2.2 **TORNADOGENESIS IN SUPERCELL STORMS – WHAT WE KNOW AND WHAT WE DON'T KNOW**

Robert Davies-Jones*
National Severe Storms Laboratory, NOAA
Norman, Oklahoma

1. COMMON OBSERVATIONS

The advent of Doppler radar, 3D numerical simulations and scientific storm chasing have led to huge advances in our knowledge of supercells during the last 35 years. However, complete understanding of tornadogenesis in supercell storms still eludes researchers. To put my discussions of current knowledge and mysteries in context, I follow Rasmussen and Straka's (1997) example by first describing features of tornadic supercells that are observed with quite remarkable repetition from storm to storm and then reviewing viable theories that are congruent with these observations. Some of the following is based on their paper.

Background on tornadic storms is contained in the most recent review article (Davies-Jones et al. 2001) and references cited therein.

1.1 *STORM AND ENVIRONMENT*

From detailed examination of radar data, which had rather coarse resolution by today's standards, Browning (1964) concluded that most tornadoes form within large, steady, and virulent thunderstorms. These appeared to be unicellular, so he called them supercells.

The introduction of pulsed Doppler radars into severe-storm research in 1971 quickly led to new results. Signatures of mesocyclones and tornadic vortices were evident in the Doppler velocity fields of a single radar. The mesocyclone typically formed aloft first and then near the ground prior to any tornadogenesis.

Fawbush and Miller (1954) identified environmental conditions that are conducive to large, long-lived tornadoes. The sounding generally has large convective available potential energy (CAPE) and strong shear associated with winds veering and increasing with height. Although both shear and CAPE are important parameters, theoreticians were bewildered by cases when tornadoes formed in environments either with high CAPE and little shear or with low CAPE and high shear. The former events occurred either in hurricanes or in mid-latitudes during the cool season, and the latter ones in mid-latitudes during the warm season. We now know that the low-CAPE, high-shear tornadoes form in mini-supercells with low tops and the high-CAPE, low shear tornadoes develop in supercells that are not very steady.

1.2 *MESOCYCLONE ALOFT*

The initial mesocyclone is a rotating updraft with maximum vertical vorticity exceeding 10^{-2} s^{-1} and a large correlation between vertical velocity and vertical vorticity. It forms aloft from tilting of low-level storm-relative streamwise vorticity associated with vertical shear in the large-scale or mesoscale environment. The resulting vertical vorticity is subsequently stretched and advected vertically in the updraft. The storm may amplify the low-level streamwise vorticity in its inflow by stretching it horizontally. Helical environments (i.e., ones with large shear vectors that veer with height in the lowest few kilometers), either on a large scale or around baroclinic boundaries are especially conducive to tornadoes. Very large helicity in the lowest 1 km is particularly favorable for tornadoes. This is probably because the mesocyclone aloft has a base that is not far off the ground.

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**Corresponding author address*: Robert Davies-Jones, National Severe Storms Laboratory, NOAA, 1313 Halley Circle, Norman, Oklahoma 73069-8493;
e-mail: Bob.Davies-Jones@noaa.gov

1.3 *NEAR-GROUND MESOCYCLONE*

In 1949 Brooks (1949) discovered from tornado passages near microbarographs that tornadoes formed within larger cyclones, which he named tornado cyclones and which nowadays are termed low-level mesocyclones irrespective of whether or not they produce tornadoes. In comparison to mid-level meso-cyclogenesis, rotation near the ground develops later in the supercell's lifetime and by a different process. It seems to await the formation of downdrafts within the mesocyclone.

Fujita (1959) collected photographs and movies of the cloud base and sides of a 1957 tornadic storm near Fargo, North Dakota, and found that the entire updraft was rotating cyclonically (Fig. 1). This was the first visual confirmation of a mesocylone.

1.4 *REAR FLANK-DOWNDRAFT*

The data from two radars with different viewing angles allowed the construction of 3D wind fields inside severe storms. It soon became evident that downdrafts played a role in tornadogenesis. Dual-Doppler analyses and observations by storm chasers revealed that tornadoes formed not in the early lifetimes of a supercell when it consisted almost entirely of a rotating updraft but later on after downdrafts reached the ground. Low-precipitation (LP) supercells seldom produce tornadoes, probably because they never develop a significant downdraft.

A supercell is generally considered to have two main downdrafts (Fig. 2) even though they may not be a gap between them. The forward flank downdraft (FFD) forms first and is collocated with precipitation on the left front side of the updraft in the northern hemisphere. [For southern-hemisphere supercells interchange left and right throughout this paper.] The rear-flank downdraft (RFD) develops at the rear of the rotating cloud tower, which may have a quite circular base initially. The RFD may arise from evaporative cooling or from a downward nonhydrostatic vertical pressure-gradient force (NHVPGF). With time it propagates around the rotating updraft, and its outflow boundary is the RFD gust front. The mesocyclone at low levels now is divided into updraft and low cloud base on its left side, and downdraft (the left side of the RFD) on its right. (Lemon and Doswell 1979). The right side of the RFD is anticyclonic and so lies outside the mesocyclone. Convergence at the RFD gust front causes the updraft to extend along it and thus become horseshoe shaped. At low levels the supercell now resembles an extra-tropical cyclone with the outflow boundaries from the FFD and the RFD in the warm-frontal and cold-frontal positions, respectively. The RFD is often visible as a clear slot, a narrow deep slot of cloud-free air that wraps around the region where the tornado develops about 5-10 min prior to its formation. Rapidly sinking and evaporating cloud fragments are often seen near its edges. The advancing RFD occludes the mesocyclone with the tornado typically forming near the point of occlusion. At this stage a new mesocyclone may be forming along the bulge in the RFD to the right of the old one (Fig. 2).

1.5 *HOOK ECHO*

With the advent of weather radar came the recognition that tornadic storms close to the radar often had an echo with a hook-shaped appendage on the right rear side (Stout and Huff 1953, Markowski 2002). The hook is often attributed to precipitation being drawn into a cyclonically rotating rain curtain by the mesocyclone (Browning 1964). If this were true, the hook would elongate gradually. However, it often seems to form all at once, suggesting that it may be associated with the sudden development of precipitation at the rear of a new updraft. The hook is often narrow, consistent with chasers' observations of thin curved rain curtains with hydrometeors that are advected horizontally by the mesocyclonic winds as they fall. At the ground the curtains typically consist of large drops. Surface measurements reveal divergent flow towards and away from the mesocyclone axis and locally higher pressure in the region of the hook. The tip of the hook may flare out both cyclonically to the right and anticyclonically to the left.

1.6 *TORNADO CYCLONE*

Tornadoes have circulations that are an order of magnitude smaller than the circulation of a typical mature mesocyclone. Fortunately nature is only able to contract a part of a strong mesocyclone into a tornado. This part is thought to be a vortex with a typical core radius of 1 km within the mesocyclone, and is named a tornado cyclone [not to be confused with Brook's (1949) tornado cyclone in Section 1]. The tornado cyclone has been observed occasionally in high-resolution Doppler radar observations. In one case (Burgess et al. 2005) it developed though a deep column within an intensifying mesocyclone. Its maximum winds were aloft and a tornado built upward from within it. The co-existence of a tornado and tornado cyclone is also evident in Doppler on Wheels observations of tornadoes with secondary wind maxima at distances of 500-1000 m from the axis (Wurman and Gill 2000). Thus, the entire tornado cyclone may not contract into a tornado.

1.7 *OCCLUSION DOWNDRAFT*

The occlusion downdraft is a small-scale downdraft that forms after the development of intense rotation and attendant low pressure next to the ground (Rotunno and Klemp 1985). Thus, it is a response to the near-ground rotation rather than an instigator of it. It is driven by strong downward NHVPGF associated with a deep low at the surface. Visually, it is practically indistinguishable from the RFD because it is located near the front edge of the RFD as it wraps around the developing tornado.

1.8 *WALL CLOUD*

In his study of the Fargo storm, Fujita (1959) realized that an abrupt lowering of the cumulonimbus cloud base was a significant feature and named it the wall cloud. It marked the lower portion of a strong rotating updraft (Fig. 1). Supercell tornadoes are generally suspended from wall clouds until they are overtaken by divergent air late in their life times. Rotating wall clouds containing strong upward motions often precede tornadoes by tens of minutes (Fujita 1959). Based on numerical simulations, Rotunno and Klemp (1985) attribute their formation to rain-cooled, nearly saturated air that descends, and flows along the ground into the updraft. The lowering is due to this air having a lower lifted condensation level than air in the storm's inflow.

1.9 *TORNADO POSITION IN STORM*

Neil Ward chased one of the tornadic supercells studied by Browning (Browning and Donaldson 1963). He observed that the tornadoes formed in the storm's main updraft and near its gust front. Chasers observed that tornadoes usually form in a region of the storm that is a few kilometers away from precipitation and the nearest cloud-to-ground lightning (Davies-Jones and Golden 1975; Fig. 3). Thus, theories that rely on electrical heating from repeated lightning strikes (Vonnegut 1960) or on a precipitation-loaded downdraft along the axis of rotation (Eskridge and Das 1976) have no observational support.

Doppler-radar analyses and chasers' observations revealed that tornadoes generally form close to the circulation center of the mesocyclone and near the interface of updraft and downdraft. Roughly speaking, they are also near the center of curvature of the wrapping rain curtain where the inward outflow from the associated downdraft converges.

Observations from chase teams showed that the tornado below cloud base was coincident in time and space with the tornadic-vortex signature (TVS). For the first time meteorologists could observe tornadoes (or more precisely their signatures) above cloud base (Brown et al. 1978). Large violent tornadoes were associated with TVSs that extended to near the tropopause. Note that, if the radar is not close enough to resolve the parent tornado cyclone, the TVS may be due at least partly to the tornado cyclone.

In numerical simulations of supercells, vertical motions intensify and pressure falls at 1-3 km above ground just prior to tornadogenesis (Wicker and Wilhelmson 1995). At these levels the poorly resolved tornado forms in large gradients of vertical velocity where the tilting term is large.

1.10 *ANTICYCLONIC VORTICITY*

At low levels, anticyclonic vorticity is often located near tornadoes. An anticyclonic flare is occasionally observed at the tip of the hook and is visible in the field as anticyclonic rotation in the base of the flanking cloud line to the right of the clear slot (Fig. 2). Sometimes an anticyclonic tornado forms at this location, usually when there is a stronger cyclonic tornado located on the other (left) side of the hook (Knupp and Brown 1980). In other cases, the region of anticyclonic vorticity advances around a strong cyclonic tornado as the RFD wraps around the tornado.

In his photogrammetric analysis of the 1957 Dallas tornado, Hoecker (1960) found a region of anticyclonic vorticity just outside the core at a roughly 100 m from the axis.

2. WHAT WE KNOW

Tornadogenesis divides naturally into three stages. The first step in the vorticity concentration is the formation of a rotating updraft.

2.1 *STAGE 1 OF TORNADOGENESIS*

Since some tornadoes occur in low-shear environments, meteorologists debated, prior to 1977, whether the concentrated vorticity in supercell tornadoes was simply a result of stretching of pre-existing planetary vertical vorticity by a large persistent and strong updraft or whether it originated ultimately from tilting of horizontal vorticity.

Stretching of planetary vorticity is at odds with the observations because it would produce rotation near the ground first where horizontal convergence is largest. In contrast, Browning and Landry (1963) hypothesized that updrafts in supercells rotated cyclonically by tilting updraft-relative streamwise vorticity present in their inflow. This mechanism would produce a mesocyclone aloft, as observed initially. Lilly (1982) and Davies-Jones (1984) developed mathematical theories of this process.

The first successful 3D numerical simulations of supercells settled this debate (Klemp and Wilhelmson 1978). The model storms resembled supercells even with the Earth's rotation switched off. In simulations with unidirectional (straight) shear, storms split as often observed into severe right- (SR) and left-moving (SL) supercells. The updraft in the SR (SL) storm rotated cyclonically (anti-cyclonically). Inclusion of Coriolis forces simply made the right mover the stronger storm, but only slightly because the Rossby number for supercells has an order of magnitude of 100. Veering of the shear vector with height enhanced the right-moving updraft and inhibited the left-moving one to a much greater degree.

Since updraft-relative streamwise vorticity is equal to the strength times the rate of veering with height of the updraft-relative winds, updraft rotation depends on updraft motion. Updrafts propagate towards (away from) the side where NHVPGF is upward (downward). Rotunno and Klemp (1985) found that in nearly straight shear, updraft propagation depends on the nonlinear part of the NHVPGF arising indirectly from the updraft-shear interaction. The updraft forms a midlevel vortex pair by pulling up loops of environmental vortex tubes. The low pressure in these vortices is associated with upward NHVPF below them. Midway between the vortices there is high pressure due to water loading and deformation with downward NHVPGF below this high. This configuration of NHVPGF causes the initial updraft to split into a cyclonically rotating SR and anticyclonically rotating SL updrafts.

When the hodograph is highly curved, Davies-Jones (2002) found that the propagation depends mainly on the linear part of the NHVPGF induced directly by the shear-updraft interaction (as first proposed by Rotunno and Klemp 1982 for nearly straight shear).

Updrafts acquire cyclonic circulation by propagating into cyclonic and out of anticyclonic regions. For example, the SR updraft maintains its rotation by propagating towards the original cyclonic vortex, which stays ahead of it because the updraft is continually tilting environmental vorticity upward at its leading edge. Davies-Jones (2004) found that the growth of circulation around the edge of an updraft at a given level is equal to the line integral around the edge of vertical vorticity times either the local propagation of the edge normal to itself or, equivalently, the local NHVPGF divided by the local gradient of vertical velocity. Thus, the first stage of tornadogenesis, the development of a mesocyclone aloft, is well understood.

2.2 *STAGE 2 OF TORNADOGENESIS*

Tilting by an updraft of horizontal vorticity fails, however, to produce rotation very close to flat ground because the vertical vorticity is generated as the air is rising (Davies-Jones 1982). This rule could be violated if streamwise vortex lines were tilted upward abruptly by a gust front and stretched by an overhead updraft as proposed for waterspouts by Simpson et al. (1986). This is an effect that is absent in simulations with limited horizontal resolution. However, parcels approaching a gust front generally start rising before they reach it and, since the vortex lines tend somewhat to be frozen into the flow, they would also begins lifting ahead of the gust front. Tornadogenesis must await the development of downdrafts that either tilt initially horizontal vortex tubes as they advect them downward or simply transport vertical vorticity downward. This second stage of tornadogenesis, the development of rotation very close to the ground, is the one that requires much more research.

2.3 *STAGE 3 OF TORNADOGENESIS*

The third stage, the formation of the tornado, appears to be simply the result of amplification of vertical vorticity in air parcels that are being stretched vertically by an updraft (Walko 1993). This view is supported by Doppler radar observations of strong low-level convergence just prior to tornado formation. Frictional interaction between the low-level mesocyclone and the ground may aid this process by inducing radial inflow along the ground (Rotunno 1986). At ‘ground zero’, stretching of vertical vorticity is the dominant term in the vertical-vorticity equation once vertical vorticity is present very near the ground. Ward’s (1972) laboratory tornado simulator exemplified this stretching process in a wide updraft and reproduced several observed features of tornadoes such as characteristic surface pressure profiles, vortex breakdown, and multiple vortices. Given sufficient time without disruptions such as cold pools spreading beneath the updraft, this stage should mimic Ward’s laboratory model. At large swirl ratios, centrifugal forces prevent the convergence of air to near the axis of rotation, in which case either there is a single large weak vortex or multiple tornadoes form around the periphery of the mesocyclone.

There is no need to find exotic energy sources for tornadoes since we now know that the “thermodynamic speed limit” can be broken (Fiedler and Rotunno 1986). The frictional interaction between the tornado and the ground drives strong radial inflow. Parcels can penetrate closer to the axis than the radius dictated by cyclostrophic balance above the boundary layer. Because their angular momentum is nearly conserved, they rotate very quickly. Their excessive kinetic energy is compensated for by loss of pressure energy. To conserve mass, the boundary layer erupts violently upward into an intense vertical jet along the axis.

When the convergence increases and the ambient angular momentum is constant with height or when the convergence is constant and the angular momentum increases with height, the tornadic vortex forms aloft because high-angular-momentum air first arrives near the axis aloft. The vortex then builds downward slowly (tens of minutes) to the surface through a dynamic pipe effect (Smith and Leslie 1978; Trapp and Davies-Jones 1997). If there is insufficient angular momentum near the ground, the vortex remains as a funnel cloud and never becomes a tornado. If the convergence and angular momentum are constant with height in the lowest few kilometers, the vortex contracts uniformly and a tornado forms rapidly in 5-10 min.

Incidentally, a popular suggestion for tornado modification is to explode a device in the core. A laboratory experiment by Chang (1976) showed that this method can disrupt a vortex temporarily, but it immediately reforms as long as the larger-scale flow near the ground remains convergent and gyratory.

3. WHAT WE DON'T KNOW

As stated above, most of the mysteries concerning tornadogenesis concern the development of rotation very close to the ground through some process that seems to be very different from midlevel mesocyclogenesis. The possibility exists that the process may not be the same one in all cases. Several processes have been suggested and none have been completely verified by field observations. Genesis of a strong long-lived tornado requires that the near-ground mesocyclone be underneath the mid-level mesocyclone so that there is a continuous wide vortex column from the ground to near the tropopause. The tornado has to terminate in a strong updraft to prevent it from filling from above.

3.1 *BAROCLINIC MECHANISMS*

High-resolution numerical cloud models now produce poorly resolved tornadoes within simulated supercells in non-rotating atmospheres. In these simulations, rotation near the ground is due to tilting of horizontal vorticity that is generated baroclinically in subsiding air that has spent considerable time (around 10 min or more) in a strong buoyancy gradient (Rotunno and Klemp 1985). Davies-Jones and Brooks (1993) showed that the vorticity in this air changes from anticyclonic to cyclonic during its descent in the baroclinic zone by the mechanism described in Davies-Jones et al. (2001). Its cyclonic vorticity is then greatly amplified as it passes into the updraft. In the simulations, the near-surface vorticity maximum or tornado-like vortex is typically located in gradients of both temperature and equivalent potential temperature.

Unexpectedly, in-situ field observations made during and after VORTEX (Verification of the Origins of Rotation in Tornadoes EXperiment) have failed to detect rain-cooled air at the surface near several strong and violent tornadoes even though the tornadoes were close to a wind-shift line. The discrepancy between observations and simulations may be due to the microphysics scheme producing too strong a cold pool too soon owing to excessive rain production too low in the cloud and the evaporation rate being too fast. The observations do not preclude the possibility that air, which enters the tornado at its base, may have passed slowly through a remote baroclinic zone that may even be above the ground.

3.2 *POSSIBLE ROLE OF MICROBURSTS*

Do microbursts sometimes trigger tornadoes or help maintain them? Radar observations and damage surveys sometimes reveal microbursts prior to the touchdown of tornadoes or on the right sides of tornado tracks. In the radar echoes of several tornadic storms, 'blobs' of higher reflectivity, perhaps associated with microbursts, have been observed within the hooks. These descend to low elevations prior to tornado touchdowns on their left forward sides. The blob in the well observed 2 June 1995 Dimmitt, Texas tornadic storm had an anticyclonic vortex on its left side and a cyclonic one that appeared to evolve into the tornado on its right side. This vorticity configuration could arise from downward transport of high-momentum air (represented by the double arrow in Fig. 2). Alternatively, it could originate from tilting by a downstream updraft of baroclinic vorticity. A downdraft that is heavy aloft owing to water loading and/or evaporative cooling would be encircled by descending quasi-horizontal vortex rings with the vorticity vectors directed clockwise. These rings would spread along the surface upon reaching it, Lifting of the leading edges in the RFD gust front convergence zone would give rise to vertical vorticity of the observed configuration. The cyclonic vortex is generally the stronger vortex and the one that turns into a tornado because it can enter the main updraft. A major question is whether enough circulation could be generated for a major tornado. The other vortex could become an anticyclonic tornado if it is stretched by an updraft in the flanking line.

3.3 *FUJITA'S BAROTRONIC MECHANISM*

In cases without significantly cool near the tornado, is there a remote baroclinic zone aloft (possibly aloft) or is a barotropic tornadogenesis mechanism operating? To show that a barotropic mechanism is possible, I built a 'bare-bones' axisymmetric model of a mesocyclone without thermodynamics. The initial condition is a Beltrami flow that consists of a cyclonic updraft (or midlevel mesocyclone) surrounded by a downdraft. If left unperturbed, the flow decays slowly without changing pattern. When hydrometeors are introduced through the top boundary above the updraft, they fall around the periphery of the updraft and drag angular momentum down to the ground. Some of the angular momentum that is transported downward advects inwards towards the axis as in Fujita's (1975) "recycling process". Fujita inferred this mechanism from eyewitness photographs that showed the rotating rain curtain tilting inwards towards a tornado (like as in Fig. 2b). In the simulation, a tornado forms and ultimately decays owing to the absence of a 'buoyant cork' aloft. The mechanism is unequivocally barotropic because differential drag forces generate azimuthal vorticity, which cannot be tilted in axisynmmetry flow. In this simulation, the rotating rain curtain instigates the tornado.

The axisymmetric model constrains the flow unrealistically by making part of the outflow from the downdraft to focus on (i.e., converge towards) an imposed axis. However, it has the advantage over a fully 3D model of being much easier to interpret.

3.4 *WALKO'S BAROTRONIC MECHANISM*

Davies-Jones (1982) proposed that a rear-flank downdraft, although divergent, is vital to the lowering of vertical vorticity and rotation to the surface. In westerly shear, the downdraft would draw down loops of vorticity, producing a north-south oriented cyclonic-anticyclonic vortex pair near the surface. The main updraft lies ahead of and to the left of the RFD, in the right position for the air with cyclonic vorticity to flow along the ground and into it. This would result in a near-ground mesocyclone through stretching. Note that the outflow from the downdraft enhances the low-level convergence in the updraft.

A numerical experiment by Walko (1993) validates this process for an idealized flow. In a westerly shear flow, Walko used a fixed heat sink and source to produce a RFD southwest of an updraft. A tornado-like vortex formed barotropically beneath the updraft on the left edge of the cold pool. Although baroclinically generated vorticity was tilted, it contributed negatively to the circulation of the vortex and hence to its genesis.

3.5 *PRE-EXISTING VERTICAL VORTICITY*

Low-level rotation could be the result of a supercell updraft concentrating pre-existing vertical vorticity on a front or shear line (Walko 1993). Since the horizontal vorticity in sheared supercell environments is an order of magnitude larger than pre-existing vertical vorticity, tilting of horizontal vorticity would provide a more abundant source of vertical vorticity. But this mechanism cannot be dismissed in the case of high-CAPE, low-shear tornadoes (see section 3.10).

3.6 *VORTEX SHEET INSTABIITY*

Another barotropic mechanism involves shearing instability on the pseudo-cold front. When unstable, the quasi-vertical vortex sheet at the wind discontinuity rolls up into individual vortices, which can be stretched by overhead convection (Barcilon and Drazin 1972; Davies-Jones and Kessler 1974; Wakimoto and Wilson 1989; Lee and Wilhelmson 1997). In some simulations of tornadic supercell storms, two or three cyclonic vortices move up the gust front and flanking line to the main updraft where they merge into a tornado-like vortex (Adlerman and Droegemeier 2005). But, in other simulations of tornadic storms, the vortices move down the gust front away from the main updraft, and so play no role in the tornadogenesis. Thus, this mechanism cannot be the only one.

3.7 *TWO-CELL MESOCYCLONE*

Agee at al. (1976) explained long-lived tornado families by postulating the existence of smaller-scale tornado cyclones that revolved around the parent mesocyclone. Tornado cyclones do exist but tornado families are due to a succession of mesocyclones within a single supercell, (Burgess et al. 1982). Rotunno (1986) Brandes (1978) and Wakimoto and Liu (1997) proposed that the cylindrical vortex sheet between cells in a two-celled mesocyclone with a central occlusion downdraft could become unstable. The mesocyclone would then transform into two or more tornado cyclones, as in Ward's simulator at large swirl ratio. The tornado cyclones could produce tornadoes through frictional interaction with the ground,

3.8 *TORNADOGENESIS FAILURE*

Why do some imminent tornadoes never develop when strong warning signs are present? Possible explanations are as follows. Markowski et al.'s (2003) axisymmetric model with idealized thermodynamics and precipitation shows that a tornado will not form if the air at the ground is too negatively buoyant and cannot be lifted. This happens in the real world when the outflow is cold and deep and the storm-relative inflow is not strong enough to prevent the density current from propagating ahead of the updraft. Presumably a tornado also will not form (at the axis) if strong centrifugal forces prevent convergence.

3.9 *NEGATIVE EDDY VISCOSITY*

Lilly (1969) attributed the existence of anticyclonic vorticity just outside the core of the Dallas tornado to inward eddy angular momentum flux, a negative eddy viscosity phenomenon that would contribute to tornado maintenance. This process requires large asymmetries of the flow, possibly in the form of spiral bands or inward moving eddies or secondary vortices.

3.10 *WARM-SEASON TORNADOGENESIS*

Storms in high-CAPE, low-shear environments occasionally produce strong and violent tornadoes. These enigmatic storms have rarely been observed during field experiments. Since there is little shear in the environment, they must either avail themselves of pre-existing vorticity along a frontal or outflow boundary or manufacture horizontal vorticity baroclinically and then tilt it towards the vertical. Since environmental inflow winds are light, the cold pool should spread out ahead of the updraft and inhibit tornadogenesis. There are two factors that may mitigate this effect (Davies-Jones et al. 2001). First, the updraft may be so strong that it creates moderate inflow winds through suction. Second, the environmental CAPE is so high that parcels at a considerable distance behind the leading edge of the cold pool still have moderate CAPE and can be lifted.

3.11 *CYCLIC TORNADOGENESIS*

Burgess et al.'s (1982) conceptual model of cyclic mesocyclone core formation, based on Doppler radar data, essentially fits the mesocyclogenesis in both simulated and observed storms. Adlerman et al. (1999) found in simulations of cyclic mesocyclogenesis that the baroclinic mechanism was common to all cycles. The succeeding cycles occurred more rapidly than the first one because cold air from the previous cycle lends to a buoyancy orientation that is favorable for horizontal baroclinic vorticity generation. Adlerman and Droegemeier (2005) simulated cyclic tornadogenesis. The model storm produced six mesocyclones, one of which produced two tornadoes and two others one each. Although some of the mesocyclones formed very near their predecessors and entrained vorticity-rich air from them (as postulated by Davies-Jones 1982), these were nontornadic.

Dowell and Bluestein (2002) analyzed data collected during VORTEX of a cyclic tornadic supercell and, in contrast to the simulations, found no cold air behind the most intense and longest-lived tornado. They concluded that "cyclic tornado formation may result if the horizontal motion of the tornadoes repeatedly does not match the horizontal motion of the main storm-scale updraft and downdraft".

High–precipitation (HP) supercells are not prodigious tornado producers, perhaps because their mesocyclones occlude too rapidly for tornadogenesis to occur.

4. *SUMMARY*

In this paper I argue that the big unknown in supercell tornadogenesis is how rotation develops next to the ground. There may be a variety of modes for this second stage of tornadogenesis. Several plausible mechanisms are reviewed.

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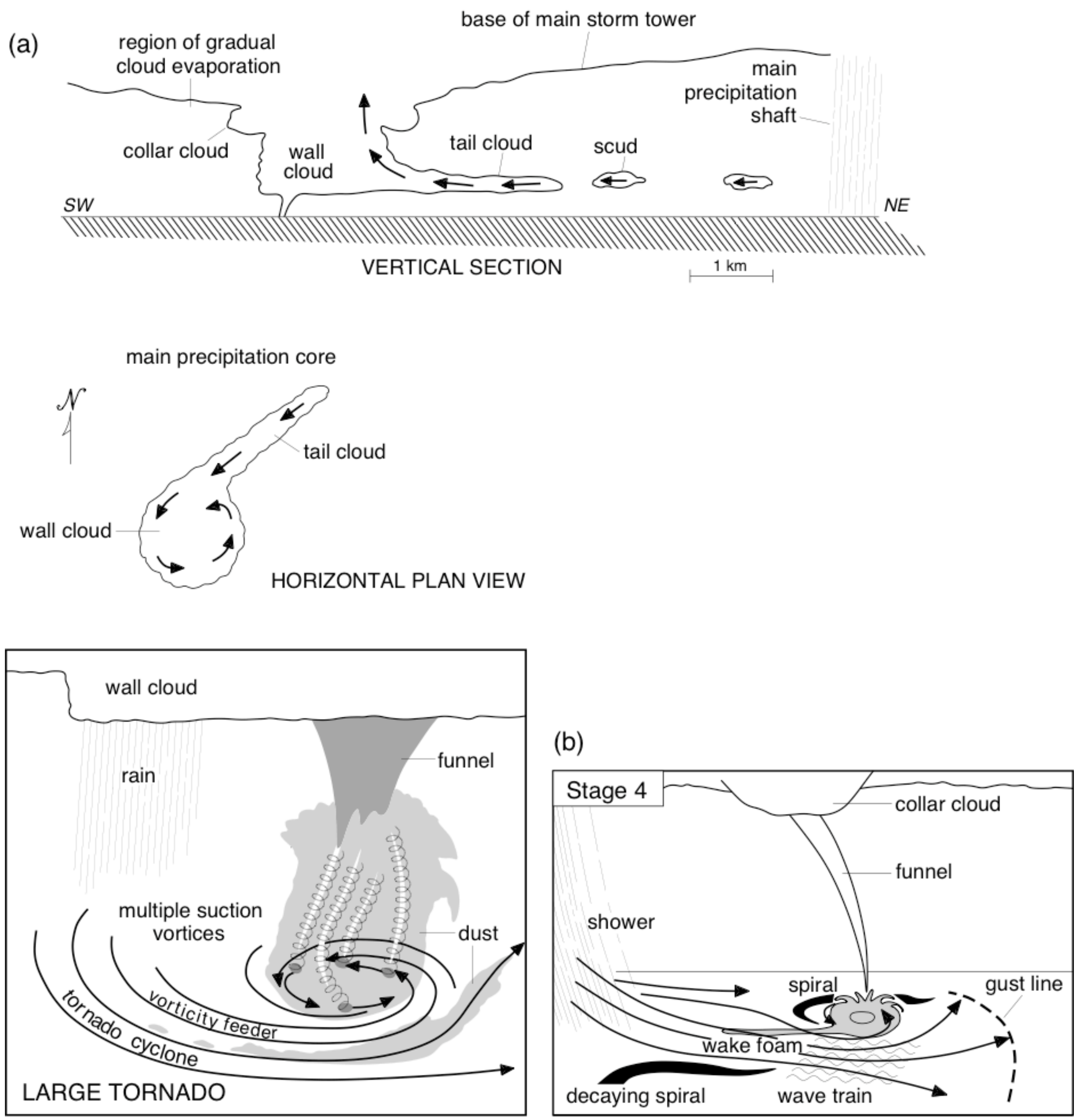

Fig. 1. Diagrams showing relationship of nearby rain shaft and cloud features to (a) tornado (based on Fujita 1959 and from Fujita et al. 1976), and (b) waterspout (based on Golden 1974).

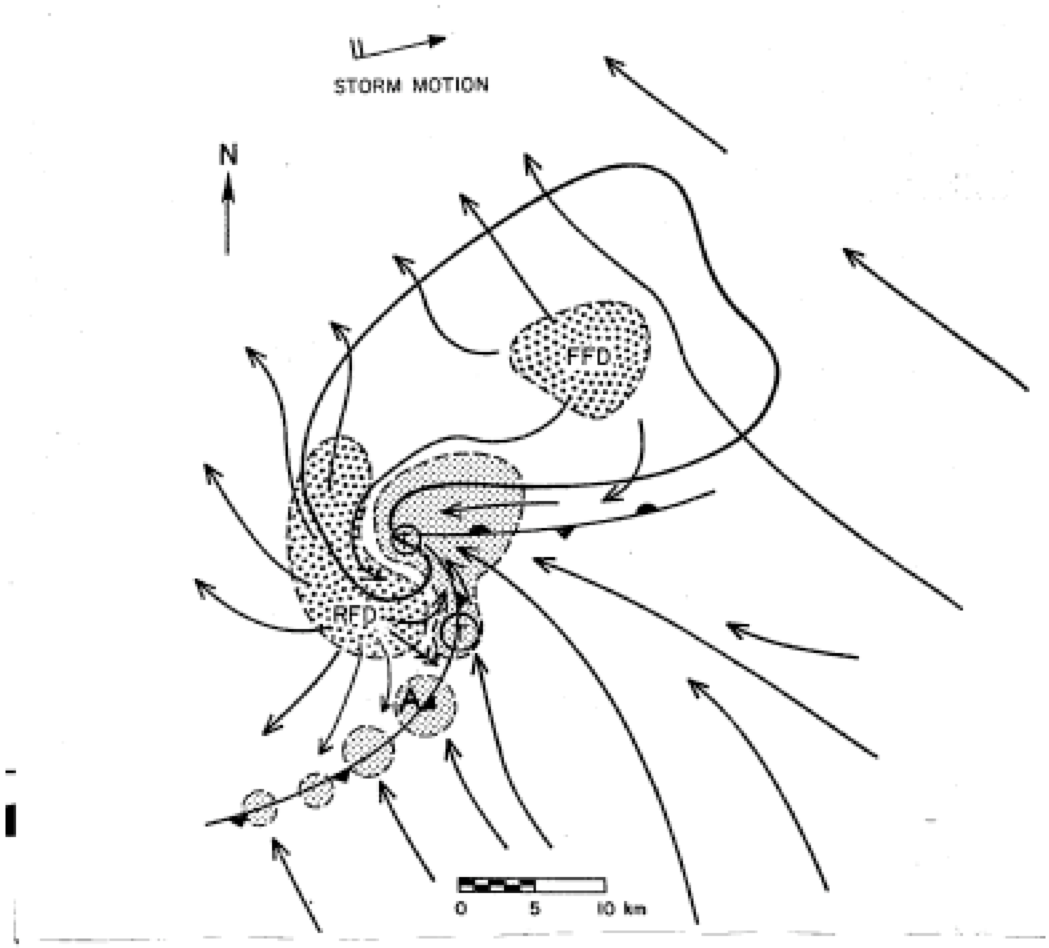

Fig. 2. Schematic plan view of an isolated SR supercell storm near the surface. Thick line encompasses radar echo (note hook on southwest side). The wave-like gust front structure, resembling a synoptic-scale cyclone, is depicted by classic frontal symbols. Low-level positions of the updrafts are finely stippled. Coarse stippling marks location of forward-flank downdraft (FFD) and rear-flank downdraft (RFD). Favored locations for tornadoes are marked by encircled 'T's. The major cyclonic tornado is most probable near mesocyclone center. A minor tornado or a new potentially major tornado may occur at the bulge in the RFD gust front. Southern T also marks position where new mesocyclone core may form as old one occludes. 'A' is most probable location of any anticyclonic tornado that forms. Thin arrows depict storm-relative streamlines (adapted from Lemon and Doswell 1979).

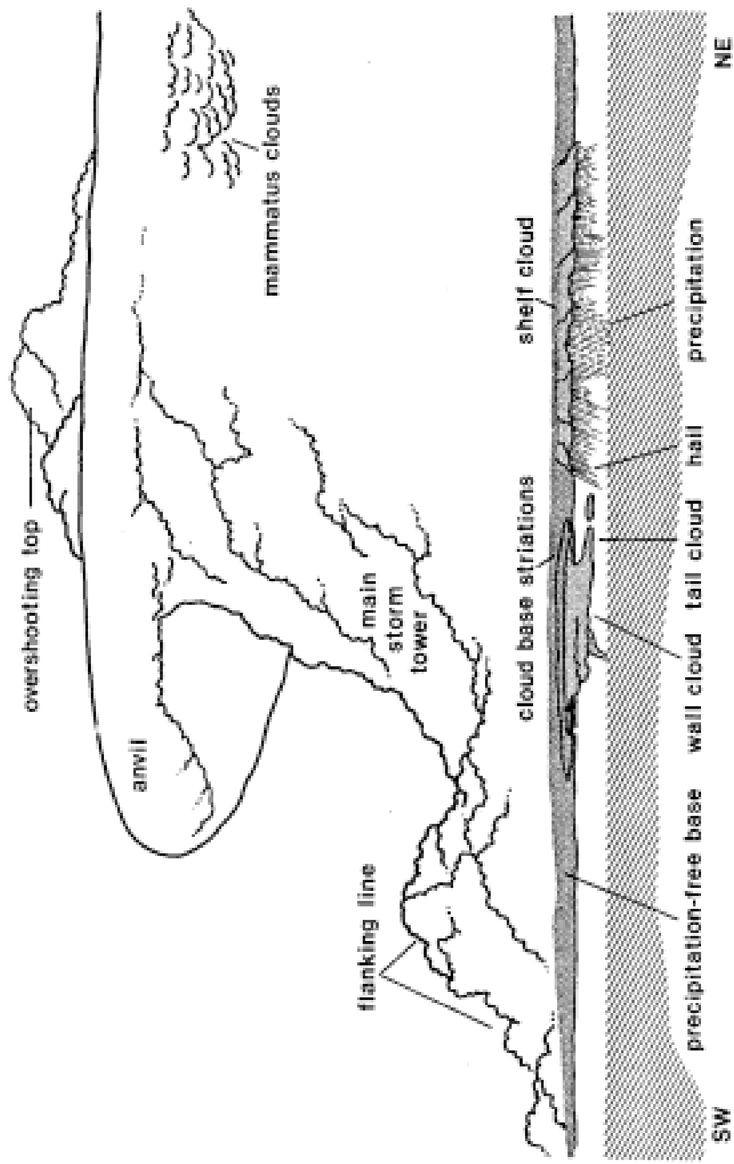

Fig. 3. Composite view of a typical tornado-producing cumulonimbus as seen from a south-easterly direction. Horizontal scale is compressed. All the features shown cannot be seen simultaneously from a single point. Shelf cloud may not be present or may be south of wall cloud instead of northeast of it. With time a spiral precipitation curtain wraps cyclonically around the wall cloud from the northeast (diagram by C. Doswell III).