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Tornadoes and Tornadic Storms: A Review of Conceptual Models

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1. INTRODUCTION

The definition of a tornado in the *Glossary of Meteorology* (Huschke 1959) begins with the following: "A violently rotating column of air, pendant from a cumulonimbus cloud, and nearly always observable as a 'funnel cloud' or tuba." This definition seems relatively straightforward, but in reality distinctions implied by the words we use tend to blur.

Our ability to make distinctions among tornadic storm types and among tornadoes has been affected by three important developments since the last Tornado Symposium:

(1) high-resolution Doppler radar observations,
(2) extensive visual observations by storm intercept teams, and
(3) detailed 3-D numerical cloud models.

The definition and classification of convective vortices and the storms which produce them have become more complex and, in many ways, more troublesome than ever before. On the other hand, the complexity we are encountering is really a positive sign that our understanding is growing.

While it was well-known long before the early 1960s that tornadoes were associated with deep, moist convection, the relationship between these intense vortices and the convective storms with which they are associated was not well understood. Beginning in the 1950s, with the deployment of weather radar, it became clear that at least some tornadic storms exhibited special characteristics (see Stout and Huff 1953, Garrat and Rockney 1962). Careful, systematic examination of such storms began in the early 1960s with the work of Browning (Browning and Donaldson 1963, Browning 1964) using reflectivity radar as the primary observational tool. Research Doppler radars began to make detailed, systematic observations of airflow in tornadic storms in the early 1970s (see e.g., Burgess and Brown 1973), just prior to the last Symposium.

In 1972, building on early pioneering work like that of Ward (1961), an organized program to intercept tornadic storms began at the National Severe Storms Laboratory, with the involvement of the Department of Meteorology at the University of Oklahoma (see Golden and Morgan 1972, Moller et al. 1974). Storm chasing (which has become a part of many scientific programs outside of Oklahoma) has provided an opportunity for meteorologists to observe the visually-recognizable characteristics of both tornadoes and the storms associated with them.

Finally, the development of computer models capable of realistic simulations of tornadic storms (Schlesinger 1975, Klemp and Wilhelmson 1978) and tornadoes (Rotunno 1979) provided a means for careful quantitative evaluation of the physical processes which yield tornadoes. With time, the sophistication of these models has continued to grow and it is now possible to produce "tornado-like vortices" within a numerical model of the entire storm (Wicker 1990).

One thing has become quite clear during this evolution: the storm type Browning called a *supercell* produces by far the most intense convective vortices, and certainly is the type of storm most likely to produce them. Indeed, most of the radar reflectivity structures that were associated empirically with tornadoes have come to be recognized as characteristic of supercells.

However, the quantitative evaluation of physical processes made possible by numerical models has made it clear that the morphology of radar reflectivity alone is inadequate for categorizing convective storm. Instead, a persistent correlation (positive or negative) between vertical velocity and vertical vorticity has come to be recognized as the most useful definition of a supercell (Weisman and Klemp 1984). That is, the airflow pattern most characteristic of a supercell is a deep and persistent cyclone, called a mesocyclone (see Burgess and Lemon 1990).

Many convective vortices are associated with non-supercellular convection, however. The ways in which these non-supercell-related events arise remain quite inadequately understood, with some efforts to deal systematically with one type having only just begun (Brady and Szoke 1988, Wakimoto and Wilson 1989).

As we study the tornadic vortices themselves, it is becoming evident that not all tornadoes are the same, and a proper classification of them is not simple. Understanding that a vortex is a kinematically-defined process rather than an object, with different air parcels participating in the flow from moment to moment, turns out to be an important notion in trying to classify observed events. This, in turn, affects our climatological record of events, as we shall discuss below.

The dynamics of vortices, such as those simulated numerically (e.g., Rotunno 1979, Gall 1983) and in the laboratory (e.g., Ward 1972, Church et al. 1979) certainly are pertinent to tornadoes. Such studies have improved our understanding of phenomena like multiple vortices and vortex breakdown, but they concern properties of vortices in general, not necessarily those of tornadoes. From a purely dynamical viewpoint, tornadoes arise from amplification of either existing or locally-created vorticity (Davies-Jones 1986). However, this is a somewhat abstract framework for understanding tornadoes. This paper attempts to review tornadoes in the context of the convective events giving rise to them. In particular, we shall distinguish between events associated with supercell storms and those produced in association with non-supercellular convection. Not everything we present will have been thoroughly investigated in the scientific literature, especially non-supercellular events; in fact, we wish to mention some of these lesser-known phenomena in hopes of stimulating their systematic study.

2. SUPERCELL STORMS

2.1. *The Supercell Spectrum*

We have chosen the presence of a deep, persistent mesocyclone to be the single distinguishing characteristic of supercells.[1] Even within the category of supercell storms, however, it turns out that distinctions can be made which appear to have significance (see Doswell et al. 1990). While we concur with the kinematic-dynamic approach for defining a supercell, first advocated by Browning (1977) and recently re-emphasized by Weisman and Klemp (1984), it appears that the amount and spatial distribution of precipitation with the convection are important indicators of the weather phenomena associated with a particular storm.

Some supercell storms produce relatively little precipitation and yet show clear visual signs of rotation (Fig. 1). Such storms have come to be called Low-Precipitation (LP) supercells (Bluestein and Parks 1983). LP supercells occur most often near the surface dryline and, owing to the sparse precipitation and relatively dry environments with little or no

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[1] By "deep", we mean a significant fraction of the depth of the cumulonimbus cloud in which the circulation is embedded (several kilometers). By "persistent", we mean in comparison to a convective time scale, defined by the time it takes for air parcels to rise from within the inflow layer of the updraft to the anvil outflow (a few tens of minutes).

intervening cloudiness, cloud structures showing rotation are visible readily to a suitably-positioned observer.

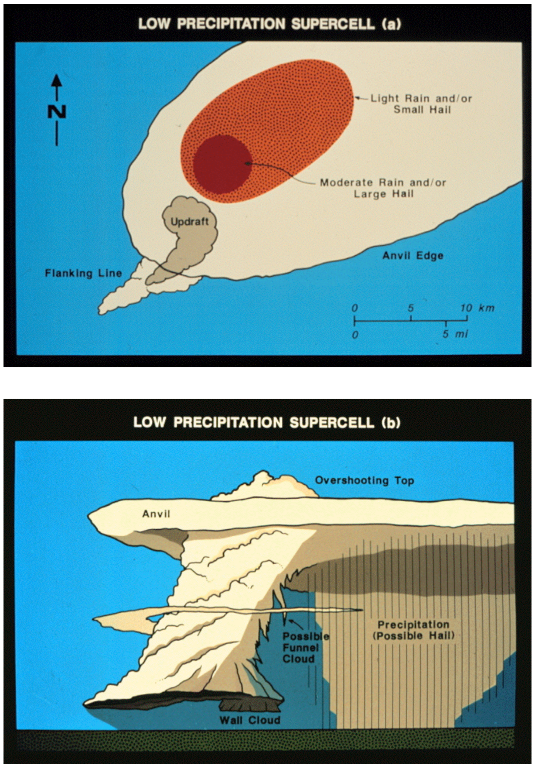

Fig. 1. Low-precipitation supercell schematics for (a) low-level radar structure and cloud features looking down from above, and (b) visual structures from the viewpoint of a nearby observer on the ground.

On the other hand, precisely because of the sparse precipitation, radar reflectivity may not reveal the circulation adequately, if at all. LP storms frequently are non-tornadic and many are non-severe despite exhibiting persistent rotation.

At the other end of the supercell spectrum are the so-called High- (or Heavy-) Precipitation (HP) supercells (Fig. 2). Whereas LP storms have little or no precipitation (and, hence, low reflectivity) within their mesocyclones, HP storms are characterized by substantial precipitation within their mesocyclonic circulations. When HP storms have a recognizable hook echo (many do not), reflectivities in the hook will be comparable to those in the precipitation core.

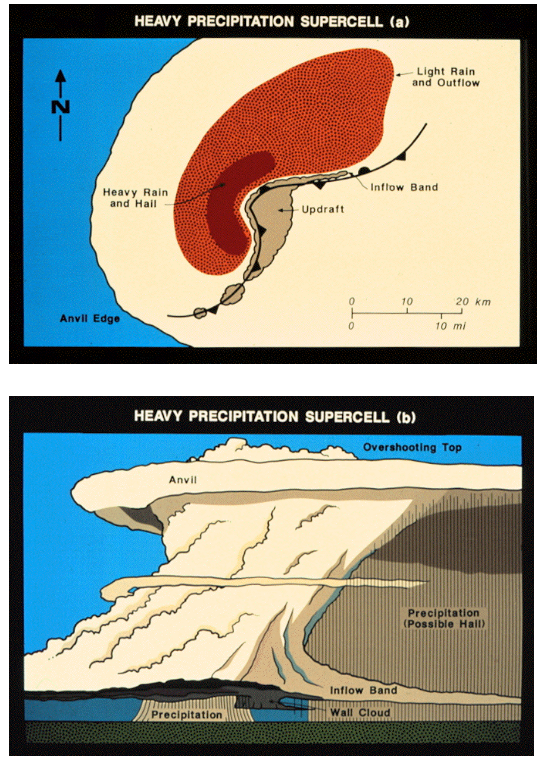

Fig. 2. High-precipitation supercell schematics as in Fig. 1.

HP supercells are probably the most common form of supercell, occurring not only in the humid half of the United States east of the Mississippi, but also westward into the high plains. They produce severe weather of all types (including tornadoes) and, unlike other types of supercells, also may produce torrential, flash flood-producing rainfalls (Moller et al. 1990). Some of the distinctive radar echoes (Forbes 1981) traditionallly associated with tornadic storms, like the so-called bow echoes, comma echoes, and Line-Echo Wave Patterns (or LEWPs -- Nolen 1959) can be associated with HP supercell storms. The rationale for including these forms in the HP supercell class is that they result from persistent mesocyclones embedded within precipitation-filled regions of the storm.

Because HP supercells often occur in humid, cloud-filled environments, visible signs of rotation may difficult to detect. In contrast, since the circulation in HP storms is embedded within precipitation, radar reflectivity usually depicts the HP storm circulations readily, sometimes even as curved bands apparently aligned with the flow.

Finally, in between these two extremes is the Classic supercell, which exhibits moderate precipitation production (Fig. 3). Such storms typically match the traditional supercell conceptual models (e.g., Browning, 1965, Lemon and Doswell 1979) and are most common in the transitional environments of the Great Plains. Many of the tornadic storms in major tornado outbreaks east of the Mississippi River are of the Classic variety, however.

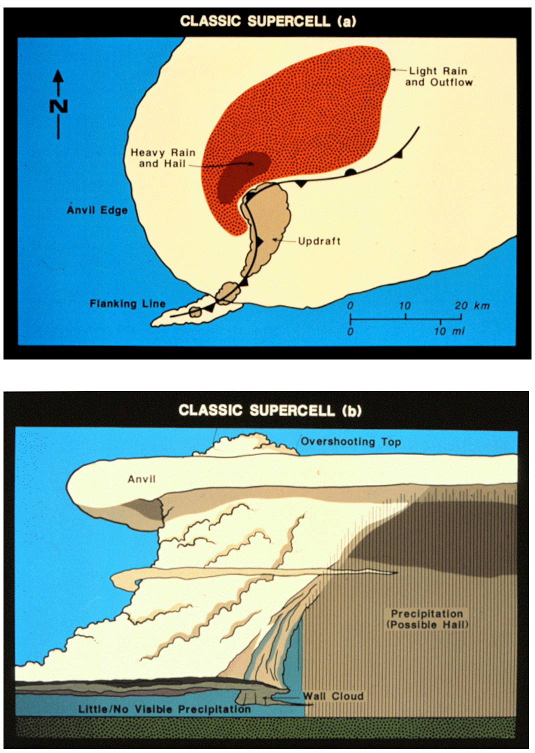

Fig. 3. Classic supercell schematics as in Fig. 1.

Although there may be some precipitation within a classic supercell's mesocyclone, it typically is not heavy.[2] If such a storm has a hook echo (and many do), the hook reflectivities will be less than those of the precipitation core. Late in a classic supercell's life cycle, during collapse of its updraft (see Lemon 1977), the mesocyclone may fill with precipitation, but this should not be considered a transition to an HP supercell, unless the mesocyclone persists well after the collapse phase.

Classic supercells are readily detectable both visually and via radar reflectivity and produce a full range of severe weather, but only rarely are associated with flash flooding. Classic supercells probably account for the majority of violent (F4-5) tornadoes.

2.2. *Hybrid Events*

Since class distinctions are much less obvious in the real atmosphere than they are in the abstract, it is quite common to see events that do not fit the preceding prototypes precisely. For example, it is likely that most LP storms do not become tornadic unless they evolve along the supercell spectrum toward the Classical structure. The 5 June 1982 Borger, Texas tornadic storm (Fig. 4) had a visual appearance that might suggest it to be an LP storm, but its appearance on radar was more like a classic supercell, exhibiting a

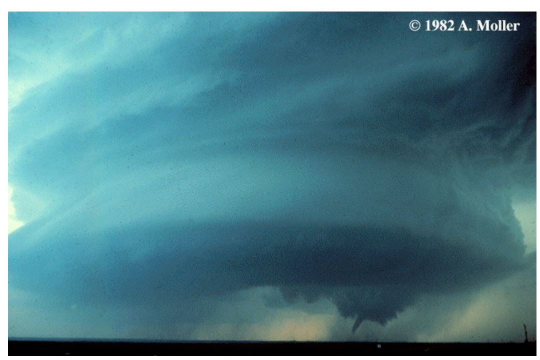

Fig. 4. A tornadic supercell in the vicinity of Borger, Texas on 5 June 1982. Photograph © 1982 by A. Moller, used by permission.

substantial hook echo. Exceptions are inevitable, naturally. The tornadic storms reported on by Burgess and Davies-Jones (1979) and Burgess and Donaldson (1979) produced intense tornadoes and

[2] Note that because a radar (even at its lowest elevations) scans a storm above the surface, a region with little or no surface precipitation may still be within radar-detectable precipitation aloft.

yet, as LP storms, they had little or no distinctive radar structure.

Supercell storms seem capable of evolving from LP to Classical, Classical to HP, and so on. As noted in Doswell et al. (1990), the variety of radar reflectivity morphologies, especially within the HP group, can be quite confusing (see also Imy and Burgess 1991). Non-supercell convection can evolve into supercells (Burgess and Curran 1985) and vice-versa. The common factor in all supercells is the deep, persistent mesocyclone, regardless of the storm's precipitation characteristics. However, the observed variations in precipitation amount and distribution make supercell recognition a challenge, especially when that recognition depends mostly on non-Doppler radar observations; a situation that will be remedied in time with the deployment of the WSR-88D network.

2.3. *Supercell Identification Criteria*

Having focused on the mesocyclone as the criterion for identifying supercells, we wish to review some of the traditionally-accepted supercell characteristics. The presence of a single, persistent "cell" is arguably the most commonly-accepted radar characteristic associated with supercells. The difficulty with this as a defining characteristic is that when observing convective storms visually or with especially high-resolution radar, it turns out that a multicellular structure can be observed to be superimposed on most convective storms, including supercells. Although the Byers-Braham prototype convective "cell" typically is depicted as "plume"-like (as in Weisman and Klemp 1986 – see their Fig. 15.1), such cells really are more "bubble"-like, even in supercells (cf. Fig 12b with Fig. 12a in Newton 1963 and see Hane and Ray 1985, esp. their Fig. 13).

Associated with the single-cell notion is another commonly-employed yardstick to identify supercells: their tendency for "steady-state" character. As with the single-cell criterion, this simply does not hold up to detailed observations. Supercells producing "tornado families" (cyclic tornado-producing storms) undergo an evolution over time scales on the order of several tens of minutes (as described in Lemon and Doswell 1979, and Burgess et al. 1982). There also is the constantly evolving cellular structure superimposed on the overall storm evolution that has a time scale of several minutes. These subprocesses make even an approximately steady state unlikely. Nevertheless, it can be argued that supercells do exhibit a long-lasting "background" process that evolves only slowly over periods of a few hours, the characteristic lifetime of the constantly regenerating supercell structure (Foote and Frank 1983). In extreme cases, supercells evolve very slowly, indeed, and may have tornadoes on the ground for periods approaching (and occasionally exceeding) an hour. Events of this character are quite rare and it is not yet understood how such steadiness arises. If such steadiness is a defining characteristic, then the supercell class is quite sparsely populated, indeed. In our opinion, there has been so much published emphasis on the steadiness and unicellularity criteria for supercells that operational identification of supercells using these characteristics often misses less prototypical (but still clearly supercellular) events.

On occasion, supercells arise in environments with relatively modest instability, as in tropical cyclones (McCaul 1991) and in strongly baroclinic systems (e.g., Gonski et al. 1989). Although the instability may be weak, there can be little doubt of the supercellular character of storms in such events. Although there always a question about the existence of a small-scale, unobserved region of strong instability, it seems unnecessary to postulate some mechanism not supported by the existing data. The evidence is substantial that supercells do not require an environment with strong instability.

Finally, there often has been considerable emphasis on the deviate motion (from the direction of the mean flow in which the storm is embedded) of the supercell, even to the point of suggesting it as a defining characteristic. Not all supercells deviate significantly from the mean wind direction (see Davies and Johns 1992); therefore, deviate motion is not required for development of a deep, persistent mesocyclone. This is especially so when hodographs are curved (see Doswell 1991b).

Hook echoes and other "distinctive" structures (as in Forbes 1981) are the direct result of the mesocyclonic circulations of a supercell. The distribution of precipitation quite clearly depends on airflow within the storm, which we have agreed is the most characteristic feature of a supercell, so such structures certainly are potentially useful in identifying supercells. Sometimes, though, such features as hook-shaped reflectivity structure can arise as a result of "configuration" instead of circulation. Thus, Lemon's (1977) emphasis on the three- and four-dimensional echo structure of storms: it is with such structural knowledge that a radar observer can separate bona fide supercell structures from "imposters" created by particular echo juxtapositions. Since LP storms typically exhibit few, if any, distinctive reflectivity features and, since detection of the classic echo features is so range- and resolution-dependent, these distinctive structures do not seem appropriate criteria for supercell identification.

Thus, on the basis of the above arguments, we advocate a de-emphasis for many of the traditional supercell identification criteria. With Doppler radar data, a time- and space-continuous mesocyclone is the best way for identifying such storms. With reflectivity alone, the three- and four-dimensional echo structure can be used to infer the presence of mesocyclones in many cases. The optimum situation for interpretation is when combining velocity and reflectivity information with a knowledge of characteristic storm structures. LP storms present a problem to any purely radar-based identification process, so visual recognition (spotters) still has an important role to play, even in the era of operational Doppler radars.

2.4. *Tornadoes Within Supercells*

The common association between mesocyclones and tornadoes in supercells hints that conservation of angular momentum may explain tornadoes associated with mesocyclones. However, even supercell tornadogenesis may be more complicated than that. Tornado development in the vicinity of the so-called wall cloud (Fujita 1960) suggests that nearby downdrafts play an important role in getting tornadic/mesocyclonic vorticity to low levels in the storm (Lemon and Doswell 1979, Davies-Jones 1982, Davies-Jones and Brooks 1992).

Intense vortices associated with supercells do not necessarily all develop via identical processes.[3] There may well be more than one mechanism operating for any given vortex associated with a supercell, or within different regions of the same supercell. Moreover, those events leading to tornado initiation may not be the same as those maintaining the large vorticity. Moller et al. (1974) have described funnel clouds on the northwest side of the Union City tornadic storm, with cool outflow at the surface, even as the primary tornado was developing on the southwestern updraft flank, near the inflow/outflow interface of the same storm. It is hard to imagine the same storm-scale processes operating in these areas, although both were intense vortices in the abstract sense.

3. NONSUPERCELL STORMS

A variety of intense atmospheric vortices can develop in association with nonsupercell storms. Terminology can be a controversial topic, but we do not wish to get involved in terminology debates.[4]

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[3] Recall the discussion in the Introduction, distinguishing between the limited number of abstract mechanisms for creating intense vortices and the processes operating at storm scales to allow the vortex dynamics to operate.

[4] See the discussion between Fankhauser et al. 1983a,b, Doswell 1983, and Moller 1983 for some sense of the terminology issues; although that debate con-

While we use certain terms that have been common in the vernacular and/or the literature, we do not necessarily endorse those terms. These events comprise several categories and we will attempt to give a brief description of each.

3.1. *Landspouts*

In an analogy with the common waterspout (Bluestein 1985), most of which develop from non-supercell storms,[5] many non-supercell tornadic events (e.g., Fig. 5) arise via intensification of pre-existing, shallow vertical vortices near the surface, through simple vortex stretching

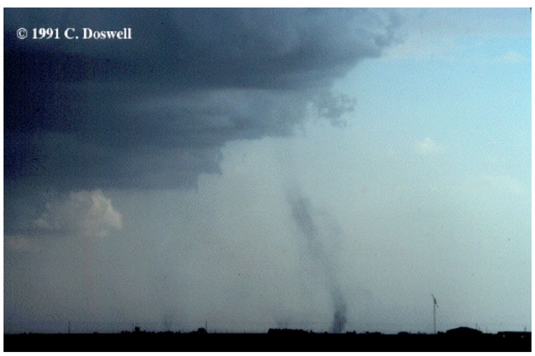

Fig. 5. An example of a non-supercell tornado event (sometimes called a "landspout") near Sublette, Kansas on 15 May 1991. Note that this is a relatively high cloudbase, estimated at about 5,000 ft. Photograph © 1991 by C. Doswell.

when a developing convective updraft moves over them (see Brady and Szoke 1988). Doppler radar evidence shows the pre-tornadic existence of these vortices on convergence boundaries (Wilczak et al. 1992). The details of the origin of these "misoscale" (Fujita 1981) vortices are as yet unclear, but such pre-existing vortices may explain the "dark spots" seen on the sea surface prior to the development of common waterspouts (Golden 1974), as noted by Wakimoto and Wilson (1989).

Perhaps a related phenomenon is the weakly unstable, linearly convective tornadic event first documented by Carbone (1983). As with landspouts, a frontal boundary may develop locally enhanced circulation centers, which subsequently can attain tornadic proportions. What makes these events distinctive is the weak buoyancy in their environment – the updrafts are forced along the frontal zone (see Carbone 1982) and the tornadic circulations are comparable in depth to the updraft (which was shallow to begin with -- only a few km). Again, such events have not been observed often enough to have been subjected to systematic study.

Pre-existing vortices at low levels also may be associated with tornadoes arising as convergence boundaries collide (e.g., Holle and Maier 1980). Such events are associated with multicellular lines and clusters, and the resulting flows can be quite complex. Although multicell storms have been the subject of many observational studies (e.g., Marwitz 1972), they have not yet been given the attention they deserve in three-dimensional numerical modelling. Therefore, the dynamics of interacting convective cells are as yet poorly understood. Tornadogenesis under such circumstances is, therefore, correspondingly poorly understood.

3.2. *Cold Pool Vortices*

To our knowledge, the sole reference to these is that by Cooley (1978). They seem to be associated with cold pools aloft, which frequently pass overhead with clear skies in the wake of cold fronts. Such cold pools aloft (not necessarily coincident with the upper circulation center) may be associated with high lapse rates if skies are clear and surface heating couples the boundary layer with the cold air aloft. In such cases, there is enough residual moisture in the post-frontal environment that deep convection ensues. In most cases, the cloud base is high owing

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cerns the names for cloud features, its flavor is characteristic of terminology debates in general.

[5] Of course, some waterspouts *do* arise from supercells. They have been called tornadic waterspouts by Golden (1971) and appear to be virtually identical to tornadoes associated with supercells over land. The distinction between a tornado and a waterspout is basically of little or no scientific value.

to lack of abundant moisture, while cloud tops are low because of a cool troposphere, giving rise to a low tropopause.

The mechanism by which these cold pool vortices form is quite unclear, because of a lack of quantitative observational studies. Since the mid-tropospheric environment in which they occur may be rich in vertical vorticity, they might result from simple vertical vortex tube stretching. The rarity of tornado touchdowns from these cold pool vortices may be associated with the relative weakness of the initial vorticity at low levels (as discussed in Smith and Leslie 1978).

These events are distinct from those along and ahead of cold fronts. If a cold pool aloft is situated over a front, rather than behind it, low-topped storms can develop in such an environment. Whereas wind shears usually are weak beneath cold pools in the post-frontal region, storms along and near fronts often arise in relatively highly-sheared environments; funnel clouds and tornadoes developing in these conditions simply are shallow versions of supercells.[6] The specific class of cold pool vortices to which we refer only arise more or less directly under the upper circulation center (where the vertical shear usually is weak) and well poleward of the surface cold front. Systematic investigation of such events has not been done, to our knowledge.

3.3. *Gustnadoes*

Very small scale, shallow vortices (Fig. 6) may develop near the surface along outflow boundaries and/or cold fronts, with or without deep convection overhead (see Idso 1974, Idso 1975, Meaden 1981, Doswell 1985). The boundary develops "lobes" and bulges, with cyclonic circulations at the cusps created by those lobes. Sometimes, for reasons that essentially are not known, those circulations become quite intense; at least as intense as weak tornadoes. If they are associated with a damaging outflow, they may create short, narrow zones of even more intense damage than is common along the rest of the outflow. They also can produce damage swaths along an otherwise non-damaging outflow.

Fig. 6. An example of a circulation along a gust front (sometimes called "gustnadoes") near Welch, Texas on 23 May 1982. In contrast to Fig. 5, this cloud base is quite low, around 500 ft or less. Photograph © 1982 by C. Doswell.

Although we have no documentation for making this distinction, we propose that they are distinguishable from "landspouts" by remaining quite shallow. Virtually no circulations can be seen at cloud base, visually or on Doppler radar. Such events seem not to depend on the superpositioning of a developing updraft above them. If such a vortex is, indeed, deepened and intensified by an overriding updraft, we believe it will undergo a transition to a landspout. Obviously, considerably greater documentation and study of these events is needed.

3.4. *Fair Weather Vortices*

There is a substantial variety of distinct fair weather convective vortices, even ignoring the "dust devil" phenomenon

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[6] At the risk of being repetitious, it is the presence of a deep, persistent mesocyclone which defines a supercell, not the depth of convection. When the mesocyclonic circulation exists through a substantial fraction of the depth of the storm, it doesn't matter if the storm is relatively shallow; it is a supercell. Storms poleward of, say, 45° latitude often have low tops because the environment is relatively cold, with a correspondingly low tropopause.

(see Idso 1974). Dust devils arise in association with dry, rather than moist convection, of course.[7]

Meteorologists operating on storm intercept teams have observed relatively long-lived funnel clouds in association with quite ordinary cumulus clouds (Fig. 7). A rather different phenomenon has been observed on fair weather days, the so-called "horseshoe vortices" (Fig. 8). These may arise in much the same way as "mountainadoes" (Bergen 1976): tilting and the associated stretching of an enhanced region of horizontal vorticity over

Fig. 7. An example of a fair-weather vortex with an ordinary cumulus cloud near Sayre, Oklahoma on 17 May 1983. Photograph © 1983 by C. Doswell.

Fig. 8. An example of a vortex associated with a dissipating cumulus cloud, sometimes referred to as a "horseshoe vortex" near Shamrock, Texas on 13 April 1976. Photograph © 1976 by C. Doswell.

some upward-protruding object, or perhaps by an isolated updraft (a small cumulus-scale version of the process depicted in Fig. 3a of Klemp 1987).

With most of these fair-weather vortices, it seems unlikely they ever would reach damaging proportions at the surface, and so it is improbable that they would (or should) be classified as tornadoes. Knowledge that they exist may be important in responding appropriately to citizen reports of such events, however.

4. CLASSIFICATION OF VORTICES

At present, our perspective has come to paraphrase Richardson's famous limerick about vortices: the extratropical cyclone contains mesolows, the convection within the vicinity of mesolows develops mesocyclones, the tornado cyclone develops within the mesocyclone, the tornado

[7] Interestingly, some citizens observing the deadly Cheyenne, Wyoming tornado of 16 July 1979 thought they were seeing a dust devil; this confusion may have arisen because of the relative rarity of tornadoes in Wyoming, along with the absence of a visible condensation funnel for the early part of the tornado's life.

within the tornado cyclone, the subvortex (or suction vortex, as in Fujita 1971) within the tornado, and so on (presumably, to viscosity). Thus, the processes associated with tornadoes (at least those developing from supercells) can be seen in a context of a larger vortex and contains smaller subprocesses within. In such a hierarchy of processes, the boundaries between events can become blurry when observed in the natural world.

Forbes and Wakimoto (1983) have presented a quite insightful discussion on classification of tornadoes. We are basically in agreement with their conclusions, which advocate a more pragmatic approach to defining a tornado than implied by the Glossary definition; namely, any damaging vortex associated with a convective storm, including its accompanying wind field, should be called a tornado. They also suggested, and we agree, that "Damaging vortices not associated with thunderstorms [ought to be] considered tornadic vortices of a particular type." However, we believe the issues can be even more difficult to resolve than they have described. These difficulties arise from improvements in observations and understanding, so the problems are really the sign of progress.

Many supercells produce tornadoes from and/or near the so-called wall cloud (see footnote #2). It has been shown observationally and numerically (see Rotunno and Klemp 1985) that the wall cloud arises from the admixture of outflow and inflow within the mesocyclone. Now, suppose the mesocyclonic circulation becomes so intense that it reaches damaging proportions, with a wall cloud reaching near, or perhaps down to, the surface. Is such a damaging circulation a tornado? It certainly meets the definition given in the Introduction, as well as that advocated by Forbes and Wakimoto. Both storm intercepts and eyewitness accounts suggest that mesocyclonic vortices can be damaging whether or not they ever produce a visible cloud to the ground. Are such damaging events "straight line" winds? How large does the radius of curvature have to be to call an event "straight winds" as opposed to a tornado?

Moreover, what about a large wall cloud that spins out visible funnels that develop damaging ground circulations every few minutes (either one at a time or several at once) over a period of a few tens of minutes? Are we seeing one tornado with many subvortices, or are we seeing several different tornadoes? Again, such events have been observed and recorded, but how one classifies such an event seems unclear to us.

As visual observations of tornadoes accumulate, it is clear that tornadoes virtually never "skip" in the sense of the circulation "lifting and descending" -- instead, the circulation at the surface may strengthen and weaken on time scales of a few seconds or more, but a significant circulation typically remains on the ground for the lifetime of the event. The funnel cloud aloft associated with the event may be continuous during such a weakening and strengthening cycle, or it, too, may dissipate and redevelop. If the winds cease to be damaging as a result of a weakening circulation and then redevelop, is this the redevelopment a new tornado or should we say that the gap is a "skip" in the path of a continuous tornado? If the answer depends on the distance and/or time between damage, is there a non-arbitrary way to establish criteria for making such classifications?

There are numerous movies and videos showing quite clearly the dissipation of one damaging funnel cloud/tornado with the nearly-simultaneous development of another within close proximity. A ground survey of the track would probably reveal a continuous damage swath, perhaps with a small offset. Are these sub-vortices within a larger, more or less continuous tornado, or are we seeing two different tornadoes? This issue is complicated by the existence of multiple vortex phases interspersed with single vortex modes.

6. DISCUSSION

A tornado, no matter how one chooses to define it, is a kinematic structure that renews itself from instant to instant via one or more dynamic processes. It is not a "thing" in the sense that a table or a book (neglecting atomic or molecular fluctuations) is the same from one moment to the next. Much confusion about tornadoes comes from thinking of tornadoes as objects rather than as the kinematic manifestation of dynamic processes. The actual physical processes are not heedful of our somewhat arbitrary classification schemes and, as scientists, we need constantly to remind ourselves that our understanding of tornadoes and tornadic storms can be clouded by an inappropriate classification scheme (see the discussion by Doswell 1991a).

The only scientific justification for a classification scheme is if that scheme proves to be useful in developing our understanding and/or in application of that understanding. While we probably have muddied the waters by mentioning additional difficulties with event classification, we believe that an appreciation for classification problems is needed in any proper use of the data derived from classification.

The more we learn about tornadoes and tornadic storms, the more they seem to be terribly complicated processes. It is possible that some insight we have yet to find will simplify our understanding of tornadoes and tornadic storms. On the other hand, new observations may not result in some simple reconciliation, but will raise new and even more confusing issues with which to deal. There is nothing that guarantees simplicity in nature.

Despite the confusion it has caused, however, our new understanding developed since the last Symposium as a result of radar, storm chasing, and numerical and laboratory modeling has been applicable in both a research and an operational sense. The recognition of a range of processes at the scale of the convective storm and at the tornado scale has been valuable to our science and to society as a whole. It is likely that numerical cloud models soon will be able to resolve tornadic flows, offering the chance for new insights into tornadoes. As new operational and research observing systems are implemented, it is virtually certain that we shall come to know much more about non-supercell events than at present. We close by noting that a considerable challenge confronts us in applying any new understanding of tornadoes and tornadic storms to benefit society; efforts to do so have been painfully slow, up to the present. We hope that operational deployment of new technologies will be associated with concomitant accelerations in the application of scientific understanding to serve society.

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