BILLION-DOLLAR TWISTER

by ROBERT HENSON

Oklahoma, America's most frequent victim of tornadoes, suffered more twister-related destruction on May 3, 1999, than ever before. What are we learning from this epic event—and could it happen somewhere else?

For drama's sake, it's tempting to say there was something spooky in the air. But as dawn broke across Oklahoma on May 3 of last year, the conditions weren't especially ominous. True, it was a bit humid and breezy, but nothing special for springtime. Wheatfields near Oklahoma City were tossing in a 25-mile-per-hour wind by midafternoon, but wind is to Oklahoma as snow is to Alaska. It's part of the fabric of life and—usually—of little consequence.

Five hours later some 8,000 buildings in central Oklahoma lay in partial or total ruin. A seemingly endless swarm of tornadoes had ravaged a 150-mile-long belt running from southwest Oklahoma diagonally across the state to near Wichita, Kan. Across this swath, at least one twister was spinning on the ground at every moment from 4:45 to 10:45 P.M.—except for a two-minute lull midway through the period, as if nature were catching its breath.

Even for storm-savvy Oklahomans, this swarm was a catastrophe beyond most people's experience. All by itself, the twister that touched down in Oklahoma City was the nation's first billion-dollar tornado. It damaged almost three times as many structures as any previous American tornado had.

As the twisters descended on Oklahoma, storm chasers, including some of the world's top tornado experts, went out in droves to meet them. Their mobile radars and other instruments collected a year's worth of data in a single day. Already the tornadoes of 1999 have provided some intriguing avenues for research and shattered a hypothesis or two along the way. The work is helping to explain why the twisters of May 3 became so fierce. It is also providing new insights into how tornadoes form and sustain themselves.

PAUL HELLSTERN *The Oklahoman*/SABA

A Cloudy Forecast Becomes Clear

Forecasters didn't exactly see apocalypse coming on the morning of May 3, but they knew there could be a twister or two. Oklahoma gets more tornadoes per square mile than anyplace else on Earth, and May is when they are most likely. A few basics, largely identified more than 50 years ago and clarified more recently, lie at the root of severe weather (including tornadoes) across the plains. Warm, moist, ground-hug-

PAUL B. SUTHERLAND *The Oklahoman*/SABA

A NEIGHBORHOOD VANISHES: The spring tornadoes that hit Oklahoma and Kansas damaged thousands of buildings, including these homes in Moore, an Oklahoma City suburb.

PAUL HELLSTERN *The Oklahoman/SABA*

PAUL B. SUTHERLAND *The Oklahoman/SABA*

THE AFTERMATH: Volunteer rescue workers in southwest Oklahoma City labored for half an hour to remove Renee Faulkinberry from the rubble of her home after it was leveled by a tornado.

ging air from the Gulf of Mexico sweeps beneath a cooler, drier layer several miles high, creating instability. Often a warm, dry layer in between serves as a buffer, preventing the layers from meeting and thus keeping a lid on the instability until late afternoon or evening. Then the air warmed by the sun breaks through this separation layer. A tornado may occur if certain other conditions are also present at that point. One is wind shear at upper levels: the wind strengthens with height or changes direction with height, or both. Another is a nearby front or other air-mass boundary (where winds collide) near the ground. And the pot is stirred if a knot of vorticity, or rotation, in the jet stream approaches the area of these disturbances.

This recipe holds up well for predicting when severe weather is possible. But what causes multiple tornadoes, known to meteorologists as a "tornadic swarm"? "We don't understand exactly why some days are prolific and others aren't," says Harold Brooks, a researcher at the National Oceanic and Atmospheric Administration National Severe Storms Laboratory (NSSL) in Norman, Okla. Singling out the really bad days in advance can be like trying to pick the future criminal out of a group of mischievous 10-year-olds.

May 3 did not stand out from the pack at first. At 6:30 A.M., forecasters at the Storm Prediction Center (SPC)—another NOAA unit based in Norman—assessed the day as having a "slight risk" for severe weather across parts of Texas, Oklahoma and Kansas. Every morning SPC rates the day's severe-weather potential as slight, moderate or high. (They also issue the nation's tornado watches.) On this Monday morning there were some indications that a tornado would be unlikely. Forecasters thought a sheet of cirrus clouds evident on satellite images might limit heating over the expanse of the southern plains. Upper-level winds were blowing at only around 50 mph, a marginal speed for supporting twisters. And a dry line in west Texas, separating sultry Gulf air from its desert-toasted counterpart, was not moving much.

It took until early afternoon for the day's true colors to become apparent. A swirl of upper-level energy, packing winds of close to 100 mph, was heading east from New Mexico. This kink in the jet stream, called a short wave, was small enough to have escaped detection by almost 100 weather balloons launched across the U.S. at 7 A.M. Oklahoma time. The next national balloon launch would not be until 7 P.M. But at midday, as the short wave approached the plains, it ran into a posse it couldn't evade: a network of 30 wind profilers. Scattered across the central U.S., these upward-pointing radars plot wind speed and direction as do the twice-daily weather balloons, but the profilers report every hour. From the profiler data, SPC could tell that upper winds would strengthen dramatically across Oklahoma that evening.

By late morning SPC had upgraded the level of risk in the southern plains to moderate. A patch of clearing skies across southwest Oklahoma and northwest Texas provided even more cause for concern: nothing in the sky would block that region from heating up enough to generate storms. Most convincing was output from a high-resolution computer forecast model that showed storms charging across Oklahoma and southern Kansas by evening. At 3:49 P.M., SPC bit the bullet and placed the area under high risk—a red-flag rating reserved for only a few days per year.

Even at this point, nobody could say which towns would be flattened two or three hours later. It's one of the fondest dreams of storm scientists to be able to provide hard numbers in advance on tornado likelihood. Brooks and his colleagues at NSSL and SPC are testing one tool that shows promise. The most familiar example of a probabilistic outlook is the percent-chance-of-rain statements that entered public forecasts in the 1960s. Each of the experimental tornado forecasts pegs the likelihood that a twister will strike within 25 miles of any given point. Last year provided a slew of tornadoes for calibrating the test

F5 TERROR: Some of the May 3 tornadoes reached F5 (261 to 318 miles per hour), the highest intensity on the Fujita scale of tornado severity (*top*). In contrast, an F0 (*bottom*), the lowest on the scale, produces winds of 40 to 72 mph.

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH/UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH/NATIONAL SCIENCE FOUNDATION (*bottom*)

JERRY LAIZURE *Newsmakers/Gamma Liaison* (*top*)

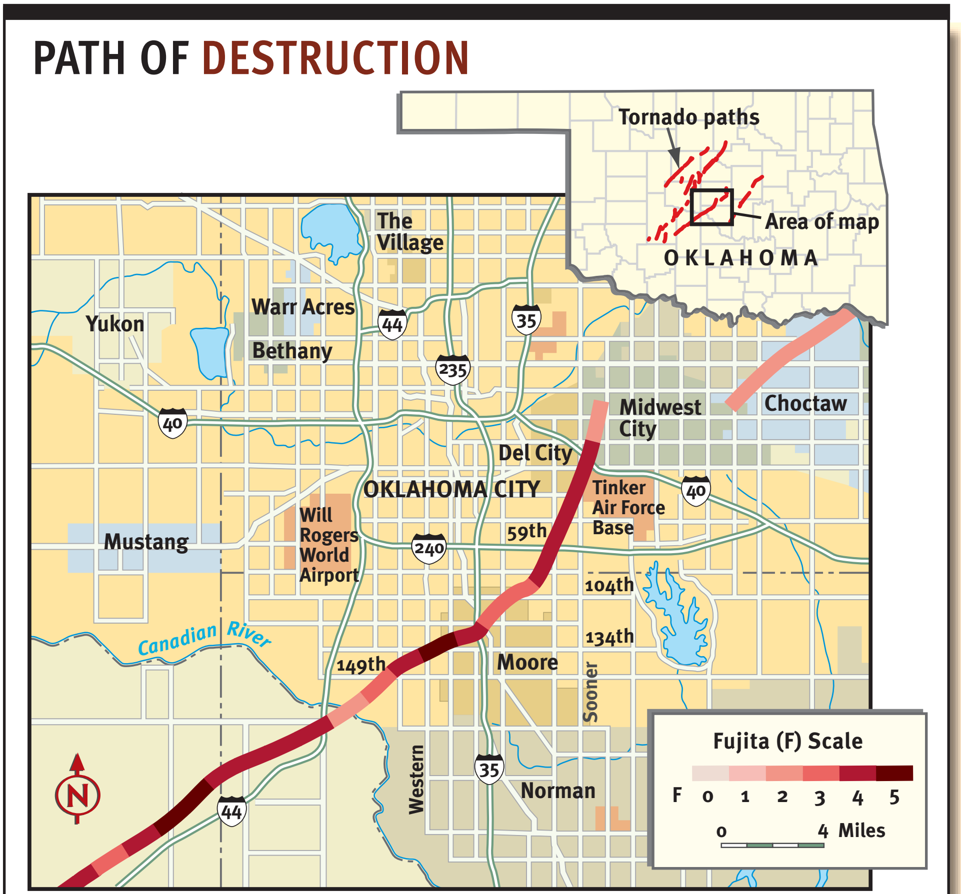
outlooks. "The response from forecasters in the field has been very positive," Brooks says. Probabilistic tornado outlooks may become a standard tool of forecasters as early as next year, although it's unlikely they will become part of public statements until more work is done.

Ground Zero in an F5

The worst havoc on May 3 occurred with the tornado that sliced across the southern outskirts of Oklahoma City and the suburb of Moore. Its 38-mile-long path was three quarters of a mile wide in spots. On the F-scale of tornado damage created by T. Theodore Fujita (the eminent University of Chicago meteorologist who also discovered microbursts), this twister was rated by surveyors as a rare F5, which corresponds to top winds from 261 to 318 mph. It destroyed more than 1,000 buildings (including 22 homes swept completely off their foundations) and damaged many more. Any F5 is unusual, but one that plows into an urban area is even more rare; this was Oklahoma City's first. Together F4s and F5s represent only 2 percent of tornadoes, but they cause two thirds of all tornado-related deaths. Even people sheltered in a small interior "safe room" may not survive an F5.

Street after street of ruined homes revealed as much about building practices as they did about the tornado itself. Typically the garage door folded inward and the windows shattered, followed by the roof lifting off and the walls caving in. A damage survey team led by Texas Tech University also found, not surprisingly, that even homes built to code—able to withstand 70- to 80-mph winds—were no match for this twister. Among the more unusual finds: a bathtub holding two shelter seekers that was airborne for almost a city block. (Both passengers survived.) The team also found significant damage up to a mile from the tornado's path. On a closer look, they noticed something new: cones of damage that flanked the tornado's path at right angles. Each one sketched the trajectory of a single chunk of debris (such as a roof blown off an especially weak building) that pelted structures in its wake as it was sucked from well outside the tornado's path into the funnel by 100-mph winds.

Mobile homes fared even more poorly. Despite their folk reputation as tornado magnets, mobile homes tend to act more like iron filings—they scatter to the wind with haste. "Trailers are good at detecting tornadoes that would otherwise not be noticed," says tornado climatologist Thomas Grazulis. An F1 tornado (winds of 73 to 112 mph) can overturn a mobile home; an F2 can demolish it. In the Oklahoma City storm, mo-



Sixty-five tornadoes on May 3 cut their way across Oklahoma; the paths of some of those funnels appear on the map at the upper right. The most severe twister plowed through Oklahoma City and its environs, with a rating that varied from an F5, at its most intense, down to an F2.

MATT KANIA

bile homes accounted for less than 2 percent of the structures damaged but a quarter of the deaths.

Although the property toll was enormous, the number of deaths was actually surprisingly low. Several tornadoes earlier in this century took more than 100 lives at once, yet the May 3 strike in Oklahoma City took far fewer. Why were so few killed? For one thing, the tornado itself was huge, visible and audible. At times, its dull roar could be heard more than half a mile away. Also, local radio and television went into saturation coverage once the first twister touched down. Warnings from the National Weather Service (NWS) gave an average lead time of 32 minutes in the Oklahoma City area, more than double the national norm.

Radar to the Rescue

The prompt warnings were made possible in part by wind-sensing radar devices. Doppler radars have been peering inside tornadoes for more than 25 years. Whereas traditional radars use the energy returning from radio waves to map precipitation, Doppler radars sense the change in frequency of those radio waves to plot winds as well. Over the past decade a national network of Dopplers has been installed at NWS offices. With software that can identify some tornadoes as they develop, the radars have helped boost lead times for tornado warnings.

In the past decade Dopplers have gone mobile. Howard B. Bluestein, a storm-chasing pioneer and a professor at the University of Oklahoma, started the ball rolling. In the late 1980s he brought to the plains a compact, continuous-wave Doppler radar developed at Los Alamos National Laboratory. (A newer version comes from the University of Massachusetts.) This radar's narrow antenna can't see beyond about six miles with clarity. Close up, though, it can dissect a tornado by measuring wind speed at points separated by as little as 20 feet. In April 1991 Bluestein set a world record for near-ground wind measurement when his radar detected 287-mph winds in an Oklahoma twister.

Four years later Joshua Wurman (now a University of Oklahoma professor as well) created Doppler on Wheels (DOW) with help from NSSL and the National Center for Atmospheric Research. Mounted on a flatbed truck, the DOW resembles a flying saucer on a pedestal. It is harder to maneuver into place than Bluestein's radar, but it can see farther. The addition of a second DOW in 1997 allows for a quick three-dimensional picture of wind vectors when both DOW units are trained on the same storm.

Both Wurman and Bluestein struck pay dirt with the Oklahoma City tornado and others that dropped earlier from the same storm. One DOW unit caught a wind gust near Moore initially estimated at between 300 and 320 mph—near the edge of the F6 category that Fujita originally labeled as "inconceivable." Once analysis has deciphered the actual speed, it's expected to be the highest tornadic wind on record.

Another tornado in the swarm set a record as well. In Mulhall, about 40 miles to the north of Oklahoma City, an F4 tornado measured roughly 1.2 miles across. "It was the most fearful-looking tornado I've ever seen," Wurman says. "If it had passed through a populated area, it would certainly have been the worst tornado of the day."

Beyond sending off much needed "take cover" alarm bells, the radars provided a new look at the interior of tornadoes. On May 3 and in two storms thereafter, Bluestein discovered that a tornado's center may not be a perfect cylinder. His radar has found cross sections that look more like squares. The corners

HOWARD B. BLUESTEIN

STORM TRACKERS: The mobile Doppler radar operated by University of Oklahoma professor Howard B. Bluestein and his colleagues measured wind speeds for a May 3 tornado.

appear to be waves or minivortices swirling around the main vortex. Multiple vortices have been photographed for decades, but Bluestein is still not sure just what the surprising radar indications really mean.

One of the key puzzles left in the debris of May 3 is why that day's storms were so durable. Almost every storm across the heart of Oklahoma that evening was a supercell—a long-lived, steady-state severe thunderstorm. And almost every supercell dropped tornado after tornado. There were 65 twisters in all, more than Oklahoma usually sees in a whole year. In southern Kansas three other tornadoes killed six people and damaged several thousand structures.

When multiple storms develop in proximity, they often interfere with one another's tornadic potential. One storm might hog the supply of atmospheric fuel, or it could dump rain-cooled air onto another. Often storms will solidify in an hour or two into a line or cluster that is ill suited for producing tornadoes. Yet at least five supercells coexisted across Oklahoma and Kansas on May 3.

A project called VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment) has been studying the birth of twisters ("tornadogenesis") for the past five years. Its leaders—NSSL tornado specialist Erik Rasmussen and University of Oklahoma professor Jerry M. Straka—are hoping that analyses of the Oklahoma swarm will help explain why the atmosphere was so efficient at producing tornadoes and why this swarm in particular took so long to run out of steam. As part of the project, Rasmussen and Straka oversee a fleet of cars with full weather stations attached to their hoods. These mobile laboratories take measurements near supercells every six seconds—a critical reading for tracking the rapid-fire shifts in pressure and wind that occur just as a tornado forms.

Data collected since the project's inception in 1994 already indicate that temperature gradients along minifronts on the east side of a storm are not as important as once thought. Rasmussen believes instead that downdrafts wrapping around the south end of the storm are key to spinning up twisters. The violently descending air may help stimulate a compensating updraft and enable this lifting air to tighten from a larger-scale circulation into a tornado.

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The May 3 event has added a new wrinkle: rain-cooled air was virtually absent. Nearly all the downdrafts observed by VORTEX were warmer than the surrounding low-level air, as compared with a typical downdraft, which is several degrees cooler. "This is broadly consistent with a new hypothesis we're testing," Rasmussen says. Warmer downdrafts may allow low-level air to stay juiced, enhancing odds for an outbreak of long-lived twisters. If so, forecasters might be able to judge a day's probable downdraft temperature in advance and use it as an outbreak prediction tool.

For all their brute force, tornadoes appear to thrive on a mysterious and delicate balance of forces. Computer models of the future may be able to better diagnose the preconditions for a tornado hours in advance. To do so, however, they will have to be fed with better observations, including information from a wider net of profilers, more sophisticated radars and the kind of dense surface networks now in place across Oklahoma. There more than 100 automated stations in a state-sponsored "mesonet" cover the area formerly served by a handful of human-operated stations. A new set of portable research radars is now under development by NSSL and several universities. Small, remotely piloted aircraft (one prototype is being built at the University of Colorado) may provide a different look inside a twister and its surroundings.

HOWARD B. BLUESTEIN

METEOROLOGICAL BOMBER: A supercell, a long-lived thunderstorm such as this one that formed May 3, 1999, may drop tornadoes.

Safety in a Closet

Technology is also working to protect people in their homes. Safe rooms, designed to withstand the ravages of both hurricanes and twisters, have become a hot item as storm-stricken areas begin the process of rebuilding. These rooms, which run $2,500 to $5,500, often double as closets and can be retrofitted into existing homes. They feature walls of steel-reinforced concrete, typically measuring six inches thick. In one survey of the Oklahoma City tornado, six of 40 rebuilt homes included safe rooms. But engineer Timothy P. Marshall found plenty of shoddy workmanship elsewhere among the 40 homes that had to be constructed anew. "In general," he says, "construction was no better in quality after the tor-

WHAT WOULD AUNTIE EM DO?

Pity Dorothy. The *Wizard of Oz* heroine ran into her home in the face of an approaching "cyclone" after being locked out of the storm cellar. Standing and stewing by her bedroom window, she was easy prey for the window's frame to blow in and knock her unconscious (and send her on to Oz).

In the real Kansas and its neighbors, people know better. Safety rules (which are not necessarily all correct all the time) have been ingrained for decades, especially at schools. The average 10-year-old can recite the basics in a flash: go to a basement or to an interior room on the lowest floor, such as a bathroom or closet; cover yourself with a blanket or mattress; don't try to drive away from the storm; and head for a ditch if you're caught in the open.

J. PAT CARTER *Associated Press*

NO REFUGE: Civil defense officials and meteorologists are trying to dispel the myth that overpasses, such as the one shown here, can provide a safe haven from a tornado.

About half of all U.S. residents come under a tornado warning each year, but weather-weary Oklahoma City is the world capital of tornado awareness. The events of May 3 bore this out. Despite unprecedented destruction, the fatalities there were relatively low. If the same tornado had struck a city of the same size in the 1940s, before the existence of modern warnings, it would most likely have killed more than 600 people, according to Harold Brooks of the NOAA National Severe Storms Laboratory.

What's even more notable is that nobody between the ages of four and 24 died. The odds of this happening by chance, according to Brooks, are more than 4,000 to 1. A poststorm survey showed that 85 percent of the kids in harm's way did something to preserve their safety and that more than 95 percent of those actions were in line with the recommended rules. One mother re-

TIMOTHY P. MARSHALL

STORM BUNKER: Steel-reinforced concrete "safe rooms" can sometimes provide protection against the fury of tornado-strength winds.

nado than before, and in some cases, the quality was worse."

What happens when a family of F4 or F5 twisters strikes the Dallas/Fort Worth metropolitan area, the St. Louis vicinity or Chicago? Each has been the victim of major tornadoes before. The Dallas/Fort Worth area is particularly at risk. Its two big cities lie only 30 miles apart on an east-west axis, so a long-lived F5 twister could chew on homes and businesses for over an hour. With any luck, forecasters of the future will be able to identify such a worst-case scenario as a possibility hours before it actually happens.

Weak tornadoes—the most common kind—will remain hard to predict, and they can do as much harm in the wrong place as an F5 in the countryside can. On August 11 a freak twister touched down in the heart of Salt Lake City with no advance notice by sight or radar. It killed one person and injured dozens more. Only eight other people had been reported hurt by tornadoes in Utah before that day. Sometimes "it can't happen here" means only "it hasn't happened here yet." W

ROBERT HENSON, a meteorologist and freelance writer, grew up with tornadoes in Oklahoma City and chased them while he was still a graduate student. He now enjoys photographing severe weather and writing about it, as he did in "Only a Storm," a contribution to the anthology *Soul of the Sky* (Mount Washington Observatory, 1999). He works as a writer/editor in the communications department at the University Corporation for Atmospheric Research in Boulder, Colo.

turned home in a panic after the storm to find her 12-year-old daughter tucked into a bathtub, a mattress over her head. In her arms were a teddy bear and a weather radio.

Does it ever make sense to drive away from your home before a tornado hits? Instinct might say yes, but official guidance says no, and there aren't yet enough data to know for sure. Several deaths in the Jarrell, Tex., tornado of May 27, 1997—another F5 with ample warning—occurred when people had come home specifically for shelter, only to be swept away with their houses. By all accounts, many people in the Oklahoma City area left their soon-to-be destroyed homes and survived. On the other hand, others were injured in traffic accidents as they fled.

Tornado-packing storms often produce large hail, and it's now common across the plains for motorists to stop in traffic beneath an overpass in an effort to protect their car's finish from damage. Horrendous traffic jams often result, and motorists become sitting ducks for tornadoes. Problems may persist even after the storm: rescue operations in the Oklahoma City area were hindered by clots of damaged cars clustered around bridges.

Just as worrisome is the "overpass issue." Thanks to an endlessly televised 1991 video from Kansas, in which a film crew experienced the winds at the fringes of a twister under a bridge's girders, overpasses have gained a false reputation as a place of safety. Many overpasses are built without girders, providing no chance of protection. Moreover, the Kansas film crew was in a rural area, and the tornado's core never passed overhead. On May 3 in Oklahoma, 17 people took shelter under an Interstate 35 overpass. All but one were blown out from their refuge; one was killed, and 14 were seriously injured. A few miles away another person was dismembered after being sucked from an overpass. In short, "overpasses are not a safe place to be," Brooks says.

Mobile homes tend to be unsafe at almost any tornadic speed; nearly half of all tornado deaths since 1975 have occurred in them. Yet few mobile-home residents have access to shelters. One recent damage survey led by Thomas W. Schmidlin of Kent State University hints that for tornadoes of F2 to F3 intensity, it could be safer for mobile-home residents to stay in parked cars than to remain in their homes. The cars, being more aerodynamic, appear far less likely than mobile homes to tip over and disintegrate when lashed by the wind. In an F4 or F5, of course, all bets are off. (Taking shelter in a ditch may not be the answer either: Schmidlin notes that this longtime recommendation has yet to be backed up by research.)

How far can we go in tailoring warning advice to fit the storm? New technology at the National Weather Service already allows forecasters to craft warnings on the fly using preworded statements. Oklahoma City's NWS office added the words "tornado emergency" on May 3 to convey the gravity of the situation. But most tornado outbursts are not so clear-cut. "We can't and don't forecast intensity now. May 3 illustrates that this is an important potential research area," Brooks says.

In the meantime, public-safety officials are loath to change warning advice too quickly or too often. After all, it's taken decades to dispel a bit of old tornado gospel—the idea that opening windows away from an approaching twister helps to equalize air pressure and reduce damage. In fact, houses don't "explode" from the pressure drop, which at best runs only about 10 percent below normal atmospheric pressure. Buildings usually disintegrate as they are unroofed and walls collapse. As Dorothy discovered, a window is no match for the onslaught of a serious cyclone. *—R.H.*