Verification of the Origins of Rotation in Tornadoes Experiment: VORTEX

Erik N. Rasmussen,*
Jerry M. Straka,+
Robert Davies-Jones,*
Charles A. Doswell III,*
Frederick H. Carr,+
Michael D. Eilts,* and
Donald R. MacGorman*

Abstract

This paper describes the Verification of the Origins of Rotation in Tornadoes Experiment planned for 1994 and 1995 to evaluate a set of hypotheses pertaining to tornadogenesis and tornado dynamics. Observations of state variables will be obtained from five mobile mesonet vehicles, four mobile ballooning laboratories, three movie photography teams, portable Doppler radar teams, two in situ tornado instruments deployment teams, and the T-28 and National Atmospheric and Oceanic Administration P-3 aircraft. In addition, extensive use will be made of the new generation of observing systems, including the WSR-88D Doppler radars, demonstration wind profiler network, and National Weather Service rawinsondes.

1. Some current problems in tornado and tornadic storm research

Our understanding of tornadoes and tornadic storms has progressed greatly in the last 20 years (Church et al. 1993) owing to Doppler radar and storm intercept observations, three-dimensional numerical simulations of cumulonimbi, theoretical insights, and numerical and laboratory modeling of tornado-like vortices. But we still have not established an accepted theory of how tornadoes form, and uncertainty still exists concerning extreme wind speeds and pressure drops in tornadoes. Forecasting of tornadoes has improved significantly, owing in part to a greater awareness of the environmental wind profiles that cause thunderstorm updrafts to rotate at middle levels. As high-resolution data become available routinely from a new generation of sensors, research findings from these new datasets ultimately should lead to more precise tornado forecasts. In order to test hypotheses concerning tornadogenesis, tornado dynamics, and kinematics, and how the environment regulates storm structure, we are planning the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX).

We begin by reviewing some current theories and point out some unresolved issues regarding tornadoes and tornadogenesis. Updrafts in supercell thunderstorms usually begin rotating at middle levels as a result of tilting by the updraft of low-level horizontal vorticity associated with strong vertical shear of the environmental winds (see review by Klemp 1987). When the storm-relative winds veer markedly with height in the lowest few kilometers, the environmental vorticity in the storm's inflow has a considerable streamwise component (i.e., in the same direction as the storm-relative wind). The updraft tilts this streamwise vorticity into vertical vorticity to form the initial midlevel mesocyclone (Davies-Jones 1984). For sustained updraft rotation, the low-level storm-relative winds must be strong to prevent the storm's cold-air outflow from surging ahead of the storm and cutting off the updraft from its low-level source. Therefore, Davies-Jones et al. (1990) proposed using storm-relative environmental helicity (SREH; the integral of storm-relative wind speed times streamwise vorticity over the depth of the inflow, nominally 3 km) as a predictor of updraft rotation. Earlier, Weisman and Klemp (1982) proposed the bulk Richardson number (BRN) as a predictor of storm type (supercell versus multicell thunderstorm). Although the SREH and BRN are both useful parameters for forecasting severe weather, both fail on occasion. Some of the failures may be ascribed to the proximity sounding not being close enough in time and space to sample the storm's inflow accurately. Helicity, *in* particular, is a very volatile parameter when the large-scale forcing is weak. Significant increases, associated perhaps with

*National Severe Storms Laboratory, Norman, Oklahoma.
+School of Meteorology, Center for Analysis and Prediction of Storms, University of Oklahoma, Norman, Oklahoma.
Corresponding author address: Erik N. Rasmussen, National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069.
In final form 23 February 1994.

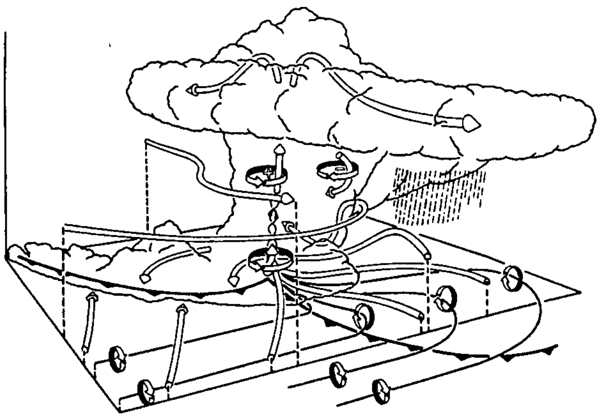

FIG. 1. (a) Schematic model of the processes hypothesized to be important in generating baroclinic vorticity leading to tornadogenesis in a supercell (from Klemp 1987): "The storm is evolving in westerly environmental wind shear and is viewed from the southeast. The cylindrical arrows depict the flow in and around the storm. The thick lines show the low-level vortex lines, with the sense of rotation indicated by the circular-ribbon arrows. The heavy barbed line marks the boundary of the cold air beneath the storm." (Reproduced with permission from the *Annual Review of Fluid Mechanics*, Volume 19. ©1987 Annual Reviews, Inc.)

the approach of mesoscale disturbances, can occur over tens of kilometers and over 1 to 2 h. This illustrates the difficulties involved in nowcasting isolated tornadoes.

The aforementioned mechanism does not explain how rotation develops near the ground because the rotation develops in warm, moist air as it is rising. Although the development of low-level mesocyclone rotation depends on midlevel rotation to produce favorable air trajectories, Rotunno and Klemp (1985), Klemp (1987), and Davies-Jones and Brooks (1993) found, from numerical simulations, that it is a separate process that awaits the formation of a rain-cooled downdraft (Fig. 1a). In contrast to midlevel rotation, low-level rotation apparently develops first in evaporatively cooled subsiding air just behind the gust front on the left rear side of the mesocyclone. First, spiraling rain curtains and a downdraft forms within the midlevel mesocyclone. In the lowest kilometer, air that has been moderately cooled by rain subsides, travels parallel to closely packed isotherms, and hence acquires considerable streamwise horizontal vorticity generated by buoyancy torques.[1] Davies-Jones and Brooks found, in a numerical simulation, that the vertical vorticity of the air actually changes from anticyclonic to cyclonic during descent as a result of simultaneous solenoidal generation and tilting of horizontal vorticity. This air is then entrained into the right rear side of the main updraft, where its spin is increased by intense vertical stretching. The production and downward transport of cyclonic vorticity in the downdraft has important implications for tornadogenesis because it transports cyclonically spinning air along the ground into the side of the updraft where tornadoes typically form. In nested-grid simulations done by Wicker and Wilhelmson (1993), a "tornado cyclone" or small-scale region (about 1 km across) of rapid rotation develops in this region of the mesocyclone. The tornado cyclone is preceded by an intensifying updraft at 3–4 km and rapid pressure falls beneath this height. When surface drag is included in the model, a tornado-like vortex develops within the tornado cyclone as a result of radial inflow (due to the imbalance between pressure and centrifugal forces) near the ground.[2]

The mechanism described in the previous paragraph is plausible for many (but probably not all) tornadoes that form in mesocyclones, but it does not account for the generally weaker class of "nonmesocyclone tornadoes" such as gust-front tornadoes, landspouts, and most waterspouts. Landspouts and waterspouts typically occur early in a storm's life along preexisting frontlike boundaries in low-shear environments during afternoons when low-level lapse rates are steep. Like mesocyclone tornadoes, nearby heavy rain showers appear critical to their formation. A possible mechanism for nonmesocyclone tornadoes is horizontal shearing instability causing the vertical sheet of vorticity at a wind-shift line to roll up into individual vortices, which are subsequently stretched vertically by convective updrafts as these pass above the vortices (Fig. 1b; Wakimoto and Wilson 1989). Wakimoto and Wilson even suggested that mesocyclone tornadoes might originate as vortices that are generated under flanking-line clouds by shearing instability and move with their parent clouds into the main updraft. In contrast, Wilczak et al. (1992) pointed out that landspouts may form quite similarly to the vortices in numerical simulations if the preexisting pseudofront and the low-level vortex arising from a shearing instability along this front act as surrogates for the supercell's gust front and midlevel mesocyclone, respectively. In their study, at least some of the landspout's vorticity appeared to be stemming from tilting of solenoidally generated vorticity on the cool side of the front. Thus, the tornadogenesis problem is complicated by the existence of at least two mechanisms, which may have some hidden similarities even

[1]An air parcel in a temperature gradient tends to spin about a horizontal axis because its warm side is more buoyant than its cold side.

[2]Anticyclonic tornadoes, when present, are generally in a flanking line updraft south of the mesocyclone where tilting of horizontal vorticity produces anticyclonic vorticity.

though they seem at first to be totally dissimilar. Some violent mesocyclone tornadoes are anomalous because they are associated with highly unstable environments with relatively weak low-level shear, quite low SREH, and BRN values outside the supercell range. Presently, it is not known if and how the formation of these tornadoes differs from that of tornadoes found in environments with moderate instability and large low-level shear.

Further advances in the understanding of tornadogenesis may lead to improved tornado forecasts and warnings and even to the remote possibility of modifying tornadoes, but advances await better cloud models and in situ or close-range field observations, especially near the ground. Such field measurements would test current theories and lead to new insights. At this time, none of the theories account for the appearance aloft of the tornadic vortex signature (TVS) on Doppler radar tens of minutes prior to strong tornadoes (Brown et al. 1978). Is the TVS a manifestation of the tornado cyclone or an embryonic tornado in the clouds that gradually descends to ground? The latter is inconsistent with current ideas that surface friction causes the radial inflow which "spins up" a tornado from the background rotation of the tornado cyclone; however, tornado-like vortices are sometimes observed as funnel clouds for several minutes without any visible evidence that they are in contact with the ground.

Despite much progress in the last 15 years, a definitive model of the tornado still does not exist (Lewellen 1993). Because of their violence, small size and relative infrequency, tornadoes have proven difficult to measure. Laboratory simulators replicate qualitative tornado features such as observed pressure profiles and a wide range of vortex structures (Ward 1972; Church et al. 1977), but scaled-up extrapolations of laboratory measurements to tornadoes must be viewed with caution. Limited-domain numerical models of tornadoes suffer from uncertainties associated with the influence of artificial boundary conditions. Therefore, better field observations of tornadoes will be of great significance to tornado theorists but, more importantly, they will be of practical benefit. For instance, VORTEX will investigate the lofting, dispersal, and fallout of debris by tornadic winds, which has important implications for transport of hazardous material. Damage surveys and engineering studies will be used to assess and possibly improve construction practices.

Davies-Jones (1986) stated in his review of tornado dynamics that "Most scientists agree that windspeeds in even the strongest tornadoes do not exceed 110–130 m/s," a position shared by Lewellen (1993). However, tornado intensity is still a hotly debated issue because of some new developments. Bluestein et al. (1993) have recently measured wind speeds at the top end of this range with a portable Doppler radar, and Fiedler and Rotunno (1986) and Fiedler (1993) have argued theoretically that the strongest tornado is the one that near the ground resembles a "supercritical end-wall" vortex. In such a tornado, air converging radially in the boundary layer erupts into an intense axial jet. The low-level part of the vortex is supercritical, meaning that it cannot adjust to conditions aloft because waves cannot propagate upstream (i.e., downward). The axial jet extends upward a few 100 meters to where the vortex core breaks down to a subcritical state; that is, it enlarges abruptly and becomes very turbulent with an axial downdraft. Vortex breakdown is a sudden transition similar to a hydraulic jump. According to Fiedler (1993), tangential and vertical velocities and pressure deficits can reach 110 m s^{-1}, 180 m s^{-1} and 330 mb, respectively, within the axial jet. Such a pressure deficit is nearly an order of magnitude larger than the hydrostatic value based on latent-heat release in an updraft. Another way for tornadoes to

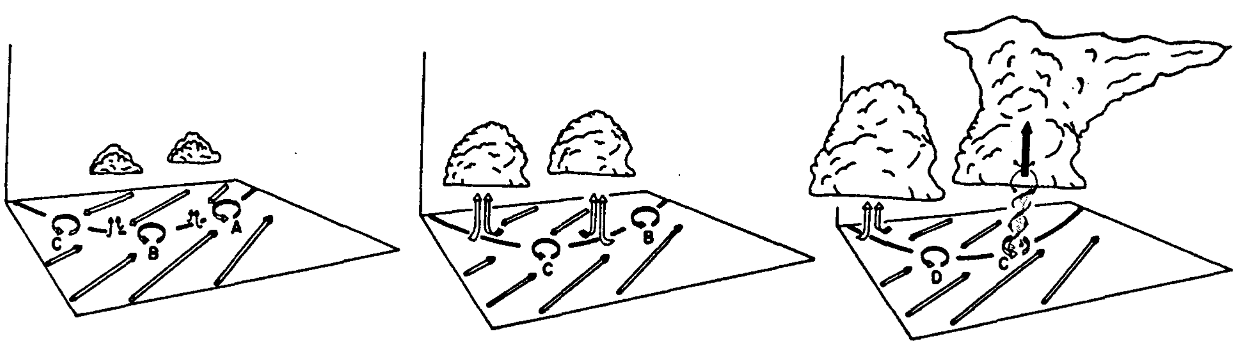

FIG. 1. (b) Schematic model of the processes hypothesized to be important in a nonsupercell tornado adapted from Wakimoto and Wilson (1989): "The black line is the radar-detectable convergence boundary. Low-level vortices are labeled with letters."

Hypothesis b.4	Tornadoes are located in strong θ_e gradients on the cool side of the storm outflow boundary; solenoidal generation of streamwise vorticity is significant for tornadogenesis.
Test	Evaluate buoyancy gradients and winds at surface using turtles, mobile mesonet, and fixed mesonet where possible. Use stereo photogrammetry to estimate wind fields near cloud base and where other tracers are available. Estimate the solenoidal generation rate. Evaluate the vorticity budget based on aircraft pseudo-dual Doppler data if available.
Refute	No significant solenoidal generation is found, based on observations.

FIG. 2. Example of an hypothesis from the VORTEX Planning Document.

attain high wind speeds is through cyclostrophic balance with the hydrostatic pressure deficit in a central hurricane-like eye. Subsidence of air from near the tropopause to the ground can increase the hydrostatic central pressure drop by a factor of 3.

In the quest for a definitive tornado model, observations will play a large role because such basic parameters as radial profiles of surface pressure and potential temperature still have not been measured reliably and in detail, especially in the tornado core where fast instrument response is needed. Without such quantitative "ground truth" there is no way to test the relevance of tornado-like vortices produced in laboratory and numerical models. Detailed mapping of tornado flow fields is also important for these comparisons, as well as for missile trajectory computations. The best mapping to date is still the one of the 1957 Dallas tornado obtained photogrammetrically by Hoecker (1960), but the effects of his underlying assumptions (steady state, axisymmetry, no correction for centrifuging of large debris) have to be considered in evaluating his analysis (Davies-Jones 1986).

Many questions remain to be answered definitively. For instance, What is the height of the maximum winds? According to Lewellen (1993), the maximum tangential velocity should occur below the top of the tornado's boundary layer (i.e., below 200 m) because air parcels in the boundary layer approach closer to the axis than those above it, and so acquire higher tangential velocities despite some loss in angular momentum. What is the axial flow and potential temperature in different tornadoes such as wide, turbulent-looking ones and smooth narrow ones? Do large violent tornadoes have "eyes?" Does vortex breakdown actually occur in some tornadoes, as suggested occasionally in funnel shapes and in photogrammetric results? How does the tornado vortex terminate aloft in the parent storm? Can tornado modelers continue to neglect asymmetries in the immediate tornado environment such as (i) tilt of the tornado itself, (ii) location of the tornado in a thermal gradient on the edge of its parent updraft with a downdraft nearby, and (iii) the inflow, which when visible seems to spiral into the tornado rather than enter axisymmetrically?

2. The VORTEX Field Experiment

a. Design and focus

The objectives of VORTEX are tightly focused on the issues discussed in the introduction concerning tornadoes and tornadic storms, with the result being that the experiment is relatively small. Moreover, the objectives of the various investigators are accommodated with relatively simple experiments. From the outset of the planning of VORTEX, all objectives are cast as testable hypotheses, which are then reviewed, discussed, and revised through collaboration of the experiment's investigators. This is done to ensure that the field experiment is both sufficient and economical. Had the objectives been stated in terms such as "to study" or "to document" various phenomena, they could not be achieved because there is little or no guidance in such statements regarding how to design an experiment to accomplish them.

The hypotheses are detailed in the VORTEX Planning Document (Rasmussen 1994; see example in Fig. 2), but in broad terms they can be summarized as addressing

- the interactions between tornadic storms and their environments,
- tornadogenesis and the roles of mesocyclones and low-level boundaries, and
- tornado flow structure and dynamics.

b. Domain

The VORTEX field experiment will be held 1 April–

15 June in both 1994 and 1995. Based on climatology, we should be able to observe sufficient numbers of tornadic storms to test our hypotheses, even if one of the years has relatively few storms. Operating over two years also allows us to improve our technologies and strategies by analyzing first-year data during the intervening off season.

The experiment will be held in the southern and central Plains states (Fig. 3). This region is ideal for observing tornadoes and tornadic storms because of the relative flatness of the terrain, a suitable road network, and the generally good visibility. By 1994, the entire region will be under the coverage of WSR-88D Doppler radars with archival capabilities.

It could be argued that storms in this region have been relatively well observed compared to other regions of the United States. However, the hypotheses we are testing in this experiment never have been evaluated in any region. Once we gain an understanding of the basic processes of tornadogenesis and of tornado dynamics, then the new knowledge can be tested for universality by observing storms in other regions.

c. Field coordination

In this experiment we will utilize about a dozen instrumented vehicles and two Doppler-radar-equipped aircraft (all described below). Each vehicle will be equipped with GPS satellite position and telemetry capabilities as well as voice communications.

Many of the field experiment operations will be supported or directed by a coordinator in the field. The field coordination tasks will be facilitated by software running on a portable computer in the coordination vehicle. This computer will display high-resolution maps of roads, towns, railroads, terrain, etc. (Fig. 4). Team positions will be plotted on these maps based on GPS position reports received from each field vehicle. This method of close coordination is, to our knowledge, unique to VORTEX.

d. Upper-air observations: Mobile ballooning, profilers

Upper-air observations will be made by three mobile laboratories (Mobile Cross-chain Atmospheric Sounding System; M-CLASS) operated by the National Severe Storms Laboratory (NSSL; Fig. 5a; see Rust et al. 1990) and a fourth operated by the National Center for Atmospheric Research (NCAR). Routine soundings and profiler data will be obtained from National Weather Service (NWS) sites (Fig. 3). Prior to storm initiation, the mobile labs will obtain soundings in the prestorm environment. These soundings will be used to assess horizontal inhomogeneities in the environment and associated variations in storm potential.

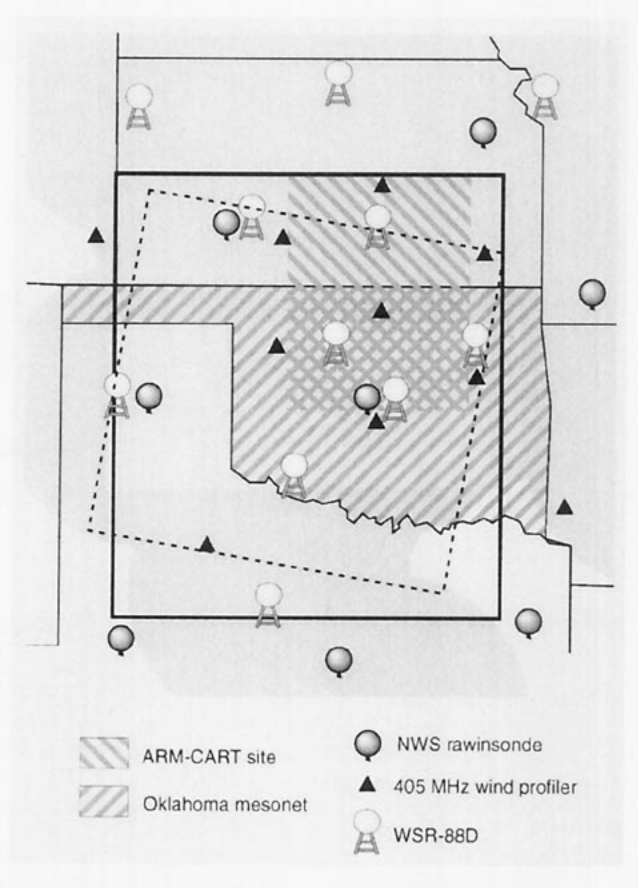

FIG. 3. Map of the VORTEX area. The heavy black rectangle encloses the area of field operations. The thin broken black rectangle is one possible O-LAPS domain. Shaded circles with nearly complete coverage are the 150-nm range coverage areas of the WSR-88D radars.

Once a target storm is selected, during the storm intercept, one mobile lab will attempt to make soundings in the main updraft of the storm, with the balloon preferably entering the cumulonimbus through the wall cloud. Whenever possible we will launch electric field meters and particle size instruments (see section 4c) without interfering with the collection of conventional meteorological sounding data. The two other NSSL labs will be used primarily to assess variations of flow and thermodynamics across the inflow region and near-storm environment in space and time. The NCAR M-CLASS team will make serial soundings in the near-storm environment to evaluate several hypotheses regarding storm–environment interaction.

e. Surface observations: OK mesonet, Mobile mesonet, ASOS, turtles

A wide variety of surface observations will be collected during VORTEX. Surface observations from NWS Automatic Surface Observing System (ASOS) sites will be available at 5-min intervals. These will be

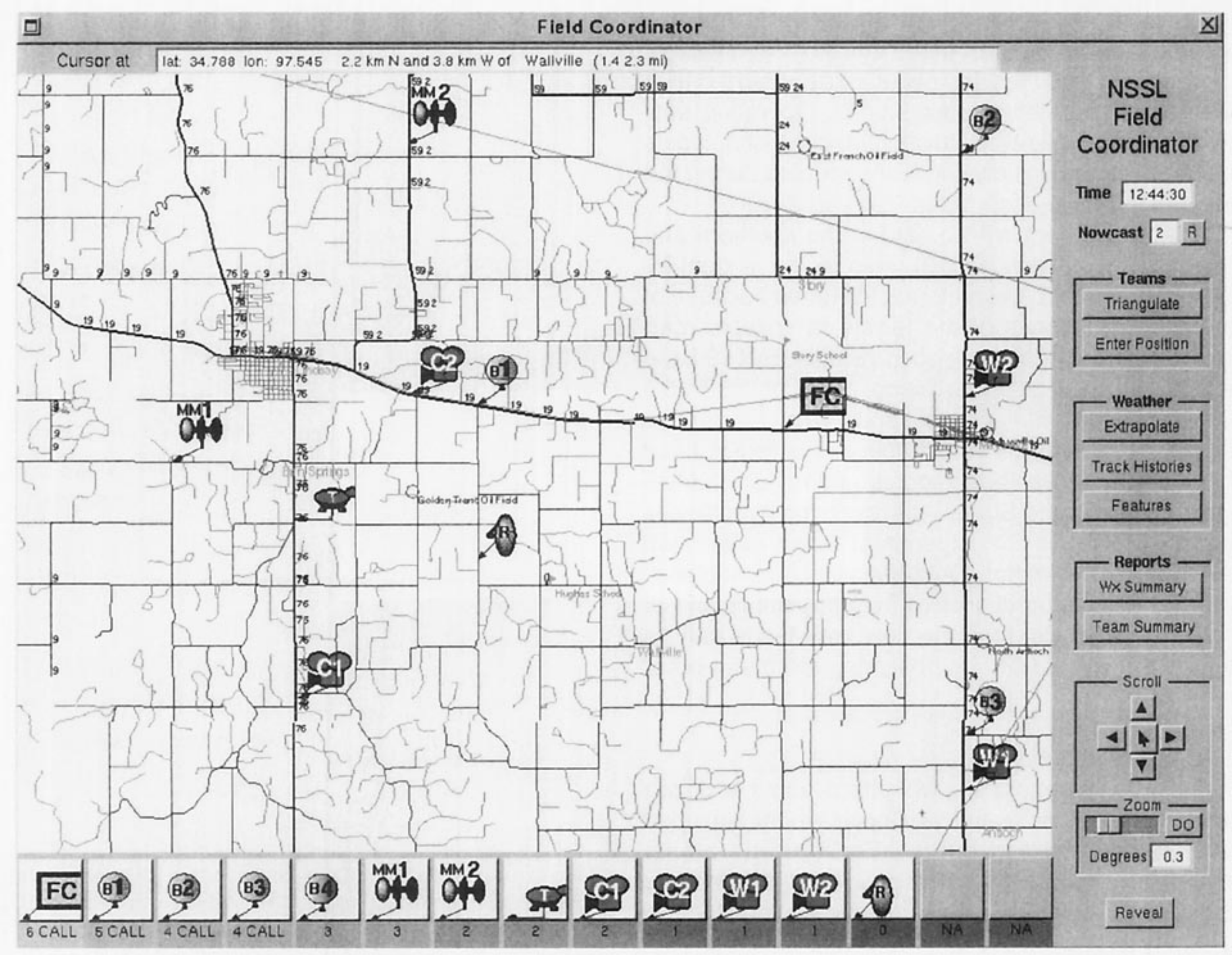

FIG. 4. A portion of the computer display from the mobile field coordinator's computer. The map shows all intercept team icons, roads, places, topographical features, railroads, transmission lines, etc. Team status is indicated below the icons at the bottom. Cursor location and nearest town appear in the window at the top.

supplemented by observations from the Oklahoma Mesonet (Crawford et al. 1994; Brock et al. 1994; see Fig. 6), which covers the state of Oklahoma with a mean spacing of 30 km and generates reports every 5 min. The data will be available in near real time and will be incorporated in the high-resolution analyses available to the NWS Experimental Forecast Facility (EFF) in Norman, Oklahoma (see section 4).

Storm-scale surface data will be collected by placing an instrument package on each vehicle and recording vehicle position, velocity, and meteorological variables (temperature, humidity, pressure, wind direction, and speed) approximately every 5 s. Vehicle velocity, determined from GPS readings, will be subtracted from vehicle winds to obtain ground-relative winds. Five vehicles will be dedicated to making measurement in regions near the mesocyclone suspected of containing large gradients of equivalent potential temperature (see Fig. 5b). One of these vehicles will be responsible for continuously locating and documenting the position and character of the surface gust front to the immediate right of the mesocyclone (relative to the direction of travel of the mesocyclone). All 15 vehicles will augment the surface observation dataset by collecting observations automatically and continuously while performing their regular missions.

Special surface datasets will be collected in mesocyclones and tornadoes by deploying approximately 20 instrumented packages called "turtles" in the path of existing tornadoes (Brock et al. 1987). Half of these will be instrumented to measure electric field and the other half to measure pressure, temperature, and possibly humidity. They will be deployed approximately every 100 to 300 m along a line orthogonal to the tornado path as road availability permits. The field coordinator will be able to extrapolate the path of reasonably well-behaved tornadoes by plotting a number of triangulated observations of the tornado location on his/her computer display.

f. Cloud and debris motion: Stereo photography

Stereo photogrammetry using images from 16-mm cameras will be valuable documentation of airflow in and near the tornado and will augment observations made by Doppler radar. Wherever there are visible, trackable features, the photogrammetric analysis should provide locally high-density sets of 3D velocity data. Two pairs of stereo photography teams will be utilized. One pair will be positioned at ranges of about 2–5 km from tornadoes. The other will be positioned at ranges of about 7–15 km from wall clouds to collect data on cloud motion in the updraft and mesocyclone region.

g. Doppler radar: P-3, ELDORA, WSR-88D, portable system

Most of the experiment domain will be covered by WSR-88D systems with level II and level III data archive capabilities. The NSSL Cimarron Doppler radar with polarimetric capabilities will be available as well. We will use the NOAA P-3 Doppler-equipped aircraft in conjunction with the NCAR ELDORA airborne Doppler to obtain three-dimensional wind and reflectivity data for the target storms. The P-3 has been used in previous years to document supercell flow using pseudo-dual-Doppler techniques (Watson et al. 1993; Dowell et al. 1993). We are investigating how these two aircraft can be used together optimally to reduce velocity errors and improve the temporal resolution of the data. In addition, two portable Doppler radar (Bluestein et al. 1993) will be deployed to obtain invaluable data on maximum wind speeds in tornadoes.

h. Data management

The majority of the data management tasks for VORTEX will be handled by the UCAR Office of Field Project Support (OFPS) in collaboration with NSSL. This will make the data readily available to the greater research community through online access (via Internet and the CODIAC system). Specialized datasets will be maintained by the organizations that collect them. Standard formats, careful documentation, and metadata will be made available to potential users.

3. Forecasting in VORTEX

In order to increase the chances for the field teams to be in proper position for the experiment, forecasts will be provided as guidance to the field operations. In addition to supporting field operations, however, the forecasts will include some experimental forecasting aspects, as in some recent field experiments (Doswell and Flueck 1989; Jincai et al. 1992). To the greatest extent possible, forecasts will be designed to serve both the field operation and the forecasting experiments simultaneously. We are committed to the notion that if forecasts are made in support of operations, they should be verifiable with the data likely to be available after the events, and a verification of those forecasts should, indeed, be carried out (Doswell and Flueck 1989).

The primary task of forecasters will be to provide their best estimate of the likelihood for supercells or tornadoes or both on each operational day. Previous experiments (e.g., Jincai et al. 1992) have suggested that our forecasters have some skill at estimating the probability of severe convective weather events over a wide area, but this is not sufficiently precise for

Fig. 5. (a) An NSSL mobile laboratory, and (b) car outfitted with prototype mobile mesonet equipment. Temperature, humidity, and wind sensors are on the short mast mounted atop the roof rack.

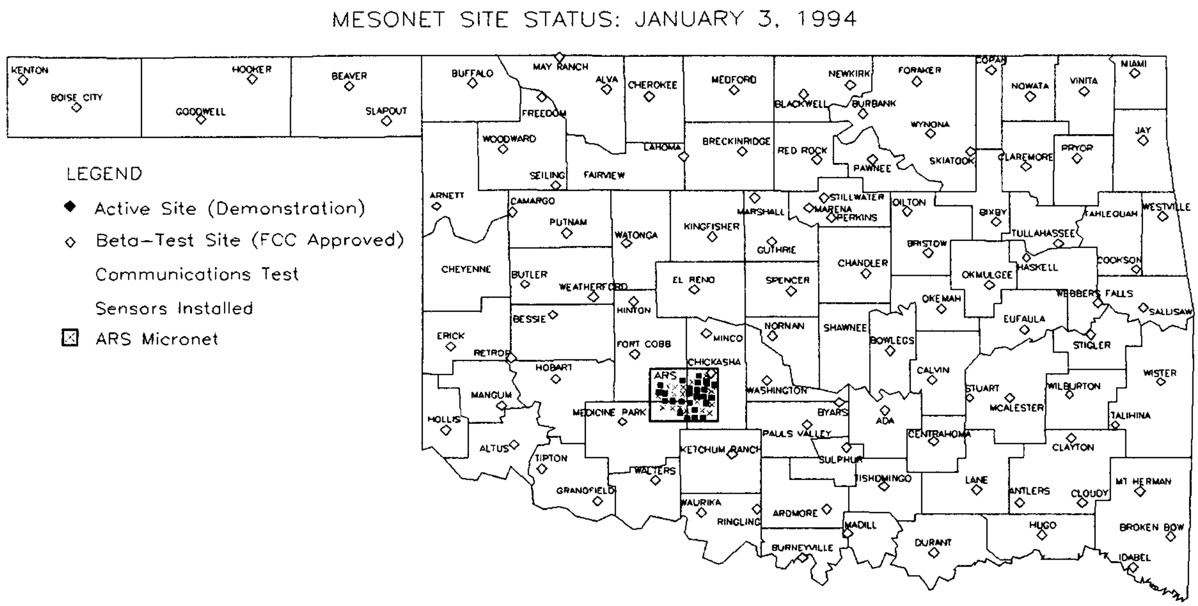

FIG. 6. Map of the Oklahoma Mesonet (courtesy of Oklahoma Climate Survey).

VORTEX. Accordingly, the primary forecast products of VORTEX will be maps showing various kinds of event probability contours over the VORTEX area of operations. Given the needs of the experiments in the project, forecast probability contours over the area of operations will be issued for the items in Table 1.

Forecasts will be used to guide the decision about whether or not field operations will be conducted on any given day and will be updated as needed to support operations. An interesting aspect to the forecasts is the extent to which later forecasts become more detailed and accurate than those issued earlier. The assumption that forecasts can be refined as the day proceeds is an often made one; previous experiments have called this into question (e.g., Doswell and Flueck 1989) and the experiments in VORTEX will be affected by our ability to succeed in this refinement. The refined forecast products will be transmitted to the field coordinator over cellular phones. At the end of each day, an advance outlook for the next day will be issued and conveyed to the field coordinator in order to plan for the next day's activities.

In view of the probabilistic nature of the forecasts, verification techniques will need to reflect this nature; the approach will be the distributions-oriented scheme devised by Murphy and Winkler (1992), in a way comparable to that described in Murphy et al. (1993). Verifying data will be as noted in Table 1, and it is expected that the field teams will be able to provide important supplements to the verification dataset.

4. VORTEX collaborative experiments

a. The CAPS forecasting experiments

To address the problem of predicting severe storms, scientists with the Center for Analysis and Prediction of Storms (CAPS), an NSF Science and Technology Center, are collaborating with investigators from VORTEX in an effort to begin making storm-scale numerical weather predictions for parts of the Southern Plains utilizing very high-resolution (1–3 km) mesoscale numerical models. The collaboration between CAPS and the EFF will enable the exchange of new knowledge between researchers and local forecasters concerning short-term forecasting of the initiation and evolution of severe convective storms.

An important hypothesis to be tested by CAPS during VORTEX is given a region of high-resolution data from a multitude of sensors, a data ingest and analysis system capable of producing gridded fields of the required variables, a state-of-the-art mesoscale/cloud numerical prediction model, and an appropriate data assimilation scheme, then quantitative short-range predictions of convective storm initiation, location, type, and evolution are possible.

The primary focus during the next several years will be on predicting the time, location, type, and evolution of the initial convection, with an emphasis on storms that evolve into supercells. There also will be attempts to initialize the models while a storm is in progress and to predict the remaining evolution of the storm system.

The ingest, quality control, and analysis of all the conventional and research datasets will be accomplished by the Local Analysis and Prediction System (LAPS) developed by scientists at NOAA's Forecast Systems Laboratory (McGinley et al. 1991). Their analysis system is being adapted by CAPS and is centered over the VORTEX data collection region during the field experiment (see Fig. 3).

The models to be used for real-time storm-scale prediction experiments include the Advanced Regional Prediction System (ARPS) (CAPS 1992) and Straka Atmospheric Model (SAM) (Straka 1994). VORTEX will provide the first opportunity to obtain the database necessary to initialize all model variables with different values at each grid point over a state-scale domain.

Various four-dimensional data assimilation (4DDA) and retrieval techniques being developed at CAPS (e.g., Liou et al. 1990; Brewster 1991; Sun et al. 1991; Straka and Zrnic 1993; Shapiro 1993; Qiu and Xu 1993) will be used by these models. These techniques, which range from simple nudging methods to full adjoint approaches, are intended to bring about four-dimensional consistency between the wind, temperature, and buoyancy fields even if only single-Doppler radial winds are used as input. Another important component to the initialization phase is to test methods to incorporate polarimetric data to initialize cloud and precipitation fields.

Our focus during VORTEX will be to produce real-time O-LAPS (Oklahoma-LAPS) analyses and begin making real-time and hind-sight storm-scale numerical predictions of convective storm formation (or lack of formation), type, evolution, and movement. Analysis products for use by the forecasting team will be produced, including mean 0–6-km winds, storm-relative helicity (based on modeled storm movement as well as mean lower tropospheric wind speeds), bulk Richardson number, convective available potential energy (CAPE), and convective inhibition (CIN). Forecast maps of weather features such as jet streaks, fronts, boundaries, and areas of focused forcing (low-level convergence) will also be produced.

b. Electrification of severe and tornadic storms

Electrical measurements will be made in VORTEX to test hypotheses about the electrical properties of tornadic storms and to explore applications of lightning strike data for NWS warning and nowcasting. Several unusual electrical characteristics have been noted in tornadic storms. For example, tornadic storms can have very large in-cloud flash rates, suppression or delay of lightning flashes that strike ground, a preponderance of cloud-to-ground flashes that lower positive charge instead of the negative charge lowered by most ground flashes (see review of lightning observations in MacGorman 1993), and rapidly repeated luminous glows on the cloud surface (Jones 1958) or luminous tornado funnels (Vonnegut and Weyer 1966). However, there is little quantitative knowledge of these phenomena.

Several scientists have noted that the unusual electrical characteristics of supercell tornadic thunderstorms cannot be explained by simple scaling of lightning flash rates and thunderstorm charging rates from small to large storms (e.g., Vonnegut and Moore 1958; Rust et al. 1981; MacGorman et al. 1989; and MacGorman and Burgess 1994). Some studies have suggested that many of the differences are caused by the extremely strong updrafts in tornadic storms. For example, MacGorman et al. (1989) have hypothesized that the large cloud flash rates in some tornadic storms are caused by unusually large updraft velocities that increase the height of the charge distribution, particularly the main negative charge. Other electrical characteristics may result from the microphysical or kinematic properties of particular classes of supercell storms. For example, MacGorman and Burgess (1994) have suggested that either long, horizontal graupel/hail trajectories or high liquid water contents may help explain why cloud-to-ground lightning in some supercell storms is dominated by flashes that lower positive charge to ground, instead of the negative charge lowered by most cloud-to-ground flashes in other types of storms.

One difficulty in testing storm-electrification hypotheses is that there are few cases in which electrical characteristics have been measured in the context of the kinematics and dynamics of tornadic storms. Furthermore, measurements of electric field profiles and charge structure, with or without other storm measurements,

TABLE 1. Forecast elements for which probability maps over the area of VORTEX operations will be issued.

Element	Verifying data	Probability	Condition
First thunder	CG lightning network	Unconditional	
Thunder	CG lightning network	Unconditional	
Severe event	Reports	Conditional	Thunder
Tornado	Reports	Conditional	Thunder
Supercell	Doppler radars	Conditional	Thunder

have been rare. The only measurements published thus far have been measurements in the anvils of isolated storms by Byrne et al. (1989) and Marshall et al. (1989) and in convective regions by Byrne et al. (1987) and Marshall and Rust (1991). In VORTEX, we hope to add to the few existing electrical measurements and provide extensive measurements of the kinematic and dynamic context in which the electrical measurements are made.

Specific electrical parameters to be measured include the following: lightning ground strike locations, electric field at the ground, and balloon-borne profiles of electric field, thermodynamics, and wind. Other parameters, such as x-rays and precipitation particle charge and size, will also be measured via balloon soundings.

c. Use of WSR-88D to identify and monitor tornadic storms

By 1995 a network of 135 Doppler weather radars will be deployed throughout the continental United States. In addition to the intensity of precipitation that can be measured with recent (and present) operational weather radars (e.g., WSR-57, WSR-74), these radars have the capability to measure the movement of precipitation, toward or away from the radar, within thunderstorms. Thus, signatures of circulations can be observed in the Doppler velocity field. One of the main reasons that these radars were procured was to detect mesocyclones and tornadic vortex signatures (TVS; Brown et al. 1978) so that meteorologists could give enough lead time to warn the general public or other users of impending tornadoes.

The WSR-88D network will provide invaluable information as to the location of circulation signatures within thunderstorms (in both the velocity and reflectivity fields). However, more study is needed to relate the characteristics of those signatures observed with weather phenomena observed near (or at) the surface, because typically the near-ground region is not observed due to earth curvature and other effects. Another complicating factor is that Doppler weather radars have different sampling resolution at different ranges; this can cause changes in the signatures due to the sampling difference alone.

In addition to the capability to estimate Doppler velocities within thunderstorms, the WSR-88D radars are very sensitive radars and thus are able to measure winds in the clear-air boundary layer. The capability to measure the three-dimensional winds in the boundary layer every 5 to 10 min can provide important information to meteorologists to help forecast the formation of mesocyclones and tornadoes.

The WSR-88D data, in combination with the other data streams and field observations, will provide important information that will help us relate radar circulation signature characteristics with the formation, strength, and longevity of tornadoes. In addition, we will examine the clear-air velocity field to determine if changes observed in the clear-air boundary layer are related to supercell and tornado formation.

5. Summary

We know that rotation usually first forms aloft in tornadic thunderstorms; this process is well detected by the WSR-88D radars. However, we have no satisfactory understanding of the connection between the middle-level storm rotation and the development of a tornado. Such an understanding is vitally important because, in general, the WSR-88D radars cannot make measurements in the near-ground region (due to earth curvature). If we can understand the process of tornadogenesis, then it is possible that we will be able to discern signatures in the available WSR-88D data that indicate, given mesocyclones, which storms are likely to produce tornadoes and which are not. This holds the promise of reducing the false alarm rate inherent in warning of tornadoes based on WSR-88D mesocyclone signatures. We will also investigate tornadoes that are not associated with preexisting midlevel rotation at all.

A number of hypotheses also were designed to substantially improve our ability to forecast and warn of severe and tornadic storms. By clarifying the role of vertical wind shear in determining storm type, evolution, and tornado potential, we will greatly enhance the value of the wind profilers and WSR-88D VAD wind profiles for forecasting. By clarifying the role of mesoscale boundaries, fronts, and other variations, we will enhance the value of ASOS, satellite, and WSR-88D clear-air capabilities for forecasting. The knowledge we acquire during VORTEX will improve the accuracy and detail of both forecasts and warnings of severe and tornadic thunderstorms. Acquisition of Oklahoma Mesonet data, mobile ballooning, mobile surface observing, and real-time numerical analysis and simulation are vital to these goals.

VORTEX provides the opportunity to acquire new knowledge of tornadogenesis and tornado dynamics through a carefully designed, narrowly focused experiment. Without experiments such as VORTEX, the required knowledge would only be acquired in a relatively haphazard and anecdotal fashion, resulting in less-than-adequate utilization of the tools of the modernized NWS, and less improvement in forecasts and warnings than would be achieved if VORTEX is successful.

Acknowledgments. The principal investigators in VORTEX are grateful for the support of the National Science Foundation (Stephan Nelson), the director of the NOAA Environmental Research Laboratories (Alan Thomas), the director of the National Severe Storms Laboratory (Robert Maddox), the director of the Center for the Analysis and Prediction of Storms at the University of Oklahoma (Douglas K. Lilly), the Office of Research Administration and the Graduate College at OU (Eddie Carol Smith, Dean), the Southern and Central Region Headquarters of the NWS, the Experimental Forecast Facility at NWS/Norman, the NWS/NMC National Severe Storms Forecast Center, the Canadian Atmosphere Environment Service, and NOAA/ERL Forecast System Laboratory (John McGinley), the MMM and ATD divisions of NCAR, and the personnel at the local NWS offices throughout the VORTEX region.

References

Benjamin, S. G., K. A. Brewster, R. Brummer, B. F. Jewett, T. W. Schlatter, T. L. Smith, and P. A. Stamus, 1991: An isentropic three-hourly data assimilation system using ACARS aircraft observations. *Mon. Wea. Rev.*, **119**, 888–906.

Bleck, R., and S. G. Benjamin, 1993: Regional weather prediction with a model combining terrain-following and isentropic coordinates. Part I: Model description. *Mon. Wea. Rev.*, **121**, 1770–1785.

Brewster, K. A., 1991: Phase correcting data assimilation. Preprints, *Ninth Conf. on Numerical Weather Prediction,* Denver, Amer. Meteor. Soc., 610–613.

Bluestein, H. B., J. G. LaDue, H. Stein, D. Speeder, and W. P. Unruh, 1993: Doppler radar wind spectra of supercell tornadoes. *Mon. Wea. Rev.*, **121**, 2200–2221.

Brock, F. D., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson, and M. D. Eilts, 1994: The Oklahoma Mesonet: A technical overview. *J. Atmos. Oceanic Technol.*, **11**, in press.

Brock, F. V., G. Lesins, and R. Walko, 1987: Measurement of pressure and air temperature near severe thunderstorms: An inexpensive and portable instrument. Extended Abstracts, Sixth Symp. on Meteorological Observations and Instrumentation, New Orleans, LA, Amer. Meteor. Soc., 320–323.

Brooks, H. E., C. A. Doswell III, and L. J. Wicker, 1993: STORMTIPE: A forecasting experiment using a three-dimensional cloud model. *Wea. Forecasting,* **9**, 352–362.

Brown, R. A., L. R. Lemon, and D. W. Burgess, 1978: Tornado detection by pulsed Doppler radar. *Mon. Wea. Rev.*, **106**, 29–38.

Byrne, G. J., A. A. Few, M. F. Stewart, A. C. Conrad, and R. L. Torczon, 1987: In situ measurements and radar observations of a severe storm: Electricity, kinematics, and precipitation. *J. Geophys. Res.*, **92**, 1017–1031.

——, ——, and ——, 1989: Electric field measurements within a severe thunderstorm anvil. *J. Geophys. Res.*, **94**, 6297–6307.

CAPS, 1992: *ARPS Version 3.0 User's Guide.* Center for Analysis and Prediction of Storms, University of Oklahoma, 183 pp.

Church, C., J. T. Snow, and E. M. Agee, 1977: Tornado vortex simulation at Purdue University. *Bull. Amer. Meteor. Soc.*, **58**, 900–908.

——, D. Burgess, C. Doswell, and R. Davies-Jones, Eds., 1993: *The Tornado: Its Structure, Dynamics, Prediction, and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 637 pp.

Cole, R. E., F. W. Wilson Jr., J. A. McGinley, and S. C. Albers, 1993: ITWS gridded analysis. Preprints, *Fifth Int. Conf. on Aviation Weather Systems,* Vienna, VA, Amer. Meteor. Soc., 56–60.

Crawford, K. C., F. D. Brock, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson, C. A. Doswell III, 1994: The Oklahoma Mesonet: A twenty-first century project. *J. Atmos. Oceanic Technol.*, **11**, submitted.

Davies-Jones, R. P., 1986: Tornado dynamics, *Thunderstorm Morphology and Dynamics,* 2d ed., E. Kessler, Ed., University of Oklahoma Press, 197–236.

——, 1984: Streamwise vorticity: The origin of updraft rotation in supercell storms. *J. Atmos. Sci.*, **41**, 2991–3006.

——, and H. E. Brooks, 1993: Mesocyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 105–114.

——, D. W. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. on Severe Local Storms,* Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 588–592.

Department of Energy, 1990: *Atmospheric Radiation Measurement Program Plan.* U.S. Department of Energy, DOE/ER-0441, 116 pp.

Doswell, C. A., III, and J. A. Flueck, 1989: Forecasting and verifying in a field research project: DOPLIGHT '87. *Wea. Forecasting,* **4**, 97–109.

Dowell, D. C., H. B. Bluestein, D. O. Blanchard, and D. P. Jorgensen, 1993: Airborne Doppler radar analysis of an Oklahoma supercell. Preprints, *26th Int. Conf. on Radar Meteorology,* Norman, OK, Amer. Meteor. Soc., 212–214.

Fieldler, B. H., 1993: Numerical simulation of axisymmetric tornadogenesis in forced convection. *The Tornado: Its Structure, Dynamics, Prediction and Hazards* (Geophys. Monogr. 79), Amer. Geophys. Union, 40–48.

——, and R. Rotunno, 1986: A theory for the maximum windspeeds in tornado-like vortices. *J. Atmos. Sci.*, **43**, 2328–2340.

Hoecker, W. H., 1960: Wind speed and airflow patterns in the Dallas tornado of April 2, 1957. *Mon. Wea. Rev.*, **88**, 167–80.

Jincai, D., C. A. Doswell III, D. W. Burgess, M. P. Foster, and M. L. Branick, 1992: Verification of mesoscale forecasts made during MAP '88 and MAP '89. *Wea. Forecasting,* **7**, 468–479.

Jones, H. L., 1958: The identification of lightning discharges by sferic characteristics. *Recent Advances in Atmospheric Electricity,* L. G. Smith, Ed., Pergamon Press, 543–556.

Klemp, J. B., 1987: Dynamics of tornadic thunderstorms. *Annu. Rev. Fluid Mech.*, **19**, 369–402.

Lewellen, W. S., 1993: Tornado vortex theory. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.* No. 79, Amer. Geophys. Union, 19–39.

Liou, Y., T. Gal-Chen, and D. K. Lilly, 1991: Retrieval of wind temperature and pressure from Doppler radar in a numerical model. Preprints, *25th Int. Conf. on Radar Meteorology,* Paris, France, Amer. Meteor. Soc., 151–154.

MacGorman, D. R., 1993: Lightning in tornadic storms: A review. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.* No. 79, Amer. Geophys. Union, 173–182.

——, and K. E. Nielsen, 1991: Cloud-to-ground lightning in a tornadic storm on 8 May 1986. *Mon. Wea. Rev.*, **119**, 1557–1574.

——, and D. W. Burgess, 1994: Positive cloud-to-ground lightning in tornadic storms and hailstorms. *Mon. Wea. Rev.*, **122**, in press.

——, ——, V. Mazur, W. D. Rust, W. L. Taylor, and B. C. Johnson, 1989: Lightning rates relative to tornadic storm evolution on 22 May 1981. *J. Atmos. Sci.*, **46**, 221–250.

Marshall, T. C., and W. D. Rust, 1991: Electric field soundings through thunderstorms. *J. Geophys. Res.*, **96**, 22 1297–22 1306.

——, ——, W. P. Winn, and K. E. Gilbert, 1989: Electrical structure in two thunderstorm anvil clouds. *J. Geophys. Res.*, **94**, 2171–2181.

McGinley, J. A., S. C. Albers, and P. A. Stamus, 1991: Validation of

a composite convective index as defined by a real-time local analysis system. *Wea. Forecasting,* **6,** 337–356.
Murphy, A. H., and R. L. Winkler, 1992: Diagnostic verification of probability forecasts. *Int. J. Forecasting,* **7,** 435–455.
——, C. A. Doswell III, S. J. Weiss, P. D. Bothwell, and H. E. Brooks, 1993: Probabilistic severe weather forecasting at NSSFC: An experiment. Preprints, *17th Conf. on Severe Local Storms,* St. Louis, Amer. Meteor. Soc., 74–78.
Qiu, C.-J., and Q. Xu, 1992: A simple adjoint method of wind analysis for single-Doppler data. *J. Atmos. Oceanic Technol.,* **9,** 588–598.
Rasmussen, E. N., 1994: VORTEX Operations Plan. 224 pp. [Available upon request from the National Severe Storms Lab, Norman, OK.]
Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.,* **42,** 271–292.
Rust, W. D., R. Davies-Jones, D. W. Burgess, R. A. Maddox, L. C. Showell, T. C. Marshall, and D. K. Lauritsen, 1990: Testing a mobile version of a Cross-chain Loran Atmospheric Sounding System (M-CLASS). *Bull. Amer. Meteor. Soc.,* **71,** 173–180.
——, W. L. Taylor, D. R. MacGorman and R. T. Arnold, 1981: Research on electrical properties of severe thunderstorms in the Great Plains. *Bull. Amer. Meteor. Soc.,* **62,** 1286–1293.
Shapiro, A., 1993: A single-Doppler velocity retrieval in the convective planetary boundary layer. Preprints, *23d Conf. on Radar Meteorology,* Norman, OK, Amer. Meteor. Soc., 441–443.
Straka, J. M., 1994: The influence of ice-phase microphysics on convective storm structure and evolution, Part I: Model description and validation. *Mon. Wea. Rev.,* submitted.
——, and D. S. Zrnic, 1993: An algorithm to deduce hydrometeor types and contents from multi-parameter radar data. *Preprints,* 26th Int. Conf. on Radar Meteor., Norman, Oklahoma, Amer. Meteor. Soc., 513–515.
Sun, J., D. W. Flicker, and D. K. Lilly, 1991: Recovery of three-dimensional wind and temperature fields from simulated single-Doppler radar data. *J. Atmos. Sci.,* **48,** 876–890.
Vonnegut, B., and C. B. Moore, 1958: Giant electrical storms. *Recent Advances in Atmospheric Electricity,* L. G. Smith, Ed., Pergamon Press, 339–411.
——, and J. R. Weyer, 1966: Luminous phenomena in nocturnal tornadoes. *Science,* **153,** 1213–1220.
Wakimoto, R. M., and J. W. Wilson, 1989: Non-supercell tornadoes. *Mon. Wea. Rev.,* **117,** 1113–1140.
Ward, N. B., 1972: The exploration of certain features of tornado dynamics using a laboratory model. *J. Atmos. Sci.,* **29,** 1194–1204.
Watson, A. I., D. O. Blanchard, D. P. Jorgensen, and D. W. Burgess, 1993: The kinematic structure of a supercell thunderstorm seen by airborne Doppler radar. Preprints, 26th Int. Conf. on Radar Meteorology, Norman, OK, Amer. Meteor. Soc., 209–211.
Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.,* **110,** 504–520.
Wicker, L. J., and R. B. Wilhelmson, 1993: Numerical simulation of tornadogenesis within a supercell thunderstorm. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.* No. 79, Amer. Geophys. Union, 75–88.
Wilczak, J. M., T. W. Christian, D. E. Wolfe, and R. J. Zamora, 1992: Observations of a Colorado tornado. I, Mesoscale environment and tornadogenesis. *Mon. Wea. Rev.,* **120,** 497–520.