



Tornadogenesis: Our current understanding, forecasting considerations, and questions to guide future research

Paul M. Markowski*, Yvette P. Richardson

Department of Meteorology, Pennsylvania State University, University Park, PA, United States

ARTICLE INFO

Article history:

Received 30 November 2007

Received in revised form 30 June 2008

Accepted 19 September 2008

Keywords:

Supercell

Thunderstorm

Tornado

Tornadogenesis

Mesocyclone

Mesocyclogenesis

Downdraft

ABSTRACT

This paper reviews our present understanding of tornadogenesis and some of the outstanding questions that remain. The emphasis is on tornadogenesis within supercell thunderstorms. The origin of updraft-scale rotation, i.e., mesocyclogenesis, above the ground is reviewed first, followed by the requisites for the development of rotation near the ground. Forecasting strategies also are discussed, and some speculations are made about the relationships between the dynamics of tornadogenesis and the forecasting parameters that have been somewhat successful discriminators between tornadic and nontornadic supercells.

When preexisting rotation is absent at the ground, a downdraft is required for tornadogenesis. Not surprisingly, decades of tornado observations and supercell simulations have revealed that downdrafts are present in close proximity to tornadoes and significant nontornadic vortices at the surface. Tornadic supercells are favored when the outflow associated with downdrafts is not too negatively buoyant. Cold outflow may inhibit vorticity stretching and/or lead to updrafts that are undercut by their own outflow. It may be for this reason that climatological studies of supercell environments have found that the likelihood of tornadic supercells increases as the environmental, boundary layer relative humidity increases (there is some tendency for supercell outflow to be less negatively buoyant in relatively humid environments). Interestingly, although supercells can modify the environmental horizontal vorticity (associated with the environmental vertical wind shear) by virtue of the baroclinic vorticity generation that accompanies horizontal buoyancy gradients within the storms, tornadic supercells appear to be favored when the environmental horizontal vorticity is large on its own without storm-scale enhancements, and when the thermodynamic properties of the environment actually suppress the formation of strong cold pools and their attendant baroclinic vorticity generation.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

The focus of this paper is on tornadogenesis within supercell thunderstorms. Although a significant fraction of tornadoes is associated with nonsupercellular convection (the exact percentage is unknown, but it is likely on the order of 20% per Trapp et al., 2005a), the vast majority of strong to violent (F2–F5) tornadoes are associated with supercell thunderstorms. Furthermore, the predictability of tornado occurrence within supercells, although not without limits, likely exceeds

the predictability of nonsupercell tornado formation in most instances.¹

A deep, persistent, rotating updraft is widely recognized as the defining characteristic of supercell thunderstorms (Dowell and Burgess, 1993). Although we know much about the dynamics of midlevel mesocyclones, where mesocyclones are defined herein as updraft-scale (roughly 2–10 km wide)

* Corresponding author.

E-mail address: pmarkowski@psu.edu (P.M. Markowski).

¹ The fact that “storm chasers” typically target supercells rather than nonsupercells is due in large part to the difficulty in anticipating tornadogenesis within nonsupercellular convection, e.g., squall lines, growing cumulus congestus clouds, etc.

cyclonically rotating vortices [vertical vorticity of $O(10^{-2} \text{ s}^{-1})$] in convective storms (Glickman, 2000), the details of how near-ground rotation arises and is amplified to tornado strength remain a challenge. We will review our current understanding of the origins of rotation in supercells and the requisites for tornadogenesis. We also will discuss the challenges for forecasters and what strategies are likely to be most fruitful given the current state of our understanding. We will conclude by mentioning what we believe are some of the most important outstanding questions pertaining to tornadogenesis and the relationship between tornadic storms and their parent environments.

2. Updraft rotation away from the ground

It is widely accepted that vertical vorticity initially arises within thunderstorm updrafts as a result of tilting and subsequent stretching of horizontal vorticity associated with mean vertical wind shear (Barnes, 1970; Rotunno, 1981; Davies-Jones, 1984; Fig. 1). Tilting of horizontal vorticity by an updraft alone (as opposed to tilting by an updraft–downdraft pair) typically results in appreciable vertical vorticity [i.e., $O(10^{-2} \text{ s}^{-1})$] only after the air has risen a significant height above the ground [nominally $\geq 1 \text{ km}$ above ground level (AGL)]. For a given horizontal gradient of vertical velocity, the height at which significant vertical vorticity is acquired decreases as the horizontal vorticity increases.

When the environmental horizontal vorticity is purely crosswise, updrafts acquire no net rotation, but consist of a dipole of equally strong positive and negative vertical vorticity extrema that straddle the updraft, with the positive (negative) vorticity extremum being located on the right (left) flank of the updraft when looking down-shear (Davies-Jones, 1984). Updrafts acquire net cyclonic (anticyclonic) rotation when the environmental horizontal vorticity has a streamwise (antistreamwise) component,



Fig. 1. Vertical vorticity is acquired by supercells via the tilting of horizontal vorticity associated with the environmental vertical wind shear. An environmental vortex line is overlaid schematically on a photo of a supercell thunderstorm, with the sense of rotation indicated by the arrows. (Photo courtesy of Jessica Higgs).

and the correlation between vertical velocity and vertical vorticity increases as the ratio of streamwise to crosswise vorticity increases, all else being equal (storm-relative wind strength, growth rate of the isentropic surface; Davies-Jones, 1984).

Three-dimensional numerical simulations of supercell thunderstorms have shown that baroclinic horizontal vorticity generation by horizontal buoyancy gradients along the forward-flank gust front can enhance the horizontal vorticity available for tilting by the updraft (Klemp and Rotunno, 1983; Rotunno and Klemp, 1985). This baroclinic vorticity generation within the forward-flank horizontal buoyancy gradient tends to be streamwise because storm-relative winds approaching the updraft from the forward flank are generally normal to the horizontal buoyancy gradient. The tilting of this locally enhanced horizontal vorticity results in significant vertical vorticity being acquired at lower altitudes than in the early stages in a storm's life, before cold pools and their attendant horizontal buoyancy gradients have become established. In simulations with relatively modest environmental windshear (although sufficient for supercells), mesocyclones (vertical vorticity $\geq 0.01 \text{ s}^{-1}$) do not develop at low levels until a forward-flank baroclinic zone develops (Klemp and Rotunno, 1983; Rotunno and Klemp, 1985). However, when environmental horizontal vorticity is exceptionally large (e.g., $>0.02 \text{ s}^{-1}$ in approximately the lowest kilometer), significant vertical vorticity can arise at altitudes as low as 750–1000 m AGL at early stages in a storm's life via the tilting of environmental horizontal vorticity alone. Recent observations reported by Shabbott and Markowski (2006) have raised some questions about the general importance of horizontal vorticity generation within the forward-flank baroclinic zone, as field experiment datasets have failed to observe strong baroclinity, at least at the surface, in a significant fraction of supercells. It is possible that the relative importance of forward-flank baroclinity increases as the environmental vorticity weakens. For cases of very strong environmental vorticity, forward-flank baroclinic generation may not be as not crucial to the vorticity budget of the mesocyclone. The issue of environmental vorticity versus storm-generated vorticity will be discussed further in Section 4.

3. Requisites for near-ground rotation

By definition, tornadogenesis requires that large vertical vorticity arises at the ground. If preexisting vertical vorticity is negligible near the ground, then vorticity stretching near the ground is initially negligible and vertical vorticity first must arise either from the tilting of horizontal vorticity or from advection toward the surface from aloft. Tilting by the horizontal vertical velocity gradients associated with an updraft alone is not effective at producing vertical vorticity near the surface because air is rising away from the surface as horizontal vorticity is tilted into the vertical (Fig. 2a–c). But if a downdraft is involved in the tilting process, then vertical vorticity can be advected toward the surface as it is produced (or after it has been produced) via tilting (Davies-Jones and Brooks, 1993; Davies-Jones et al., 2001), where it subsequently can be stretched to form a tornado (Fig. 2d–e). For these reasons, it has been argued that a downdraft is needed for tornadogenesis when preexisting rotation is

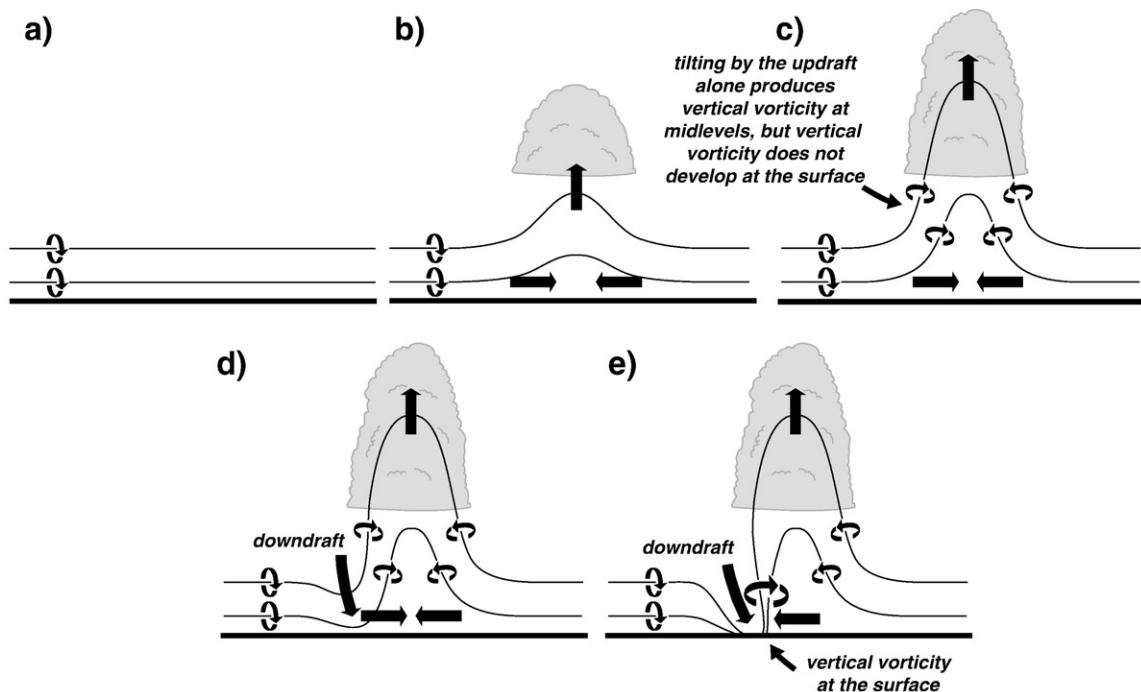


Fig. 2. Simple vortex line demonstration of why a downdraft is needed in order for significant vertical vorticity to develop at the ground beneath a thunderstorm in the absence of preexisting vertical vorticity at the surface. (a)–(c) Evolution of vortex lines as a result of tilting by an updraft alone. (d)–(e) Possible evolution of vortex lines following the formation of a downdraft. There is assumed to be no baroclinic vorticity generation; thus, the vortex lines in (a)–(e) are assumed to be “frozen” in the fluid and move as material lines. This is obviously an oversimplification, for there must be baroclinity at least somewhere or else a buoyant updraft could not exist in the first place (rainy downdrafts and their associated baroclinity, if it is even just a result of hydrometeor loading, also are a virtual certainty at least somewhere in the vicinity of a thunderstorm updraft). Nonetheless, the basic conclusion reached from considering only a purely barotropic redistribution of vorticity is not changed; if tilting of vortex lines is accomplished by an only an updraft, significant vertical vorticity cannot arise at the ground because air is rising away from the ground as it is tilted. On the other hand, if a downdraft is involved, a positive contribution to the vertical vorticity tendency can arise from tilting even as air is sinking toward the ground.

absent near the ground (Davies-Jones, 1982a,b). (This conclusion depends on eddies being too weak to transport vertical vorticity downward against the flow. Furthermore, once a tornado is established, tilting of surface-layer horizontal vorticity by the extreme vertical velocity gradient associated with the tornado updraft itself probably contributes to the near-ground vertical vorticity in a significant way. However, such abrupt upward turning of streamlines, strong pressure gradients, and large vertical velocities are not present near the ground prior to tornadogenesis; thus, such tilting in the absence of a downdraft cannot be invoked to explain the amplification of near-ground vertical vorticity that results in tornadogenesis.)

The aforementioned theoretical arguments for the importance of downdrafts in tornadogenesis have been verified in numerical simulations (e.g., Rotunno and Klemp, 1985; Walko, 1993; Grasso and Cotton, 1995; Adlman et al., 1999). Moreover, nearly countless observations exist (e.g., Fig. 3) of rear-flank downdrafts (RFDs), hook echoes, and “clear slots” in close proximity to tornadoes (Markowski, 2002). Furthermore, trajectory analyses in a limited number of observed supercells indicate that at least some of the air entering the tornado passes through the RFD prior to entering the tornado (e.g., Brandes, 1978). Numerical simulation results also have emphasized the importance of the RFD and have

shown similar trajectories of air parcels entering modeled vortices resembling tornadoes (Wicker and Wilhelmson, 1995; Xue, 2004).

Analyses of vortex lines in the vicinity of low-level mesocyclones reveal that vortex lines form arches that join counter-rotating vortices (one of which is the cyclonic vortex associated with the tornado parent circulation) on opposite sides of the RFD (Straka et al., 2007; Markowski et al., 2008; Fig. 4). Such vortex line structures suggest an important role for baroclinic vorticity generation within a downdraft in the development of rotation near the ground. The arching vortex line structure also bears a striking resemblance to the structure of the vortex lines that pass through the line-end vortices of bow echoes (Weisman and Davis, 1998). In bow echoes, baroclinically generated vortex lines within the outflow are lifted out of the outflow along the outflow's leading edge, leading to the counter-rotating, line-end vortices. It is tempting to wonder whether similar dynamics are at work in the RFD region of supercell thunderstorms, i.e., a baroclinic process like that suggested by the vortex line configuration evident in Fig. 4, rather than simply a redistribution of environmental vorticity (Fig. 2d–e).

When there is preexisting rotation at the surface, a downdraft such as the RFD is not needed for tornadogenesis. In these cases, near-ground convergence alone can amplify vertical

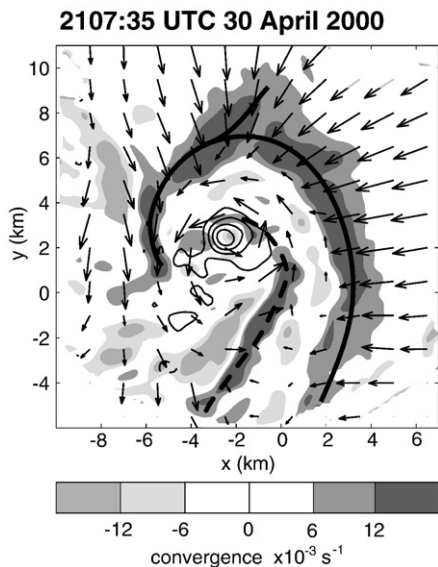


Fig. 3. Horizontal cross-section of convergence (shaded), vorticity (contoured), and storm-relative wind (vectors) at 150 m AGL in a tornadic supercell on 30 April 2000 (the tornado is located approximately at the location of maximum analyzed vorticity). The outermost contour of vertical vorticity is 0.02 s^{-1} , incremented by 0.025 s^{-1} . Gust fronts are indicated with solid heavy lines, and a secondary RFD gust front is indicated with a dashed heavy line. Note the occluded gust front structure and how the tornado is completely encircled by downdraft air. Adapted from Marquis et al. (2008).

vorticity to tornado intensity (Fig. 5). It seems as though nonsupercell tornadoes like waterspouts and landspouts (e.g., Wakimoto and Wilson, 1989; Roberts and Wilson, 1995), and perhaps most other geophysical vortices, commonly arise in this manner.

4. Challenges to forecasters

Although supercells might be regarded as being relatively easy to anticipate, predicting which supercells will spawn tornadoes is one of the most arduous tasks facing forecasters and researchers alike. A recent study in the U.S. has confirmed prior anecdotal evidence of the relative infrequency of tornadoes even within supercells; Trapp et al. (2005b) reported that only about a quarter of all radar-detected mesocyclones were associated with tornadoes, using fairly stringent mesocyclone detection criteria. Tornadoes occur over a broad range of midlevel mesocyclone intensities, with some of the most intense mesocyclones ever documented being observed in nontornadic supercells (Wakimoto et al., 2004).

Except in rare circumstances, radars only detect tornado parent circulations (i.e., mesocyclones)—they cannot resolve tornadoes themselves. One of the most fruitful strategies undertaken in the U.S. for improving tornado warnings has been to combine real-time radar data with observations of the near-storm environment.

Two parameters seem to offer the most promise in discriminating between nontornadic and tornadic supercells: (1) boundary layer water vapor concentration and (2) low-level vertical wind shear (Fig. 6). Boundary layers with large relative humidity and low-level vertical shear (relative to the average supercell environment) are most favorable for tornadic supercells. This might explain why some supercells suddenly become tornadic upon encountering pre-existing mesoscale boundaries (e.g., outflow boundaries, warm fronts; Maddox et al., 1980; Markowski et al., 1998; Rasmussen et al., 2000); the depth of the boundary layer moisture is often enhanced within such mesoscale convergence zones (Wilson et al., 1992), and the low-level horizontal vorticity is often augmented by

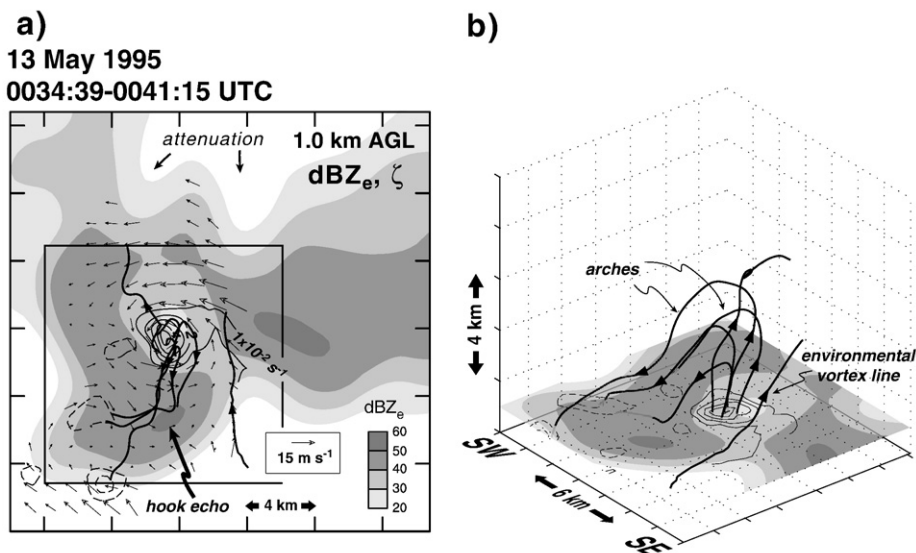


Fig. 4. (a) Equivalent radar reflectivity factor (dBZ_e ; shaded) at 1.0 km AGL at 0034:39–0041:15 UTC 13 May 1995. Dual-Doppler derived, storm-relative wind vectors and vertical vorticity contours (10^{-2} s^{-1} contour interval; the zero contour is suppressed and negative contours are dashed) at the same altitude also are overlaid, as are projections of select vortex lines (bold solid lines) onto the ground. The direction of the vorticity vector is indicated by the arrow heads. Five of the vortex lines pass through points centered on and surrounding the vertical vorticity maximum at 1.0 km. A sixth vortex line originates in the environment ahead of the gust front. The region enclosed by the square is shown in (b). (b) A three-dimensional perspective of the vortex lines emanating from the low-level mesocyclone center. Adapted from Markowski et al. (2008).

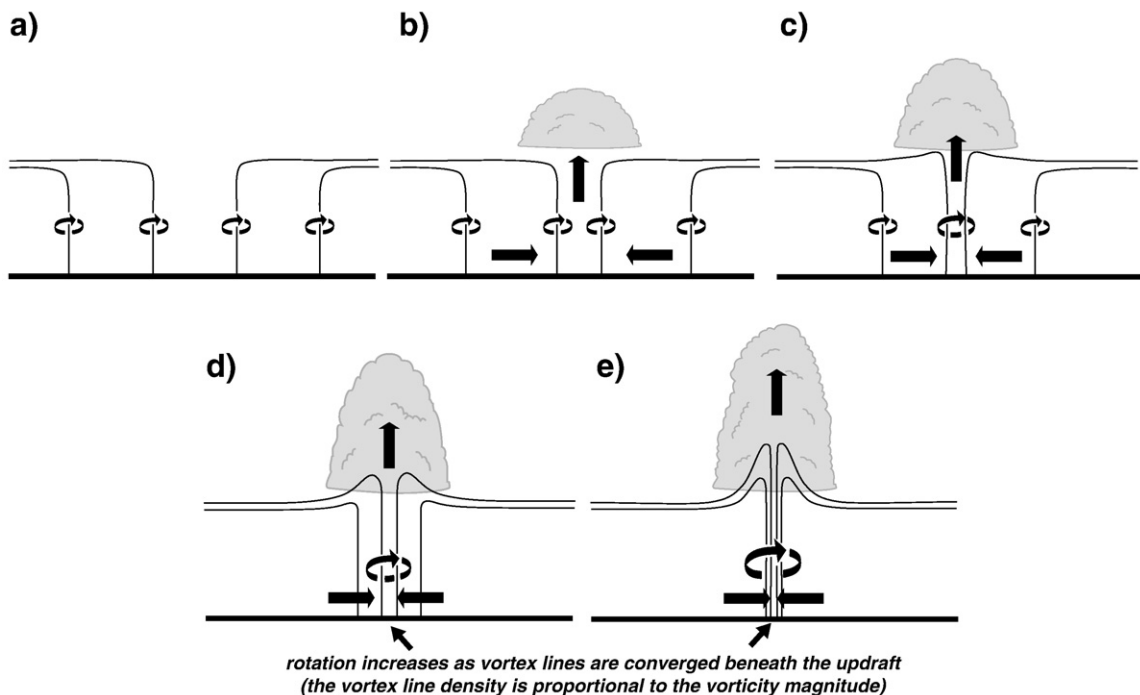


Fig. 5. (b) As in Fig. 5, but for the case of preexisting vertical vorticity at the surface that is amplified by convergence alone beneath an updraft.

baroclinic vorticity generation along mesoscale boundaries (Markowski et al., 1998).

There is growing evidence that strong cold pools and excessive negative buoyancy are detrimental to tornadogenesis (Markowski et al., 2002, 2003; Shabbott and Markowski, 2006;

Grzych et al., 2007; Fig. 7), and these findings are consistent with climatological studies (Rasmussen and Blanchard, 1998; Thompson et al., 2003) showing that tornadic supercells are favored in environments having a low cloud base (environments with a low cloud base, i.e., large boundary layer relative

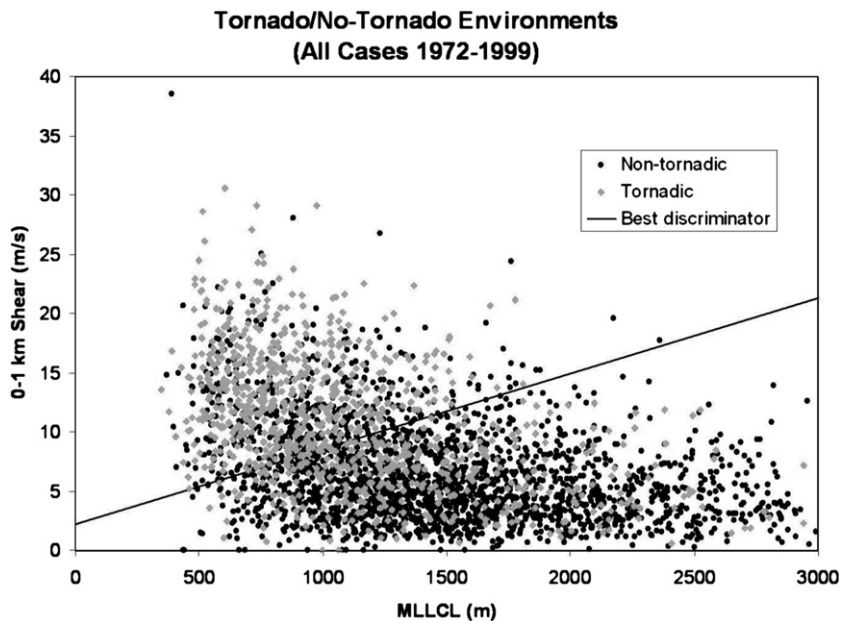
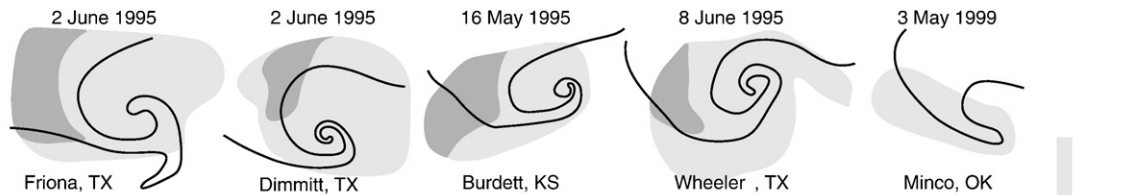


Fig. 6. Observations of tornadic versus nontornadic supercells as a function of low-level shear and mean boundary layer relative humidity of the environment (what actually is displayed on the axes is the magnitude of the 0–1 km vertical wind shear vector and the LCL computed by lifting an air parcel having the mean potential temperature and specific humidity of the lowest 1 km). Tornadoes are favored in environments containing large low-level relative humidity and low-level wind shear. Although this combination of environmental parameters has been found to be the most promising to date, much overlap still exists between the tornadic and nontornadic occurrences (the overlap is somewhat reduced if weak tornadoes are filtered). Courtesy of Harold Brooks.

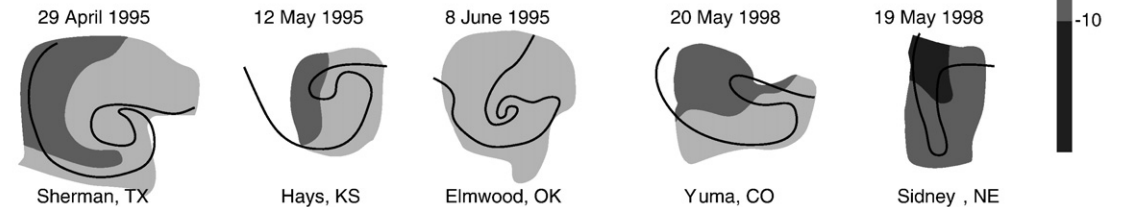
SIGNIFICANTLY TORNADIC ♦



WEAKLY TORNADIC ♦



NON TORNADIC ♦♦



♦ Sampled within 5 min of tornadogenesis

♦♦ Sampled within 5 min of strongest rotation on lowest tilt of nearest WSR-88D

Fig. 7. Surface virtual potential temperature perturbations measured by mobile mesonets (Straka et al., 1996) within the hook echo and RFD regions of supercells. The black contours outline the 40 dBZ radar echoes of the storms in order to emphasize the hook echoes. Regions left unshaded represent regions that were not sampled by the mobile mesonets. Supercells that spawned significant tornadoes were associated with warmer RFD outflow, on average, compared to nontornadic or weakly tornadic supercells. Adapted from Markowski et al. (2002).

humidity, can limit the production of exceptionally cold outflow.² These observations might be surprising given the aforementioned vortex line analyses in supercell low-level mesocyclone regions (Fig. 4), which suggest that baroclinic vorticity generation is important. However, though baroclinic vorticity generation might be important, this does not necessarily imply that storms having the strongest cold pools and baroclinic vorticity generation are the most likely to produce tornadoes. It is possible that the optimal amount of baroclinic vorticity generation is a “Goldilocks” problem, whereby some baroclinic vorticity generation is crucial (after all, convective storms unavoidably have at least some baroclinity), but that excessive baroclinic vorticity generation is associated with effects that inhibit tornadogenesis.

It seems as though tornadic supercells might benefit from large low-level horizontal vorticity that is not accompanied by large negative buoyancy; strong cold pools have a tendency to either undercut updrafts (e.g., Brooks et al., 1993) and/or

suppress vorticity stretching beneath the updraft (e.g., Leslie and Smith, 1978; Markowski et al., 2003). When the ambient horizontal vorticity is only relatively modest, then perhaps tornadogenesis requires significant baroclinic enhancement of the ambient horizontal vorticity. Such enhancement might be difficult to accomplish without strong storm-induced baroclinity (which is suppressed by large ambient low-level relative humidity), but strong baroclinity is difficult to achieve without fairly strong cold pools. It is worth noting that there is some tendency for mesoscale boundaries to more strongly favor tornadogenesis following supercell–boundary interactions when the air mass containing enhanced vertical wind shear (typically the cool side of the boundary) does not have a large amount of convective inhibition (Markowski et al., 1998). When storms move into regions of large convective inhibition, they may become “elevated” (Colman, 1990a,b)—elevated supercells are predominantly nontornadic—or dissipate altogether.

One might surmise that the lifting of baroclinically generated vortex lines originating in the outflow of a storm such as that shown in Fig. 4 would be facilitated if the outflow is not too negatively buoyant (therefore less work is required to lift air against the stratification) and when the dynamically-driven, low-level updraft is strong. The strength of this updraft generally ought to increase with increasing environmental low-level wind shear. It is perhaps for these reasons

² Of course, the thermodynamic properties of outflow also are affected by the entrainment of environmental (typically dry and potentially cold) air aloft, in addition to the melting of graupel and hail (which are enhanced in humid environments). In spite of this, the buoyancy of low-level outflow, in supercells at least, has been found to be most strongly a function of the low-level relative humidity (Markowski et al., 2002; Shabbott and Markowski, 2006).

that the combination of high boundary layer relative humidity and vertical wind shear favor tornadic supercells over nontornadic supercells (Fig. 6).

5. Future research

There are a number of aspects of supercell thunderstorms and tornadogenesis that remain poorly understood. Among these are the four-dimensional forcings of RFDs and their dynamical role in tornadogenesis (e.g., vorticity redistribution versus vorticity generation within the RFD), the importance of microphysical differences among supercells and how those microphysical differences arise (Tartaglione et al., 1996; Gilmore et al., 2004; van den Heever and Cotton, 2004), the thermodynamic characteristics of supercells above the ground, the effects of radiative transfer processes on storm dynamics (Markowski and Harrington, 2005; Frame and Markowski, 2006), the dynamics of storm–storm (Lee et al., 2006) and storm–boundary interactions (Atkins et al., 1999; Rasmussen et al., 2000), and the importance, if any, of meso- γ -scale variability (such as that due to dry boundary layer convection) on storms (Markowski and Richardson, 2007). We are optimistic that substantial gains in understanding can be achieved in the not-too-distant future as a result of new field projects [e.g., the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) scheduled for 2009; it will be important to complement the three-dimensional wind observations, which will be nested down to the tornado scale, with much better thermodynamic observations, and perhaps microphysics observations inferred from mobile dual-polarimetric radars], continually increasing computing power, used not just for simulations but also to improve diagnoses of storm morphology via data assimilation (Snyder and Zhang, 2003; Dowell et al., 2004; Zhang and Snyder, 2007), and a growing interest in severe convective storms worldwide.

Acknowledgments

We are indebted to our current and former students at Penn State University who have worked on problems related to supercell thunderstorms (Zack Byko, Jeff Frame, Mario Majcen, Jim Marquis, and Chris Shabbott), and collaborators (Curtis Alexander, Harold Brooks, Don Burgess, Chuck Doswell, David Dowell, Jerry Harrington, Erik Rasmussen, Jerry Straka, Lou Wicker, and Josh Wurman). We also are grateful for the support of the National Science Foundation (awards ATM-0338661, ATM-0437512, and ATM-0644533).

References

- Adlerman, E.J., Droegemeier, K.K., Davies-Jones, R., 1999. A numerical simulation of cyclic mesocyclogenesis. *J. Atmos. Sci.* 56, 2045–2069.
- Atkins, N.T., Weisman, M.L., Wicker, L.J., 1999. The influence of preexisting boundaries on supercell evolution. *Mon. Weather Rev.* 127, 2910–2927.
- Barnes, S.L., 1970. Some aspects of a severe, right-moving thunderstorm deduced from mesonet rawinsonde observations. *J. Atmos. Sci.* 27, 634–648.
- Brandes, E.A., 1978. Mesocyclone evolution and tornadogenesis: some observations. *Mon. Weather Rev.* 106, 995–1011.
- Brooks, H.E., Doswell III, C.A., Davies-Jones, R.P., 1993. Environmental helicity and the maintenance and evolution of low-level mesocyclones. Tornadoes and tornadic storms: a review of conceptual models. The Tornado: Its Structure, Dynamics, Prediction, and Hazards. Geophys. Union, pp. 97–104. No. 79.
- Colman, B.R., 1990a. Thunderstorms above frontal surfaces in environments without positive CAPE. Part I: a climatology. *Mon. Weather Rev.* 118, 1103–1122.
- Colman, B.R., 1990b. Thunderstorms above frontal surfaces in environments without positive CAPE. Part II: organization and instability mechanisms. *Mon. Weather Rev.* 118, 1123–1144.
- Davies-Jones, R.P., 1982a. A new look at the vorticity equation with application to tornadogenesis. Preprints 12th Conf. on Severe Local Storms. Amer. Meteor. Soc., San Antonio, TX, pp. 249–252.
- Davies-Jones, R.P., 1982b. Observational and theoretical aspects of tornadogenesis. In: Bengtsson, L., Lighthill, J. (Eds.), *Intense Atmospheric Vortices*. Springer-Verlag, pp. 175–189.
- Davies-Jones, R.P., 1984. Streamwise vorticity: the origin of updraft rotation in supercell storms. *J. Atmos. Sci.* 41, 2991–3006.
- Davies-Jones, R.P., Brooks, H.E., 1993. Mesocyclogenesis from a theoretical perspective. Tornadoes and tornadic storms: a review of conceptual models. The Tornado: Its Structure, Dynamics, Prediction, and Hazards. Geophys. Monogr. Amer. Geophys. Union, pp. 105–114. No. 79.
- Davies-Jones, R.P., Trapp, R.J., Bluestein, H.B., 2001. Tornadoes and tornadic storms. *Meteor. Monogr. Amer. Meteor. Soc.*, pp. 167–221. No. 50.
- Doswell, C.A., Burgess, D.W., 1993. Tornadoes and tornadic storms: a review of conceptual models. The Tornado: Its Structure, Dynamics, Prediction, and Hazards. Geophys. Monogr. Amer. Geophys. Union, pp. 161–172. No. 79.
- Dowell, D.C., Zhang, F., Wicker, L.J., Snyder, C., Crook, N.A., 2004. Wind and temperature retrievals in the 17 May 1981 Arcadia, Oklahoma supercell: ensemble Kalman filter experiments. *Mon. Weather Rev.* 132, 1982–2005.
- Frame, J., Markowski, P., 2006. Simulations of a supercell thunderstorm with radiative transfer, surface physics, and a soil model. Preprints 23rd Conf. on Severe Local Storms. Amer. Meteor. Soc., St. Louis, MO.
- Gilmore, M.S., Straka, J.M., Rasmussen, E.N., 2004. Precipitation and evolution sensitivity in simulated deep convective storms: comparison with liquid-only and simple ice and liquid phase microphysics. *Mon. Weather Rev.* 132, 1897–1916.
- Glickman, T.S. (Ed.), 2000. *Glossary of Meteorology*, 2d ed. Amer. Meteor. Soc., 855 pp.
- Grasso, L.D., Cotton, W.R., 1995. Numerical simulation of a tornado vortex. *J. Atmos. Sci.* 52, 1192–1203.
- Grzych, M.L., Lee, B.D., Finley, C.A., 2007. Thermodynamic analysis of supercell rear-flank downdrafts from Project ANSWERS. *Mon. Weather Rev.* 135, 240–246.
- Klemp, J.B., Rotunno, R., 1983. A study of the tornadic region within a supercell thunderstorm. *J. Atmos. Sci.* 40, 359–377.
- Lee, B.D., Jewett, B.F., Wilhelmson, R.B., 2006. The 19 April 1996 Illinois tornado outbreak. Part II: cell mergers and associated tornado incidence. *Weather Forecast.* 21, 449–464.
- Leslie, L.M., Smith, R.K., 1978. The effect of vertical stability on tornadogenesis. *J. Atmos. Sci.* 35, 1281–1288.
- Maddox, R.A., Hoxit, L.R., Chappell, C.F., 1980. A study of tornadic thunderstorm interactions with thermal boundaries. *Mon. Weather Rev.* 108, 322–336.
- Markowski, P.M., 2002. Hook echoes and rear-flank downdrafts: a review. *Mon. Weather Rev.* 130, 852–876.
- Markowski, P.M., Harrington, J., 2005. A simulation of a supercell thunderstorm with emulated radiative cooling beneath the anvil. *J. Atmos. Sci.* 62, 2607–2617.
- Markowski, P.M., Richardson, Y.P., 2007. Observations of vertical wind shear heterogeneity in convective boundary layers. *Mon. Weather Rev.* 135, 843–861.
- Markowski, P.M., Rasmussen, E.N., Straka, J.M., 1998. The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Weather Forecast.* 13, 852–859.
- Markowski, P.M., Straka, J.M., Rasmussen, E.N., 2002. Direct surface thermodynamic observations within the rear-flank downdrafts of nontornadic and tornadic supercells. *Mon. Weather Rev.* 130, 1692–1721.
- Markowski, P.M., Straka, J.M., Rasmussen, E.N., 2003. Tornadogenesis resulting from the transport of circulation by a downdraft. *J. Atmos. Sci.* 60, 795–823.
- Markowski, P.M., Straka, J.M., Rasmussen, E.N., Davies-Jones, R.P., Richardson, Y.P., & Trapp, R.J., 2008. Vortex lines within low-level mesocyclones obtained from pseudo-dual-Doppler radar observations. Accepted by *Mon. Weather Rev.*, pending revisions.
- Marquis, J.M., Richardson, Y., Wurman, J., and Markowski, P., 2008. Single- and dual-Doppler analysis of a tornadic vortex and surrounding storm-scale flow in the Crowell, TX, supercell of 30 April 2000. Submitted to *Mon. Weather Rev.*
- Rasmussen, E.N., Blanchard, D.O., 1998. A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Weather Forecast.* 13, 1148–1164.
- Rasmussen, E.N., Richardson, S.J., Straka, J.M., Markowski, P.M., 2000. The association of significant tornadoes with a baroclinic boundary on 2 June 1995. *Mon. Weather Rev.* 128, 174–191.

- Roberts, R.D., Wilson, J.W., 1995. The genesis of three nonsupercell tornadoes observed with dual-Doppler radar. *Mon. Weather Rev.* 123, 3408–3436.
- Rotunno, R., 1981. On the evolution of thunderstorm rotation. *Mon. Weather Rev.* 109, 577–586.
- Rotunno, R., Klemp, J.B., 1985. On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.* 42, 271–292.
- Shabbott, C.J., Markowski, P.M., 2006. Surface in situ observations within the outflow of forward-flank downdrafts of supercell thunderstorms. *Mon. Weather Rev.* 134, 1422–1441.
- Snyder, C., Zhang, F., 2003. Assimilation of simulated Doppler radar observations with an ensemble Kalman filter. *Mon. Weather Rev.* 131, 1663–1677.
- Straka, J.M., Rasmussen, E.N., Fredrickson, S.E., 1996. A mobile mesonet for fine-scale meteorological observations. *J. Atmos. Ocean. Technol.* 13, 921–936.
- Straka, J.M., Rasmussen, E.N., Davies-Jones, R.P., Markowski, P.M., 2007. An observational and idealized numerical examination of low-level counter-rotating vortices toward the rear flank of supercells. *E.J. Severe Storms Met.* 2 (8), 1–22. <http://www.ejssm/article/view/32>.
- Tartaglione, N., Buzzi, A., Fantini, M., 1996. Supercell simulations with simple ice parameterization. *Meteorol. Atmos. Phys.* 58, 149–159.
- Thompson, R.L., Edwards, R., Hart, J.A., Elmore, K.L., Markowski, P.M., 2003. Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Weather Forecast.* 18, 1243–1261.
- Trapp, R.J., Tessendorf, S.A., Savageau Godfrey, E., Brooks, H.E., 2005a. Tornadoes from squall lines and bow echoes. Part I: climatological distribution. *Weather Forecast.* 20, 23–34.
- Trapp, R.J., Stumpf, G.J., Manross, K.L., 2005b. A reassessment of the percentage of tornadic mesocyclones. *Weather Forecast.* 20, 23–34.
- van den Heever, S.C., Cotton, W.R., 2004. The impact of hail size on simulated supercell storms. *J. Atmos. Sci.* 61, 1596–1609.
- Wakimoto, R.M., Wilson, J.W., 1989. Non-supercell tornadoes. *Mon. Weather Rev.* 117, 1113–1140.
- Wakimoto, R.M., Cai, H., Murphey, H.V., 2004. The Superior, Nebraska, supercell during BAMEX. *Bull. Am. Meteorol. Soc.* 85, 1095–1106.
- Walko, R.L., 1993. Tornado spin-up beneath a convective cell: required basic structure of the near-field boundary layer winds. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards. Geophys. Monogr. Amer. Geophys. Union*, pp. 89–95. No. 79.
- Weisman, M.L., Davis, C.A., 1998. Mechanisms for the generation of mesoscale vortices within quasi-linear convective systems. *J. Atmos. Sci.* 55, 2603–2622.
- Wicker, L.J., Wilhelmson, R.B., 1995. Simulation and analysis of tornado development and decay within a three-dimensional supercell thunderstorm. *J. Atmos. Sci.* 52, 2675–2703.
- Wilson, J.W., Foote, G.B., Crook, N.A., Fankhauser, J.C., Wade, C.G., Tuttle, J.D., Mueller, C.K., 1992. The role of boundary-layer convergence zones and horizontal rolls in the initiation of thunderstorms: a case study. *Mon. Weather Rev.* 120, 1785–1815.
- Xue, M., 2004. Tornadogenesis within a simulated supercell storm. *Preprints 22nd Conf. on Severe Local Storms. Amer. Meteor. Soc., Hyannis, MA.*
- Zhang, F., Snyder, C., 2007. Ensemble-based data assimilation. *Bull. Am. Meteorol. Soc.* 88, 565568.