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HISTORY OF TORNADO RESEARCH

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1. INTRODUCTION

The focus of this presentation is on early measurements and observations of tornadoes, laboratory-vortex models, severe-storm intercept field programs (“storm chasing”), in-situ measurements made both intentionally and by chance, Doppler radar observations of tornadoes and their parent storms, and theory. Numerical modeling will be discussed very briefly, in deference to the later presentation by Morris Weisman in 9.1.

All of the aforementioned topics will be discussed in some sense of, but not exactly, in chronological order. I will, however, attempt to convey a sense of historical context. I do not have enough time here to detail or critique each contribution in this short overview. It is recognized at the outset that there is overlap among the sub-disciplines of tornado research and that there has been much cross-fertilization of ideas. Branches of research topics are highly intertwined and as such one cannot describe progress in a linear fashion.

For the sake of brevity, I will not spend much time, if any, on tornado forecasting, aspects of convective storms not related to tornadoes, acoustic-wave research, electrical research, recent contributions from newer instruments such as UAVs, portable surface probes, etc., data assimilation, non-supercell waterspouts and other funnel clouds/small vortices, damage studies, and exotica such as rocket probes . The period of time covered in my review is from the early 1950s until just before VORTEX2.

2. EARLY MEASUREMENTS AND OBSERVATIONS

After the *Thunderstorm Project* in the late 1940s, serendipitous radar observations of tornadic storms were first made in 1953 in Illinois (9 April) and Massachusetts (9 June 1953) by radars at the Illinois State Water Survey and M. I. T., respectively. Other similar observations were made at Texas A&M by Stuart Bigler. These early observations showed that hook echoes are related to tornadoes.

From the late 1950s onward, and especially in the 1960s and 1970s, Ted Fujita at the University of Chicago made painstaking analyses of tornado damage, tornado photographs, and integrated these analyses with “mesoanalysis” of surface data. Based on photographs of the Fargo, ND tornado of June 1957, he introduced terminology such as “wall cloud” and “tail cloud,” which persists to this day. He introduced what became known as the “Fujita Scale” in an attempt to estimate wind speeds in tornadoes on the basis of the characteristics of damage inflicted. While not calibrated, his technique remains today, though in a modified form. After viewing tornado damage from aircraft, he documented cycloidal ground marks and associated them with multiple-vortex tornadoes. On the basis of aircraft flights over a tornadic storm in 1977 he suggested that downdrafts in thunderstorms may play a role in tornadogenesis.

In the late 1950s, Chester and Harriett Newton suggested in a seminal paper based upon analysis of a squall line in 1949, that vertical shear in the environment of a convective storm leads to propagation of its updraft as a result of interactions between the storm updraft and the momentum in its environment at different heights. Their idea later became the physical basis for our later understanding of supercell behavior, which is intimately related to tornadogenesis.

On 4 May 1961, Neil Ward, who was participating in the National Severe Storms Project (NSSP), made the first scientific tornado chase. He traveled with the Oklahoma Highway Patrol and, receiving information by phone about echoes seen on a WSR-57 radar, observed a tornado in western Oklahoma. He postulated, on the basis of his visual observations, that cold outflow in the parent storm may have played a role in tornadogenesis. Keith Browining and Ralph Donaldson, in an important 1963 paper, noted a similarity of a radar vault to that observed in the famous Wokingham, England hailstorm of 9 July 1959. They showed an echo hole in the storm, a feature we now recognize as being associated with tornadoes and/or strong updrafts.

Keith Browning continued his work with an analysis of a tornadic supercell in Oklahoma on 26 May 1963. Observed by the Weather Radar Lab in Norman and documented visually by Ralph Donaldson, it was suggested in 1965 that there is an ordered sequence of events leading up to tornadogenesis.

3. LABORATORY MODELS

In order to understand how intense vortices such as tornadoes interact with the ground, laboratory models of vortices, "vortex chambers," have been built. They have been used to elucidate tornado behavior, but do not address the question of how tornadoes form in storms, because the parent storms are not represented, save for an exhaust fan that simulates the updraft.

Neil Ward at NSSL in 1972 reported on his early laboratory studies conducted in the mid 1960s. His seminal work was followed by experiments at the University of Oklahoma (OU) with the "Viney tornado simulator" by Martin Jishke and Gene Wilkins and students. John Snow, Chris Church and graduate students conducted similar experiments in Purdue beginning in the late 1970s. In the mid 1990s, Snow and his group pioneered the use of a laser Doppler velocimeter to map the wind field without disturbing the flow and without having to resort to the use of sometimes smelly tracers. (Smoke was used in the simulator at OU.)

Numerical simulations of laboratory vortices were first done by Rich Rotunno, at NCAR, in a series of studies conducted in the late 1970s and early 1980s. An advantage of numerical simulations is that one knows all the variables in space as a function of time without having to measure them, and one can more easily conduct controlled experiments since one can easily vary parameters and boundary conditions. Most recently, Dave and Steve Lewellen at West Virginia University have been doing LES model experiments and are able to reproduce vortex behavior with startling resemblance to reality.

Both laboratory models and numerical simulations have demonstrated the importance of the swirl ratio to vortex behavior and the phenomenon of vortex breakdown. Bob Davies-Jones at NSSL has also analyzed lab model behavior and produced a long-standing and widely reproduced figure illustrating the effect of swirl ratio on tornado structure and behavior. Lewellen and Lewellen have recently proposed that "corner flow collapse" may be responsible for triggering tornadoes when the rear-flank downdraft (RFD) cuts off flow around a developing vortex.

4. THEORY

Theoretical work has progressed in a number of areas. Bob Gall at the Univ. of Arizona in the late 1970s and early to mid 1980s did linear stability analyses of vortices and explained the multiple-vortex phenomenon in terms of a dynamic instability. Bob Walko in the early 1990s at OU pioneered the use of a simple, idealized model to elucidate physical mechanisms of vortex formation. Jeff Trapp and Brian Fiedler at OU in the 1990s continued studies in the same vein, while more recently Paul Markowski at Penn State has conducted more studies. These "toy" models make use of positively and/or negatively buoyant bubbles released in environments of vertical shear.

Lance Leslie and Roger Smith in 1978 introduced the "dynamic pipe effect" (DPE) as an explanation of how vortices produced aloft can propagate downward. Jeff Trapp and Bob Davies-Jones, twenty years later, did idealized numerical simulations to identify conditions amenable to the DPE and those not amenable to the DPE. Observations of the DPE were made using

WSR-88D Doppler radar data by Jeff Trapp and collaborators.

Over the years there has been a flurry of studies trying to explain tornado windspeeds. Doug Lilly in an influential NCAR publication (an unrefereed report) in 1969 explained the hydrostatic consequences of a vortex in cyclostrophic balance. Dergagarbedian and Fendell in 1970 came up with a theory for the maximum windspeeds in tornadoes based on hydrostatic balance. Brian Fiedler, as a post doc at NCAR in the mid 1980s, worked with Rich Rotunno to show how the "thermodynamic speed limit" may be exceeded when there is a supercritical end-wall vortex. Bob Walko in 1988 investigated the causes of subsidence inside tornadoes. It had been postulated that subsidence inside tornadoes could be responsible for warming and a hydrostatic warm core.

Doug Lilly at OU in the mid 1980s introduced the idea that helicity might act to stabilize storms and promote longevity. He emphasized the importance of Beltrami flow. Bob Davies-Jones at NSSL, on the other hand, emphasized the importance of the related streamwise vorticity in forming mesocyclones. He subsequently published a series of papers investigating the baroclinic generation of vortices and the propagation of convective storms. Morris Weisman and Rich Rotunno at NCAR questioned how useful helicity is in describing vortex formation. They and Bob Davies-Jones engaged in a spirited conversation on the role of curvature in environmental hodographs on convective-storm behavior. At issue was that storm-relative helicity depends on storm motion, which in turn depends on the mean wind and on propagation: it is not Galilean invariant.

The role of downdrafts in tornadogenesis was probably first proposed by Ted Fujita in his "twisting downdraft" schematic and hinted at in his analyses of the tops of supercells. In the past ten years, Paul Markowski and collaborators have investigated the role of downdrafts in an idealized model and Eric Rasmussen and collaborators have suggested that descending reflectivity cores (DRCs) in supercells might play a role in tornadogenesis. A statistical study of radar case studies by Aaron Kennedy at OU and collaborators was inconclusive. Bob Davies-Jones picked up on suggestions by Ted Fujita in the early 1970s and by Das in the early 1980s that rain-filled downdrafts might initiate tornadogenesis. Davies-Jones' theory is that descending rain curtains transport momentum downward, which can lead to vortex intensification. Most recently, Byko and collaborators used mobile Doppler radar data and idealized modeling to investigate the causes and consequences of the DRCs.

5. EARLY SEVERE-STORM INTERCEPT ACTIVITIES

The reader is referred to Bluestein (1999) for a summary of severe-storm intercept field programs prior to the late 1990s. In 1963 Frank Ludlam, a prominent British convection researcher at Imperial College in London, stated in an AMS Monograph that "…the tornado, which energetically is only a detail in the severe storm. However, its importance as a hazard and the interest of the problems which it poses makes it desirable to indicate its probable place in the cumulonimbus model." Storm chasers, beginning in the early 1970s set out to do just that. By chasing storms, one could dramatically increase the number of case studies possible when remaining at a fixed site over that by waiting for storms to come to the site.

Joe Golden at NSSL, who had done pioneering work on observations of waterspouts in South Florida and the Keys, did similar studies at NSSL, most significantly for the Union City tornado on 24 May 1973. He and Dan Purcell produced a composite figure illustrating the relationship between the tornado and storm cloud features, precipitation, and airflow. On the basis of many observations, Al Moller at OU and subsequently at the NWS in Ft. Worth published a schematic of the visual features in a tornadic supercell in 1978, the basic aspects of which are still being reproduced today. Les Lemon at NSSL and Chuck Doswell summarized early Doppler radar observations and storm-intercept observations in the late 1970s and produced a very influential schematic of the surface features in a tornadic supercell including the rear-flank and forward-flank downdrafts, and the notion of a divided mesocyclone structure. Their conceptual model is still being discussed and slight modifications have been suggested recently.

The first visual tornado data to be analyzed quantitatively were movies showing debris flying through the air. Hoecker, in 1960 published a seminal photogrammetric analysis of airborne debris in a tornado that hit Dallas, TX in 1957. This pioneering study was based on a serendipitously obtained movie. Subsequent similar studies were conducted by Joe Golden and Dan Purcell for movies of the Union City tornado in 1973 and by Erik Rasmussen and collaborators for the Tulia, TX tornado in 1980, both during deliberate storm-intercept missions. The results of these studies showed that flow in tornadoes resembled that of a combined Rankine vortex. Efforts to obtain movies of tornadoes showing flying debris continued through the early 1980s.

6. DOPPLER-RADAR STUDIES

J. Q. Brantley and Daniel Barczys of the Cornell Aeronautical Laboratory first suggested in 1957 that Doppler radar could be used to detect tornadoes. Smith and Holmes first used a continuous wave (CW), X-band, Doppler radar acquired by the Weather Bureau from the Navy and modified appropriately, to obtain Doppler wind spectra in a tornado that hit El Dorado, KS on 10 June 1958. Roger Lhermitte made many contributions to radar meteorology, especially during the 1960s when he suggested using pulsed Doppler radar for studies of convective storms. Ralph Donaldson on 9 August 1968 used a pulsed, C-band, Doppler radar from the Air Force Cambridge Research Laboratories to detect cyclonic shear in a supercell over Marblehead, MA. His innovative display was called the “plan shear indicator” (PSI).

Since severe convective storms contain heavy precipitation that heavily attenuates signals at X-band and C-band, efforts were made at NSSL, under the leadership of Ed Kessler, its first director, to probe severe convective storms at S-band. The tornado vortex signature (TVS) was discovered during the subsequent analysis of data from the Union City, OK tornadic supercell of 24 May 1973 and published by Don Burgess and colleagues in 1978. This study marked the turning point in the direction of subsequent Doppler radar studies of tornadoes and their parent storms. Les Lemon and collaborators demonstrated that for the Union City storm there was a temporal relationship between the collapse of the BWER and tornadogenesis, which is suggestive of a possible dynamic relationship between collapse of the updraft and subsequent tornadogenesis.

At NSSL a second S-band Doppler radar was installed northwest of the Norman Doppler radar to form a dual-Doppler network, discussed by Rodger Brown in a 1975 publication. Under the leadership of Peter Ray at NSSL, there were a number of important studies conducted in which tornadic supercells passed through the network. Peter Ray and colleagues first demonstrated that good analyses were possible for data collected for a storm on 20 April 1974. Significant case studies for tornadic supercells on 6 June 1974, 8 June 1974, 22 May 1977 (the much studied and modeled Del City storm), and 17 May 1981 ensued. Ed Brandes and collaborators published extensively on dual-Doppler analyses, beginning in 1977. Gerry Heymsfield at OU published an early study in 1978 for the 8 June 1974 storm. Storm structure during tornadogenesis and vorticity production were described from the dual-Doppler analyses. Carl Hane at NSSL, in a 1981 publication, demonstrated that thermodynamic variables can be “retrieved” from the three-dimensional wind field synthesized from dual-Doppler analyses.

While collection of dual-Doppler data for the analysis of the storm-scale wind field in tornadic supercells was a major objective, Doppler spectra in tornadoes were collected by Dusan Zrnic and collaborators at NSSL for a number of cases. This important work produced estimates of the maximum windspeed in tornadoes that did not depend on photogrammetric analysis or in situ measurements.

7. NON-HYDROSTATIC CLOUD MODELING AND RELATED THEORETICAL STUDIES

At the same time Doppler radars were being used for the first time to probe the internal structure of tornadic supercells, 3-D non-hydrostatic models were being developed and used to simulate them. Based on early work by Yoshi Ogura at the Univ. of Illinois at Champaign-Urbana and Norm Phillips at MIT that was published in 1962, a model was devised that did not include the complicating effect of sound waves. Bob Schlesinger at the Univ. of Wisconsin at Madison was the first to exploit their work and constructed a working 3-D anelastic model in the mid to late 1970s. At the same time, however, Joe Klemp at NCAR and Bob Wilhelmson at the Univ. of Illinois at Champaign-Urbana constructed a working 3-D model that included sound waves (i.e., was fully compressible). This model became known as the Klemp and Wilhelmson model and was soon exploited for many studies of supercell behavior.

The seminal and most influential work was done at NCAR by Morris Weisman and Rich Rotunno. In a series of papers published in the early and mid 1980s, the importance of vertical shear and CAPE were demonstrated, the consequences of dynamically induced vertical perturbation pressure gradients on storm propagation were explained, and in 1983 a seminal paper by Rich Rotunno and Joe Klemp was published in which the origin of low-level rotation in supercells was explored and explained using the Klemp and Wilhelmson model and a one-way nested grid. In the mid 1990s, Lou Wicker and Bob Wilhelmson at the Univ. of Illinois expanded and improved on the earlier work by Rotunno and Klemp and demonstrated the importance of the upward-directed perturbation pressure gradient underneath the mesocyclone in amplifying vorticity. Louie Grasso and Bill Cotton at CSU, using the RAMMS model and three nested grids, explored similar issues.

Subsequent ultra-high resolution model simulations at the Univ. of Illinois at NCSA and by Ming Xue and collaborators at OU produced realistic-looking simulations of tornado-like vortices down to scales as low as 12 m. As already noted, Lewellen and collaborators produced simulations as fine as 2.5 m in the horizontal and 1.5 m in the vertical, but not for the whole parent storm.

8. MEASUREMENTS MADE BY INSTRUMENTS DURING SEVERE-STORM MISSIONS

The first attempts to make in situ measurements in severe storms were in 1980, when Al Bedard and Carl Ramzy at the Wave Propagation Lab in Boulder collaborated with the author to design and build TOTO (Totable Tornado Observatory), a 400 lb, instrumented package intended to make measurements of wind and thermodynamic variables when left in a tornado's path. The author and his graduate students used it in 1981 – 1983, and subsequently Lou Wicker at NSSL used it, with some success, but no great observational insights followed since direct hits were rare.

Fred Brock at OU and collaborators developed the "Turtle," in the late 1980s to make in situ measurement in tornadoes, but in a much smaller and lighter package which could be deployed en mass, in order to increase the likelihood of a direct hit. The Turtle has evolved into the HITPR (Hardened In-situ Tornado Pressure Recorder) by Tim Samaras and collaborators. On 24 June 2003 in Manchester, SD, an HITPR recorded a pressure fall of ~ 100 hPa in a tornado.

While small deployable packages have been used to make limited measurements directly in tornadoes, mobile mesonets (networks of instrumented vehicles), originally developed for VORTEX in 1994 and 1995, were first used by Jerry Straka at OU and collaborators to make more detailed measurements in selected regions of supercells. Two main scientific questions posed for mobile mesonet deployments have been as follows: Are there any temperature anomaly differences between those in the rear-flank downdraft of tornadic supercells and those in non-tornadic or weakly tornadic supercells? How strong is the baroclinic zone, if any, along the edge of the forward-flank downdraft? Paul Markowski and collaborators have reported on results from VORTEX deployments and deployments during the 3 May 1999 tornado outbreak in Oklahoma. Gryzch et al. have recently reported on results in supercells in the Northern High Plains using a different mobile mesonet.

During the 2004 storm season, we used a commercially available digital infrared camera to photograph tornadoes and wall clouds with the intent of estimating temperature gradients at cloud base. Robin Tanamachi and collaborators reported in 2006 that intervening precipitation interfered with efforts to make meaningful measurements, though it was found that the lapse rate along a tornado condensation funnel was approximately moist-adiabatic, as expected.

In situ soundings in and near tornadic supercells were first attempted using a radiosonde package in 1984 by the author and his collaborators. The first attempt failed as an underinflated balloon skimmed along the ground upstream from a tornado on 26 April. For subsequent successful ascents, an optical theodolite was used to determine balloon location as a function of time so winds could be computed. Several case studies based on successful launches in the mid and late 1980s, including a direct release into the updraft of a tornadic supercell in the Texas Panhandle, were reported in the literature. In the late 1980s, Dave Rust and colleagues at NSSL began to release CLASS sondes, which were developed at NCAR. These portable radiosondes made use of LORAN navigation signals to determine their location as a function of time. More recently, NSSL has used GPS sondes developed at NCAR to obtain soundings in and near severe convective storms.

9. TORNADO CLASSIFICATION

Storm chasers have identified a number of other types of tornadoes, in addition to the supercell tornado. Ernie Agee and a collaborator at Purdue recently have proposed taxonomy of tornado types. One of the most significant types other than the most commonly documented supercell tornado, is the non-mesocyclone tornado: some of them the author called “landspouts,” owing to their similarity to Florida waterspouts. Other non-mesocyclone tornadoes that occur along the leading edge of gust fronts are called “gustnadoes,” a term first used by storm chasers.

Many studies were conducted in the mid and late 1980s in eastern Colorado, especially during CINDE. Jim Wilson at NCAR, Roger Wakimoto at UCLA, and other colleagues at NCAR (e.g., Rita Roberts), NOAA (Ed Szoke), and U. Wyoming (Brooks Martner) published a series of papers on observational studies using fixed-site Doppler radars; most of the studies were based on single Doppler radar, while one on 15 June 1988 in the Denver area was based on dual-Doppler measurements. Roger Wakimoto did a detailed study combining photographs with Doppler radar data. It should be noted that Fred Bates from St. Louis University in the early and mid-1960s discussed what may have been similar tornadoes observed from aircraft. Non-mesocyclone tornadoes were successfully simulated and studied by Bruce Lee and Bob Wilhelmson at the Univ. of Illinois. It is now understood that non-mesocyclone tornadoes develop from vorticity along pre-existing boundaries.

Tornadoes and misocyclones have also been reported in quasi-linear convective systems (QLCSs). Interestingly, it was thought in the 1940s that squall lines were responsible for tornadoes, but later studies pointed to the importance of isolated cells or cells embedded in lines prior to their evolution into squall lines. We’ve come full circle: Tornadoes were documented by Rit Carbone in a study of a California rainband in the early 1980s and by Greg Forbes and Roger Wakimoto, then at the Univ. of Chicago, in a study of a bow echo in Illinois. Jeff Trapp at Purdue and Morris Weisman demonstrated in the early 2000s using numerical simulation experiments how strong vortices could be produced in QLCSs.

The former published a climatology of QLCS tornadoes in 2005.

It has been recognized for many years that tornadoes can also appear in tropical cyclones, especially when they make landfall. Novlan and Gray in 1974 produced a seminal climatology of these tornadoes. Bill McCaul at OU studied tornadoes in Hurricane Danny in 1985 and in 1991 published a study of the composite environment of hurricane tornadoes. More recently, Spratt et al. in 1997 discussed WSR-88D observations of tropical cyclone tornadoes in Florida and Baker and colleagues studied tornadoes in Hurricane Ivan over the Gulf in 2004. It appears that the parent storms of many tornadoes both over the ocean and after landfall are shallow supercells, while others are not associated with mesocyclones.

Perhaps similar to shallow supercells in tropical cyclones are “low-top” or “mini-supercells,” sometimes observed near upper-level cyclones, where the tropopause is low, but vertical shear is strong. Cooley in 1978 described “cold-air funnels” that also occur near upper-level cyclones.

Tornadoes have been classified not only according to how and where they form, but by their sense of rotation. It was recognized long ago that anticyclonic rotation in tornadoes is rare. Based on visual documentation of one in Iowa on 13 June 1976 by John Brown and Kevin Knupp, one near Grand Island, NE on 3 June 1980 by Ted Fujita, one near Geary, OK on 29 May 2004 and one near El Reno, OK on 24 April 2006 by the author and his students, it is now recognized that when they are observed they often occur in conjunction with another nearby cyclonic tornado.

10. DOPPLER RADARS USED DURING SEVERE-STORM INTERCEPT OPERATIONS

In 1987 Wes Unruh at the Los Alamos National Laboratory and I repeated the Smith and Holmes 1958 experiment, this time using a battery-powered, portable, CW/FM-CW, X-band, Doppler adapted also for applications not originally intended for the original instrument. We used this radar up to the first year of VORTEX to acquire close-range Doppler wind spectra in tornadoes. In a series of papers in the early - mid 1990s, we verified F-5 wind speeds in a tornado near Red Rock, OK on 26 April 1991 and determined wind spectra as a function of range with 78 m range resolution, near Northfield, TX on 25 May 1994. This radar, however, had a relatively broad beamwidth of 5^0 and was steerable only by hand, and not automatically scanned.

While Bob Crane at OU suggested mounting an old, Ka-band radar on a truck and having automatic scanning, I chose to use a scanning W-band radar from the Microwave Remote Sensing Laboratory at the Univ. of Massachusetts in Amherst, under the supervision of Bob McIntosh, because a very narrow beam antenna could easily be mounted on a small truck. The first system was developed by Andy Pazmany and first used in 1993 with a 0.6^0 (half-power) beam. We collected fine-scale data along gust fronts and wall clouds, but not in a tornado until VORTEX during year 1 on 25 May 1994. Alas, while scanning the nearby tornado the system failed owing to an incorrectly made electrical connection. It was not until the 1999 storm season that an updated system with a larger antenna having a 0.18^0 beam was used and tornadoes on 3 May near Verden, OK, 15 May near Stockton, KS, and 5 June near Bassett, NE, at close range were probed, at one elevation angle and data successfully recorded. Significant datasets were also collected on 5 May 2002 near Happy, TX and 12 May 2004 near Attica, KS, when high-resolution, vertical cross sections through and surrounding the weak-echo hole were obtained. In addition, measurements showing the vertical variation of Doppler velocity near the ground were made near the tornado core. Wen-Chau Lee’s GBVTD algorithm was implemented. In addition, horizontal-vortex shear signatures were found along the edge of the tornado.

The first proposal to use airborne Doppler radars to map the wind field in convective storms was made by Roger Lhermitte in 1971. He proposed using two aircraft, each having its own radar, flying at perpendicular flight paths to collect dual-Doppler data.

Airborne, X-band Doppler radars were used by NOAA beginning in the 1980s to map the winds in hurricanes. The first supercell probed by one of the NOAA P-3 airborne radars was on 27 May 1985, near Oklahoma City, during PRE-STORM, through the collaboration of Dave Jorgensen of NOAA and Peter Ray of NSSL. For this case, dual-Doppler analyses were synthesized using data from the airborne radar and data separately from each of the two NSSL ground-based, fixed-site, S-band Doppler radars. The radar-equipped aircraft flew by supercells again, under the leadership of Dave Jorgensen from NOAA, in the spring of 1991, this time using "FAST" (fore-aft scanning technique), for which only one aircraft was needed to collect "pseudo"-dual-Doppler data. The first chance to collect data in a tornadic supercell came during COPS-91, on 26 April, but the aircraft could not fly owing to a mechanical problem. Later in the season, successful data were collected in supercells for the first time. David Dowell at OU and collaborators published the first analyses of these supercells in 1997.

During VORTEX, late in the season of 1994 and on many occasions in 1995, excellent datasets were collected. In the latter year the NOAA P-3 was joined by NCAR's ELDORA, which made use of frequency hopping to increase the number of independent samples and reduce the time for getting Doppler velocity measurements having acceptably small errors as the aircraft flew rapidly by the targeted storm. The design of ELDORA was a collaboration between Peter Hildebrand at NCAR and colleagues and collaborators from France. The airborne field experiment using ELDORA was led by Roger Wakimoto. In 1994 the Newcastle, TX tornadic storm was probed on 29 May, and in 1995 the Garden City, KS tornadic storm was documented on 17 May, the Dimmitt and Friona, TX tornadic storms were probed on 2 June, and the McLean, TX cyclic tornadic storm was probed on 8 June. A number of significant papers by Roger Wakimoto and his students were published, along with others by David Dowell and me, Conrad Ziegler at NSSL and his collaborators, and Erik Rasmussen and Jerry Straka.

During year 2 of VORTEX, Josh Wurman at OU and collaborators at OU, NSSL, and NCAR, developed the first truck-mounted X-band Doppler radar, the "Doppler on Wheels" (DOW) and successfully collected data in a tornado in the Garden City storm on 17 May 1995. Subsequently data were collected in tornadoes on 2 June. Since then data collection efforts using the DOW and future generations of DOWS have been very successful.

The first mobile, dual-Doppler dataset for a tornadic supercell was collected by two DOWs in eastern Oklahoma, near Kiefer and Glenpool, on 27 May 1997, but at low elevation angle only. Volumetric mobile dual-Doppler data were first collected successfully near Bridgeport, NE on 20 May 1998. Since then, Mike Biggerstaff at OU has used two mobile C-band radars, the SMART-Rs, to collect mobile dual-Doppler data on a tornadic supercell near Geary, OK on 29 May 2004, an effort which was reported by MacGorman et al. in 2008.

A significant single-Doppler dataset was collected by a DOW in Spencer, SD on 30 May 1998; the tornado damage path was correlated with the Doppler wind data by Josh Wurman and his student, Curtis Alexander. Data from the Spencer storm exhibited multiple vortices, as did DOW data from the Mulhall, OK tornado on 3 May 1999. The highest wind speeds in a tornado ever recorded (135 m s^{-1}) were made by a DOW in Bridgecreek, OK on 3 May 1999. Double gust front structure was documented near Crowell, TX on 30 April 2000. Wen-Chau Lee and Josh Wurman deduced 3-D tornado structure in the Mulhall tornado using the former's GBVTD analysis technique. To date, successive generations of DOWs have been used to probe hundreds of tornadoes and have facilitated a climatology of various tornado parameters.

A poor-person's version of the DOW was built at the Univ. of Mass. at Amherst and first used in 2001 for surveillance of reflectivity only. The radar system was based on a commercially available marine radar. In 2002, both Doppler and polarimetric capabilities became available.

During IHOP, in 2002, another DOW having polarimetric capability, which had been built by Josh Wurman for the government of Greece, but not used to detect tornadoes, was used in the field. The UMass X-band radar became known as the UMass X-Pol to distinguish itself from the Greek-gov't radar.

Early work with a fixed-site, S-band, polarimetric Doppler radar at NSSL (KOUN) by Alexander Ryzhkov, and collaborators demonstrated that a tornado debris signature could be detected (most clearly evident as a region of low ρ_{hv}). The first case reported was in a tornadic storm near Oklahoma City on 3 May 1999.

Since IHOP, the most significant datasets collected by the UMass X-Pol were on 12 May 2004 near Attica, KS, when a tornado debris signature was clearly detected at close range along with visual documentation, and on 7 May 2007, when the formation of the Greensburg, KS tornadic supercell was documented.

Because tornadoes evolve on very fast time scales (~ 10 s or less), rapid-scan radars have been developed. Josh Wurman and colleagues at NCAR developed the rapid-DOW, which first scanned a tornado in 9 June 2005 in Kansas. The rapid-DOW is an X-band, Doppler radar that scans mechanically in azimuth, but in electronically in elevation at six different angles, by changing frequency.

The MWR-05XP is a mobile, X-band, phased-array, Doppler radar that ProSensing, Inc. in Amherst, MA adapted for meteorological use from a military phased-array radar acquired by the Naval Postgraduate School in Monterey, CA. Both the rapid DOW and the MWR-05XP can scan sector volumes of storms in 10 s or less; the latter is faster and can scan more elevation angles nearly simulatneously, but the former has finer azimuthal resolution. The MWR-05XP first successfully scanned a tornado on 23 May 2008 in Kansas.

11. CURRENT AND FUTURE TORNADO RESEARCH

The history of tornado research consists of a series of both serendipitous and planned observations and measurements, numerical studies with idealized models, laboratory-vortex experiments, and numerical simulations. Observations have improved in step with advances in technology, most prominently with increasingly more sophisticated radar systems. Numerical simulations have improved with increased computer power, speed, and storage capabilities.

Soon we will be able to analyze convective storms simulated with ultra-fine spatial resolution so that the tornado and its parent storm are both resolved adequately (on scales < 10 m). When we finally are able to do controlled experiments and resolve all features adequately, then what? Will the simulations be too complex to advance our understanding easily?

Soon we will have observations that document tornadoes in the act of forming along with all that goes on in the parent storm, using rapid-scan (via mechanically scanning, phased-array, or imaging techniques), and fine-scale, polarimetric Doppler radar measurements. Will these observations be adequate to advance our physical understanding, or will complexity again hinder us? We cannot do controlled experiments in the atmosphere.

Finally, can we address what is cause and what is effect when processes are detected nearly simultaneously? This and the aforementioned questions are our challenges for the future.

12. POSTSCRIPT

This manuscript is a draft based on the actual presentation given at the conference. I did not have time to include in this manuscript the dozens of figures and the hundreds of references used. As a draft, there are probably some factual errors and some important events or studies were inadvertently not mentioned. I would appreciate receiving corrections in fact and suggestions for other significant studies not cited.

13. ACKNOWLEDGMENTS

NSF grant AGS-0934307 supported the author at the time of this review.

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