What we know and don’t know about tornado formation

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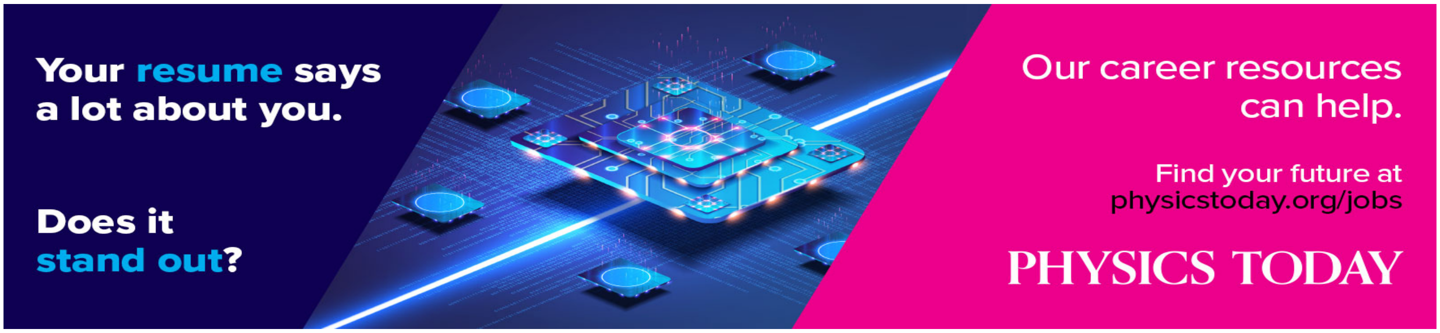

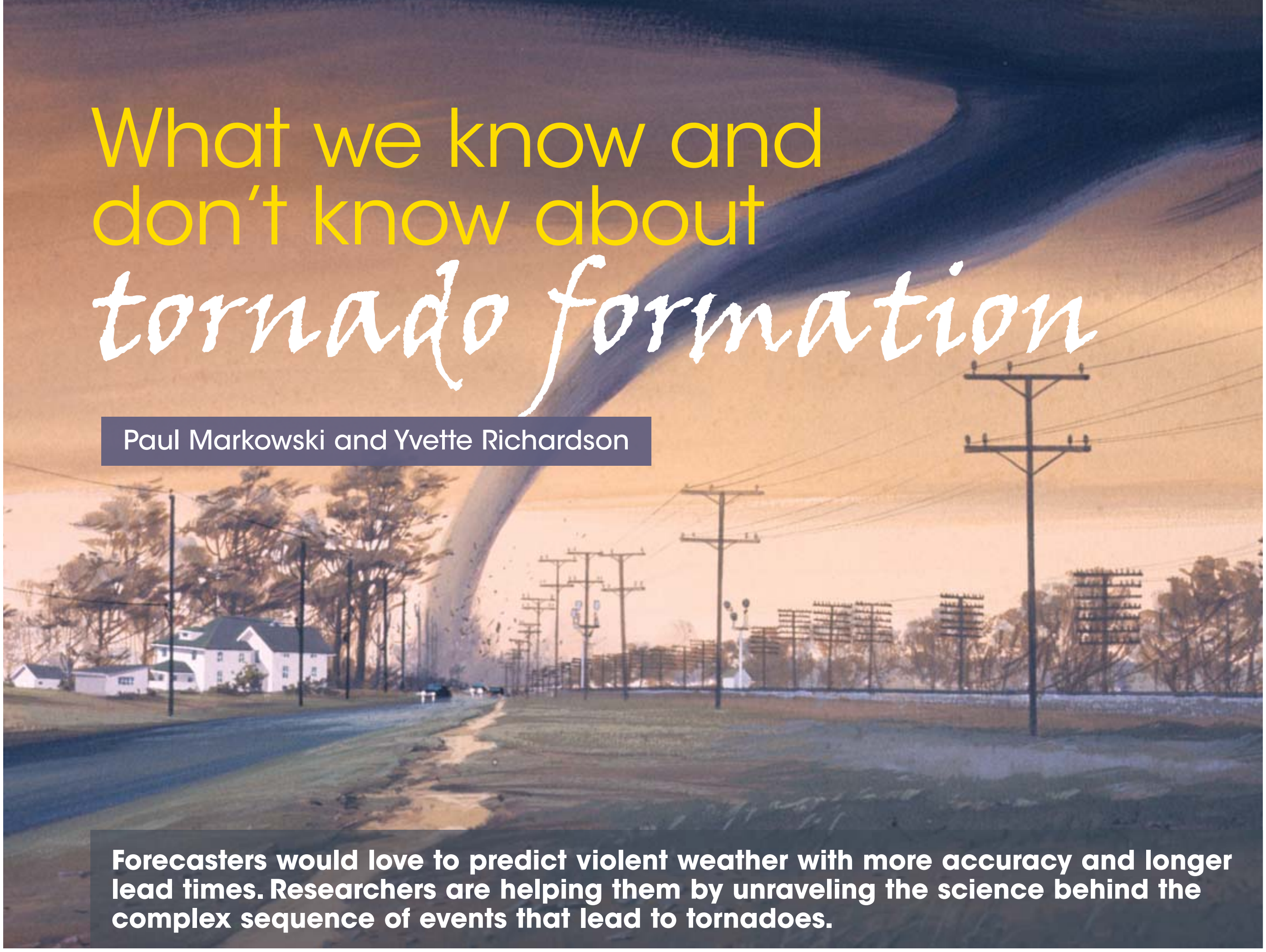

NOAA LEGACY ARTWORK

What we know and don't know about tornado formation

Paul Markowski and Yvette Richardson

Forecasters would love to predict violent weather with more accuracy and longer lead times. Researchers are helping them by unraveling the science behind the complex sequence of events that lead to tornadoes.

Tornadoes and their parent thunderstorms are among the most intensely studied hazardous weather phenomena. The vast majority of tornado research today is conducted in the US, where tornadoes occur more frequently than anywhere else on Earth. Theoretical contributions, computer simulations, and field observations, such as those from the 1994–95 Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) and subsequent projects, like the recently completed VORTEX2, have revealed a great deal.[1] (See box 1 for an overview of the different approaches to studying tornadoes.) In this article we draw on roughly a half century of prior work to summarize the latest understanding of how tornadoes form, and we discuss where gaps in our understanding remain.

Deep moist convection

Atmospheric convection is the relatively small-scale upward and downward movement of air resulting from an imbalance between the vertical pressure-gradient force and the gravitational force. Most of the time, the two forces are nearly in balance, and vertical accelerations are very small, with air moving predominantly horizontally. But when small-scale pockets of air become cooler and denser or warmer and less dense than their surroundings, the forces can become out of balance. In fluid dynamics, we call such a pocket of air a parcel: an imaginary fluid element of arbitrary size, much smaller than the characteristic scale of the variability of its environment but large enough to avoid the complexities associated with the molecular nature of fluids.

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The resulting net force on a given parcel of air is the familiar buoyancy force, which depends on the difference between the density of the parcel and that of its surroundings, with larger differences resulting in larger accelerations. It's a bit more complicated because the pressure field can also be perturbed and change the force balance. We call such a departure of pressure from a reference state of hydrostatic balance the perturbation pressure.

On sunny days convection is ubiquitous in the atmosphere's boundary layer (typically the lowest 1–2 km), as any air traveler sensitive to the bumps experienced in low-altitude flight can attest. Boundary-layer convection is driven by the heating of air as it comes in contact with the warm ground. The right conditions can trigger so-called deep moist convection, with large vertical displacements and accelerations of air; in extreme cases the displacement approaches 20 km and the acceleration

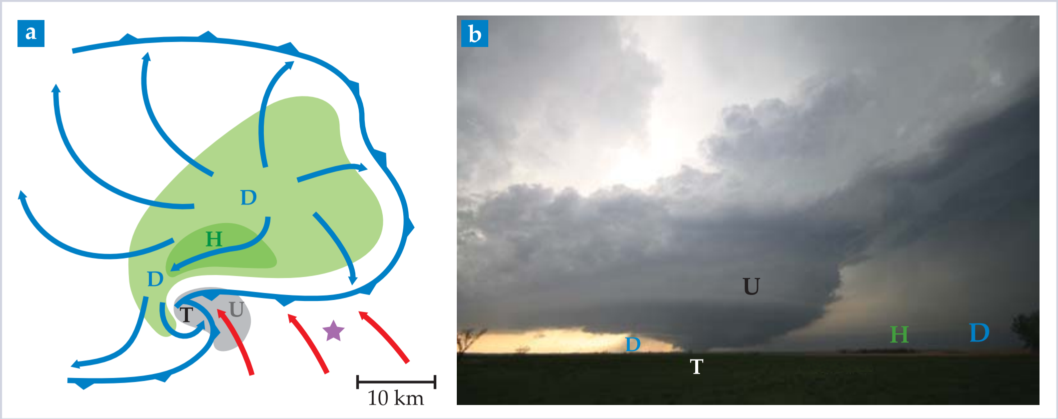


Figure 1. The parts of a supercell thunderstorm shown in **(a)** an idealized horizontal cross section. The gray-shaded updraft region is labeled U, and the downdraft, D. Green shading indicates precipitation; the location of most intense precipitation and largest hail is shaded dark green and marked H. The location of tornado formation, if one develops, is labeled T. The blue barbed line delineates the gust front, which separates warm, humid air in the environment from cool air that has descended to the surface in downdrafts. The blue and red arrows indicate the airflow near the surface within the cool and ambient warm air masses, respectively. (Adapted from L. R. Lemon, C. A. Doswell III, *Mon. Weather Rev.* **107**, 1184, 1979.) **(b)** The same labels are superimposed on a photograph of a tornadic supercell near Bowdle, South Dakota, taken on 22 May 2010 from a vantage point near the purple star in panel a. (Photo courtesy of Walker Ashley.)

0.1 *g*, where *g* is the gravitational acceleration. Those numbers hint at the enormous amounts of energy that drive thunderstorms. Box 2 explains how that energy can be quantified.

Air parcels expand and cool as they move upward into lower ambient pressure, but the cooling can lead to phase changes for water vapor in the air. In deep moist convection, heat release during condensation—and, to a lesser extent, freezing—slows the cooling rate of the parcels as they continue upward. The rate of temperature decrease in the surrounding environment varies considerably from day to day, from region to region, and in different layers in the vertical direction. If the ambient temperature decreases rapidly enough with height, then the rising air parcels will have a higher temperature and lower density than their surroundings, which will give them positive buoyancy and upward acceleration.

An atmosphere supporting that kind of vertical air movement is said to be unstable. The rising, buoyant air parcels can be anywhere from a few degrees warmer than their surroundings to as much as 10–15 °C warmer in an atmosphere with extreme instability. The cauliflower appearance of the middle and upper portions of a thunderstorm updraft, like the one in figure 1, is a visual manifestation of tremendous buoyancy.

Air parcels at ground level aren't necessarily buoyant to begin with. Oftentimes they must first rise through a layer in which they have negative buoyancy before they can experience phase changes and eventually reach a level where they become positively buoyant. Convection initiation is an interesting and difficult problem. But in a nutshell, deep moist convection often gets started on elevated terrain features or along boundaries, like cold fronts, warm fronts, and drylines, that separate air masses having different properties. All are places where air is forced to rise.[2]

Supercell thunderstorms

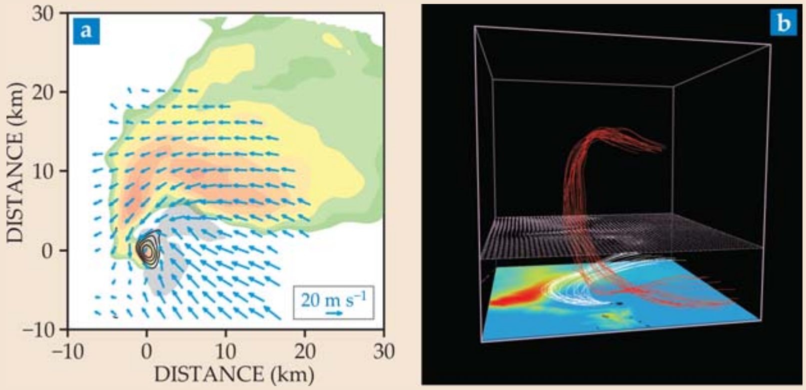
The overwhelming majority of damaging tornadoes are spawned by what are known as supercell thunderstorms. Figure 1 illustrates the structure of a supercell and its various parts. The defining characteristic of a supercell storm is its persistent, rotating updraft. The storm can be visually stunning, with the rotation often plainly visible to the naked eye. The scale of the updraft's rotation, typically 5–10 km wide, is much broader than that of a tornado.

The rotation can be quantified by vorticity, which is the curl of the wind velocity vector. For a supercell updraft, the vertical component of the vorticity, or simply the vertical vorticity, is on the order of 10^{-2}/s. In midlatitudes, where supercells are most common, that's roughly 100 times the vertical vorticity associated with the spin of Earth about its axis. Cyclonic rotation (counterclockwise in the Northern Hemisphere, clockwise in the Southern Hemisphere) is more commonly observed than anticyclonic rotation in supercell updrafts. The focus in the remainder of the article, therefore, is on cyclonically rotating supercell storms and cyclonic tornadoes; however, the general principles apply to anticyclonic tornadoes as well.

Figure 2 summarizes tornado formation in supercell thunderstorms. In step 1 of the process, a supercell develops updraft-scale cyclonic rotation—a mesocyclone—within its updraft high above the ground. The cyclonic rotation comes from the tilting of streamwise horizontal vorticity in the storm's inflow. Streamwise means that the vorticity vector is aligned with the low-altitude horizontal winds. Box 3 describes just how such tilting occurs. The horizontal vorticity is attributable to vertical wind shear—the change with height of horizontal winds in the storm's environment (see figure inset in box 2). For example, winds at the surface are often from the southeast in supercell environments, while winds aloft commonly blow from the southwest at a much greater speed.

Mesocyclones produced by the upward tilting of environmental vorticity are strongest in midaltitudes (3–7 km above the ground) and weaker toward the ground, because vertical vorticity develops within the updraft only as air parcels rise away from the ground. Air parcels do not acquire mesocyclone-strength vertical vorticity until they have ascended at least several hundred meters, and in many cases more than a kilometer. So the updraft's tilting of the horizontal vorticity can produce neither a near-

Box 1. How do we know what we know?



The large strides made in understanding tornadoes and their parent storms are the result of observations, numerical simulations, clever applications of theoretical fluid dynamics, and, to a lesser extent, laboratory simulations. That multipronged approach has been essential for generating new knowledge because observations, simulations, and theory each have their own strengths and weaknesses.

Dual-Doppler radar observations use at least two different radars from different viewing angles to scan a storm quasi-simultaneously. Such measurements from mobile, truck-borne platforms are commonly used to retrieve three-dimensional wind fields in storms. The example in panel a depicts a supercell thunderstorm intercepted by VORTEX2 in southeastern Wyoming on 5 June 2009, just minutes before a tornado developed. The color shading represents the reflectivity measured by the radars, with darker red indicating areas of heaviest precipitation. The blue vectors, gray shading, and black contours indicate horizontal winds, updraft region, and vertical vorticity, respectively. We show only contours for vertical vorticity in excess of 10^{-2}/s to emphasize the mesocyclone. The storm is probably the best documented in history.

Unfortunately, even in the best case, we can't see everything at all times. For example, it generally takes a few minutes for radar to scan an entire storm, but vorticity in a storm can increase by a factor of 10–100 during those few minutes. Thermodynamic observations, such as temperature, humidity, and pressure, have been even harder to gather than wind observations, which is unfortunate since tornadogenesis appears to be sensitive to those variables.

Moreover, real storms are often too complex to draw definitive conclusions, and since so few storms have been thoroughly observed, it is unclear whether the conclusions from analyzing a particular storm are generally applicable. In the history of severe storms research, we have observations of the 3D wind field in only a few dozen storms, and simultaneous observations of wind and temperature within key parts of the storm are even rarer.

Numerical simulations are another way to look inside tornadoes and supercells. Panel b shows the updraft (red) and downdraft (white) trajectories through a computer-simulated supercell thunderstorm; it also shows the simulated radar reflectivity field (color shading). Such simulations are useful because they can isolate physical processes one at a time. Of course, simulations are only as good as the approximations they use. For example, they are notoriously sensitive to how the microphysics of precipitation processes is parameterized. A typical thunderstorm simulation has a grid spacing on the order of 100–1000 m. Obviously, processes like condensation and evaporation must be represented in a credible simulation (there'd be no updrafts or downdrafts otherwise!) even though those molecular processes fall well below the resolution of the simulation.

Theoretical studies are often inhibited by nonlinearity in the governing equations and complexities associated with precipitation processes. And laboratory simulations have been limited to the study of tornado dynamics, given that it is difficult to emulate the parent thunderstorm in a laboratory. Nonetheless, theory also has proven to be indispensable in the interpretation of numerical and laboratory simulations.

ground mesocyclone nor a tornado, which by definition is in contact with the ground.

Ground-level rotation

All indications are that a downdraft is needed for the development of vertical vorticity next to the ground—step 2 in tornado development shown in figure 2a—at least when there is no significant vertical vorticity in the storm's environment. Some tornadoes, such as waterspouts and landspouts, occasionally can develop by feeding off the vertical vorticity already present along wind-shift lines in the storm environment, but tornadoes that develop without downdrafts are almost always weak.

In addition to updrafts, all thunderstorms have downdrafts, which tend to coincide with regions of precipitation. In cyclonically rotating supercells, precipitation tends to fall east and poleward (to the north in the Northern Hemisphere) of the updraft, with the heaviest precipitation particles, such as large hailstones, falling nearest to the updraft (see figure 1). The mesocyclone also can wrap some of the precipitation around the updraft to the rear flank. Because most of the precipitation falls outside of the updraft, a large downdraft region coexists with the updraft in a nearly steady state.

The downdrafts are associated with negative buoyancy because of both the weight of the precipitation particles and the lower temperatures. The evaporation of rain and, to a lesser extent, the melting of hail and snow chill the air and lead to horizontal buoyancy gradients at low altitudes. Parcels residing in those buoyancy gradients experience a torque that generates horizontal vorticity that can be comparable to, or even exceed by several times, the environmental horizontal vorticity associated with the ambient vertical wind shear.

More importantly, as an air parcel passes through the downdraft region of the supercell, the wind field surrounding the parcel can tilt the horizontal vorticity upward even as the parcel descends toward the ground; that tilting can allow the parcel to have vertical vorticity when it reaches its lowest point.[3–5] Indeed, both numerical simulations and field observations strongly suggest that vorticity generated by buoyancy gradients is the dominant contributor to the development of near-ground mesocyclones in supercells.

Tornadogenesis: The Goldilocks problem

Many, if not most, supercells appear to develop significant vertical vorticity next to the ground via the mechanism described above. However, the mere presence of near-surface vertical vorticity does not a tornado make. In fact, near-ground rotations fail to intensify to tornado strength in perhaps 80% of supercells or more.

Making a tornado requires one more step: intensification of near-ground rotation—step 3 of tornadogenesis shown in figure 2b. That intensification occurs predominantly via the conservation of angular momentum, which amplifies vertical vorticity by a factor of roughly 100. As air converges toward the axis of rotation, mass conservation requires that it also move upward. The degree to which angular momentum can be contracted depends on how well the air can be accelerated upward.

Because air parcels that have descended through a cool downdraft tend to have negative buoyancy, work is required to accelerate them upward. The other main force that drives the up-and-down motion of air is the vertical perturbation pressure-gradient force. It is a result of variations in the flow field and accelerates air from high perturbation pressure toward low perturbation pressure. It turns out that perturbation pressure is low where the wind field is dominated by rotation, as it is in the strong mesocyclone that is aloft. Thus, supercells possess an upward-directed perturbation pressure-gradient force, or dynamic suction, at low altitudes that aids the contraction of angular momentum beneath the midlevel rotation.

One trick to tornadogenesis is to get the angular momentum to end up in that region of strong dynamic lifting. Recent numerical simulations also suggest that the dynamic suction increases as the overlying mesocyclone strength increases at relatively low altitudes—about 1 km above the ground.[6] Looking back to how a mesocyclone forms aloft in the first place, the strength of the low-altitude dynamic suction is well correlated with the strength of the low-altitude environmental vertical wind shear. On tornado outbreak days, the wind shear can be so extreme that winds can vary by 20 m/s within the lowest 1 km.

In addition, the less negatively buoyant the air is, the more able it is to experience a net upward acceleration. In tornadic supercells, air entering a developing tornado is often just a few degrees colder than the environment, whereas nontornadic supercells are often characterized by downdraft temperatures that are 5–10 °C lower than the ambient environment. Tornadogenesis in supercells is therefore a Goldilocks problem: Air feeding into the incipient tornado has to be just the right temperature. Downdrafts and their accompanying negative buoyancy are crucial, but excessive negative buoyancy appears to be detrimental to tornadogenesis. Figure 2c is an example of a failed tornado. Low-altitude relative humidity turns out to be a decent predictor of downdraft coldness. Lower relative humidity allows for more evaporation and typically colder downdrafts. On tornado outbreak days, the lower troposphere can be so humid that cloud bases are just a few hundred meters above the ground.

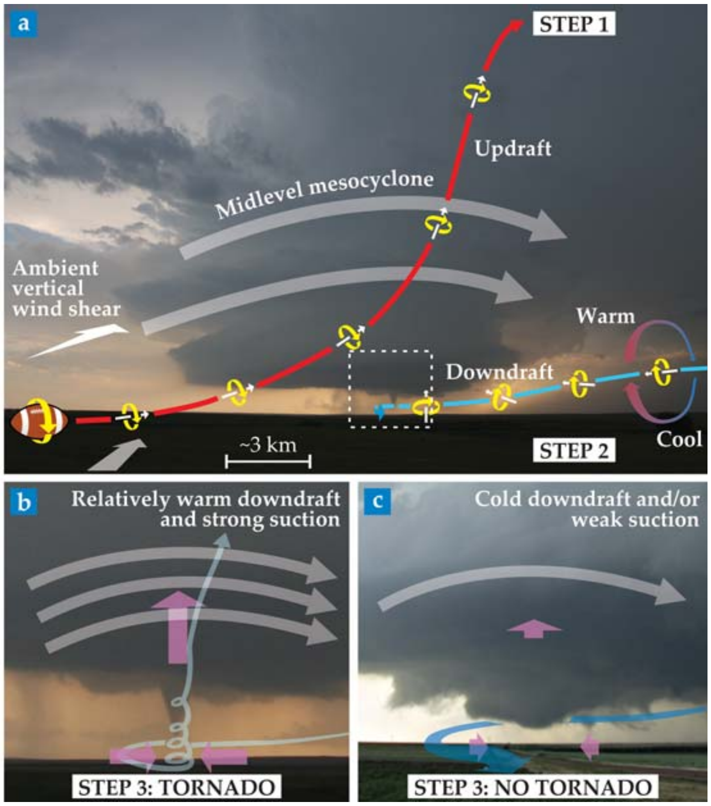


Figure 2. Our present understanding of how a tornado develops in a supercell thunderstorm. **(a)** A tornadic supercell near Deer Trail, Colorado, intercepted by the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) on 10 June 2010. The white arrows show the orientation of the vorticity vector, the yellow curved arrows indicate the sense of spin, and the red and blue lines indicate the paths taken by updraft and downdraft air parcels, respectively. In step 1 of tornadogenesis, the storm acquires large-scale rotation—a midlevel mesocyclone—by tilting the horizontal vorticity in winds entering the storm's updraft. In step 2, buoyancy gradients due to relatively warm and cool air straddling either side of downdraft air parcels generate horizontal vorticity. That horizontal vorticity is then tilted upward by surrounding wind fields as the parcels descend. **(b)** A closeup of the region inside the dashed box in panel a. In step 3, conservation of angular momentum amplifies the now vertical vorticity as air converges toward the axis of rotation while being sucked upward by the strong mesocyclone above. **(c)** A nontornadic supercell with tornadogenesis failure in progress, intercepted by VORTEX2 near Panhandle, Texas, on 13 June 2009. (Adapted from P. M. Markowski, Y. P. Richardson, *Weatherwise*, July–August 2013, p. 12. Photos in panels a and b courtesy of William T. Reid. Photo in panel c by Paul Markowski.)

Future of tornadogenesis research

Forecasters have become skillful in identifying environments capable of supporting strong to violent tornadoes. For example, large outbreaks are now routinely predicted by the National Oceanic and

Atmospheric Adminstration's Storm Prediction Center days in advance, and strong tornadoes rarely hit with no tornado watch in place. The ability to make such predictions largely stems from our understanding of the favorable combination of not-so-cold downdrafts and strong low-altitude upward suction within supercells. Those conditions favoring tornadic supercells are unobservable in real time, but meteorologists can anticipate them using computer forecasts and readily available, albeit coarse-resolution, meteorological data obtained through routine observations, like readings from weather balloons or surface observing stations.

Unfortunately, even if the environment is known to be extremely favorable for supercell tornadoes, forecasters have a limited ability to say when or if a specific storm will produce a tornado. Even on tornado outbreak days, not all the supercells are tornadic. Moreover, tornadic supercells are not tornadic all the time. So researchers have been investigating triggers for tornadogenesis, such as small-scale downdraft surges and descending precipitation shafts on the supercell's rear flank, as well as the processes that sustain tornadoes once they form. But as of now, if a tornado is occurring, forecasters have practically no ability to provide guidance to the public on the tornado's current intensity (spotter reports are about the only source of information), future intensity, or expected duration.

Another active area of research looks at the precipitation characteristics of supercells, like the size distributions of raindrops and hailstones, and how those characteristics affect supercell downdraft regions, vorticity generation, and, ultimately, the formation and maintenance of tornadoes. Significant shortcomings in both simulations and observations of the precipitation characteristics and buoyancy fields of thunderstorms make the topic especially challenging. Our understanding of the role of surface friction on tornadogenesis also is incomplete and is similarly hampered by both our simulation and observing capabilities. And our knowledge of the effects of terrain on tornadoes and their parent thunderstorms is mediocre at best.

A few technological advances in tornado short-term forecasting are worth mentioning. The recent dual-polarization upgrade of National Weather Service radars improves the characterization of what is sampled by the radar beam. Instead of merely identifying where precipitation exists, the radars now can identify whether the precipitation comprises large or small hail, large or small raindrops, or even debris. Such observations benefit research on how a storm's precipitation characteristics might influence tornado development. Identifying debris obviously does not improve tornado warning lead times, but a late warning is better than no warning.

Given the average spacing of about 250 km

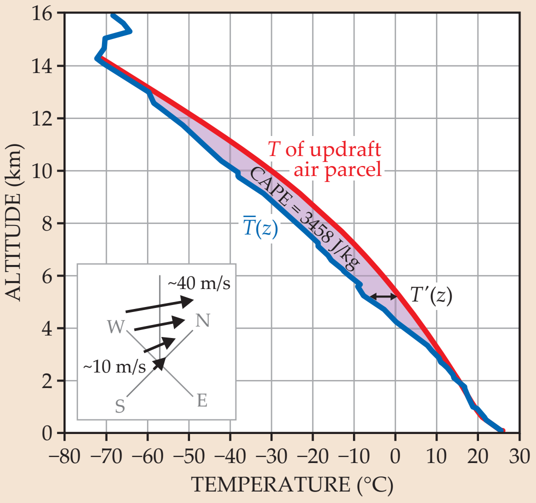
Box 2. Convective available potential energy

Thunderstorms derive their energy from convective available potential energy. Shown here is a CAPE estimate for a deadly tornadic storm that hit near Birmingham, Alabama, on 27 April 2011. To a good approximation,

$$\mathrm{CAPE} = g \int \frac{T'}{\bar{T}}\, dz,$$

where T' is the temperature difference between a rising air parcel within an updraft and $\bar{T}$ is the ambient temperature far outside the updraft. The integral is computed over the layer in which the rising parcels are warmer than the environment and possess positive buoyancy, which usually extends from an altitude of roughly 1–2 km above the surface to the upper troposphere, with an altitude of about 9–15 km. Meteorologists can measure the ambient temperature $\bar{T}$ using weather balloons, as was the case here. When making CAPE forecasts, they can turn to computer simulations to predict the $\bar{T}$ profile. The temperature of a rising parcel is derived from the first law of thermodynamics. As an air parcel rises to lower pressures, it expands and cools, and the relative humidity of the parcel steadily increases. Once the air parcel becomes saturated at a relative humidity of 100%, heat released by condensation slows the cooling rate.

The shaded area in the figure is proportional to the CAPE, which at 3458 J/kg is very large in our example. In such an extremely unstable environment, the energy released over several hours can easily surpass 1 PJ. The upper limit on the vertical speeds acquired by buoyant updraft parcels is in the neighborhood of $(2\,\mathrm{CAPE})^{1/2}$; our 3458 J/kg of CAPE yields top updraft speeds of a whopping 83 m/s. Ordinary thunderstorms typically fall well short of that thermodynamic speed limit, but supercell updrafts occasionally exceed it. The extra energy comes from the upward-directed dynamic perturbation pressure-gradient force, which ultimately is the result of large vertical wind shear found in supercell environments. The inset shows how the horizontal winds can change with altitude and reveals tremendous wind shear, with winds from the south at approximately 10 m/s at the surface and from the southwest exceeding 40 m/s at an altitude of 5 km.



Box 3. Development of vertical vorticity

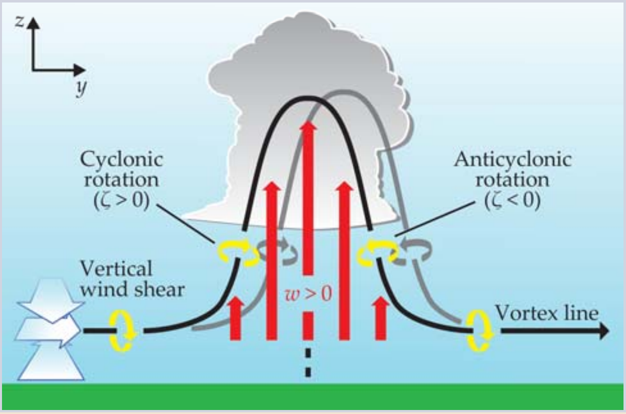
The evolution of the vertical vorticity within a thunderstorm updraft is well-governed by

$$\frac{\partial\zeta}{\partial t} = \underbrace{-\mathbf{v}\cdot\nabla\zeta}_{\text{I}} + \underbrace{\boldsymbol{\omega}_\mathrm{h}\cdot\nabla w}_{\text{II}} + \underbrace{\zeta\frac{\partial w}{\partial z}}_{\text{III}},$$

where $\mathbf{v} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$ is the wind velocity relative to the movement of the updraft, $\zeta = \partial v/\partial x - \partial u/\partial y$ is the vertical vorticity, and $\boldsymbol{\omega}_\mathrm{h} = (\partial w/\partial y - \partial v/\partial z)\mathbf{i} + (\partial u/\partial z - \partial w/\partial x)\mathbf{j}$ is the horizontal vorticity vector, with $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$ unit vectors in the x-, y-, and z-directions.

Term I represents what meteorologists call the advection of vertical vorticity—that is, the three-dimensional transport of vertical vorticity by the wind. Term II is responsible for the initial development of vertical vorticity within the updraft by tilting horizontal vorticity into the vertical. The horizontal vorticity in the storm's environment away from the updraft region is, to a good approximation, $(-\partial v/\partial z)\mathbf{i} + (\partial u/\partial z)\mathbf{j}$. In other words, the variation of horizontal wind components with height, known as the vertical wind shear, determines the horizontal vorticity. The figure shows an example in which, relative to the updraft, the winds in the storm's environment are into the page near the ground and out of the page aloft, spiraling clockwise with height. The x-component of the wind increases with height ($\partial u/\partial z > 0$) and the vorticity points toward the right. Vertical wind shear is relatively large in supercell environments. A difference of roughly 20 m/s between the winds at the surface and winds at an altitude of 6 km is typically sufficient to produce a mesocyclone.

The tilting is accomplished by horizontal gradients of vertical velocity, which are maximized on the updraft flanks. The lengths of the red arrows in the figure indicate the magnitude of w at different positions in the updraft. The tilting effect is easily visualized by the upward-bending of the vortex line (black), a field line that is everywhere parallel to the vorticity vectors. The yellow curved arrows indicate the sense of rotation. And to first order, the vortex line is simply deformed by the horizontal w gradient associated with the updraft.



To the left of the maximum updraft, $\partial w/\partial y > 0$, making the tilting term positive. To the right, the opposite is true and the tilting term is negative. That change in sign from left to right means the tilting of horizontal vorticity associated with the wind shear produces a couplet of counterrotating vortices that straddle the updraft, with cyclonic rotation to the left and anticyclonic rotation to the right.

Because of the wind component from the left, the axis of horizontal rotation in the storm's environment is aligned with the vertically averaged wind there, like the spiral of a well-thrown football. As a result, advection (term I) shifts the vorticity couplet so that the cyclonic rotation is located within the updraft, as illustrated by the gray vortex line. The anticyclonic rotation ends up outside the updraft in a region of sinking air.

Term III is the stretching term, which exponentially increases the vertical vorticity that is co-located with the horizontal convergence of air. That is the familiar enhancement of spin owing to the conservation of angular momentum when fluid is contracted. Vorticity stretching can further strengthen mesocyclones aloft, but more importantly, it intensifies near-surface rotation to tornado strength.

between National Weather Service radars, most tornadoes occur too far from a radar to be resolved or are simply overshot by the radar beam. Mesocyclones are relatively easy to detect aloft, but detecting a mesocyclone is not the same as detecting a tornado. One solution, though likely many years away on a national scale, might be gap-filling radars—low-cost, low-power radars used to augment the existing radar network. A demonstration network already exists in the Dallas–Fort Worth area.[7]

Lastly, NOAA scientists are exploring the feasibility of a concept called warn-on-forecast to make thunderstorm-specific predictions as opposed to diagnoses.[8,9] The idea is to use multiple extremely short-range, high-resolution computer simulations that are updated in real time with observations. The intrinsic limits on the predictability of thunderstorms are a daunting challenge to face. But if successful, warn-on-forecast could dramatically increase lead times for severe weather warnings.

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