically has been called a mesocyclone and, in general, supercells exhibit mesocyclones that have lifetimes at least on the order of tens of minutes and are present through a substantial fraction of the convective storm's depth.

While it is not our intent here to present a complete storm spectrum (see Moller and Doswell, 1988), it is important to understand that the boundary between a supercell and a non-supercell can be quite "fuzzy". Real storms are difficult to classify because the reality of convective storms is better represented as a continuous spectrum rather than a collection of boxes with hard boundaries. Further, at present, it is not possible in operations to evaluate either vertical vorticity or vertical motion on the scale of the storm. Nevertheless, it appears useful to attempt to distinguish supercells from other storm types for the simple reason that <u>such classifications make it possible to anticipate what a given storm is likely to do in the future</u>; i.e., for warning and forecasting purposes.

With respect to this primary application for the supercell concept, it has become increasingly apparent to us that within the general category of supercells, there are important similarities and differences among particular examples. If one concentrates solely on the differences, it is possible to conclude each storm is so unique that all one has is a jumble of individual events. On the other hand, if one focuses solely on the similarities, the conclusion might be that each storm is virtually a carbon copy of every other storm in the class. It is our position that both of these extreme views are inappropriate, especially in applications.

This paper is an attempt to present some of the similarities and some of the differences that we perceive within the supercell class of convective storms. The basic concept advanced by Browning remains essentially unchanged, but while supercell processes remain the same, the visual and radar manifestations can change substantially, especially as a function of geographical variations in the typical storm environment. Some storms occur in relatively dry environments, some in quite moist environments, and some in transitional environments.

2. OVERVIEW OF THE SUPERCELL SPECTRUM

2.1 Classical supercells

It appears that previously-presented supercell models, from Browning's day to the recent past (the so-called "classical" supercells), have been drawn mostly from the transitional environments of the southern Great Plains. These storms frequently comprise relatively isolated convection, developing well apart from any competing storms. They have classical radar signatures, with the hook (or pendant) echo structure revealed in relatively low reflectivity. Visually, they often exhibit flanking convective lines with visually precipitation-free bases and a reasonably well-defined lowering (a so-called "wall" cloud) from which tornadoes descend. Note that while the updraft base may be rain-free to the eye, hail and

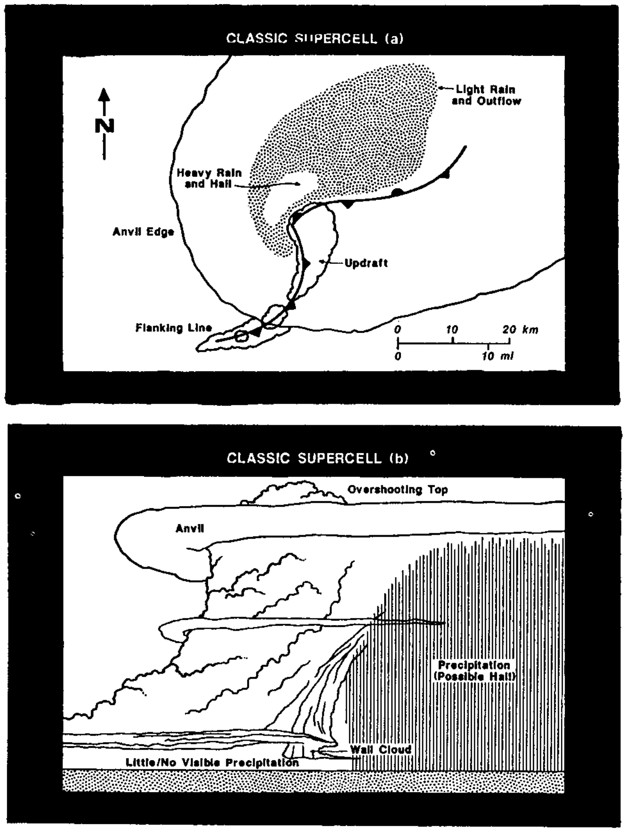

Figure 1. Schematic radar (a) and visual features associated with a classic supercell storm.

large drops may be falling in this area, creating "curtains" of precipitation that may rotate around the mesocyclone as the storm evolves (seen on radar as the hook). The basic features of this type of supercell are summarized in Fig. 1.

2.2. Low-precipitation supercells

In the mid-1970s, storm intercept teams began to observe that some storms did not have most of the classical radar appearances, but could be visually spectacular in revealing rotation (e.g., Burgess and Davies-Jones 1979). First known as "dryline" storms among storm chasers in the plains, they came to be called "low precipitation" or "LP" supercells by Bluestein and Parks (1983). It remains the case that such storms are virtually unique to the dryine environment, within the western part of the Great Plains and the High Plains east of the Rocky Mountains. LP storms can appear benign on radar, often exhibiting low reflectivities despite producing large hail. As shown in Weisman and Bluestein (1986), such storms can be simulated numerically by artificially preventing precipitation in a three-dimensional cloud model; the simulated storms bear a striking resemblance to the observed storms. Clearly, LP storms usually do produce some precipitation, but they tend to be smaller in diameter

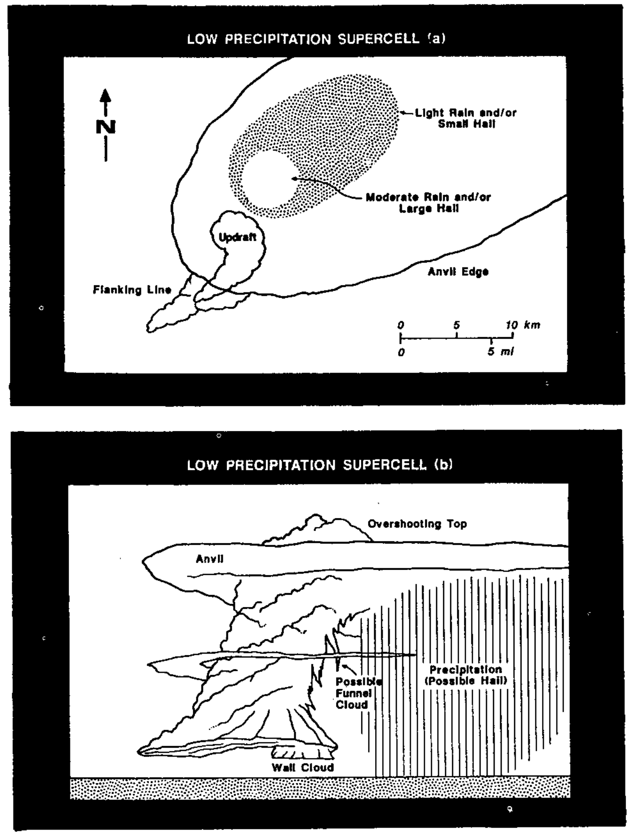

Figure 2. As in Figure 1, except for a low-precipitation supercell.

than classical storms and so radar resolution may play a major role in how they appear on radar. Figure 2 summarizes the features of LP storms.

2.3. Heavy-precipitation supercells

Given low-precipitation forms of the supercell, it is logical to expect there to be heavy-precipitation (HP) forms as well. Moller et al. (1990) present a detailed conceptual model for this type of supercell. It appears that the high-precipitation form of supercell is not uncommon over the Great Plains, but as one goes eastward across the United States, it becomes the dominant form of supercell. It is noteworthy that major tornado outbreaks east of the Mississippi (such as Palm Sunday [11 April 1965], or 3 and 4 April, 1974) seem to produce supercell storms that can show more "classical" characteristics than non-major outbreak storms.

HP storms have precipitation, extremely heavy at times, in areas where the classical form is visually rain-free. Moreover, such storms may not be as clearly isolated from surrounding convection, although they remain distinctive in character. Figure 3 summarizes the radar and visual features of HP storms. The range of radar echo configurations associated with HP supercells is considerably more diverse than with the other supercell forms. Nevertheless, all such forms are associated intimately with the rotational character of the supercell, regardless of their details.

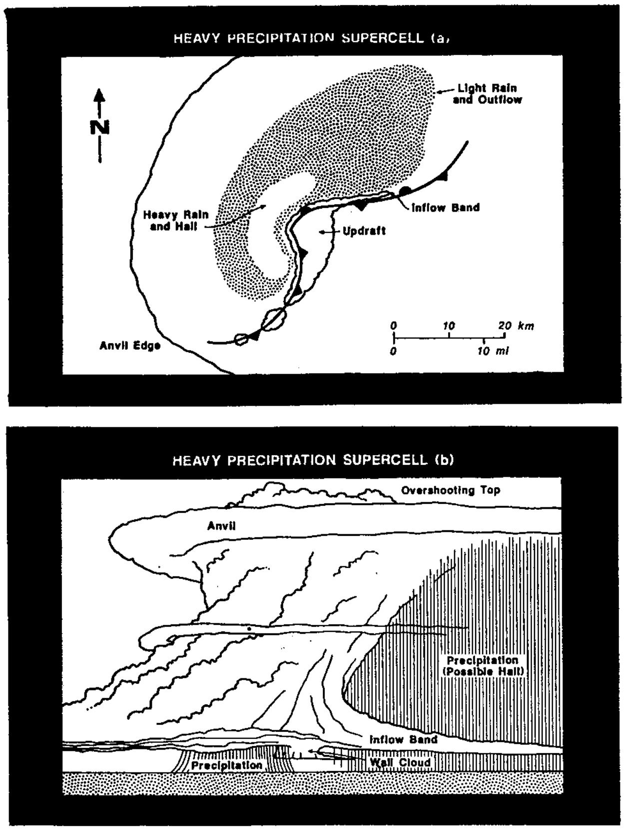

Figure 3. As in Figure 1, except for a heavy-precipitation supercell.

A sample of radar echoes one might associate with HP supercells is given in Fig. 4, but this sampling is by no means exhaustive. Note that HP supercell echo configurations characteristic of circulation often involve high reflectivities, suggesting that tornadoes and associated severe weather occur within (or near) heavy precipitation. Echoes that reveal spiral bands, "S" shapes, hooks, and so on are obvious manifestations of the effect of rotation on precipitation. This makes visual identification by spotters much more difficult and proper radar interpretation much more critical than with classical supercells. Low ceilings and the presence of nearby non-supercell convection further muddies the picture because they make it impossible to see any storm structure above cloud base.

As noted in Moller et al. (1990 op cit.), HP storms often produce torrential rainfalls. This trait means that in addition to severe weather phenomena, HP storms have a significant flash flood potential. Futher, the production of severe weather in HP supercells can occur over long, relatively broad swaths. This suggests that derecho events (see Maddox et al. 1990, and Johns and Hirt, 1987) may include HP supercell storms as components of a mesoscale complex of storms.

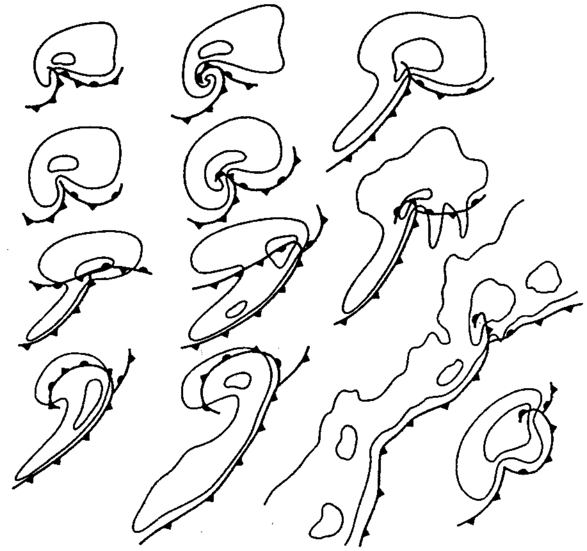

Figure 4. A collection of possible radar structures for low (say, VIP1) and high reflectivities (say, VIP4) seen in HP supercell storms. Also shown are the gust front structures with conventional frontal symbols.

3. SUPERCELL CHARACTERISTICS

There is little outside the definition given above that most will agree upon as being the set of "supercell characteristics". However, there are many ancillary aspects of supercells that people use from time to time as being indicative of a supercell storm. Perhaps the most common such characteristic is the notion of a supercell as a <u>steady-state</u> convective storm. This has been the subject of considerable controversy and we probably will not resolve all of that debate here, but it is our view that supercells generally undergo a time evolution. Classic supercells often evolve more or less in the manner described by Lemon and Doswell (1979). Moller et al. (1990, op. cit.) describe some possible evolutions for HP supercells. There certainly are variations in how rapidly these evolutions take place, but our observations suggest a characteristic time scale for the evolutions in the range of 20-60 minutes. Thus, we believe it is not reasonable to take the position that an evolving storm cannot be a supercell.

Another characteristic commonly used to discriminate supercells is the notion of supercells as a <u>single, continuous</u> cell. Again, we do not think we will put to rest here all the debate that has go on about this issue, but it seems clear to us that this is largely a question of the time and space resolution of the radar being employed. However, regardless of the details of the cellular structure, the important issue for supercell identification is the <u>persistent association of updrafts with rotation</u>. In deciding the question of whether or not a given storm is a supercell, the multicellular traits (if any) are not relevant. Note that we are <u>not</u> saying that the multicellular traits (if present) are not pertinent to other aspects of the storm, such as the timing and spacing of cyclic severe weather production. What we are saying is that a supercell storm need not be clearly unicellular. The sort of long-lived storm that produces tornadoes cyclically is most certainly composed of more than a single cell.

One common feature that is ascribed to supercells is <u>deviate motion</u>. In the Northern hemisphere, this is generally accepted to be to the right of the mean winds. First of all, this prevents the left-moving member of a split pair from being given supercell status, even if it shows a persistent correlation (of the opposite sign from the right-mover, of course) between vertical vorticity and vertical velocity. Second, the rightward movement is the result of propagation, which may or may not be a significant component of the storm motion in situations with strong winds through most of the troposphere. Thus, we believe is is not necessary that all supercells exhibit movement substantially to the right of the mean winds.

Yet another common misconception is the necessity for large values of CAPE for supercells in highly sheared environments. The occurrence of storms that clearly are supercells in environments that are only weakly unstable (as in the northernmost storms in Indiana on 3 and 4 April 1974; or the Raleigh, North Carolina tornadic storm on 28 November 1988) suggests that supercells depend mostly on the environmental wind profile and if it is possible to sustain a convective storm for more than a brief time in a highly-sheared environment, then supercells (with significant tornadoes) are possible. This is most clearly manifest in hurricane-spawned tornadoes (see McCaul, 1987), which arise in weakly unstable, but highly sheared environments. Of course, not all highly sheared environments are equally favorable, but this is outside the scope of this paper.

4. SUPERCELL ENVIRONMENTS

This brings us to the enviroments for supercells. Recent numerical modelling efforts (e.g., Klemp, 1987) and observations (e.g., Burgess and Curran, 1985) focus on environmental wind shear as the primary element in supercell formation, as just noted. Of course, the "classical" weather situations associated with tornadic thunderstorms (e.g., Miller, 1972) are characterized by highly baroclinic, synoptic scale systems in which strong wind shears are obvious. At times, the wind profiles sampled at the sparse operational raob network sites do not reveal significant flow field features that are relevant to supercell development (see Burgess, 1988). Thus, for the foreseeable future, there will continue to be uncertainty about the environments "seen" by convective storms. That environment is still somewhat elusive to define.

In an effort to do so, we wish to draw a distinction between <u>internal</u> and <u>external</u> processes associated with any given storm. By internal, we mean those processes that arise solely as a result of the convective storm's presence. In particular, internal processes are those that one might hope to simulate in a cloud model with horizontally homogeneous initial conditions. Such initial conditions describe an "environment" with which the storm interacts, of course. That interaction may change the "environment" as seen by the storm.

On the other hand, external is taken to mean those processes that would have gone on without the convective storm (e.g., old outflow boundaries from previous storms). In particular, external processes cannot be incorporated in a model with horizontally homogeneous initial conditions. Thus, the initial conditions must describe an environment which involves more than the "internal" processes. If a convective storm develops in such an environment, its interaction with those pre-existing processes is almost certainly going to be more complex than when initial, pre-storm conditions vary only in the vertical.

The point of making this distinction is that some of the things that create a favorable environment for a supercell may well arise because of the interaction of convection with external processes, processes initially independent of the storm itself. Of course, such complex interactions may not always be necessary, given the right sort of vertical structure in a horizontally homogeneous situation.

In effect, horizontal variations in initial conditions as used in a cloud model are <u>mesoscale</u> variations. Thus, the smooth variations as seen by our sounding network and which one identifies with <u>large-scale</u> processes can be neglected in a numerical cloud model. In some cases, the success of the numerical simulations provides clear evidence that this is a valid approach. In other cases, for which the model simulations have failed to reproduce the convection properly (and which tend not to appear in the published literature!), the mesoscale variations necessitating inhomogeneous initial conditions may well have been an important factor in the convective evolution.

Klemp and Rotunno (1983) have suggested that the horizontal vorticity created by the storm-produced boundary ahead of the mesocyclone can be a significant contributor to the development of tornadic vorticity. From our perspective, that would be an internal process, since their hypothesis is based on simulations with a cloud model initialized with horizontally homogeneous initial conditions. If theirs is a valid hypothesis, it could explain why supercell storms usually take considerable time to produce their first tornado and then produce them in rapid succession thereafter. It would take time to create the boundary and its associated horizontal vorticity but, once it was created, it would be there for the duration of the supercell.

Moller et al (1990 op. cit.) have indicated that HP supercells seem to show a preference for moving along old boundaries. This indicates that at least some HP storms may require augmentation of the large-scale wind shear by mesoscale, external processes. That is, at least some of them might never have developed supercell characteristics without the aid of pre-existing mesoscale processes associated with the environment. Although the evidence is not yet complete, it appears that tornadic HP supercells arise in large-scale environments clearly characterized by significant helicity in the lowest few km, whereas non-tornadic HP supercells may arise in helicity-poor large-scale environments.

This suggests that an externally-created (mesoscale) source of horizontal vorticity, in an environment with (horizontally homogeneous) marginal shear, could be sufficient to produce supercell storms when their large-scale environment suggests they would be unlikely to develop supercell character. Another means by which mesoscale environments may enhance the chances for supercells comes through their effects on storm propagation -- for supercells, it is the storm-relative helicity that is physically important (Davies-Jones 1984). When simulating supercell storms, the numerical modellers have emphasized that complex behavior, including storm splitting, can arise in horizontally homogeneous environments. While this is most certainly the case, it is not necessarily true that all forms of supercell behavior can be simulated well with horizontally homogeneous intial data. If our supposition is correct, then a non-homogeneous initialization would be needed for certain supercell cases.

5. OPERATIONAL APPLICATIONS

It is important to emphasize to those wishing to apply these conceptual supercell models in operations that storms are neither completely unique nor completely identical. One ought not to treat our models as templates against which all storms must be compared to fit within the supercell concepts we have developed. Real storms are not stamped out with a cookie cutter, each one identical in all aspects to every other one. If a given storm does not match our conceptual models in every aspect, one ought not to focus on the differences and reject the possibility that the storm is a supercell.

Rather, when using these concepts, it is important first to recognize the capacity of the large-scale environment to produce such storms. If that large-scale environment is not clearly favorable for supercells, the mesoscale details become quite important. There may well be clues in the data to suggest that supercells are still not out of the question. If one makes an assessment that supercells are possible on a given day, even if one cannot be absolutely certain, then one is much less likely to fail to respond to the clues seen on a radar or those called in by spotters.

Second, one should be prepared to recognize what Forbes (1981) called "distinctive" radar echoes by the reflectivity signatures that signal strong, persistent rotation. This can be done even better with Doppler wind fields, of course, but it is necessary to be able to relate Doppler velocity data with the reflectivity if one is to get the most from the Doppler capability. We have tried to present some of the reflectivity structure variations within the supercell class of convective storms, to facilitate this recognition. As already noted, our presentation is not exhaustive, so users of these models should be prepared to see things that do not fit our models exactly.

Third, there are natural environmental variations associated with different geographical areas that will impose variations on what sees even though the storms are basically similar. In moist regions, supercells often are not as obviously isolated from neighboring echoes as they may be in transitional or dry environments; they may be embedded within broad areas or lines of weak reflectivity (e.g., connected at VIP1 or VIP2, but quite distinct at VIP3 and greater). In dry regions, the radar may not show any of the reflectivity structures normally associated with supercells.

6. ACKNOWLEGEMENTS

The authors wish to thank Ms. Joan Kimpel for her usual superb work in drafting the figures. Also, Dr. Robert Davies-Jones contributed valuable and stimulating comments to an earlier version of this work.

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