# A History of Severe-Storm-Intercept Field Programs

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## ABSTRACT

Efforts to study severe convective storms and tornadoes by intercepting them either on the ground or on airborne platforms are highlighted. Airborne sorties into or near waterspouts in the Florida Keys with instruments were made in the late 1960s and the 1970s. The main goals of the first organized ground-based severe storm intercept field programs in the 1970s at the National Severe Storms Laboratory and at the University of Oklahoma were to verify severe weather signatures detected by a remote Doppler radar, to identify cloud features that could aid storm spotters, and to estimate wind speeds in tornadoes based on the photogrammetric analysis of tornado debris movies. Instruments were subsequently developed that could be carried along on intercept vehicles to measure in situ electric field change, thermodynamic variables, and wind, near the ground and aloft. Beginning in the late 1980s, portable and mobile Doppler radars were developed that could be used to make estimates of the maximum wind speeds in tornadoes and to map out the wind field in tornadoes. Airborne radar systems developed and flown in hurricanes in the 1980s were further refined and used in the 1990s to map out the wind field in severe convective storms. All these instruments were used in 1994 and 1995 in a large, coordinated, storm-intercept field program. Other efforts over the years have focused on collecting hail and on recording the sound from tornadoes.

Some of the most important scientific results are summarized. Among the most significant are the identification of the visual architecture of tornadic supercells, the discovery of different modes of tornado formation and other types of vortices, and the verification of extremely high wind speeds in tornadoes previously only inferred from damage.

## 1. Introduction: Early history and related airborne waterspout studies

In order to learn about the nature of severe convective storms and tornadoes, it is necessary to observe them. At a fixed location, the probability of observing a severe convective storm or tornado close up is very small (Davies-Jones and Kessler 1974) because convective storms and tornadoes affect only very small areas and are relatively fleeting. The first organized storm-intercept (colloquially known as chase) programs dedicated to the study of severe convective storms and tornadoes in the plains of the United States began in the early 1970s (Golden and Morgan 1972; Bluestein and Golden 1993). The purpose of this paper is to present a historical summary of the field programs that have had severe-storm-intercept activities as a component (regardless of whether the entire project consisted of intercept activities or only a small portion of the project consisted of intercept activities), including a list of technological advances in instrumentation and highlights of the most important scientific findings.

Prior to the early 1970s, what we knew about tornadoes came in large part from serendipitous eyewitness encounters by people who did not have scientific training (Flora 1953); other information was gleaned from chance, close encounters near radar sites (e.g., Stout and Huff 1953; Donaldson and Lamkin 1964). Scientists analyzed storm and tornado photographs and movies taken by others. T. Fujita analyzed photographs of the Fargo, North Dakota, tornado and its parent cloud from 20 June 1957 (Fujita 1960). His landmark study produced the first terminology of storm architecture in what would years later be called a supercell: Fujita coined the terms ‘‘wall cloud’’ and ‘‘tail cloud,’’ which are still used to this day. [Espy (1841), in the nineteenth century, might actually be the first to have observed cloud-base lowerings such as wall clouds, though his explanation for them was incorrect. He also apparently recognized the importance of surface outflow in storms.] Hoecker (1960) photogrammetrically analyzed debris movies of the Dallas, Texas, tornado of 2 April 1957. His analysis provided the first reliable estimates of wind speeds in tornadoes.

In the 1950s, two pioneers, neither of whom were professional meteorologists, ventured out into the field

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with the hope of observing storms at close range. Roger Jensen began chasing storms in 1953; David Hoadley began in 1956 and continues to chase as of the time of this writing.

Neil Ward, who began chasing in 1961, was probably the first research meteorologist to storm chase (Ward 1961; Browning and Donaldson 1963); transportation and communication were furnished by the Oklahoma Highway Patrol, and radar information was provided by the Weather Bureau in Oklahoma City. The tornadoes Ward observed on 4 May 1961 near Geary, Oklahoma, were in a storm whose structure was recognized as unusual, and which three years later became known as a supercell.

The University of Wyoming began field efforts in 1964 to collect hailstones, with guidance based on radar observations (Auer and Marwitz 1969). Similar techniques were used in 1965 and 1966 in South Dakota and briefly in northeastern Colorado during Project Hailswath (Goyer et al. 1966). Efforts to collect hailstones using mobile hail collectors were first organized at the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma, in 1966 with station wagons equipped with cold-storage facilities (Browning and Beimers 1967; Browning et al. 1968).

The ability to chase successfully over a long period of time requires a knowledge of how to forecast severe weather. It is therefore fitting that the subject of this historical review appears in this journal, whose focus is on forecasting. Johns and Doswell (1992) have acknowledged observational studies as leading to several new techniques that help forecasters assess the potential for severe storm development.

Chasing storms has not been limited to ground-based vehicles. The first deliberate aircraft penetrations into convective storms occurred during the Thunderstorm Project in the late 1940s; however, severe storms in particular were not targeted. Squall lines were penetrated beginning in 1956 during the Tornado Research Airplane Project (TRAP) by pilots that eventually became known as the Rough Riders (Galway 1992), who in subsequent years also penetrated isolated cells (Schumacher 1963). Bates (1963) reported on what was likely the first nonpenetrating chase in an aircraft, during the summer of 1961 in Kansas. He documented a tornado, along the flanking line, that was relatively far removed from the precipitation core of its parent storm.

In the late 1960s and in the 1970s, scientists aboard aircraft chased waterspout-producing clouds in the Florida Keys. Rossow (1969, 1970) made electric field measurements near waterspouts that suggested that they were not electrically driven. Golden (1974a,b) used visual observations to propose a waterspout life cycle. Church et al. (1973) and Leverson et al. (1977) reported on in situ data collected by a waterspout-penetrating aircraft. Schwiesow (1981) and Schwiesow et al. (1981) reported on the wind structure of waterspouts based on remote measurements made with a continuous-wave (CW; i.e., with no ranging capability) Doppler lidar.

## 2. Field programs focussed on visual observations: 1972–87

At about the same time as the airborne waterspout campaigns were conducted, observations of storms were made during NSSL's Tornado Intercept Project (Golden and Morgan 1972). This project had been stimulated by Bruce Morgan, an engineer at Notre Dame University, who had proposed to intercept tornadoes with an armored vehicle (tank). Using conventional automobiles rather than tanks, NSSL personnel and volunteers from the University of Oklahoma (OU) confirmed Fujita's earlier findings that had been based on visual observations from only one storm. Don Burgess provided the field crew with radar information. C. Doswell and A. Moller, who were students at the time at OU, synthesized intercept observations of tornadic supercells into a visual model (Moller 1978), which is still used by spotters and chasers to help identify that part of a storm where tornadoes are most likely to form.

A methodology for intercepting a storm with the intent of taking photographs and movies was developed in the 1970s on the basis of experience and the visual model. An area is targeted early in the day based on morning surface, sounding, and model data; chasers try to arrive in the target area before or as storms are forming. If storms do form, chasers try to position themselves 2–5 km ahead and just to the right of the anticipated path of the wall cloud or updraft base in the storm thought most likely to produce a tornado. This range of distances usually allows one to see a tornado, if there is one and it is not hidden behind a curtain of precipitation, but is not so close that one is in danger of being hit by tornadic debris or by large hail. When possible, Doppler radar information is used to locate potential tornado producers. It was found that it is often not safe to drive blindly through heavy precipitation to arrive at the preferred location.

The first comprehensive case study of a tornadic supercell in which visual observations made by storm chasers were combined with remote Doppler radar data was based on analyses of a powerful tornado that hit Union City, Oklahoma, on 24 May 1973 (Moller et al. 1974; Golden 1976; Golden and Purcell 1978a,b). A morphological model of the life history of the tornado was proposed and compared to that of the Florida Keys waterspout; wind speeds as high as 80 m $s^{-1}$ were estimated 90 m above the ground in the tornado from an analysis of debris movies. An analysis of the sequence of Doppler radar observed mesocyclone and tornadic vortex signatures in the Union City storm, which were correlated with the visual life history of the tornado, became the basis for the issuance of radar-indicated warnings when the Weather Surveillance Radar-1988

Doppler (WSR-88D) radar network was implemented over 10 years later (Crum and Alberty 1993).

There were extensive hail chasing activities in northeastern Colorado from 1972 to 1974 by teams from the National Center for Atmospheric Research (NCAR), the University of Wyoming, and the Desert Research Institute at the University of Nevada. The operations were part of the National Hail Research Experiment (NHRE; Knight and Knight 1979; Knight 1981); results were used to evaluate the effectiveness of a randomized seeding experiment to suppress hail. There were other hail chasing activities in Switzerland, South Africa (Knight 1981), and in 1979 in Alberta (Knight and English 1980), and also in earlier years in Alberta as part of the Alberta Hail Studies Project and subsequent field experiments. Time-lapse movies of clouds were also taken in Alberta. There were also some unsuccessful attempts to collect hail in Bulgaria (C. Knight 1998, personal communication).

Bob Davies-Jones was the leader of the Tornado Intercept Project at NSSL from 1975 to 1986. Storm intercept missions in the 1970s (Alberty et al. 1977; Ray et al. 1977; Bumgarner et al. 1981; Burgess et al. 1982b; Davies-Jones 1983; Kimpel et al. 1976; Kimpel et al. 1977; Lee et al. 1981) were coordinated from a tiny room at NSSL, where the position of nowcaster was first developed. The nowcaster was John Weaver, who in the mid- and late 1970s provided field crews with up-to-the minute surface observations, satellite interpretation, short-term forecasts, and Doppler radar information relayed from the Doppler radar room, usually by Burgess, who was perhaps the first nowcaster, having provided storm-intercept crews with radar information as early as 1972 and 1973 (C. Doswell 1998, personal communication). Radio contact with storm-intercept crews when they were in central Oklahoma was made with the aid of a repeater located atop an instrumented television tower in northeast Oklahoma City or elsewhere by radiotelephone or pay phone.

The existence of anticyclonic tornadoes was confirmed near Alva, Oklahoma, during a chase on 6 June 1975 (Burgess 1976). On 2 May 1977 an OU intercept crew observed a splitting storm in central Oklahoma, which was simultaneously being probed by the NSSL Doppler radar (Bluestein and Sohl 1979). This was the first time close-up visual observations of a splitting storm were correlated with Doppler radar data. [Prior to this storm, Achetemier (1969) had correlated his visual observations of a splitting storm in Iowa in 1965 with conventional radar images.]

A summary of radar observations combined with visual and other observations by Lemon and Doswell (1979), for storms studied in the early and mid-1970s, indicated the coincidence of supercell tornadogenesis with the rear flank downdraft and its visual manifestation, the ''clear slot.'' The storm observations and photographs from Davies-Jones's Tornado Intercept Project were used in a NOAA-produced storm-spotting movie and in a slide collection for storm spotters (Lee et al. 1981).

During the 1978 storm season, the focus of the Joint Doppler Operational Project (JDOP; Burgess et al. 1979) conducted by NSSL (also in the preceding two years) was the verification of radar signatures observed back at the Norman (NSSL) Doppler radar. The successful verification of many of the radar signatures led to the use of Doppler radar in issuing severe thunderstorm and tornado warnings. The future development and deployment of the WSR-88D, the national operational Doppler radar weather radar system, a decade later, was influenced in very large part by the efforts of JDOP (Whiton et al. 1998).

In addition to documenting tornadoes, large hail, and strong straight-line winds, the intercept crews also noted other phenomena: Gustnadoes [Doswell (1985); Wilson (1986); referred to as ''gust front whirls'' in Bluestein et al. (1978)] were documented; the life cycle of a low-precipitation (LP) supercell [previously called a ''bell shaped'' cumulonimbus by Davies-Jones et al. (1976) and a ''dryline storm'' by Burgess and Davies-Jones (1979)] was observed and a time-lapse movie taken of it (Bluestein and Parks 1983; Bluestein 1984a; Doswell 1985; McCaul and Blanchard 1990); high-based funnel clouds pendant from cumulus congestus having ragged bases were photographed (Bluestein et al. 1978; Bluestein 1994; Doswell 1985). The documentation of these features was important for spotters. Gustnadoes were rarely destructive and high-based funnel clouds were never destructive, even though both could be mistaken for tornadoes. However, Fujita (1979) documented a fatality in an F1 tornado in Illinois during Project NIMROD (Northern Illinois Meteorological Research on Downburst) that may have been a gustnado (Fujita 1979). On the other hand, LP storms produced large hail, even though they lacked a menacing-looking, dark precipitation region.

Also during JDOP a multiple-vortex wall cloud in a supercell was filmed in time lapse in west Texas (Bluestein 1984b); this film provided evidence that mesocyclones, like tornadoes, can also exhibit multiple-vortex structure.

Bates (1968) had noted a relationship between the flanking line and some tornadoes, and Lemon (1976) had proposed the importance of the flanking-line portion of a storm in its intensification. The visual appearance of flanking lines in supercells was hypothesized to be related quantitatively to parameters such as shear and buoyancy (Bluestein 1986), which had been found to be related to convective storm type (e.g., Weisman and Klemp 1984). Bluestein (1986) proposed a technique to determine storm severity based on the appearance of the flanking line in rapid-scan, high-resolution satellite images.

During the Severe Environmental Storms and Mesoscale Experiment (SESAME) conducted during the spring of 1979, tornadic debris movies were taken of a large tornado in Seymour, Texas, on 10 April and of a multiple-vortex tornado near Orienta, Oklahoma, on 2 May (Bluestein 1980). Photogrammetric analyses of the films indicated wind speeds as high as 90 m $s^{-1}$ at a height of 30 m above the ground in the Seymour tornado (Lee et al. 1981). An OU crew collected canceled checks, newspaper clippings, and papers from grade school notebooks from Wichita Falls, Texas, in a field about 40 km to the north just after a tornado on 10 April had severely damaged the town (Bluestein 1980). Such debris fallouts have become the focus of more recent studies (Snow et al. 1995).

Efforts were also made to collect hail while intercepting severe storms. The locations of the hail fall and the sizes of the hail could be compared with that expected based upon dual-Doppler analyses of the parent storm and the use of a hail growth model (Nelson and Knight 1982; Ziegler et al. 1983).

Storm intercept activities began informally in the middle and late 1970s at Texas Tech University in Lubbock (R. Peterson 1998, personal communication). More organized activities were led by graduate students Erik Rasmussen and Tim Marshall. More movies of tornado debris were taken in west Texas and the Texas panhandle on 30 May 1980 by Rasmussen. However, more importantly, his detailed analysis of the behavior of the parent storm led to the proposal of the cyclical tornadogenesis model (Rasmussen et al. 1982; Burgess et al. 1982a).

Burgess et al. (1979) noted that during JDOP several tornadoes occurred during the ‘‘developmental stages of the storm systems at the time of initial rapid growth of echoes on radar,’’ and that they were not accompanied by a mesocyclone signature. An OU crew on 22 April 1981 documented by accident (while the crew was heading to a supercell in Texas, tornadoes were seen out the back window!) two small tornadoes in south-central Oklahoma that were associated with a line of developing convective storms; no precipitation was seen while the tornadoes formed (Bluestein 1985b). H. Bluestein named these tornadoes ‘‘landspouts’’ because they looked like and seemed to behave like the waterspouts frequently observed in the Florida Keys. Landspouts represented a new type of tornado that was not as easily detected by radar, since they are not associated with a mesocyclone, or even an intense radar echo. In subsequent years, during storm-intercept field experiments conducted in conjunction with real-time forecasting exercises at the National Oceanic and Atmospheric Administration’s (NOAA) Program for Regional Observing and Forecasting Services (PROFS) in Boulder, Colorado, (Brewster 1986; Brady and Szoke 1989) they would be studied in the Denver, Colorado, area, where they are quite common (Wakimoto and Wilson 1989).

Several other features were documented visually in 1981: On 22 May the complete life cycle of a tornado near Cordell, Oklahoma (Lee et al. 1981), was filmed; it exhibited a similar life cycle to that observed in the Union City storm. Also, a wall cloud with an eye was documented in southern Kansas on 19 June (Bluestein 1985a); it was hypothesized that the eye may have indicated sinking motion.

During the Cooperative Convective Precipitation Experiment (CCOPE), conducted in southeastern Montana in 1981, several distinctive cloud features near a mesocyclone were observed and explained in terms of inhomogeneities in the water vapor field and in terms of the wind field (Fankhauser et al. 1983). Triple-Doppler analysis of the wind field and in situ measurements made by an instrumented aircraft aided in their interpretation. Fankhauser et al. argued that the term ‘‘rain-free base,’’ suggested by Moller (1978), is a misnomer because the cloud base retains its appearance even when there are bursts of rain and hail. Although they suggested using the term ‘‘shelf cloud’’ instead, this terminology has not enjoyed wide usage.

## 3. The first use of instruments to make systematic, in situ measurements: 1978–87

Since storm-intercept crews had proven that they could safely position themselves near severe storms and tornadoes, it became possible to attempt to collect, in a systematic way, in situ data with instruments carried in the chase vehicles. Dave Rust at NSSL and Roy Arnold at the University of Mississippi in 1978 began a multiyear effort, which still continues at NSSL, to study the electrical aspects of severe convective storms (Rust 1989). At first a slow antenna only was used to measure the electrical field change. Charge transfers in cloud-to-ground lightning flashes were determined, in-cloud lightning flashes were detected, and the flash rates tabulated. Other instruments, to be described later, have been added over the years.

NSSL’s mobile lab was used to determine systematic azimuth errors of magnetic lightning ground strike direction finders caused by local site anomalies and to provide verification for determining the efficiency of ground strike location systems. Important early findings included the documentation of the predominance of in-cloud flashes in severe convective storms. In addition, positive cloud-to-ground flashes were confirmed in severe storms; in subsequent years the relationship of positive flashes to tornadoes using network data has been investigated (e.g., MacGorman and Burgess 1994; Bluestein and MacGorman 1998).

In 1980 Al Bedard at the Wave Propagation Laboratory in Boulder and H. Bluestein at OU collaborated on the construction of a 180-kg instrument package named TOTO (Totable Tornado Observatory; Bedard and Ramzy 1983), after Dorothy’s dog in *The Wizard of Oz.* First tested during the summer of 1980 in eastern Colorado, TOTO was designed to be transported by a pickup truck and deployed down a ramp in about 30 s or less into the path of an oncoming tornado, whereafter the pickup truck would strategically retreat. With ad-

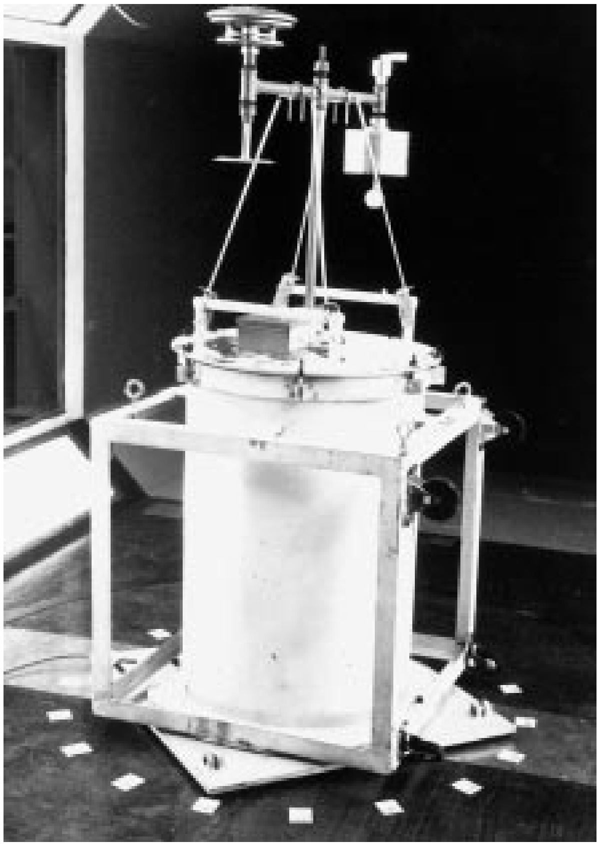

FIG. 1. TOTO in a wind tunnel at Texas A&M University on 21 Mar 1983 (copyright H. Bluestein).

ditional support from NSSL, TOTO was used from late in the storm season of 1981 through 1985 (Lee et al. 1981; Davies-Jones et al. 1984) to record, on paper strip charts, measurements of wind speed, wind direction, pressure, temperature, and corona discharge close to tornadoes and wall clouds (Bluestein 1983a,b; Davies-Jones et al. 1984; Burgess et al. 1985). A ''parent vehicle'' guided the pickup truck with TOTO in the field. Although TOTO was never placed directly in a major tornado, it was placed under many wall clouds; it was found that the pressure deficits under wall clouds are typically on the order of 2–5 mb (Bluestein 1983a,b; Burgess et al. 1985). Efforts to use TOTO were abandoned when it became apparent that the chances of placing it directly into the path of a tornado were small. It was furthermore determined in wind tunnel tests conducted at Texas A&M University in March 1983 that TOTO (Fig. 1), when not staked down, could tip over at wind speeds of only 50 m $s^{-1}$, much less than than the maximum wind speed in many tornadoes. (Incidentally, TOTO was the inspiration for the device named ''Dorothy'' in the 1996 movie *Twister.*)

Another more exotic device for making measurements in tornadoes was developed by Stirling Colgate, a physicist at Los Alamos National Laboratory. He attempted for three seasons in the early 1980s to launch small, lightweight rockets, each weighing less than 1 kg, from a small airplane over Oklahoma and adjacent states (Colgate 1982). The idea of launching instrumented rockets into tornadoes had originated at Purdue in the late 1960s (Agee 1969; Agee 1970; Geddes et al. 1970). Each rocket was equipped to measure pressure, temperature, ionization, and electric field. Although Colgate was able to launch a few rockets into tornadoes, the rockets, which were built in accord with restrictive Federal Aviation Administration regulations, were too lightweight and fragile. Many rockets missed their target because they misfired after they had become soaked with water as the aircraft flew in heavy precipitation near the tornado. In addition, in 1982 the aircraft experienced extreme turbulence as it was caught in strong inflow to a tornado near cloud base, and had to make an emergency landing in an open field.

From 1976 to 1981, R. Arnold at the University of Mississippi tried to deploy instrument packages, designed to record sound, into or near the path of tornadoes (Burgess et al. 1982b; Arnold 1983; D. Rust 1998, personal communication). Based on a serendipitous recording made of a tornado, he had hoped to record what were supposed to be unusual sounds made by tornadoes. Known as ''sound chase,'' this effort was not successful.

During CCOPE in 1981, in situ measurements in a supercell by an armored T-28 aircraft (Sand and Schleusener 1974) indicated updrafts as high as 50 m $s^{-1}$ in the weak echo region around 7 km above ground level (AGL); (Musil et al. 1986). Microphysical measurements were also made in the updraft, which indicated liquid water, but no ice.

In 1984 Bluestein and his students at OU first began to release portable radiosondes using a commercially available system developed by Atmospheric Instrumentation Research in the early 1980s. On 26 April they attempted to release a radiosonde into a tornado in north-central Oklahoma; unfortunately, the balloon was underinflated; the radiosonde skipped over a wheat field toward the tornado, but never actually reached it (Bluestein and Woodall 1990). The group had more success in the succeeding three years (Fig. 2): radiosondes were successfully released underneath a wall cloud in a splitting supercell in northwest Texas on 27 May 1985 (Bluestein et al. 1990a); near a developing, splitting, LP storm on 28 May 1985 (Bluestein et al. 1990b); into the updraft of a tornadic supercell in the northern Texas panhandle on 7 May 1986 (Stensrud and Burgess 1987; Bluestein et al. 1988); into the updraft of a developing, tornadic supercell in the northern Texas panhandle on 25 May 1987 (Bluestein et al. 1989); and along various locations with respect to the dryline, especially in 1985 (Bluestein et al. 1987). Winds were computed when the balloon was visible and tracked by an optical theodolite. Vertical velocity was estimated by subtracting the neutral-air ascent rate from the radiosonde vertical velocity

FIG. 2. Radiosonde just launched from an OU intercept vehicle upstream from a developing severe convective storm in western Oklahoma on 6 May 1986 (copyright H. Bluestein).

estimated from a series of hydrostatically computed heights (Davies-Jones 1974).

Some significant findings from these early portable radiosonde launches are as follows: An updraft of 50 m $s^{-1}$ was found in a tornadic supercell, which could be explained by parcel theory alone (Bluestein et al. 1988); the in-updraft sounding and a nearby environmental sounding were used to estimate the updraft due to buoyancy. Although the estimated updraft speed was additional evidence of intense updrafts in a supercell, the agreement with parcel theory may have been fortuitous. Furthermore, latent heat release from the freezing of supercooled water drops was not taken into account. Weisman and Klemp's (1984) numerical experiments with supercells in idealized environments suggest that an upward-directed perturbation-pressure gradient force should also contribute significantly to updraft speed. It might have been that water loading counteracted the perturbation-pressure gradient force, so that parcel theory only appeared to work. It was also found that significant mesoscale variations in the depth of the moist layer did indeed exist along and ahead of the dryline (Bluestein et al. 1990b). Deep convection did not occur along the dryline even when the sounding indicated that the temperature was within 1 K from convective temperature (Bluestein et al. 1987).

Dave Rust at NSSL and Tom Marshall from the University of Mississippi, in 1986, first began to release portable radiosondes in Alabama during the Cooperative Huntsville Meteorological Experiment (COHMEX). Their instruments were capable of measuring the electrical field (Rust 1989). In 1987 NSSL began to use a sounding system in which the location of each balloon was determined from Loran C signals (Rust et al. 1990). The sounding system, which had been developed at NCAR (Lauritsen et al. 1987) during the mid-1980s, was installed in an NSSL van and named the Mobile-Cross chain Loran Atmospheric Sounding System (M-CLASS). An apparatus was developed that allowed Rust and his coworkers to release balloons even when the surface winds were relatively strong (Rust and Marshall 1989).

Three mobile sounding systems were also used during the Convective Initiation and Downburst Experiment (CINDE) in 1987 (Wakimoto and Wilson 1989; Wilson et al. 1992). Some were used to detail the thermodynamic structure of the boundary layer in studies of convective initiation along low-level convergence zones.

Rawinsondes released in convective storms in the late 1980s and early 1990s were used to devise a conceptual model of the electrical structure of convective storms and mesoscale convective systems (Hunter et al. 1992; Marshall and Rust 1993; Stolzenburg et al. 1994; Bateman et al. 1995; Marshall et al. 1995; Rust and Marshall 1996).

The M-CLASS system from NCAR was used by Bluestein and his students in the spring of 1992 (Bluestein 1993). This effort, named ''CLASS for class,'' gave students the opportunity to gain experience releasing rawinsondes into and near storms (Fig. 3), and to integrate their data with other operational datasets and thereby examine some aspects of convective storm behavior. It was found time and time again, unfortunately, that high levels of electrical noise near supercells, even in the absence of cloud-to-ground lightning flashes, made it difficult or impossible to use the Loran signals to compute the location of the rawinsondes and, hence, impossible to determine the wind.

In order to overcome the difficulties of using TOTO, Fred Brock, with assistance from G. Lesins and R. Walko, developed 10 small instrument packages at OU, which, owing to their appearance, were named ''turtles'' (Brock et al. 1987) (Fig. 4). Able to measure only pressure and temperature, they were first tested during the spring of 1986 in Oklahoma and Texas. The advantages of the turtles are that the probability of deploying one directly in the path of a tornado is increased because, unlike TOTO, more than one can be set out along the anticipated tornado path, they are much easier to deploy and retrieve quickly, and a small-scale network can be set up around a tornado or mesocyclone.

FIG. 3. OU students releasing an NCAR M-CLASS rawinsonde in the Texas panhandle near Shamrock on 31 May 1992 (copyright H. Bluestein).

Turtles have been deployed a number of times, especially in 1988, 1989, 1991, and 1993 (J. LaDue and M. Shafer 1988, 1991, personal communication; M. Magsig 1993, personal communication). The results indicate that pressure deficits of around 5 mb are often present near tornadoes and in mesocyclones, findings that corroborate the earlier results from TOTO.

FIG. 4. OU student Mike Magsig displaying a ''turtle'' in Sep 1993 (copyright H. Bluestein).

Bates (1963) first proposed that in situ measurements might be made in and near tornadoes with a drone. K. Bergey and his aerospace and mechanical engineering and electrical engineering students at OU in 1987–88 (Bluestein and Golden 1993) developed a remotely piloted vehicle (RPV) with the ultimate purpose of probing tornadoes and their environment. Two planes were developed, but although a video camera was successfully installed, neither plane was ever equipped with meteorological sensors.

## 4. Early studies using airborne Doppler lidar and airborne Doppler radar: 1981–91

McCaul et al. (1987) in June 1981, in an effort involving OU, NSSL, and the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center, used an infrared, pulsed, Doppler lidar mounted in a NASA aircraft to probe the clear-air motions along a gust front in a convective storm in central Oklahoma. The lidar beam was aimed at angles alternately fore and aft of the flight track to obtain a lattice of intersecting radar volumes at the altitude of the aircraft (Fig. 5). Using this technique, a dual-Doppler analysis could be obtained using only one lidar. The wind field analysis revealed the gust front and small-scale vortices along it. Although the lidar beam could not penetrate very far into the cloud along the gust front, the clear-air motions were well resolved.

It had been hoped that the airborne Doppler lidar system would be used in subsequent years during tornado season to map the clear-air wind field in and near tornadoes and under wall clouds in the plains. Unfortunately, after a fire on the aircraft in 1985, the system was not used again. NCAR had been designing and testing its own pulsed lidar system (Schwiesow 1987; Schwiesow et al. 1989), but it was not developed to the point that it could be used on an aircraft to study convective storms and tornadoes.

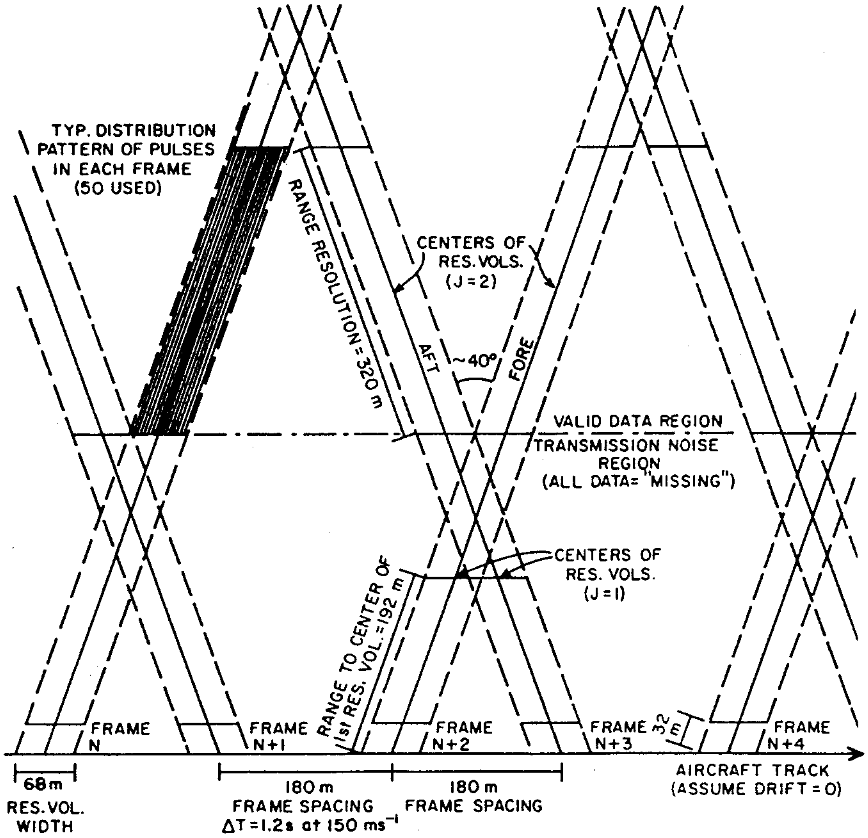

FIG. 5. Typical arrangement of fore and aft lidar beam trajectories used in data collection by the NASA system in 1981 (from McCaul et al. 1987).

Beginning in the early 1980s, a NOAA Orion P-3 aircraft used a 3-cm wavelength, pulsed Doppler radar to collect data in hurricanes (Marks and Houze 1984). To get dual-Doppler coverage, the aircraft had to fly along pairs of flight legs at varying angles with respect to each other. With such a flight pattern, the time difference between scans from common volumes was longer than the time scale of convective elements. The technique of flying a radar by a feature to be viewed from two different viewing angles at two different times was named "pseudo-dual Doppler analysis" (Jorgensen et al. 1983). [The analysis technique used by McCaul et al. (1987) was in fact pseudo-dual-Doppler analysis, although it was not referred to as such.]

During the Cooperative Oklahoma Profiler Studies (COPS-91) field program in the spring of 1991, airborne Doppler radar data were collected in supercells in the southern plains (Dowell et al. 1997) for the first time by the NOAA P-3 radar system, using the fore–aft scanning technique (FAST); in FAST, the radar beams are scanned alternately fore and aft at an angle to the the flight track (Fig. 5) and around circles about the flight track (the antennas are located in the tail of the aircraft). Since the aircraft flew at around 3–4 km AGL, it was not possible to revolve the horizontal wind field well at very low altitudes. In addition, the timing of the flight tracks was such that tornadic storms were probed just after or while tornadoes were dissipating, so that no information on tornado formation was realized. Other shortcomings of the first airborne Doppler radar system were that because the maximum unambigous velocity was only $\pm 12.9$ m $s^{-1}$, unfolding of the velocity data was extremely difficult in regions of high shear; velocity data were "speckled" at high altitudes, perhaps owing to turbulence, especially above strong updrafts; and there was inadequate sensitivity to probe clear-air regions.

## 5. Remote sensing from the ground: The first portable and mobile Doppler radars, 1987–93

Probing remotely by radar is an alternative to the direct sensing of tornadoes and their environment, at least for the wind field. Zrnic et al. (1985), who had been analyzing Doppler wind spectra collected by the NSSL fixed-site, pulsed radar when tornadoes passed within range (Zrnic and Doviak 1975; Zrnic et al. 1977; Zrnic and Istok 1980), proposed that higher resolution could be attained if a portable radar were carried out and placed close to the tornado. Use of a portable radar, furthermore, would increase the number of datasets. In addition, by getting closer to tornadoes, the sensitivity

FIG. 6. OU students probing a tornado north of Enid, OK, on 12 Apr 1991, with the LANL portable Doppler radar (copyright H. Bluestein).

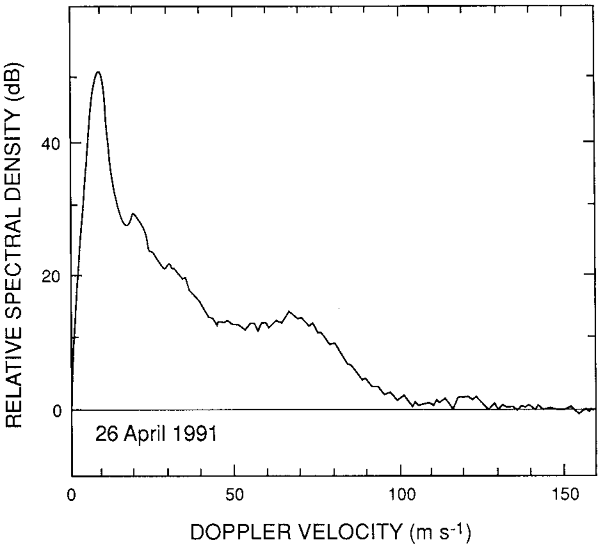

FIG. 7. LANL portable Doppler radar data for the Red Rock, OK, tornado at around 2350 UTC 26 Apr 1991. Doppler wind spectrum for receding motions only. The radar beam was centered near the right side of the tornado's condensation funnel at approximately 150–190 m AGL. The peak in the spectrum near 120–125 m $s^{-1}$ lies within the F-5 region; it probably represents windborne debris.

to the highest wind speeds would be increased. A nearby portable radar could sample volumes closer to the ground and allow for simultaneous visual documentation (Bluestein and Golden 1993).

H. Bluestein was contacted in 1986 by T. Morton of Texas Instruments and made aware of a portable, 3-cm wavelength, CW, Doppler radar at the Los Alamos National Laboratory (LANL). The radar was an improved but low-power, battery-operated, solid-state, portable version of the first meteorological Doppler radar (Brantley 1957) used to collect Doppler wind spectra in a tornado in Kansas in 1958 (Smith and Holmes 1961). With the collaboration of W. Unruh from LANL, the radar was adapted for the purpose of recording Doppler wind spectra in tornadoes (Bluestein and Unruh 1989). Unlike the old radar, both approaching and receding spectra were recorded separately. In the summer of 1988, FM-CW operation and signal processing (Strauch 1976) were added so that range information, in addition to wind velocity information, could also be recorded (Bluestein and Unruh 1993).

The LANL radar was operated in the southern plains from 1987 to 1995 (Fig. 6), initially with support from NSSL during the Doppler/Lightning (DOPLIGHT '87) project (Forsyth et al. 1990), and later with support from the National Science Foundation (NSF). Most of the useful data were collected during the 1990 and 1991 storm seasons. The most significant scientific findings included observational evidence that the thermodynamic speed limit of tornadoes (Lilly 1969; Snow and Pauley 1984) is usually exceeded by a comfortable margin, as suggested and explained by Fiedler and Rotunno (1986); confirmation of F-5 (Fujita 1981) wind speeds in a tornado (Fig. 7) [previously, wind speeds in tornadoes as high as F-5 intensity had been indirectly estimated from photogrammetric analysis of debris movies or inferred from damage; wind speed estimates based on the Fujita scale alone, which is not calibrated, are probably not very accurate (Doswell and Burgess 1988)]; and measurements of relatively high wind speeds in a tornado even while it was in the rope stage (Bluestein et al. 1993), when tornadoes tend to be nearing the end of their lives. Davies-Jones et al. (1978), using damage survey information, had also found evidence of very strong winds in the Union City, Oklahoma, tornado even when it was in the rope stage.

A major disadvantage of the LANL portable radar was that its resolution was too low to resolve the substructure of the wind field in tornadoes. With its 5° beamwidth antennas, its cross-beam resolution was 250–300 m or more at safe distances from a tornado, even though its along-the-beam resolution in FM-CW mode was only 78 m. To attain finer resolution in the cross-beam direction, larger antennas would have had to have been used, which would have rendered the system less portable or not portable at all.

It was then decided to use a higher-frequency radar; with such a system, an antenna having the same size as that in the LANL system would have much finer resolution. The main disadvantage to using a higher-frequency radar system, however, is that attenuation could be a serious problem and it was not known whether or not such a radar could see out about to about 5 km, the typical range of tornadoes we intercept, especially in the presence of heavy rain or hail.

In 1993 Bluestein et al. (1995) tested a high-power, pulsed, 3-mm wavelength, Doppler radar from R. McIntosh's radar group at the University of Massachusetts at Amherst. The radar was mounted in an OU van; the antenna poked out, like a periscope, through a hatch in the roof (Fig. 8). To achieve a relatively high maximum unambiguous velocity, the group at the University of Massachusetts implemented a scheme utilizing interleaved pairs of orthogonally polarized pulses (Doviak and Sirmans 1973). In 1993 data were successfully collected in an LP storm in eastern New Mexico and in a mesocyclone at the intersection of a squall line and another area of convection in central Oklahoma. Although horizontal resolution in the cross-beam direction as small as 30 m at a range of a slightly over 3 km was realized, no tornado datasets were collected. Because the radar system could not be operated with the hatch open in heavy rain, it was not possible to collect data in two tornadoes that were intercepted because the van was in heavy rain and/or the tornado dissappeared behind a curtain of heavy precipitation.

## 6. VORTEX: A coordinated field experiment

During the springs of 1994 and 1995 a multiplatform, coordinated, storm-intercept, field experiment named VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment) was conducted in the southern plains (Rasmussen et al. 1994), the main purpose of which was to test various hypotheses for tornado formation. Many different storm-intercept vehicles were coordinated by E. Rasmussen in the mobile, field-coordinator (FC) vehicle. This was the first intercept experiment in which the decisions involving the placement of many platforms were made in the field by someone in a mobile vehicle, rather than back at a fixed base such as NSSL or OU. A number of new observing systems were tested, while other older systems such as the NOAA P-3 airborne Doppler radar, the LANL portable Doppler radar, the University of Massachusetts high-frequency mobile Doppler radar, turtles, and M-CLASS units were also used.

J. Straka at OU, along with Rasmussen and S. Frederickson, developed the mobile mesonet (Straka et al. 1996), which consisted of an armada of cars instrumented to measure and record wind speed and direction, temperature, and humidity (Fig. 9). Another innovation was the use of global positioning system satellites to document the location of all the data collected and to allow the FC to keep track of the locations of all the units in the field. Each member of the mobile mesonet was called a ''probe.'' Using the mesonet, observations could be recorded at strategic locations in and near supercells.

There were many significant first-ever data collection opportunities during the first year of VORTEX. On 25 May, the LANL portable Doppler, near Northfield, Texas, at a range of 4–5 km, recorded an FM–CW dataset, which for the first time was good enough to determine the Doppler velocity spectrum across a supercell tornado and its parent mesocyclone with a range resolution of only 78 m (Fig. 10; Bluestein et al. 1997a). Wind speeds in the mesocyclone were about 40 m $s^{-1}$; wind speeds in the tornado reached as high as 60 m $s^{-1}$. Unfortunately, the NOAA P-3 aircraft was unable to fly a pattern by the storm while the tornado was developing owing to intervening convection. However, analysis of airborne radar data before the tornado had formed and analysis of the portable radar data suggested that the tornado had formed in a circulation along the leading edge of the hook echo.

On 29 May the complete life cycle of a tornado was captured, for the first time, by the NOAA P-3 airborne Doppler radar, near Newcastle, Texas (Wakimoto and Atkins 1996). Unlike in COPS-91, the aircraft flew near cloud base, when possible, rather than at higher altitudes, so that the wind field near tornadoes could be better resolved. In addition, by flying near or just below cloud base, turbulence in growing convective towers aloft could be avoided and features under cloud base could be seen. The disadvantage of this strategy was that motions at high levels in the storm could not be resolved adequately, owing to the very high elevation angles required to probe the upper reaches of the storm. The ground crews targeted a mesocyclone just to the east of the tornado, which did not produce a tornado. Wakimoto et al. found that the tornado formed from a low-level feature along the flanking line under an intense updraft along the flanking line, rather than in association with the preexisting midlevel mesocyclone to the east. It thus appeared as if a landspout mechanism may have been responsible for tornadogenesis, even though the storm contained a mesoyclone.

On 8 June the NOAA P-3 aircraft flew to eastern Colorado, where its radar probed a decaying tornado. Unfortunately, no data were obtained during its formation phase (Wood et al. 1996). However, an excellent set of photographs was taken that allowed, for the first time, 3D visualization from a pair of photographs taken at slightly different times and viewing angles (Bluestein 1996).

In addition to the new findings based on Doppler radar analyses, there were some first-time observations obtained with the Mobile Mesonet (Straka et al. 1996). On 6 May two members of the Mobile Mesonet collected data in the path of a damaging mesocyclone near Kaw Lake, Oklahoma. On 26 May an extensive dataset was

FIG. 8. The University of Massachusetts mobile 3-mm wavelength Doppler radar system mounted in an OU van, probing a convective storm on 7 Jun 1993 in central Kansas (copyright H. Bluestein).

collected in a supercell near Lubbock, Texas. Details of the low-level structure showed storm-scale boundaries and a region of strong low-level divergence west and southwest of the main updraft and mesocyclone.

The second year of VORTEX built on the expertise gained in 1994. The recently developed Electra Doppler Radar (ELDORA; Fig. 11) from NCAR (Wakimoto et al. 1996) flew patterns coordinated with the NOAA P-3 aircraft in order to obtain higher temporal resolution. Ideally the two airborne radars were to fly near cloud base, one following the other, so that each would be making a pass by the storm while the other was turning around to set up its approach. The ELDORA was an improvement over the NOAA P-3 radar in a few ways: The sensitivity was improved through the averaging of more independent samples, by making use of signals transmitted at multiple frequencies. In addition to increasing the range at which clear-air returns can be detected, this procedure allows the rotation rate of the antenna to be faster, so that the along-track resolution can be higher. In addition, the signals were transmitted at multiple pulse-repetition frequencies (PRFs), which yield a maximum unambiguous velocity of $\pm 80$ m s$^{-1}$; without multiple PRFs, the maximum unambiguous velocity is only $\pm 16$ m s$^{-1}$. Thus, editing of the data is simplified when multiple-PRF processing is implemented.

Significant data were recorded on a number of days: On 6 May clear-air data were collected near a dryline in the Texas panhandle (Atkins et al. 1998); the finescale structure that was analyzed resolved horizontal convective rolls and density-current-like behavior. The formation of tornadoes in supercells was documented on 16 May near Garden City, Kansas (Wakimoto et al. 1998; Wakimoto and Liu 1998), on 2 June in west Texas, and in the Texas panhandle on 8 June. The 16 May case was significant in that it was the best documented case of tornadogenesis by a Doppler radar to date. The 2 June dataset unfortunately was compromised because the aircraft was forced to fly relatively far from the targeted storms, owing to intervening convective storms. In addition, since the flight was very turbulent, the pointing angles of the radar beams were not all parallel. The 8 June dataset is the best documentation of cyclical tornadogenesis (Rasmussen et al. 1982; Burgess et al. 1982a) to date. Nontornadic supercell hailstorms were well documented in central Kansas on 12 May and in the eastern Texas panhandle on 22 May. Datasets were also collected in other supercells, along a squall line containing a strong mesocyclone, and across the dryline. Analyses of many of these cases is still in progress (Bluestein et al. 1998). Many of them include supporting data from the ground crews, especially on 2 June when the most extensive dataset involving the Mobile Mesonet and mobile soundings was collected.

Analysis of proximity soundings such as those made with M-CLASS during VORTEX have inspired modelers to propose hypotheses for how the low-level shear profile may influence the formation of low-level mesocyclones and tornadogenesis (Wicker 1996).

Also during VORTEX 95, the first mobile, 3-cm wavelength, pulsed Doppler radar system (Doppler on Wheels—DOW) was constructed and installed in an NSSL truck (Wurman et al. 1997; Fig. 12). It was first used on 12 May and on 16 May it recorded data for the

FIG. 9. The VORTEX armada of Mobile Mesonet vehicles lined up and ready for duty at NSSL on 13 May 1995. B. Davies-Jones is pointing out hail damage suffered the day earlier in a hailstorm in north-central Kansas (photograph courtesy of F. W. Gallagher III).

first time in a tornado (Wurman et al. 1996). Other data were collected at closer range in tornadoes near Dimmitt and Friona, Texas, on 2 June and in the eastern Texas panhandle on 8 June. The Dimmitt radar images are particularly striking (Fig. 13); they show hollow rings of higher radar reflectivity created by debris and spiral bands of radar echo. While doughnut-shaped reflectivity regions seemed to be characteristic of tornadoes, some were also found in much weaker circulations (e.g., on 8 June in the Oklahoma panhandle) (not shown); thus, it appears that the hollow ring reflectivity signature does not necessarily indicate that there is a circulation of tornadic intensity.

Measurements with the Mobile Mesonet on 2 June were particularly revealing because they showed that there was no baroclinic zone at the surface just east of the tornado as had been hypothesized (Rasmussen et al. 1994). Other Mobile Mesonet analyses are in progress (Bluestein et al. 1998); a number of papers dealing with results from the Mobile Mesonet and the DOW in VORTEX are currently in press or in review, and are not summarized here.

On 17 May, the University of Massachusetts, mobile, 3-mm wavelength Doppler radar recorded close-range data in a convective storm along a rear flank downdraft; counterrotating vortices on the 500-m scale were resolved (Bluestein et al. 1997b) (Fig. 14). These data were the finest-scale measurements (valid for radar volumes 30 m a side) ever made in a convective storm. It was speculated that these vortices could be the ‘‘seeds’’ for tornadoes.

A group from New Mexico Tech made pressure measurements on 8 June in a large tornado near Allison, Texas, using a turtlelike instrument. W. Winn and his colleagues found pressure deficits as high as 50 mb or greater (W. Winn 1998, personal communication; Fig.

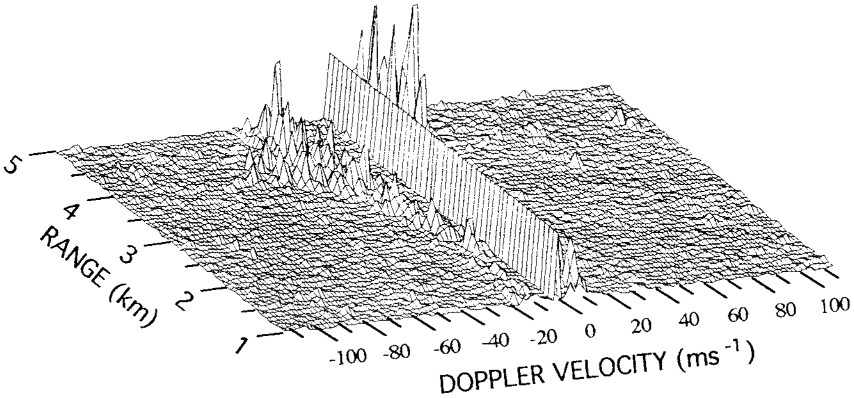

FIG. 10. Mesh plots of FM–CW Doppler wind spectra (velocity scale is 1.8 m s$^{-1}$) as a function of range (range resolution is 78 m) in a tornado on 25 May 1994 near Northfield, TX. The radar’s view was centered to the left of the tornado. The ‘‘fence’’ at zero velocity has been inserted for display purposes. The linear vertical scale is the spectral density. Approaching (receding) velocities are negative (positive). The maximum winds that appear above the noise floor are around 60 m s$^{-1}$ at a range of just under 4 km, which is in the tornado’s damage path (courtesy of Wes Unruh).

FIG. 11. The NCAR Electra aircraft outfitted with ELDORA at Oklahoma City during VORTEX-95; the antenna is mounted in the tail section (copyright H. Bluestein).

15). The full meaning and accuracy of the measurements are not known at this writing.

## 7. Recent findings from the Doppler on Wheels (DOW): 1996–97

During the storm season in 1996, J. Wurman and his crew collected more DOW data in a tornado near Rolla, Kansas. This dataset was significant in that the entire life of the tornado was documented.

Bluestein et al. (1995) suggested that two intercept vehicles, each equipped with radars, could be used to collect dual-Doppler data in tornadoes. In 1997 a second DOW was constructed and on 26 May, near Kiefer, Oklahoma, mobile dual-Doppler data were collected for the first time in and near a tornado (J. Wurman 1998, personal communication). It was thus demonstrated that mobile Doppler radars could be used successfully to calculate the horizontal (two-dimensional) wind field in and near tornadoes.

## 8. Summary and outlook for the future

Severe-storm-intercept projects have progressed from the early, relatively small efforts to film and document severe storm phenomena; provide ground truth for remote, fixed-site Doppler radars; and make various in situ measurements, to more recent, coordinated, larger efforts involving ground-based and airborne, mobile Doppler radars, mobile sounders, and other mobile instrumentation (see the appendix). The success of storm-intercept projects has been enhanced by synthesizing data collected on a variety of different platforms and with data collected by instruments at fixed sites. Although much has been learned about the types of tornadoes that exist in nature and about the behavior of their parent convective storms, we still do not have a good understanding of why some storms produce tornadoes and others do not. To make progress, we must continue to improve our techniques for observing tornadoes and their parent storms. At the time of this writing, we still do not have time-dependent, high-spatial-resolution measurements of the three-dimensional wind field in developing tornadoes, or the thermodynamic fields around them as they develop. In the spring of 1999, high-spatial resolution data were collected in tornadoes with the University of Massachusetts' 3-mm wavelength mobile Doppler radar, which was outfitted with a 0.18° antenna (H. Bluestein 1999, unpublished manuscript). In addition, the DOWs collected time-dependent dual-Doppler data in tornadoes (J. Wurman 1999, personal communication) and thermodynamic data were collected by the Mobile Mesonet around a number of tornadoes (J. Straka 1999, personal communication). These fields are needed to test existing theories and to formulate other potentially more accurate theories.

The history of the scientific accomplishments of storm chasing has been driven substantially by progress in technology. Future projects will likely feature new attempts to use improved versions of older instruments, as well as attempts to use some completely new types of instrumentation. For example, efforts are now under way to develop and use lightweight instrumented rockets, to be fired into tornadoes from the ground, rather than from the air (E. Rasmussen 1998, personal communication). Lightweight rockets will also be used to fill radar-echo-free areas with radar reflective chaff so

FIG. 12. The first Doppler on Wheels (DOW) and J. Wurman, in Norman, OK, on 30 Aug 1996 (copyright H. Bluestein).

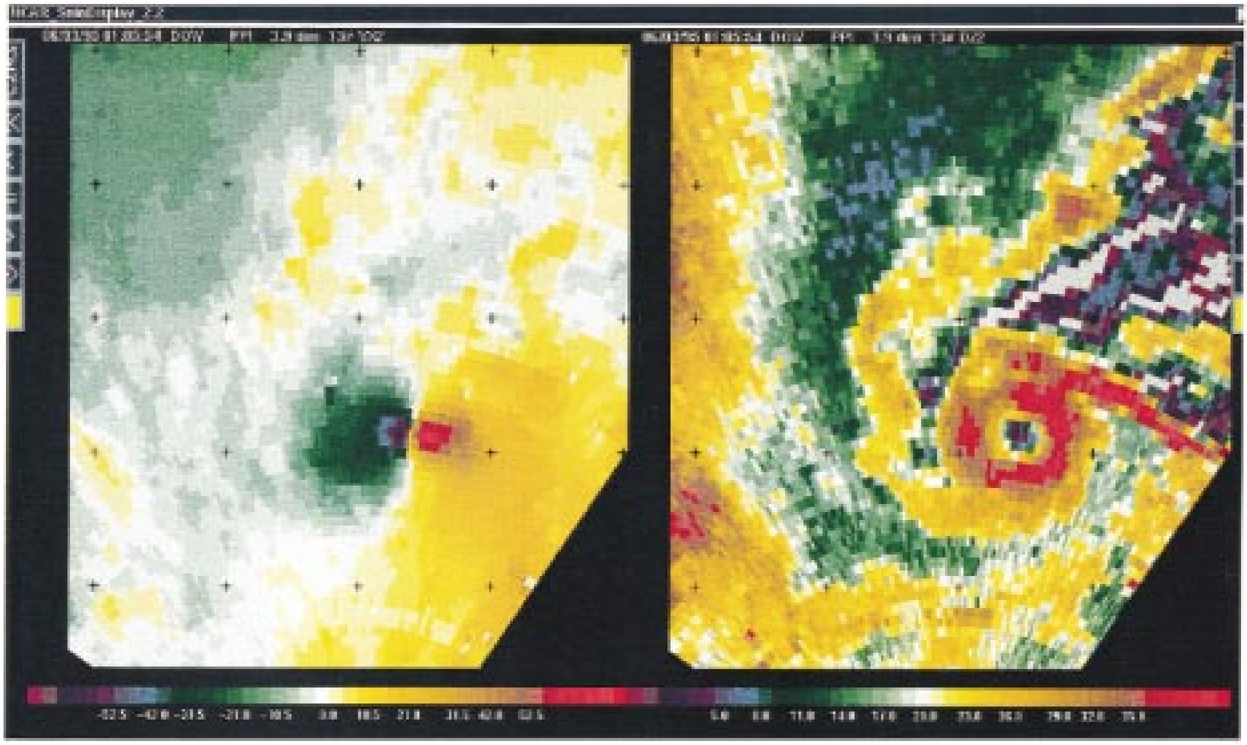

FIG. 13. DOW data for the Dimmitt, TX, tornado at 0106 UTC 3 Jun 1995: (left) Unfolded Doppler velocities in m s$^{-1}$, color coded below; (right) radar reflectivity factor (approximate) in dB*Z*, color coded below. The radar is located approximately 1.5 km below the center of the bottom edge of the data region in the figure. Grid spacing between crosses is 1 km; elevation angle is 3.9°. The tornadic vortex signature is collocated with a weak echo hole (courtesy of Josh Wurman).

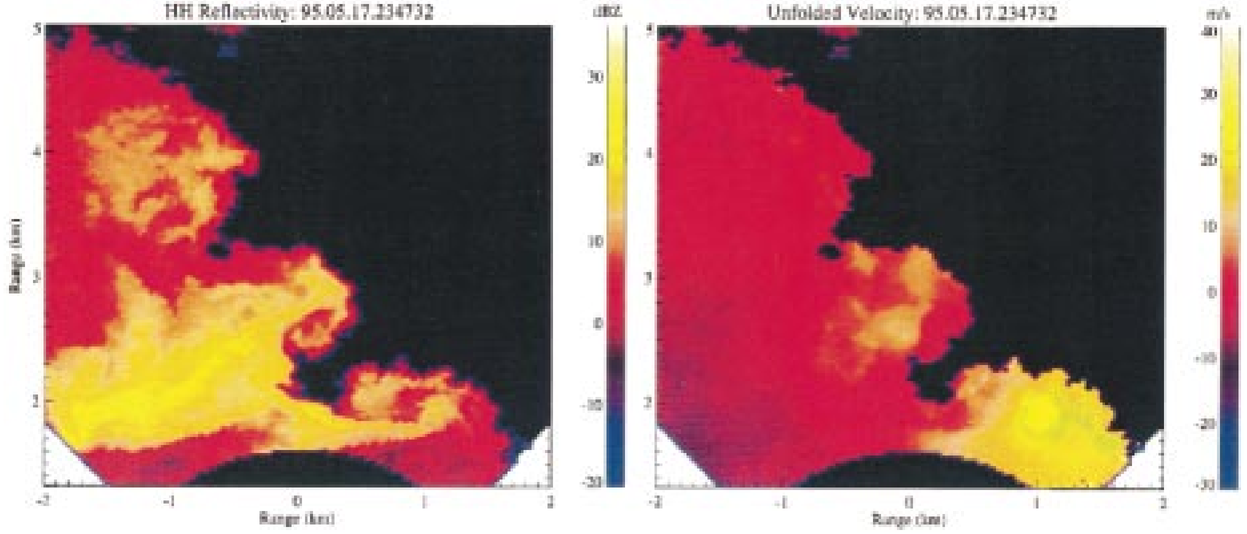

FIG. 14. Data from the University of Massachusetts 3-mm wavelength, mobile Doppler radar for the rear flank downdraft of a supercell in northeast Oklahoma at 2350 UTC 17 May 1995. (left) Radar reflectivity factor in d$BZ_e$; (right) unfolded Doppler velocities in m $s^{-1}$. Radar reflectivity factor and Doppler velocities color coded to right of each panel. Elevation angle is 6.2°; horizontal scale indicated along edges of panels. For interpretation of radar reflectivity at 3-mm wavelength, and for details on method of unfolding Doppler velocities using diversity pulse-pair processing, see Bluestein et al. (1995).

that mobile radars can be used to document the precipitation-free rear flank downdraft region in supercells.

RPVs are being designed to fly near severe storms (N. Renno 1998, personal communication). Mobile boundary layer profilers will be used to document storm-scale variability of the low-level wind shear profile and thermodynamic profile (K. Knupp 1998, personal communication). Airborne Doppler lidars may be used to probe the clear-air environment of tornadoes (Rothermel et al. 1998).

Ground-based mobile radars have proven to be a safe and useful way of mapping the wind field in and near tornadoes. Ongoing and future projects will involve attempts to document the complete formation and structure of tornadoes, especially near the ground, using pairs of mobile, 3-cm wavelength radars, and to investigate the finescale structure and behavior of tornadoes using a mobile, millimeter-wavelength radar whose spatial resolution is 10–15 m. Electronic scanning techniques need to be implemented to increase the speed with which a radar volume can be sampled. Bistatic radar techniques (Wurman 1994) will be developed for dual-Doppler analysis using a network consisting of many mobile passive receivers, but only one active radar. The radar analyses will be enhanced significantly if they are combined with other observations made by other instruments.

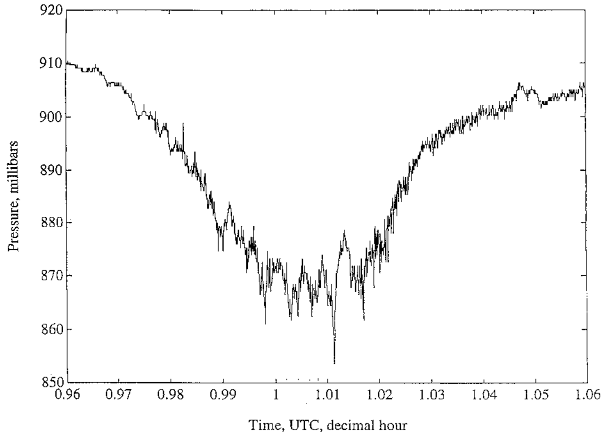

FIG. 15. Pressure measurements as a function of time made by B. Winn, S. Hunyady, and G. Aulich from the Langmuir Laboratory for Atmospheric Research at New Mexico Tech in Socorro, on 8 Jun 1995 in a tornado near Allison, TX, in the eastern Texas panhandle. The pressure minimum took place over a 5-min period; there is one brief dip in pressure of about 15 mb in a few seconds. A windmill was found blown down to the south near the instrument.

Other advances may come from improvements in the type of mobile platforms used. For example, helicopters (Pauley and Snow 1988; Golden and Bluestein 1994), gliders, and balloons have not been fully exploited as carriers of radars and other instrumentation.

It has been proposed that studies of infrasound (Georges 1983) generated by tornadoes may lead to techniques for their remote detection using passive devices (A. Bedard 1998, personal communication). Efforts to correlate acoustic signatures with tornadoes could involve a storm-intercept effort.

While most of the efforts in studying severe storms and tornadoes have been concentrated in the plains region of the United States, efforts should be undertaken to study tornadoes in landfalling hurricanes along the coastal regions of the Gulf of Mexico and the southeastern United States (McCaul 1991). Very little is known about these tornadoes because they are much harder to chase, owing to poor visibility, to their relative infrequency of occurrence, and to hazards posed by the hurricane's winds.

It is reasonable to expect that in the next 5–10 years severe-storm-intercept field efforts will increase our understanding of tornadogenesis and tornado structure substantially. The results of these experiments need to be communicated to and successfully applied by forecasters and modelers to improve the reliability of short-term forecasts and thus save lives; in turn, forecasters need to define their operational problems and communicate them to the researchers, who can then design experiments that might help them solve the problems.

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## APPENDIX

### A Summary of Milestones in Storm-Intercept History

Early chases by Jensen (1953) and Hoadley (1956)
Rough Riders' aircraft penetrations of storms during TRAP and subsequent projects (1956 and later years through early 1960s)
Ward's chase of the Geary, OK, tornadoes (1961); observations incorporated into a radar study (1963)
Bates's chase of a tornado in an aircraft over KS (1961)
Hail chases guided by radar, organized at the University of Wyoming (1964)
Hail chases in AB (1960s)
Hail chases in SD and northeast CO during Project Hailswath (1965–66)
Hail chases in OK, organized at NSSL (1966 and later years)
Waterspout chases in the Florida Keys on aircraft by Rossow and Golden (late 1960s and early 1970s)
Inception of NSSL's Tornado Intercept Project (1972); program continued for over a decade; storm spotter aids developed (1970s); tornado debris movies taken and analyzed
Hail chasing in northeastern CO during NHRE (1972–74)
Union City, OK, intercept (1973); life cycle of tornado documented both visually and on Doppler radar; observations incorporated into studies (1978)
Sinclair's waterspout penetrating aircraft in the Florida Keys (1974)
Schwiesow's CW Doppler–lidar measurements of waterspout wind spectra, from aircraft, in the Florida Keys (1976)
Arnold's sound chase (1976–81)
JDOP (1978); verification of Doppler radar signatures
Electrical measurements by NSSL and University of Mississippi (1978 and later years)
SESAME (1979); tornadic debris movies taken; wind speeds estimated
Texas Tech chases (late 1970s and later); development of cyclical tornadogenesis model by Rasmussen (and Burgess)
Discovery of nonsupercell tornadoes during JDOP (1978) and later (1981)
Development of TOTO by Bedard at NOAA (1980); first use by Bluestein in 1981 (continued at OU and NSSL through mid-1980s); measurements under wall clouds
NASA airborne Doppler lidar observations in OK (1981); first use of a fore–aft scanning technique; gust front circulations analyzed
CCOPE in southeastern MT (1981); T-28 supercell updraft penetrations
Colgate's instrumented rockets launched from an airplane (early 1980s)
Portable soundings by Bluestein and students (1984–90); tornadic supercell updraft sounding (1986)
PROFS real-time forecasting exercises (mid-1980s); nonsupercell tornadoes documented in CO
Brock's turtles (1986 and later years); measurements near wall clouds
COHMEX (1986); portable electrical soundings
Mobile-CLASS at NSSL and NCAR (1987 and later years)
CINDE (1987); mobile soundings near surface boundaries
LANL portable 3-cm wavelength CW Doppler radar used by Bluestein and Unruh (1987–95); FM–CW capability (1988); F-5 wind speeds in tornado documented (1991)
Bergey's RPV (1987–88)
NOAA P-3 airborne Doppler radar used in COPS-91 (1991); FAST implemented
University of Massachusetts 3 -mm wavelength, mo-

bile, pulsed Doppler radar, used by Bluestein and Pazmany (1993 and later years)

NOAA–National Geographic Waterspout Expedition (1993); filming of waterspouts in Florida Keys from a helicopter

VORTEX (1994–95); organized, multiplatform effort in the southern plains, with mobile field coordinator

Mobile Mesonet developed and used by Straka et al. (1994 and later years)

ELDORA used in VORTEX by Wakimoto et al. (1995); tornado life histories documented

Doppler on Wheels developed and used by Wurman et al. (1995 and later); tornado data first collected (1995)

New Mexico Tech pressure measurements in a tornado (1995)

SUB-VORTEX in the southern plains (1997); mobile mesonets in the southern plains

Dual-Doppler data collection of a tornado in OK by two DOWs from Wurman's group (1997)

SUB-VORTEX RFD (1998); mobile mesonets in plains, organized by Rasmussen

ROTATE (1998); two DOWs in the plains, Wurman and students

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