Project Summary

The Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) is a multi-agency field program to investigate (i) tornadogenesis, maintenance, and demise, (ii) tornado near-ground wind field, (iii) relationships among tornadoes, their parent thunderstorms, and the larger-scale environment, and (iv) numerical weather prediction of supercells and tornadoes. The second field experiment of VORTEX (VORTEX2) is proposed in the United States Great Plains region during the months of April–June, 2009–2010. It will be conducted as a two-phase experiment. A "tethered" phase, utilizing an adaptable observation network tethered to fixed observing facilities in central Oklahoma and conducted in each April and early May, will address foci related to storm-environment and storm-storm interactions, as well as numerical predictability. A "fully mobile" phase will take place in mid-May through June over a broad region of the central United States, with a focus on tornadogenesis and tornado wind fields.

Results from the first VORTEX experiment (VORTEX1), conducted in 1994–1995, advanced our understanding of the kinematic similarities between tornadic and nontornadic supercell thunderstorms and the implied sensitivity of supercell evolution and tornadogenesis to fine-scale heterogeneity, both pre-storm and storm-induced. Recent improvements in National Weather Service warning statistics may be attributable in part to the application of VORTEX1 findings pertaining to the role of the near-storm environment (e.g., enhanced low-level vertical wind shear, cloud base height, mesoscale boundaries) in determining the potential for tornado formation.

Despite (and because of) the broad successes of VORTEX1, many new questions have emerged regarding the circulation sources for tornadoes, the role of downdrafts and their thermodynamics and microphysics in tornadogenesis, the relationship between tornadoes and larger scales of motion, and the relationship between tornadic winds and damage. Furthermore, technological advances that have occurred since VORTEX1 (e.g., advances in ground-based mobile radar technology and improvements in our ability to obtain thermodynamic and microphysical observations) will allow investigators to explore aspects of tornadoes and their formation that they could not pursue in VORTEX1. These advances have increased both our ability to resolve small spatial and temporal scales within thunderstorms and our mobility while collecting these data. VORTEX2 will take full advantage of cutting-edge remote and in situ mobile and fixed observing systems, as well as data assimilation techniques that can improve analyses by combining the dense observations with governing dynamical equations.

The four foci of VORTEX2 are summarized below:

Tornadogenesis. Role of downdrafts in tornadogenesis; sensitivity of tornadogenesis to microphysical and thermodynamic characteristics; role of vorticity maxima along gust fronts in tornadogenesis and/or maintenance; modes for the development of significant tornadoes in supercells.

Near-ground wind field in tornadoes. Range of observed tornado characteristics, such as vertical, radial, and swirling velocity profiles, asymmetries, multiple vortices, and angular momentum budgets; relationships between damage and wind speed, acceleration, and duration.

Relationships between supercell storms and their environments. Interactions among storms that are/are not favorable for tornadogenesis; effects of environmental heterogeneity on supercells and tornadogenesis.

Storm-scale numerical weather prediction (NWP). Analysis and prediction of supercells, mesocyclones, and tornadoes; assessment of parameterization errors for storm-scale models and data assimilation methods for the storm scale; optimal use of observations; analysis and prediction of the pre-storm mesoscale environment.

Intellectual merit. VORTEX2 is designed to improve our understanding of tornadogenesis, which ultimately will better allow us to assess the likelihood of tornadoes in supercell thunderstorms and possibly even tornado intensity, longevity, and cyclic behavior. Moreover, VORTEX2 is expected to improve vastly our understanding of the range of tornado structures and the relationships between tornado structure and characteristics of the parent thunderstorm.

Broader impacts. VORTEX2 is expected to lead to further improvements in tornado warning skill. It is believed that storm-scale numerical weather prediction must play a prominent role in the initiative to improve short-term forecasts of severe weather; multi-sensor and multi-scale VORTEX2 datasets will serve as a testbed for numerical storm-scale prediction experiments. VORTEX2 will better our understanding of the relationships between tornadoes, their parent convection, and the larger-scale environment. Better insight into these relationships is essential if reliable long-term predictions are to be made of changes in the frequency and geographical distribution of tornadoes due to climate change. Quantification of the actual temporal and spatial distribution of winds impacting structures will enable better engineering standards to be developed. Lastly, VORTEX2 includes an innovative educational component in which students will participate in a series of scientific seminars presented in the field by the many participating severe storm expert PIs.

Project Description

1. Introduction

The second field experiment of the Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX2) is designed to improve our understanding of tornadogenesis, tornado near-ground winds and damage, the environments of severe convective storms, and storm-scale numerical weather prediction (NWP). Not only will this new knowledge better allow us to assess the likelihood of tornadoes in supercell thunderstorms, but it will improve our understanding of the relationship between tornado structure and damage, and perhaps even lead to advances in forecasting tornado intensity and longevity. A better understanding of the relationships among tornadoes, their parent thunderstorms, and the larger-scale environment will have much broader benefits as well. For example, improvements in our understanding of tornadogenesis are essential if extrapolations are to be made of changes in the frequency and geographical distribution of tornadoes as a result of the modification of thunderstorm environments due to climate changes.

The first VORTEX experiment (VORTEX1; Rasmussen et al. 1994) was conducted during the spring seasons of 1994 and 1995. VORTEX1 was a highly collaborative effort designed to increase understanding of tornadogenesis and supercell thunderstorms. VORTEX1 produced a wealth of new knowledge. For example, it was found that strong to violent tornadoes often were associated with storms encountering preexisting mesoscale boundaries. VORTEX1 increased the awareness of mesoscale heterogeneity even in the absence of obvious mesoscale boundaries, which has, in turn, motivated a number of subsequent simulation studies exploring the sensitivity of convective storms to small changes in the ambient kinematic and thermodynamic environment. VORTEX1 led to improved conceptual models of low-level mesocyclones. For example, it is now known that a large fraction of even nontornadic supercell thunderstorms contain circulations near the surface. Further, the previously suspected importance of downdrafts in tornadogenesis was bolstered by VORTEX1 observations, and there is evidence that the thermodynamic properties of the downdrafts may exert some control on tornadogenesis as well as tornado intensity and longevity. VORTEX1 also produced the first ever three-dimensional mapping of tornado structure itself, quantifying the horizontal and vertical distribution of winds, a central downdraft, the extent of debris lofting, and structural changes during demise, as well as the variability of these structures among several tornadoes. Finally, one of the most important observations made in VORTEX1 might be the striking kinematic similarities between tornadic and nontornadic supercells at scales larger than the tornado cyclone, which may be a manifestation of the fact that tornadogenesis is a highly nonlinear, perhaps even fragile process.

Additional, smaller field activities have built on VORTEX1 in recent years. Some of these efforts have further advanced VORTEX1 findings, such as the association between downdraft thermodynamic properties and tornadogenesis. Equally important, post-VORTEX1 activities have resulted in the development, testing, and maturation of new technologies. Perhaps the most important technological advances made in recent years are in mobile radar technology, communications, and the ability to acquire in situ measurements at very close range to tornadoes. These advances have enabled the collection of high-resolution radar observations of tornado structure and in situ observations in and near tornadoes. These data have confirmed several previously unverified laboratory and numerical simulation predictions, but also have raised questions concerning our prior beliefs regarding the relationship between wind speed and damage. Moreover, dual-Doppler observations of supercells from mobile, ground-based radars have become more commonplace in recent years.

Although VORTEX1 and post-VORTEX1 activities have provided much new insight into tornadoes and their parent storms and environments, a number of questions remain (section 5), which largely have been a result of data inadequacies. For instance, detailed analyses of the vorticity budgets of tornadoes and their antecedent circulations have been precluded in the past by insufficient temporal and spatial resolution. Thermodynamic observations above the ground have been limited to a dearth of direct measurements made by soundings and suspect indirect observations from retrievals derived from Doppler wind syntheses. Rigorous attempts have not yet been made to investigate the range of microphysical characteristics of supercell thunderstorms, particularly within downdrafts, and the possible sensitivity of tornadogenesis to these microphysical characteristics. The aforementioned technological advances, however, along with improved analysis techniques, allow many of the previous data hurdles to be overcome. These significantly enhanced data and analysis capabilities, coupled with newly refined scientific questions, argue for another closely coordinated field campaign—VORTEX2.

VORTEX2 is a collaborative, multi-agency field program having four foci:

- Tornadogenesis
- Near-ground wind field in tornadoes
- Relationships between supercell storms and their environment
- Storm-scale NWP

The **tornadogenesis** component includes an investigation of the roles in tornado formation and maintenance of the rear-flank downdraft, microphysical and thermodynamic characteristics in the mesocyclone region, and vorticity maxima commonly observed along gust fronts. This component also is designed to elucidate the relationship between low-level and midlevel mesocyclones, and to explore whether more than one mode exists for the development of significant tornadoes in supercell thunderstorms. The primary observing systems supporting this component include X- and C-band ground-based mobile Doppler radars, some of which will have dual-polarization and rapid-scan capabilities, unmanned aeronautical vehicles (UAVs), a mobile mesonet array, a rapidly deployable network of instrument packages mounted on tripods ("stick net"), rawinsondes, and cameras to enable stereo photogrammetric analyses.

The **near-ground wind field in tornadoes** component is designed to establish the range of observed tornado characteristics, such as the profiles of swirling, radial, and vertical velocities, as well as how these relate to dynamical and thermodynamical structures in the environment surrounding the tornado. This component also is designed to determine the nature and frequency of asymmetries and multiple vortices and the relationship between wind and damage. The primary observing systems supporting this component include rapidly deployable in situ probes and ground-based mobile Doppler radar (X-band and W-band), some of which will have rapid-scan capabilities. Damage surveys and photogrammetric observations also will be used.

The **relationships between tornadic storms and their environments** component is designed to investigate interactions among storms that are favorable or unfavorable for tornadogenesis, and the effects of environmental heterogeneity on supercells, tornadogenesis, tornado intensity, longevity, and cyclic behavior. This component is supported by both mobile observing systems and the a dense array of fixed observing systems (see section 3). The primary mobile observing systems supporting this component include rawinsondes, ground-based mobile Doppler radar (C-band and X-band), a mobile mesonet array, UAVs, and stick net.

The **storm-scale NWP** component seeks to improve forecasts of supercells and improve our understanding of the predictability of supercells and tornadoes. Cloud and mesoscale models will be initialized by assimilating dense observations obtained in the field into these models. Data assimilation will also be a useful *analysis* tool supporting the other foci described above. The primary mobile observing systems supporting this component include rawinsondes, ground-based mobile Doppler radar (C-band and X-band), mobile mesonet, UAVs, and stick net. This component also relies heavily on the fixed observing network in and near Oklahoma (section 3).

2. Relationship of VORTEX2 to national research priorities

The rationale for VORTEX2 closely mirrors current national and international research priorities. In addition to the rather obvious relevance of VORTEX2 toward improving severe weather warnings, the new knowledge produced by VORTEX2 may lead to advances in tornado damage mitigation and may even be of considerable interest to the climate change community, given the economic importance of extreme weather and the potential shifts in the frequency and geographical distribution of extreme events resulting from climate change. Furthermore, it is believed that storm-scale numerical weather prediction must play a prominent role in the National Weather Service (NWS) initiative to increase tornado warning lead time. VORTEX2 datasets should become a testbed for numerical storm-scale prediction experiments. These motivations for VORTEX2 are expanded upon below.

2.1 Tornado warning skill

The past two decades have seen substantial improvements in the quality of tornado warnings, with the improvements often being made in stepwise fashion (Fig. 2.1). Causality is not certain, but it seems likely that the installation of the WSR-88D network, the application of many VORTEX1 findings in operations, better training, and better guidance forecasts from the Storm Prediction Center (SPC) have contributed to the gains (Brooks 2004). It is even tempting to attribute the jump in tornado warning forecast skill occurring in the 1995–1998 period to VORTEX1, as many VORTEX1 observations already were being communicated to forecasters as early as summer, 1995. It is anticipated that further improvements from VORTEX2 in our understanding of tornadogenesis—and also tornado maintenance and demise—will better allow us to distinguish tornadic thunderstorms from nontornadic thunderstorms and possibly will improve short-term predictions of tornado longevity and intensity.

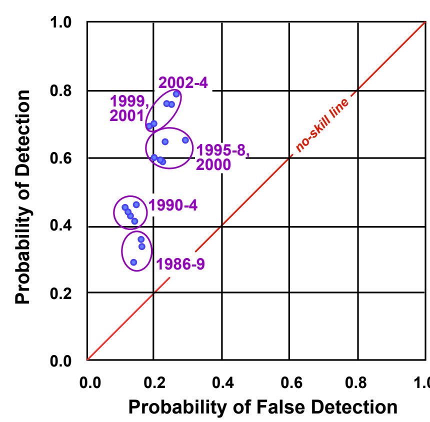

FIG. 2.1. Tornado warning performance from 1986–2004 (courtesy of H. Brooks).

2.2 Tornado damage mitigation

Wind and building engineers are seeking to better quantify the tornado wind threat, and have recently adopted an enhancement to the Fujita-scale. However, the underlying assumption of the suggested wind speed relationships, that damage is related only to peak gusts, is nearly untested with actual observations, and certainly not quantified, precluding intelligent improvement in building design or codes. VORTEX2 will compare measurements of low-level winds to damage, permitting testing and quantification of wind versus damage relationships.

2.3 Climate change and extreme events

An improved understanding of the relationship between tornadoes and their environments also is crucial to the study of how the frequency of extreme events might change as a result of climate change. Extreme events and their societal impacts have received considerable attention, both from the U. S. Global Change Research Program and the U. S. Weather Research Program. The numerous publications and dozens of workshops held in just the last few years are testaments of this scrutiny. Extreme weather events have received so much attention largely because of their enormous economic impact. Annual losses in the United States due to tornadoes currently average approximately $3 billion.

Despite recent cinematic portrayals of a changing global climate and perhaps somewhat more factual discussions of such in nonrefereed publications and on Internet websites, there is no compelling evidence to suggest that the global frequency and intensity of tornadoes are increasing at present. Changes in tornado activity in *future climates* influenced by increased greenhouse gas concentrations and sulfate aerosols is unclear: as stated in the Third Assessment Report (TAR) 2001 of the Intergovernmental Panel on Climate Change (IPCC), little guidance concerning this phenomenon (as well as lightning and hail) can be offered by atmosphere-ocean global climate model (AOGCM) projections, owing to their coarse gridpoint spacing relative to the scale of individual thunderstorms (IPCC 2001). Hence, we are limited at this point to making physical arguments based on the characterization of the large-scale environment provided by AOGCMs, necessarily disregarding any feedback of the tornadic storms to the larger scale. The validity of predictions of the future frequency and intensity of tornadic thunderstorms is limited by the neglect of this feedback as well as our current ability (or relative *inability*) to unambiguously link tornado occurrence and intensity to particular environmental parameters. To determine the relationship between the future climate and tornado frequency, spatial distribution, and intensity distribution, it is essential that we improve our understanding of how the large-scale environment is related to tornado formation.

2.4 Storm-scale data assimilation and numerical weather prediction

Assimilation of high-resolution, multi-sensor observations into numerical cloud models and explicit predictions of convective storms by these models are recognized as essential for improving warnings of hazardous weather (tornadoes, other damaging winds, hail, lightning, and floods) and improving quantitative precipitation forecasts in general (Fritsch et al. 1998; Droegemeier et al. 2000; Dabbert et al. 2000; U.S. Dept. of Commerce 1999). To support the development of the storm-scale NWP systems of the future, observations from focused field programs are needed now that can be used to verify and improve data-assimilation and modeling methodologies (Fritsch et al. 1998). Although a number of prototype storm-scale prediction systems are available already, and although these systems have demonstrated some skill at predicting convective mode, it has not been possible to determine with much certainty the causes of poor point-specific forecasts. Was the initial state of the convective storm/system in the model unrealistic? Was the storm's environment poorly analyzed and/or predicted? Did model deficiencies (coarse resolution, errors in parameterizations of moist processes, etc.) contribute to poor forecasts? Has an inherent atmospheric predictability limit been reached?

VORTEX2 will collect multi-scale and multi-sensor observations of isolated convective storms unlike those available from the operational network or previous field programs. During the research phase following the field program, researchers will use VORTEX2 observations to initialize storm-scale models and evaluate the model forecasts. Through sensitivity studies, the relative contributions to analysis and forecast uncertainty of factors such as model resolution, surface inhomogeneities, and parameterizations of precipitation microphysics will be evaluated.

VORTEX2 will address national research priorities in storm-scale NWP in multiple ways. First, VORTEX2 research will contribute to basic understanding of convective storms, particularly interactions between cloud dynamical and microphysical processes. Second, VORTEX2 datasets will become a research testbed for storm-scale prediction experiments. Unprecedented multi-sensor and multi-scale observations will be available for model initialization and forecast verification, enabling one to determine the optimal mix of observations, adaptive observing strategies, data-assimilation methods, and forecast models needed for successful storm-scale numerical weather prediction in future operational systems.

3. Experiment overview

VORTEX2 will use numerous carefully-coordinated observing platforms to document the four-dimensional wind, thermodynamic, and microphysical fields of supercell thunderstorms and their environments. VORTEX2 will comprise two phases:

Phase A A “tethered” phase, based in central Oklahoma (Fig. 3.1). This phase is designed to study relationships between tornadic storms and their environments (focus 3, described in section 5.3), in addition to obtaining data in support of the storm-scale data assimilation and NWP component of VORTEX2 (focus 4, described in section 5.4). This phase will occur early each project season and will employ the multi-faceted observational assets available in Oklahoma [e.g., the National Weather Radar Testbed-Phased Array Radar (NWRT-PAR), prototype dual-polarization WSR-88D (KOUN), other WSR-88Ds (e.g., KTLX, KFDR, KVNX) that could have polarimetric upgrades by the start of VORTEX2, Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) radar network, Kessler Farm Field Laboratory, Oklahoma Mesonet, and micronets]. In addition, mobile assets including mobile mesonets, stick net, mobile C- and X-band radar systems (at least two of which will have dual polarization), UAVs, and mobile sounding systems will augment the fixed observing systems.

Phase B A fully mobile phase, with no home base (Fig. 3.2). This phase is designed to study tornadogenesis, maintenance, and demise (focus 1, described in section 5.1), as well as tornado structure and the near-ground wind field in proximity to tornadoes (focus 2, described in section 5.2). This phase will occur in late spring during two project seasons and will employ only the mobile assets.

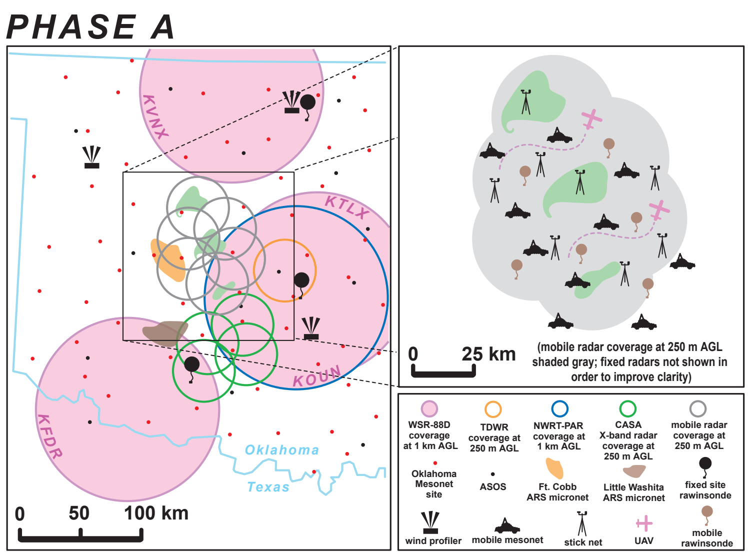

FIG. 3.1. General deployment strategy for the tethered component of VORTEX2 (phase A). Green shading represents the precipitation regions of supercell thunderstorms. All other symbols and icons are defined in the legend. The deployment depicted above serves only as an example to acquaint the reader with how instruments might be deployed to gather data needed to answer the science questions posed in section 5. More detailed deployment maps are provided in the Experiment Design Overview (EDO).

As has proven valuable in the success of VORTEX1 and subsequent tornado field experiments, a multi-year effort is ideal, for it ensures the sampling of a wide variety of supercell days. The tethered phase (phase A) is proposed for two years, from approximately **1 April–10 May, 2009–2010**. The April to early May period is when severe convection is climatologically very likely in central Oklahoma (Hocker and Basara 2007). Experience also has shown that storms occurring during this period tend to be more difficult to target with mobile observing platforms owing to their tendency to be fast-moving. During phase A, the mobile observing systems will not be pursuing storms; rather, mobile instruments will be deployed strategically (many potential deployment sites will be determined from surveys prior to the experiment itself), based on the forecast arrival and/or development of convection in central Oklahoma. Essentially, we are proposing a deployable, adaptable storm-scale and mesoscale observing network. This strategy supports the storm-environment and storm-scale NWP missions (foci 3 and 4) of VORTEX2 better than a strategy whereby all of the mobile assets would converge upon and pursue a single storm.

The fully mobile phase (phase B) is proposed for the same two years, from approximately **11 May–25 June, 2009–2010**. Storms tend to be slower-moving during this part of the spring storm season, thereby presenting a better opportunity to obtain the high-resolution observations needed in support of foci 1 and 2. Furthermore, the later start date affords many more students and university faculty the opportunity to participate in this component of the field work (only a limited number of students will be able to participate in phase A owing to its overlapping with the academic calendar). We are encouraged by the efficiency and success of recent “fully mobile” experiments such as Radar Observations of Tornadoes and Thunderstorms Experiment (ROTATE) and the Bow Echo and Mesoscale Convective Vortex (MCV) Experiment (BAMEX).

The observational domain for phase B is shown in Fig. 3.2. The domain is restricted to those areas with favorable terrain, road availability, and land use to enable mobility as well as unobstructed radar and visual viewing from vantage points on the ground. Our experience shows that full mobility is essential because, in any given year, the large-scale pattern tends to favor smaller regions for repeated supercell activity. For example, some years have frequent supercell activity on the dryline in western Texas, while other years have activity focused in the central Plains. Sometimes, several-day episodes of supercells shift from one part of the Plains to another. The overall cost of this phase of the experiment should be less than that for an experiment of comparable duration having a fixed home base, because travel miles (vehicle wear, fuel expenses, and participant fatigue) will be reduced compared to the previous paradigm in which long ferries to and from a base site occurred frequently. To aid the fully mobile phase in making repairs to mobile platforms, garage space will be rented in three strategic locations within the domain [Fig. 3.2; maintenance also can be performed at the National Severe Storms Laboratory (NSSL) in Norman, and at the Center for Severe Weather Research (CSWR) in Boulder].

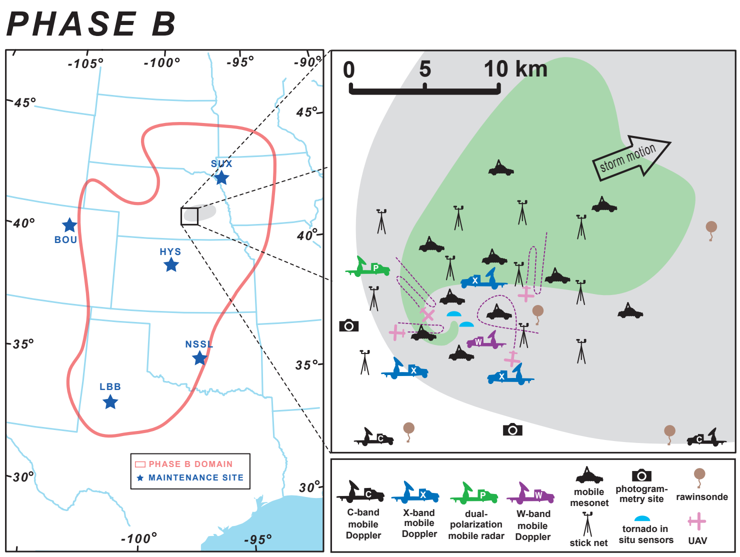

FIG. 3.2. As in Fig. 3.1, but for the fully mobile component of VORTEX2 (phase B). The red boundary (left panel) indicates the approximate phase B domain, defined by the region where the dominant land use tends to be agricultural. The relatively dense road networks and lack of trees implied by such land use are conducive to visual and radar observations and are thus favorable for the phase B field activities proposed herein. Green shading represents the precipitation region of a supercell thunderstorm and gray shading indicates the approximate cloud boundary as viewed by satellite. As was the case with Fig. 3.1, the deployment depicted above serves only as an example to acquaint the reader with how instruments might be deployed to gather data needed to answer the science questions posed in section 5. More detailed deployment maps appear in the EDO.

The primary target of the VORTEX2 observing facilities will be supercell thunderstorms. Most strong tornadoes (F2–F3) and virtually all violent tornadoes (F4–F5), which account for a disproportionate fraction of tornado damage and casualties, are associated with supercell thunderstorms. Although it is recognized that many tornadoes are associated with nonsupercellular parent convection (e.g., Wakimoto and Wilson 1989; Tessendorf and Trapp 2000), nonsupercell tornadogenesis intercepts will only be attempted on a "target-of-opportunity" basis, i.e., when such an event appears imminent and VORTEX2 facilities are at relatively close range.

4. Instrumentation overview

The tethered phase of VORTEX2 (phase A) takes advantage of a tremendous assortment of National Oceanic and Atmospheric Administration (NOAA) and other fixed observing facilities in Oklahoma. Among these are the NWRT-PAR and WSR-88D radars (KOUN, KTLX, KFDR, and KVNX), the CASA radar network (this is a network of X-band radars mounted on cell phone towers), the Terminal Doppler Weather Radar (TDWR) at Will Rogers World Airport, the Atmospheric Research Measurement (ARM) Southern Great Plains (SGP) Central Facility, the NOAA Profiler Network (NPN), the Kessler Farm Field Laboratory [which hosts a 915 MHz boundary layer radar and a 404 MHz wind profiler with radio acoustic sounding system (RASS) capabilities (this profiler is part of the NPN)], the Oklahoma Mesonet, and the Agricultural Research Service (ARS) Micronets at Little Washita and Fort Cobb. In addition to the VORTEX2 mobile soundings, soundings will be launched from the ARM SGP site, Fort Sill, and NWS forecast office in Norman (Fig. 3.1). In addition to the KOUN polarimetric WSR-88D, there are tentative plans to upgrade some additional neighboring WSR-88Ds (e.g., KTLX, KFDR, KVNX, KDDC, and KICT) with dual-polarization capability in the 2009–2010 timeframe, and also to enable the NWRT-PAR to obtain refractivity measurements. The impressive fixed radar network may be further augmented by including some of the radars in the vicinity of the Oklahoma City metropolitan area that are operated by the local television stations (not shown in Fig. 3.1).

With regards to mobile observing systems, probably the most visible technological advance since VORTEX1 is in ground-based mobile radar technology. The only mobile Doppler radars available to VORTEX1 for the experiment duration were a pair of airborne Doppler radars [Electra Doppler Radar (ELDORA) and the NOAA P3 tail radar] and a ground-based W-band radar (Bluestein et al. 1997). The first Doppler On Wheels (DOW) mobile radar (X-band) was deployed on a few missions near the end of VORTEX1 (Wurman et al. 1997), but no dual-Doppler datasets were obtained from ground-based radars. During the Radar Observations of Tornadoes and Thunderstorms Experiment (ROTATE), subsequent to VORTEX1, several dual-Doppler data sets have been obtained (e.g., Richardson et al. 2001; Dowell et al. 2002; Wurman et al. 2007a,b), but not in the context of the dense array of thermodynamic measurements provided in VORTEX. In contrast, the deployment of seven truck-borne Doppler radars is proposed in VORTEX2. In phase A, two C-band and four X-band radars would be deployed with 20–40 km dual-Doppler baselines (Fig. 3.1). In phase B, two C-band radars, which are ideally suited for sampling the broad precipitation regions of storms, will be deployed with a relatively long (20–30 km) dual-Doppler baseline; X-band radars will be deployed with somewhat shorter (5–15 km) dual-Doppler baselines in order to sample the mesocyclone region; a W-band radar will be deployed at close range (2–5) in order to sample tornado structures (Fig. 3.2). At least one of the radars will have rapid-scan capability (e.g., Rapid-Scan DOW; Wurman and Randall 2001), permitting 5–10 s three-dimensional updates in the rapidly occurring tornadogenesis phase. This scanning also will allow rapidly changing tornado structural changes to be resolved. Furthermore, at least one C-band

Science focus	Required observing systems	Phase
Tornadogenesis	C-band and X-band radars (at least two of which have dual polarization and one of which has "rapid scan" capability), mobile mesonets, stick net, mobile soundings, UAVs, photogrammetry	B
Near-ground wind field in proximity to tornadoes	X-band (one of which has "rapid scan" capability) and W-band radars, tornado in situ sensors, photogrammetry, damage surveys	B
Relationships between supercell storms and their environments	Fixed observing systems (e.g., NWRT-PAR, S-band radars; see section 4), C-band and X-band radars, mobile soundings, mobile mesonets, stick net, UAVs	A
Storm-scale NWP	Fixed observing systems (e.g., NWRT-PAR, S-band radars; see section 4), C-band and X-band radars, mobile soundings, mobile mesonets, stick net, UAVs	A

TABLE 4.1. Core instruments proposed for VORTEX2. Also see Section I.

radar and one X-band radar will have dual polarization.

In the investigation of tornadogenesis and tornado structure (sections 5.1 and 5.2), much finer scales will be observable by the VORTEX2 mobile radar network compared to what was observed in VORTEX1. Dual-X-band (dual-C-band) radars focusing on the mesocyclone (storm) scale (Fig. 3.2) will obtain sector volume scans every 1 min (2–3 min), enabling much better understanding of storm evolution than for VORTEX1 cases. For typical ranges of 7.5 km from the X-band radars to the mesocyclone, the effective beamwidth (for DOWs) will be 125 m (red circle in Fig. 4.1). Furthermore, these radars have short gate lengths (∼30 m) and will employ oversampling both in elevation angle (particularly near the surface) and azimuth angle. In the lowest kilometer, observations at many different levels will be obtained (red squares in Fig. 4.1). This dense sampling is particularly critical owing to the need to resolve divergence (for kinematic estimation of vertical velocity) and vertical shear (for calculation of horizontal vorticity) near the ground. Considering both space and time, *the four-dimensional density of dual-Doppler, mesocyclone-scale observations in VORTEX2 will be 100–1000 times that in VORTEX1.*

Single-Doppler *tornado-scale* observations will be obtained at extremely fine spatial and temporal resolutions. For example, at a range of 2 km, the beamwidth of the UMass W-band radar is only 6 m (Fig. 4.1). In cases when a tornado passes within 1 km of a ground-based mobile radar, the wind field down to approximately 10–25 m AGL can be resolved (e.g., Bluestein et al. 2004; Alexander and Wurman 2005; Wurman et al. 2007c).

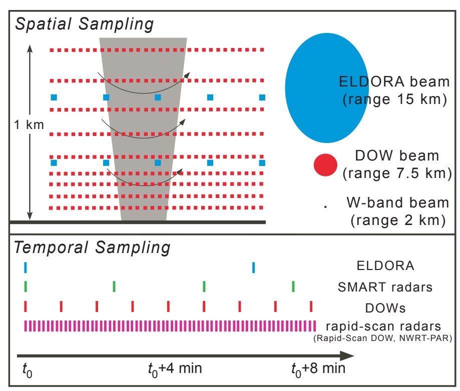

FIG. 4.1. Comparison between spatial and temporal radar sampling in VORTEX1, in which pseudo-dual-Doppler radar observations were obtained by ELDORA, and VORTEX2, in which dual-Doppler observations will be obtained from a network of ground-based C-band (e.g., SMART radars) and X-band (e.g., DOW, Rapid-Scan DOW) mobile radars, and single-Doppler observations will be obtained from a truck-borne W-band radar. Effective beamwidths are shown (upper right) for ranges to the tornado of 15 km, 7.5 km, and 2 km for ELDORA pseudo-dual-Doppler, DOW dual-Doppler, and W-band single-Doppler observations, respectively. Typical radar-sample locations for the ELDORA (blue squares) and DOW (red squares) dual-Doppler data are indicated (upper left) in a vertical cross section that is perpendicular to the baseline. Typical times for consecutive volume scans for each radar type are depicted by the graph at the bottom.

VORTEX2 also will benefit from advances in the temporal resolution of mobile radar data. For example, the Rapid-Scan DOW (Wurman and Randall 2001) simultaneously emits and receives beams at six different elevation angles, thereby reducing the typical time for a sector volume scan by a factor of six, or to 5–10 s. When the VORTEX2 fleet is near the NWRT-PAR in Norman, OK, there will be an opportunity for coordinated, fast-update data collection, even rapid-scan dual-Doppler. Another possible improvement in ground-based mobile radar capabilities, currently under development and planned for testing with the support of a proposal submitted in parallel to this one, is a system that will permit accurate multiple-DOW wind retrievals from data collected while the DOWs are moving and unleveled, thereby significantly reducing the duration of data gaps during redeployments.

VORTEX2 is motivated strongly by the need for the simultaneous collection of thermodynamic and microphysical data (section 5.1) to complement the radar-derived, three-dimensional kinematic fields of supercell thunderstorms, which, as described above, can today be obtained in spatial and temporal resolution far superior to that attainable in VORTEX1. A fleet of 8–12 mobile mesonet vehicles, like those designed for VORTEX1 (Straka et al. 1996), also will be used in VORTEX2 (e.g., Grzych et al. 2007; Hirth et al. 2007). Surface in situ observations will be further augmented by a rapidly deployable network of sensors mounted on tripods having a separation of 1–5 km ("stick net;" http://www.webpages.ttu.edu/rovega), in addition to much more rugged tornado in situ probes. Six mobile sounding units will augment the fixed sounding network. Stereo photogrammetric observations will be obtained by cameras deployed south and west of storms in order to relate radar observations to cloud boundaries and other visual characteristics.

UAVs will sample storm-scale thermodynamic fields in the 100–1000 m layer. The UAVs will be visually and electronically tethered to the mobile mesonet vehicles. UAV technology is developing rapidly and has great potential [e.g., UAVs have been deployed successfully in tropical cyclones (Lin 2006; Rogers et al. 2006); also see http://recuv.colorado.edu]. Admittedly, the use of UAVs for meteorological purposes is still in its infancy. It is for this reason that our proposed use of UAVs in VORTEX2 is fairly conservative (e.g., the UAVs will be tethered to vehicles on the ground).

The dual-polarization mobile radars will enable the retrieval of microphysical characteristics within storms (Straka et al. 2000; Zrnic et al. 2001). Raindrop size distribution parameters can have a significant influence on evaporative cooling rates; the thermodynamic properties of supercell outflow are increasingly believed to be highly relevant in tornadogenesis (section 5.1). Conditions near where tornadogenesis occurs are too severe and too variable to obtain in situ observations of raindrop size distributions. However, polarimetric radar data can be used to retrieve rain rates in addition to parameters such as total number concentration, median drop size, and distribution shape parameter (e.g., Bringi et al. 2002) in order to estimate evaporative cooling rates. Such observations would be very useful to modelers who have found that cool pools in simulated supercells are generally too cold (section 5.1).

The aforementioned instruments are considered to be the highest priority ("core" or "tier 1") instruments for VORTEX2. A number of additional, lower priority ("tier 2") observing systems will be requested as well. For example, dropsondes would be an attractive supplement to the ground-based soundings in order to improve the characterization of the meso-β-scale environment, especially when obvious heterogeneities are present, such as mesoscale boundaries. The installation of particle sensors on at least one UAV and multiple mobile mesonet vehicles also will be pursued in order to provide "ground truth" microphysical measurements necessary to validate dual-polarization radar observations and numerical cloud modeling experiments.

Table 4.1 summarizes the relationships between the core (tier 1) VORTEX2 observing facilities and science issues. Additional details concerning the proposed observing facilities and their prioritization appear in Section I, and more detailed deployment descriptions are described in the EDO. We emphasize that *the critical scientific issues that VORTEX2 is designed to address can be investigated using mainly technologies that already are available and proven.* Even the critical instrument platforms that have not yet been fully demonstrated contain components that individually have demonstrated success (e.g., the navigation systems needed to enable ground-based Doppler radar data collection while moving are available, but their use with mobile radars is still in development), and a parallel proposal is being submitted to test in the field and integrate new technologies that are low-risk and critical for VORTEX2, specifically, simple UAV operation visually and electronically tethered to cars, fully mobile radar data collection, and an integrated situational awareness display.

5. Scientific goals and hypotheses

5.1 Tornadogenesis

Perhaps the most outstanding question pertaining to tornadogenesis is the role of downdrafts in the amplification of near-ground vorticity. Davies-Jones (1982a,b) has argued that a downdraft is *necessary* to obtain large vertical vorticity at the ground in an environment in which vortex lines are initially quasi-horizontal. Tornadoes may arise in the absence of a downdraft in environments containing preexisting vertical vorticity at the surface; such preexisting circulations seem to be a prerequisite for nonsupercell tornadoes (Wilson 1986; Wakimoto and Wilson 1989; Roberts and Wilson 1995; Lee and Wilhelmson 1997a,b, 2000). If a Beltrami model is crudely assumed to represent the flow in a supercell (Davies-Jones and Brooks 1993), then vortex lines are coincident with streamlines and air parcels flowing into the updraft at very low levels do not have significant vertical vorticity until they have ascended a few kilometers. Otherwise, abrupt upward turning of streamlines, strong pressure gradients, and large vertical velocities would be required next to the ground (all are present when tornadoes are in progress, but are not present *prior* to tornadogenesis). Davies-Jones concluded that in a sheared environment with negligible background vertical vorticity, an "in, up, and out" circulation driven by forces primarily aloft would fail to produce vertical vorticity close to the ground. Although Davies-Jones' conclusion depends on eddies being too weak to transport vertical vorticity downward against the flow, numerical simulations have given his arguments much credibility (e.g., Rotunno and Klemp 1985; Walko 1993).

Rear-flank downdrafts (RFDs) have been long surmised to play an important role in tornadogenesis within supercell thunderstorms. Their precise dynamical role in tornadogenesis has remained somewhat elusive, despite a well-documented association between RFDs (and their associated radar-observable "hook echoes") and tornado formation (e.g., Stout and Huff 1953; Ludlam 1963; Fujita 1975; Burgess et al. 1977; Lemon and Doswell 1979). Observations of counter-rotating vorticity couplets straddling the hook echoes of both tornadic and nontornadic supercells (e.g., Ray et al. 1975, 1981; Brandes 1977; 1978, 1981, 1984a; Fujita and Wakimoto 1982; Brandes et al. 1988; Dowell and Bluestein 1997, 2002a,b; Wakimoto and Liu 1998; Wakimoto and Cai 2000; Ziegler et al. 2001) are possible indications that the tilting of horizontal vorticity by large horizontal vertical velocity gradients in the vicinity of RFDs is an important contributor to the generation of near-ground rotation.The potential importance of the RFD in tornadogenesis also is suggested by observations that air parcels entering the tornado or incipient tornado pass through the hook echo and RFD (Brandes 1978; Klemp et al. 1981; Dowell and Bluestein 1997). Visual observations of mesocyclones being occluded by the RFD, as evidenced by the relatively common observations of cloud erosion around much of the updraft base during and just prior to the tornadic stage (e.g., Lemon and Doswell 1979; Rasmussen et al. 1982; Jensen et al. 1983), also may imply that the air entering the tornado comes from the RFD. Although three-dimensional simulations of supercells, until very recently (e.g., Wicker et al. 2002; Romine et al. 2004; Xue 2004), have not had the resolution necessary to resolve tornadogenesis, past supercell simulations have indicated that air parcel trajectories pass through the RFD en route to intensifying near-ground circulations (Davies-Jones and Brooks 1993; Wicker and Wilhelmson 1995; Adlerman et al. 1999). Furthermore, the noteworthy time tendency of increasing positive vertical vorticity for parcels passing through the RFD in the simulation studies is a result of vorticity reorientation and baroclinic generation; however, observations of a lack of surface baroclinity within the RFDs of many tornadic supercells (e.g., Markowski et al. 2002; Finley and Lee 2004) raise questions as to the importance of baroclinic vorticity generation within observed RFDs. *Thermodynamic observations above the ground in VORTEX2, in addition to finer scale (especially in time) kinematic observations in supercells, will be critical in determining the role of the RFD in the modifications of the three-dimensional vorticity field (either by redistribution or generation) that lead to tornadogenesis.*

A clear understanding of the origin and forcing for the RFD also has not yet been achieved. Browning and Ludlam (1962) and Browning and Donaldson (1963) hypothesized that the RFDs in the storms they studied were driven by negative buoyancy (i.e., "thermodynamically forced") due to evaporation. The "thermodynamic forcing" hypothesis was proposed at least partly because of findings by Browning and Ludlam (1962) and Browning and Donaldson (1963) of low equivalent-potential-temperature (θ_e) air, which apparently had midlevel origins, in the wakes of the Wokingham and Geary storms. Later observations of echo erosion in the midlevel and upper-level hydrometeor field on the rear flank of supercells also have contributed to the popularity of this hypothesis (Nelson 1977; Barnes 1978; Lemon et al. 1978; Forbes 1981), as have dual-Doppler observations and thermodynamic retrievals in a few of the supercells sampled by the Doppler radar network in central Oklahoma in the late 1970s (e.g., the well-documented Del City supercell; Brandes 1981, 1984a). Precipitation loading also has been suggested as a potentially important contributor to the initiation of the RFD (Klemp et al. 1981). This viewpoint may find new support in the recent observations of Rasmussen et al. (2004b).

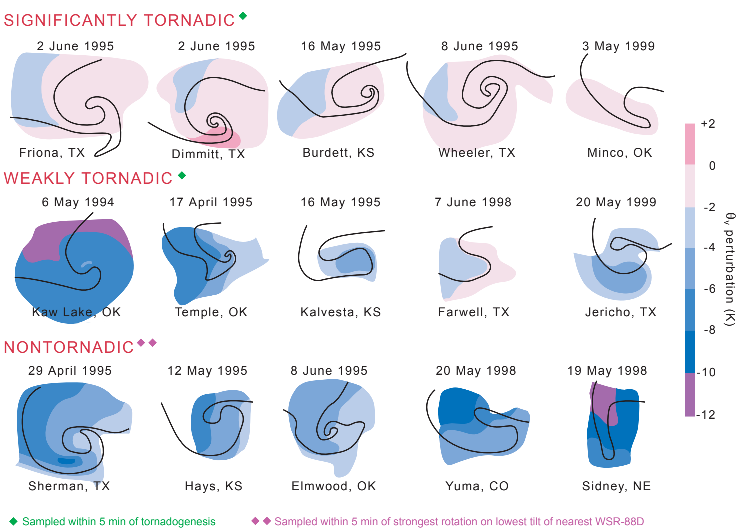

FIG. 5.1. Surface virtual potential temperature perturbations measured by mobile mesonets within the hook echo and RFD regions of supercells during VORTEX1 and in smaller post-VORTEX1 field activities. The black contours outline the 40 dBZ radar echoes of the storms in order to emphasize the hook echoes. Regions left unshaded represent regions that were not sampled by the mobile mesonets. Adapted from Markowski et al. (2002).

Dynamic vertical pressure gradients also have been hypothesized as providing significant contributions to the initiation of the RFD (Bonesteele and Lin 1978; Lemon and Doswell 1979; Brandes 1984a), and in the forcing of the small-scale "occlusion downdraft" (Klemp and Rotunno 1983) that develops near the low-level circulation center, based on both observations (Brandes 1984a,b; Hane and Ray 1985; Brandes et al. 1988) and numerical simulation studies (Klemp and Rotunno 1983; Trapp and Fiedler 1995; Wicker and Wilhelmson 1995; Adlerman et al. 1999). The general consensus regarding the forcing of the occlusion downdraft—that it is driven dynamically by strong low-level rotation and an associated downward-directed pressure gradient force—leaves unanswered the broader questions of how the RFD is forced, as well as whether the RFD is even ultimately the cause of the occlusion downdraft because it somehow promotes the intensification of low-level rotation. Furthermore, the wide range of surface thermodynamic conditions within RFDs observed in VORTEX1 and other recent field campaigns (Markowski et al. 2002; Fig. 5.1) suggests that the forcings for the RFD likely vary across the supercell spectrum, and perhaps within a single supercell as a function of location within the RFD and evolutionary stage of the storm. In fact, tornadogenesis itself, in addition to the intensity and longevity of tornadoes, seems to be sensitive to the thermodynamic characteristics of the near-ground air (which includes RFD air) that enters the developing vortex (Leslie and Smith 1978; Markowski et al. 2002, 2003), with tornadogenesis being inhibited by excessively cold near-ground air. This sensitivity also is consistent with VORTEX1 observations by Trapp (1999) of low-level mesocyclones within tornadic supercells having smaller core radii and being associated with larger vertical vorticity stretching than mesocyclones associated with nontornadic supercells. *Thus, a complete understanding of* *tornadogenesis may require an equally comprehensive understanding of the forcing for the RFD.*

Recent mobile Doppler observations (e.g., Bluestein et al. 2003; Marquis et al. 2006) and high-resolution numerical simulations (e.g., Wicker et al. 2002; Orf and Wilhelmson 2004; Romine et al. 2004; Xue 2004) have identified another curious, possibly important aspect of RFDs and their gust fronts. Small-scale ($\sim$1 km or less) vortices have been observed along many, perhaps most, RFD gust fronts (Fig. 5.2). Such features have not been identified previously owing to inadequate spatial resolution of both the observations and the numerical models used to simulate supercells. One naturally wonders whether these vorticity maxima, which seem to be drawn along the gust front toward the larger-scale circulation center, contribute in any significant way to the mesocyclone or tornado.

Similarly, *preexisting* concentrations of vertical vorticity along boundaries have been implicated in tornadogenesis in several VORTEX1 studies. In the case of the Newcastle tornadic supercell (Wakimoto and Atkins 1996), the preexisting vortex was found on a gust front trailing an ongoing supercell. In another case (Garden City tornadic supercell; Wakimoto et al. 1998) the vortex was on a stationary front and appeared to be associated with the interaction of horizontal convective rolls with the front. Despite the identification of the preexisting vortex in the Newcastle case, Ziegler et al. (2001) demonstrated that the tornadogenesis process was very similar to that observed in other tornadic supercells without documented preexisting vortices. Further, many aspects of the Garden City storm resemble other tornadic supercells documented previously. The role played by preexisting vertical vorticity remains to be studied. For example, one wonders whether the documented vortices evolved into the observed tornadoes because they did not contain particularly large circulation. However, it is quite possible that they contributed circulation to the eventual tornadic vortex, and there may be other roles for preexisting vortices in the chain of dynamical processes that leads to tornado formation.

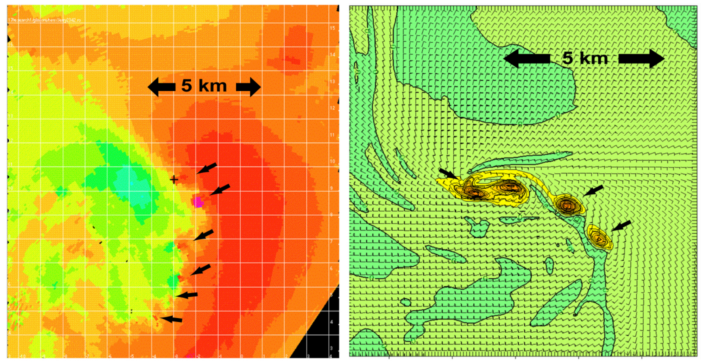

FIG. 5.2. (Left) Radial velocity data obtained from the Doppler On Wheels radar near the Friona, Texas, tornado of 2 June 1995, observed during VORTEX1. Numerous vortices are present along the gust front of the RFD (indicated by arrows). Image courtesy of M. Gilmore and J. Wurman. (Right) Near-surface vertical vorticity in a numerical simulation of a supercell (warm colors indicate positive vorticity maxima), also showing several vorticity maxima along the gust front of the RFD. Image courtesy of B. Lee and C. Finley.

Uncertainties also remain with respect to the forward-flank downdraft (FFD) of supercell thunderstorms. Recognized for some time (Lemon and Doswell 1979), the possible dynamical importance of FFDs was not established until numerical simulations revealed that horizontal vorticity generation within the forward-flank baroclinic zone was critical to the generation of low-level rotation within simulated supercell storms (Klemp and Rotunno 1983; Rotunno and Klemp 1985). Despite the dynamical significance implicated by past modeling studies, observations in FFDs have been relatively scarce. In situ measurements within FFDs have been very limited (most were made in VORTEX1), and attempts to assess baroclinic vorticity generation along the forward-flank baroclinic zone using buoyancy retrievals from multi-Doppler wind syntheses have produced somewhat conflicting results. For example, in analyses of two different supercells, Brandes (1984a) found opposite senses of baroclinic vorticity generation. It is not clear if the buoyancy retrievals simply were not reliable enough for the sort of analysis undertaken, or whether a wide range of FFD characteristics exists. Some recent analyses of in situ observations in FFDs also suggest a wide range of buoyancy gradients within the FFDs of supercells (Shabbott and Markowski 2006), with the implication being that the dynamical importance of baroclinic vorticity generation, suggested by numerical simulations (e.g., Klemp and Rotunno 1983), may not be universal across the spectrum of supercell types. At the very least, it seems safe to conclude that *we still do not have a clear understanding of the how the thermodynamic characteristics of FFDs and their associated dynamical importance vary from storm to storm, nor what specific role FFDs may play in tornadogenesis.*

The instrument platforms in VORTEX2 also will be capable of observing cyclic tornadogenesis. VORTEX1 provided the first detailed observational documentation of the cyclic tornadogenesis process (Dowell and Bluestein 2002a,b). Moreover, recent numerical simulations have explored the conditions that promote cyclic mesocyclogenesis (Adlerman et al. 1999) and tornadogenesis (Adlerman and Droegemeier 2005). Nonetheless, our conceptual model of cyclic tornadogenesis remains to be generalized—and numerical simulations await validation—through the observations of additional cyclic supercells. Cyclic geneses are of considerable importance to forecasters owing to the enhanced danger presented to the public and the opportunity for relatively long warning lead time.

Even though advances in computing power and visualization software now permit the use of 25–50 m grid spacings in three-dimensional numerical simulations of supercells (e.g., Wicker et al. 2002; Orf and Wilhelmson 2004; Romine et al. 2004; Xue 2004) such that even tornadogenesis can be resolved, observations such as those sought in VORTEX2 will be essential for evaluating the realism of the simulations. Processes to which tornadogenesis is likely very sensitive unavoidably must be parameterized in numerical simulations. For example, the thermodynamic fields within thunderstorms are known to be sensitive to the subgrid-scale mixing and microphysics (Gilmore et al. 2004) parameterizations. Numerical simulations using warm rain microphysics have routinely produced cold RFDs (e.g., Klemp and Rotunno 1983; Rotunno and Klemp 1985; Wicker and Wilhelmson 1995; Adlerman et al. 1999), despite numerous observations of RFDs in tornadic supercells having very small temperature deficits at the surface (e.g., Fig. 5.1). This cold bias in the outflow may be at least partly because the exclusion of ice leads to more concentrated downdrafts (the inclusion of ice leads to the distribution of hydrometeors over a larger horizontal region and a reduction of the outflow intensity in close proximity to the updraft; Johnson et al. 1993; Gilmore et al. 2004). VORTEX1 observations by Wakimoto and Cai (2000) that the "...only difference between the Garden City (tornadic) storm and Hays (nontornadic) storm was the more extensive precipitation echoes behind the rear-flank gust front for the Hays storm" are just one example suggesting an important role for precipitation microphysics in tornadogenesis. *Given the likely importance of thermodynamics in supercell processes, including tornadogenesis, and the sensitivity of thermodynamics, among other storm characteristics, to what are often simplistic and/or incomplete model parameterizations, it is critical that high-resolution thermodynamic, microphysical, and kinematic observations be made in VORTEX2 to complement the ongoing advances in the simulations.*

Some specific questions pertaining to tornadogenesis that VORTEX2 is designed to address appear below. Detailed descriptions of how VORTEX2 (phase B) instrumentation will be used to investigate each question appear in the EDO.

- What processes lead to the rapid intensification of low-level vorticity that results in tornadogenesis? How are these processes affected by the thermodynamic fields and microphysical characteristics of the parent storm? Does tornadogenesis require a balance between low-level buoyancy and angular momentum in the incipient vortex? What is the role of vortices along the rear-flank gust front in tornado formation?
- Is vorticity generation during the vortex-maintenance stage different than during the genesis? What processes are associated with tornado strengthening, weakening, and/or dissipation? Are the answers different in long-lived versus short-lived, and strong versus weak tornadoes?
- What is the orientation and magnitude of baroclinity above the surface in tornadic and nontornadic supercells?
- How is the vortex line distribution within supercells related to downdrafts (particularly RFDs)? Does the relationship vary from storm to storm? Is tornado likelihood a function of this relationship?
- What are the dominant forcings for RFDs, as a function of location within the RFD, stage in storm evolution, and supercell type (e.g., tornadic vs. nontornadic, low-precipitation vs. high-precipitation)?

5.2 Near-ground wind field in tornadoes

Although better forecasting of tornadoes through an improved understanding of tornadogenesis is likely to result in decreased mortality, homes and other structures still will be impacted by the damaging effects of strong tornadoes. A single tornado event can cause many millions of dollars of property damage. The cost of extreme events such as the 3 May 1999 Oklahoma-Kansas tornado outbreak can exceed $1 billion. In some cases (e.g., 3 May 1999; Speheger et al. 2002), most of the damage is to non-engineered structures such as one- and two-story wood-frame houses (Marshall 2002). Some recent events, however, also highlight the risk even to engineered structures. For example, the Cash America International Building was heavily damaged by the tornado that struck Fort Worth on 28 March 2000. The Davis-Besse Nuclear Station in Ohio was struck by a tornado on 24 June 1998. A better understanding of the low-level winds in tornadoes and how they affect structures will permit more intelligent building design and assessment of risk.

Long-standing conceptual models (e.g., Lewellen 1976; Davies-Jones 1986; Davies-Jones et al. 2001) typically idealize a tornado as a vortex symmetric about a vertical axis. This axisymmetric vortex can be subdivided into five interacting regions (Fig. 5.3) based on the salient features of the swirling or tangential, radial, and vertical flow and the governing vortex dynamics. The depth of the tornado's boundary layer, intensity of the rotating core, and effective depth and intensity of the corner region are all mutually dependent on the swirl ratio, i.e., the ratio of the amount of swirling flow in the outer region (Ia) to the amount of suction or vertical flow aloft (IV). For example, theory and computer/laboratory models suggest that the most intense tornadoes should occur at some critical swirl ratio whereby vortex breakdown occurs in the corner region, very near the ground.

Laboratory models (e.g., Ward 1972; Davies-Jones 1973, 1976; Church et al. 1979; Snow and Lund 1989; Church and Snow 1993; LaDue 1993) and computer models (e.g., Rotunno 1977, 1982, 1984; Smith and Leslie 1978, 1979; Leslie and Smith 1978; Lewellen and Sheng 1980; Gall 1982, 1983, 1985; Walko and Gall 1984, 1986; Fiedler 1993; Fiedler and Rotunno 1986; Howells et al. 1988; Lewellen et al. 1997, 2000, 2004) of tornadoes have improved our understanding of complex tornado dynamics in a simplified environment. The recent large-eddy simulation (LES) results of Lewellen et al. (2004) (e.g., Fig. 5.4) are arguably the most realistic looking yet. One inherent problem with all laboratory and numerical simulations of tornadoes, however, is the inherent decoupling of the simulated tornado from the forcing by the parent storm (Fiedler 1994; Davies-Jones et al. 2001). Another regards the inflow boundary conditions on the radial and tangential velocities, which are not constrained by or explicitly based on observations from tornadic storms. Furthermore, the effects of debris loading only recently have been addressed (Lewellen et al. 2004; Dowell et al. 2005).

In spite of the increasing realism, computer, laboratory, and conceptual models of tornado vortices are largely unsubstantiated by reliable quantitative observations of actual, non-laboratory generated tornadoes, with isolated and mainly recent exceptions (Wurman and Gill 2000; Burgess et al. 2002; Wurman 2002; Lee and Wurman 2003; Bluestein et al. 2004; Alexander and Wurman 2005; Wurman and Alexander 2005; Wurman et al. 2007c). In order to have confidence in tornado conceptual models and theories developed from laboratory and numerical experiments, especially given the unavoidable questions raised above regarding model design, quantitative observations are desperately needed in a variety of actual tornadoes having a variety of observed structures. *VORTEX2 is motivated by the belief that we cannot mitigate tornado damage without a concurrent, equally strong emphasis on understanding the tornado itself.*

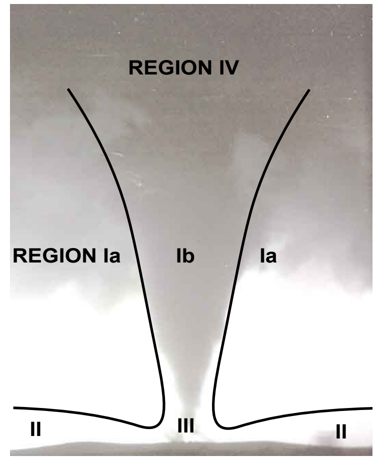

FIG. 5.3. Schematic representation of the flow regions in an tornado, adapted from Lewellen (1976).

Model simulations with a wind engineering focus such as those conducted by Fouts et al. (2003), Sarkar et al. (2003) and Selvam and Millett (2003) have sought to modify traditional, straight-line wind engineering studies, including those based on wind tunnel experimentation. Selvam and Millett have developed a computer model prototype which introduces a cuboid building into an LES. Preliminary results suggest that changing winds produce more damage than static wind conditions. McDonald (2001), Marshall (2002), and Marshall (2004) have suggested that the wind speed-damage relationships implied in the Fujita scale overestimate the peak winds in tornadoes. They have proposed changing the peak wind speed versus damage relationship through a major modification to the Fujita scale (Marshall 2004). Recently however, based on comparisons of direct radar observations and observed damage, Wurman and Alexander (2005) proposed that changing wind speeds and directions, and/or the integrated effect of wind-speed moments, are correlated with damage as well as peak-wind-gust Fujita-scale-type metrics. Except in a single case analyzed by Wurman and Alexander (2005), there exists no extensive field validation of measured winds compared to damage. Furthermore, the basic underlying assumption of the wind speed relationships associated with the Fujita scale and Enhanced Fujita Scale (Marshall 2004), namely that damage is a function of the peak wind gust and not wind duration, wind direction, etc., is completely untested in actual tornadoes except for the single case reported in Wurman and Alexander (2005). *Unless the actual nature of the tornado low-level wind threat is quantified, building codes cannot be intelligently designed to mitigate it.*

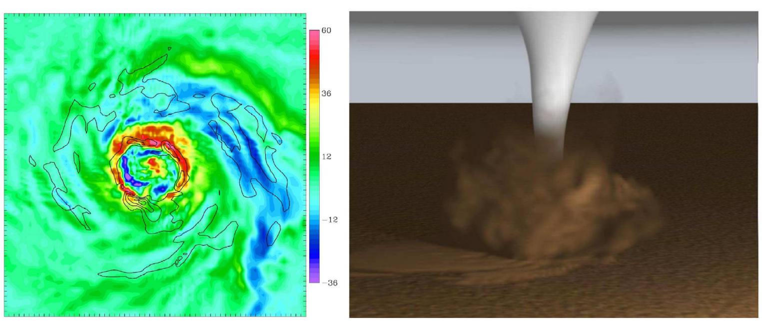

FIG. 5.4. (Left) Instantaneous vertical wind velocity (color) and debris loading (contour lines with 0.25 interval) on a 300 × 300 m horizontal cross section 50 m above the ground through a simulated tornado. From Lewellen et al. (2004). (Right) Visual appearance of the debris and funnel cloud from a simulated medium swirl F3–F4 tornado translating from left to right at 15 m s^{-1}, ingesting 1 mm diameter "sand" from the surface.

Although observational studies of the low-level and core-flow regions (Ib, II, and III in Fig. 5.3) are challenging, observations by radar and in situ instruments have been obtained occasionally. The most frequent observations have been by mobile radars at close range to tornadoes (e.g., Wurman et al. 1996, 1997; Wurman and Gill 2000; Bluestein and Pazmany 2000; Wurman 2002; Lee and Wurman 2003; Bluestein et al. 2004; Wurman and Alexander 2005; Alexander and Wurman 2005), and occasional in situ observations have been reported as well (Winn et al. 1999; Lee et al. 2004; Wurman and Samaras 2004). In a limited number of cases, some basic predictions of the conceptual and computional models have been confirmed. These include the quasi-linear relationship between wind speed and distance to the axis of rotation in the core flow region. Subvortices within large tornadoes also have been mapped on occasion (Wurman 2002), as have the vertical distribution of wind speeds (Wurman and Gill 2000; Alexander and Wurman 2005; Wurman et al. 2007c), with suggestions of convergent inflow at the lowest levels being observed (Alexander and Wurman 2005; Wurman et al. 2007c). The successful resolution of verifiably consistent kinematic and dynamic structures of some recent tornadoes using single Doppler velocity data and the ground-based velocity track display (GBVTD) technique (e.g., Bluestein et al. 2002; Lee and Wurman 2003; Tanamachi et al. 2004) provides confidence in our ability to examine tornado dynamics on a variety of strengths and sizes of tornadoes using data from already demonstrated technology. It also has been demonstrated that much can be learned from mapping high-resolution radar observations to damage (e.g., the 31 May

1998 Spencer, South Dakota, tornado; Wurman and Alexander 2005). Vertical (RHI) cross-sections obtained with X-band and W-band radars offer the promise to resolve finescale vertical structures in tornadoes, particularly in the corner flow region (Bluestein et al. 2004; Wurman and Samaras 2004; Alexander and Wurman 2005).

Specific questions pertaining to the near-ground wind field in proximity to tornadoes are listed below. A detailed description of how the VORTEX2 (phase B) instrumentation will be used to investigate each of the questions appears in the EDO.

- Is the standard conceptual model of tornado structure correct? What is the depth of the tornado inflow layer? Does the structure of the tornado depend as predicted on the swirl ratio? What dynamical and thermodynamical structures affect the swirl ratio? Does the behavior of any multiple vortices conform to predictions?
- What is the relationship between observed winds and structural damage?

5.3 Relationships between supercell storms and their environments

Interactions of multiple storms

A great deal has been learned about vortex formation in supercells by analyzing numerical simulations of *isolated* supercells (e.g., Rotunno and Klemp 1985). By imposing idealized initial conditions (that is, a single warm bubble in an otherwise homogeneous environment), the interpretation of storm evolution is simplified, enabling one to more easily diagnose storm processes that are related to tornadogenesis. However, real cases are typically more complex (e.g., Ziegler et al. 2001). Often, supercells develop from multiple smaller cells (Bluestein and Parker 1993), with the mature supercell continuing to interact with other cells during its lifetime. Rapid changes in supercell strength can occur after merger with another cell (e.g., Lemon 1976; Lee et al. 2000; Bluestein and Gaddy 2001). Furthermore, there seems to be a relationship between cell mergers and tornadogenesis. More often than can be explained by mere coincidence, tornadogenesis in mature supercells often occurs immediately after a cell merger (e.g., Lee et al. 2000; Houston and Wilhelmson 2002b; Dowell and Bluestein 2002a,b; Magsig and Dowell 2004). Wurman et al. (2007a) hypothesized that tornadoes resulting from cell mergers might tend to be weak and short-lived (as they observed) because the merging process, though it might initially enhance surface convergence and therefore amplify vorticity, also would tend to result in an extensive rain-cooled air mass in precisely the region where vorticity is being amplified.

From previous observations, it has been difficult to determine why some cell mergers seem to promote tornadogenesis. For example, Dowell and Bluestein (2002b) noted in their case study that although the formation of the first tornado occurred immediately after a small precipitation core of a dying storm merged into the precipitation core of the main storm, pseudo-dual-Doppler wind syntheses failed to reveal why the dying storm would have promoted tornadogenesis. In other cases, cell mergers appear to be destructive instead, promoting dissipation (e.g., the hailstorm documented by Ray et al. 1981) or temporary weakening (Lindsey and Bunkers 2004) of the main supercell. Apparently, minor differences in how cells interact can lead to major differences in future storm evolution. Detailed observations are needed that reveal how severe convective storms interact with each other. Particularly, reasons why some interactions are constructive and others are destructive must be identified if operational tornado forecasting is to be improved. It is hypothesized that the following factors are important: dynamical interactions of multiple updrafts and mesocyclones, microphysical interactions of multiple precipitation cores, and low-level outflows (Westcott 1984; Turpeinen 1982).

The high-resolution multi-storm observations to be collected during phase A of VORTEX2 will provide an unprecedented opportunity to understand how cell interactions affect supercells and tornadogenesis. Since there has been much recent interest in studying cell interactions that occur in numerical cloud simulations (Richardson 1999; Bluestein and Weisman 2000; Jewett et al. 2002), the observations collected during VORTEX2 will complement these numerical studies. In fact, recent advances in storm-scale data assimilation provide an opportunity to study storm interaction by directly combining the observations and cloud models. During VORTEX2, interactions between the target storm and other storms are expected on occasion, so the observing strategy will be designed to document this process when it occurs (as described in the EDO). Answers are sought to the following questions:

- What are the dynamical, thermodynamic, and microphysical natures of interactions between supercells and other supercells? Between supercells and ordinary cells?
- When tornadogenesis occurs during a cell merger, does low-level outflow from the neighbor cell increase low-level convergence, low-level horizontal vorticity, or both, in the main cell?
- Do relatively warm (cool) outflow from other cells promote tornadogenesis (tornado dissipation)?
- During a cell merger, do microphysical and thermodynamic interactions aloft lead to downdraft formation and tornadogenesis?
- Can these scenarios be identified in an operational setting?

Mesoscale environmental variability

Previous studies have identified significant environmental variability on multiple scales in the environments of convective storms (Maddox et al. 1980; Marwitz and Burgess 1994; Brooks et al. 1994, 1996; Weckwerth et al. 1996; Markowski et al. 1998a; Rasmussen et al. 2000; Markowski and Richardson 2004). These studies make it clear that the environment of a convective storm cannot be represented by a single sounding and highlight difficulties in relating observed storm behavior to predictions based on numerical parameter-space studies, which typically employ idealized, homogeneous environments (Brooks et al. 1994; Weisman et al. 1998; Richardson 1999).

In VORTEX2, the interaction between supercells and mesoscale surface boundaries (e.g., Markowski et al. 1998c; Atkins et al. 1999; Houston and Wilhelmson 2002) will be investigated in more detail than has been possible previously. The 2 June 1995 case during VORTEX1 (Fig. 5.5; Rasmussen et al. 2000; Gilmore and Wicker 2002) featured numerous convective storms on both sides of a remnant outflow boundary that had been produced by convection many hours earlier. Among approximately 20 long-lived storms, the only storms that produced tornadoes were those that passed from the warm side of the boundary to the cool side and those that developed and remained on the cool side. On the other hand, in many other cases, storms weaken after crossing boundaries, suggesting that the evolution of storms that cross boundaries could be quite sensitive to both the characteristics of the boundary and the state of the storm when it reaches the boundary.

The availability of new instruments provides the opportunity to study the interaction between storms and boundaries in great detail during phase A of VORTEX2. At least a few interactions between potentially tornadic storms and boundaries can be expected to occur in the domain during the field program. VORTEX2 aims to answer the following questions about storms interacting with boundaries:

- What kinematic, thermodynamic, and microphysical changes occur in storms as they cross low-level boundaries?
- Which types of boundaries (in terms of their thermodynamic and kinematic characteristics) are most apt to lead to storm enhancement during a storm-boundary interaction?
- As a mature storm encounters increasing environmental convective inhibition (e.g., on the cool side of the boundary), how are the low-level updraft and mesocyclone affected?

A second source of environmental variability to be studied during VORTEX2 is associated with the shadows of anvil canopies. Markowski et al. (1998b) observed surface temperature differences of up to 5°C over distances of ∼20 km between the sunny environment and the anvil shade of supercells, and hypothesized that in some cases, these baroclinic zones could be significant sources of the low-level horizontal vorticity that interacts with the updraft. An important but unresolved issue is whether a baroclinic zone associated with the anvil shadow is deep enough to produce a significant layer of horizontal vorticity. Another unresolved issue is whether there is a feedback between the storm and its environment through changes in boundary-layer eddies. As the shade of the anvil passes over the surface and the heat flux from the surface decreases, boundary-layer eddies could weaken and/or change character. Interaction between supercells and boundary-layer eddies could be significant but has not been studied in great detail (Crook and Weisman 1998). A few of the motivating questions include

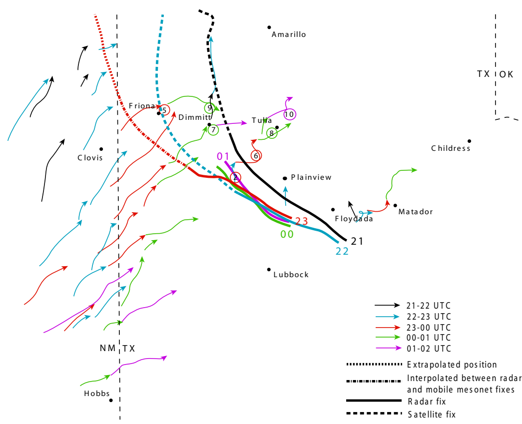

FIG. 5.5. Echo centroid tracks for five 1-h periods on 2 June 1995, depicted with the various line types shown in the legend. Thick lines represent outflow boundary positions according to the symbols in the legend, and apply to the start of the 1-h periods. Numbers in circles indicate tornado reports. From Rasmussen et al. (2000).

- How deep and strong are the baroclinic zones associated with daytime anvil shadows? What are the characteristics (magnitude and depth) of the low-level horizontal vorticity produced by these baroclinic zones?
- What differences develop between the boundary-layer eddies in the shade and those in the sunny environment? What are the natures of any boundary-layer circulations that interact with the main updraft?

5.4 Storm-scale numerical weather prediction

Various real-time experiments during the last decade have demonstrated that explicit prediction of convective storms (Lilly 1990) is becoming computationally feasible (e.g., Droegemeier et al. 1996; Xue et al. 1996; Wicker et al. 1997; Sun and Crook 2001; Crook and Sun 2002; Done et al. 2004; Weisman et al. 2007). Initial storm-scale NWP attempts required restricted domains, coarse resolution, and/or simplified initializations, but as computational power continues to increase each year, more and more sophisticated numerical weather prediction techniques are possible. In 2005, the

Center for Analysis and Prediction of Storms (CAPS) produced a daily convective storm forecast covering much of the continental U.S. with a 2-km horizontal grid spacing. By 2009, we anticipate having ensembles of forecasts available at such resolutions. VORTEX2 will include a real-time prediction component led by the University of Oklahoma (particularly CAPS), NSSL, and the National Center for Atmospheric Research. Daily 0–36 hr ensemble forecasts that explicitly predict convective storms and hourly 0–24 hr mesoscale ensemble forecasts that are initialized with the latest observations will aid in planning and refining each day's mission. Furthermore, qualitative and quantitative assessment of these forecasts will be provided by researchers and forecasters through the annual NSSL-SPC spring program (Kain et al. 2006).

Although VORTEX2 will push the real-time limits of explicit prediction of convective storms, the VORTEX2 storm-scale NWP effort after the field phase should provide the greatest contribution to advancing understanding and prediction capability. This NWP research will take advantage of the fixed observing network augmented with mobile platforms (Fig. 3.1). The datasets that are collected will serve as a testbed for storm-scale prediction experiments. That is, these data will be assimilated into numerical cloud and mesoscale models, forecasts will be produced, and the field data will be used for model verification.

A number of techniques have been developed for assimilating radar and other observations into numerical models, including repeated model insertions of fields obtained by static retrieval methods (e.g., Ziegler 1985; Weygandt et al. 2002), 3D variational (3DVar) methods (Hu et al. 2006), 4D variational (4DVar) methods (e.g., Sun and Crook 1997; Sun 2005; Fig. 5.6), and ensemble Kalman filter (EnKF) methods (Snyder and Zhang 2003; Dowell et al. 2004; Tong and Xue 2005). With these methods, features such as the main updraft and mesocyclone of a supercell can be retrieved from limited observations (e.g., Doppler measurements from only one radar). In addition, model forecasts initialized with these analyses have shown some skill at maintaining and evolving storms (e.g., Fig. 5.6).

A problem common to all storm-scale NWP experiments is verifying the analyzed and predicted fields (Dowell et al. 2004). Independent storm-scale data (i.e., data other those that were assimilated) are typically not available for verification. Furthermore, since Doppler velocity and reflectivity observations are usually the only storm-scale observations available, the analyses and predictions of important variables such as temperature, pressure, water vapor, cloud water, and hydrometeor species and concentration cannot be evaluated. This lack of information makes it difficult to determine the nature of poor forecasts. Parameterizations of precipitation microphysics, surface fluxes, and boundary-layer processes are often considered significant sources of forecast uncertainty (e.g., Gilmore et al. 2004), but operational data provide only a few clues about problems with these parameterizations.

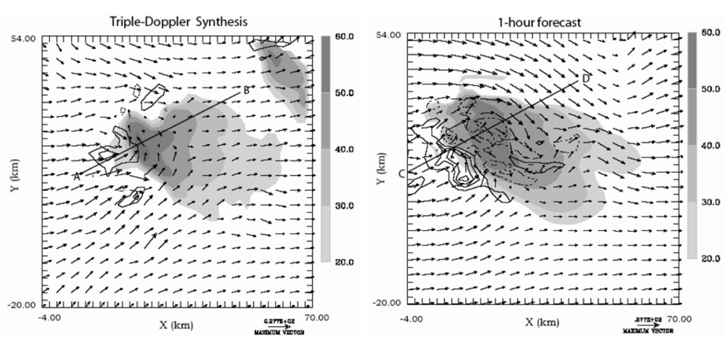

FIG. 5.6. Observed (left) and forecast (right) reflectivity (shading at increments of 10 dBZ), vertical velocity (contoured every 2.5 m s^{-1}), and horizontal winds (vectors) at 0.75 km AGL in a supercell near Bird City, KS, on 29 June 2000. The observed winds (left) were retrieved with a triple-Doppler synthesis method. The forecast (right) was produced by using a 4DVar method to assimilate single-Doppler radar observations into a cloud model and then integrating the model 1 h. From Sun (2005).

VORTEX2 datasets will provide unique opportunities to refine storm-scale NWP by assessing errors in storm-scale analyses and forecasts. The observational strategy proposed in phase A (Fig. 3.1) will allow multi-scale and multi-variable aspects of analyses and forecasts to be verified. VORTEX2 will emphasize collecting measurements that are not routinely available: high-resolution Doppler measurements obtained from multiple angles; storm-scale thermodynamic measurements obtained with in situ probes at the surface, soundings, and perhaps UAVs; and microphysical measurements obtained with disdrometers and inferred from polarimetric radar. We will particularly emphasize data collection in cold pools and baroclinic zones associated with rain-cooled air and sun-shade constrasts because these features greatly affect storm evolution but seem difficult to predict accurately with current modeling techniques.

As suggested by recent real-time prediction experiments (Weisman et al. 2007), meso- and larger-scale errors also contribute significantly to poor storm-scale forecasts. Some VORTEX2 research will aim to improve analyses and forecast on these larger scales. Numerous environmental soundings will be obtained in/near Oklahoma during phase A data collection (Fig. 3.1). The impact on storm-scale forecasts of assimilating these and other data (Oklahoma Mesonet data, wind profiler data, special 1800 UTC NWS soundings, etc.) into nested mesoscale and storm-scale models will be examined.

Targeting supercell storms during the field program is consistent with desires to improve storm-scale NWP because (i) supercells, relative to other types of cells/systems, produce a disproportionately large amount of the severe weather that must be predicted; and (ii) the isolated nature of supercells makes them more easily observable (i.e., it is more feasible to collect enough observations to verify model analyses and forecasts of these storms) than larger, more-complicated convective systems. In addition to being necessary for initializing numerical models, the methods for storm-scale and mesoscale data assimilation will also be useful analysis tools to support other VORTEX2 foci. For example, analyses obtained through assimilation of multi-sensor data will be useful for studying RFD formation, tornadogenesis, multi-storm interactions, storms interacting with boundaries, etc.

VORTEX2 storm-scale NWP research will attempt to answer the following questions:

- What mix of observations, numerical models, and data-assimilation methods is required to produce accurate analyses and forecasts of (i) updrafts and mesocyclones, (ii) cold pools, and (iii) hydrometeor species and number concentration?
- Given multi-scale observations and state-of-the-art modeling and data-assimilation methods, what is the practical predictability limit of supercell mesocyclones? Of supercell tornadoes?

6. Broader impacts of VORTEX2

As discussed in section 2, the new knowledge produced by VORTEX2 is expected to lead to further improvements in tornado warning skill. Furthermore, it is believed that storm-scale NWP must play a prominent role in the initiative to improve short-term forecasts and warnings of severe weather. The multi-sensor and multi-scale VORTEX2 datasets will serve as a testbed for numerical storm-scale prediction experiments.

VORTEX2 will better our understanding of the relationships between tornadoes, their parent convection, and the larger-scale environment. Better insight into these relationships is essential if reliable long-term predictions are to be made of changes in the frequency and geographical distribution of tornadoes due to changes in the characteristics of thunderstorm environments owing to climate change. Furthermore, quantification of the actual temporal and spatial distribution of winds impacting structures will enable better engineering standards to be developed.

Finally, it will be difficult to accomplish the research goals of VORTEX2 without a considerable level of student participation. In VORTEX1 and in the recent International H_2O Project (IHOP), data collection efforts heavily relied upon both graduate and undergraduate students [the latter by way of Research Experiences for Undergraduates (REU) programs], with students demonstrating proficiency in operating observing systems such as mobile mesonets, radars, and soundings. It is anticipated that VORTEX2 will involve a similar level of student participation, with close oversight by experienced scientists and field coordinators (see the EDO for additional details). Furthermore, our need for student support in the successful pursuit of our research objectives allows us to quite naturally combine the research objectives with a unique educational component by way of a “mobile” scientific seminar series. VORTEX2 PIs will present seminars (approximately 1 h in length, focusing on current research) to audiences largely composed of students on days when data collection is not attempted. In addition, group discussions of recent VORTEX2 IOPs are planned. Supercell outbreaks are typically episodic, so we anticipate multi-day down periods between outbreaks when crews will remain in the same location in the field. The seminars and IOP discussions will occur during these down periods.

7. Results from prior NSF support

Josh Wurman. ATM-9616417 (“Observation and Analysis of the Structure of Tornadoes by Means of High Resolution Data from Mobile Doppler Radars and Photogrammetry”), ATM-9703032 (“CAREER: Bistatic and Multiple-Dopppler Analysis”), and ATM-0437512 (“Collaborative Research: Study of the Genesis, Evolution, Structure, and Dynamic Climatology of Tornadoes and Their Environments”). These projects both utilized radar data from the DOW to investigate the structure of tornadoes. High-resolution radar measurements from the DOW radars permitted the characterization of the three-dimensional wind field of tornadoes for the first time, including central downdrafts, vortex breakdown, complex velocity structures, multiple vortex behavior, and vertical distribution of winds. Detailed comparisons of observed winds and resultant damage in a tornado also were made. Comparisons of Dual-Doppler-derived, three-dimensional wind fields in nontornadic and tornadic supercells are in progress. (See publication list in PI biography.)

Erik Rasmussen. ATM-9617318 (“The Concentration of Vorticity at the Ground by Precipitation Processes in Supercells and Other Severe Thunderstorms”), ATM-0003869 (“Concentrating Vorticity Near the Ground: An Investigation of the Interaction of Precipitation Processes and Flow Dynamics in Supercells and Other Severe Thunderstorm Types”), and ATM-0338661 (“Collaborative Research: Concentrating Vorticity Near the Ground: Investigation of Supercell Rear-Flank Precipitation, Vorticity Generation, and Transport Processes”). Mobile mesonet, photographic, and radar documentation were used to analyze the genesis of the Dimmitt, TX, tornado, revealing a descending reflectivity maximum associated with the presence of a counter-rotating vortex pair. An arch-like pattern of vortex lines near the ground was observed, indicative of baroclinic generation of rings of vortex lines about the RFD. An observational study of the Newcastle, TX, tornado was completed, as well as a study of the electrification and updraft characteristics of the entire family of supercells that was observed by VORTEX1 on 2 June 1995. (See publication list in PI biography.)