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

Paul Markowski
Department of Meteorology, Pennsylvania State University,
University Park, Pennsylvania, USA, pmarkowski@psu.edu

I. INTRODUCTION

Although we know much about the dynamics of midlevel updraft rotation—the defining characteristic of supercell thunderstorms—the details of how near-ground rotation arises and is amplified to tornado strength remain a challenge. I will review our current understanding of the origins of rotation in supercells and the requisites for tornadogenesis. I also will discuss the challenges for forecasters and what strategies are likely to be most fruitful given the current state of our understanding. I will conclude by mentioning what I believe are some of the most important outstanding questions pertaining to tornadogenesis and the relationship between tornadic storms and their parent environments.

II. UPDRAFT ROTATION AWAY FROM THE GROUND

It is widely accepted that vertical vorticity arises within thunderstorm updrafts (away from the ground) as a result of tilting and subsequent stretching of horizontal vorticity associated with mean vertical wind shear (Barnes 1978; Rotunno 1981; Davies-Jones 1984). 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 downshear (Davies-Jones 1984). Updrafts acquire net cyclonic (anticyclonic) rotation when the environmental horizontal vorticity has a streamwise (antistreamwise) component, 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 isentropic surface; Davies-Jones 1984).

Three-dimensional numerical simulations of supercell thunderstorms have shown that baroclinic horizontal vorticity, generated by the horizontal buoyancy gradient along the forward-flank gust front, can be tilted into the vertical and stretched, just as environmental horizontal vorticity associated with the mean vertical wind shear is tilted and stretched (Klemp and Rotunno 1983; Rotunno and Klemp 1985). This horizontal vorticity tends to be streamwise because storm-relative winds approaching the updraft from the forward flank are generally normal to the horizontal buoyancy gradient. Whereas the tilting of environmental horizontal vorticity has been shown to be fundamental to the formation of midlevel mesocyclones, the tilting of horizontal vorticity originating within this baroclinic zone has been implicated in the formation of low-level mesocyclones (Klemp and Rotunno 1983; Rotunno and Klemp 1985), where "low-level" typically has referred to approximately a few hundred meters to ∼1 km above ground level. Recent observations reported by Shabbott and Markowski (2006), however, have raised some questions about the importance of horizontal vorticity generation within the forward-flank baroclinic zone.

III. 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. But if a downdraft is involved in the tilting process, then vertical vorticity can be advected toward the surface as it is produced via tilting (Davies-Jones and Brooks 1993), where it subsequently can be stretched to form a tornado. For these reasons, it has been argued that a downdraft is needed for tornadogenesis when preexisting rotation is 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 next to 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). Moreover, nearly countless observations exist of rear-flank downdrafts (RFDs), hook echoes, and "clear slots" in close proximity to tornadoes. 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).

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 vorticity to tornado intensity. 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.

IV. 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 operational meteorologists 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. (2005) 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. Boundary layers with large relative humidity and low-level vertical shear (relative to the average supercell environment) are most favorable for tornadic supercells. 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), 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 humidity, can limit the production of exceptionally cold outflow). 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., Markowski et al. 2003). When the ambient horizontal vorticity is only relatively modest, then perhaps tornadogenesis requires significant 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.

V. 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 the dynamical role of RFDs in tornadogenesis, the importance of microphysical differences among supercells and how those microphysical differences arise, the thermodynamic characteristics of supercells above the ground, the effects of radiative transfer processes on storm dynamics, the dynamics of storm-storm and storm-boundary interactions, and the importance, if any, of meso-γ-scale variability (such as that due to dry boundary layer convection) on storms. I am optimistic that substantial gains in understanding can be achieved in the not-too-distant future as a result of new field projects, continually increasing computing power, and growing interest in severe convective storms worldwide.

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VII. REFERENCES

Available upon request.