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VORTEX2: The Verification of the Origins of Rotation in Tornadoes Experiment

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1. Introduction

This paper describes the second Verification of the Origins of Rotation in Tornadoes Experiment, VORTEX2, the field phases of which occurred in 2009 and 2010. The VORTEX2 experiment is designed to explore (a) the mechanisms of tornadogenesis, maintenance, and demise, (b) the wind field near the ground in tornadoes, (c) the relationship between tornadoes and their parent thunderstorms and the relationship among tornadoes, tornadic storms and the larger scale environment, and (d) how to improve numerical weather prediction and forecasting of supercell thunderstorms and tornadoes. VORTEX2 was by far the largest and most ambitious observational and modeling study of tornadoes and tornadic storms ever undertaken. It employed fourteen mobile mesonet instrumented vehicles, ten ground based mobile radars, several of which were dual-polarization and two of which were phased-array rapid-scan, five mobile balloon sounding systems, thirty-eight deployable in situ observational weather stations, an unmanned aerial system, video and photogrammetric teams, damage survey teams, deployable laser disdrometers, and other experimental instrumentation as well as extensive modeling studies of tornadic storms. Participants were drawn from more than 15 universities and laboratories, and at least five nations, including the United Kingdom, Germany, and The Netherlands. Over 80 students participated in field activities. The VORTEX2 field phases spanned two years in order to increase the probability of intercepting significant tornadoes, which are uncommon. VORTEX2 made special efforts to operate near a unique, extensive, and diverse network of stationary instrumentation in Oklahoma including a phased array radar, an array of small stationary radars, a prototype dual-polarization operational radar, and a statewide mesonet. Additionally, the project made special efforts to operate in regions where unmanned aerial system flights were permitted. Approximately three dozen supercells were observed with unprecedented detail and diversity. Preliminary data and analyses are shown.

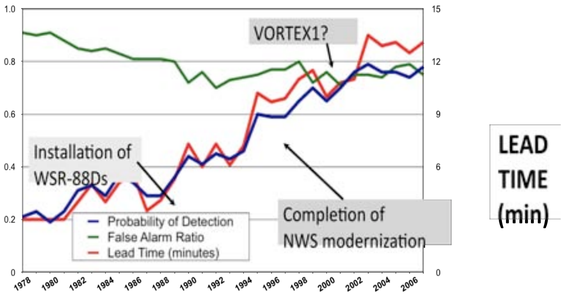


Figure 1. Probability of Detection (POD), False Alarm Rate (FAR), and Average Lead Time of tornado warnings in the United States. Improvements occurred at the time of the installation of the WSR-88D network and after the National Weather Service Modernization, and possibly after improvements in knowledge provided by VORTEX1.

2. Motivation

The VORTEX2 project was conceived to better understand and to document the processes underlying tornadogenesis, intensification, maintenance, and demise and identify properties of the local environment that are influential in the tornado life cycle. As previous advances in observational technology and in theoretical understanding may have been linked to recent improvements in tornado forecasts (Fig. 1), understanding the aforementioned processes was thought to be critical to efforts focused on improving the accuracy, lead time, and false alarm rates of tornado warnings. Understanding the often subtle, and poorly understood and observed, differences among non-tornadic supercells, weakly-tornadic supercells and violently-tornadic supercells, was felt critical for further improvement to forecasts.

Additional foci of VORTEX2, believed to be important to forecast skill, were how storms interact with other storms and their environment and how these interactions affect tornadogenesis, maintenance and demise. Lastly, as many of the details concerning tornado structure, such as the vertical distribution of winds and the intensity and variability of winds near the surface, are not well understood, detailed documentation of tornado structure and its relationship to damage were sought

3. Major outstanding questions in tornado science

3.1 Tornadogenesis

The most pressing problems in tornado science are centered on predicting the occurrence of significant tornadoes. Put simply: 'When/where will significant tornadoes occur? How can we better forecast them?' Identifying storms that produce significant tornadoes is critical because most fatalities and catastrophic damage are associated with the small fraction of tornadoes that exhibit the most intense wind speeds and the even smaller fraction that impact densely populated areas.

While most significant tornadoes are pendant from supercell thunderstorms, most supercell thunderstorms do not produce tornadoes. Typically, if a tornado does occur, it only occurs during a small portion of the lifetime of the supercell. Finally, most tornadic supercell thunderstorms, even when producing tornadoes, do not produce significant tornadoes (tornadoes containing the most intense winds that have the most potential to cause substantial damage to structures and loss of life).

The basic mechanisms through which supercell thunderstorms acquire rotation are believed to be well understood; namely supercells begin to rotate as environmental streamwise horizontal vorticity is tilted towards the vertical, then stretched in updrafts. Observations from VORTEX1 and from subsequent field projects (e.g., ROTATE) revealed that the existence of rotation, even in the low levels, while perhaps necessary, is not sufficient for tornadogenesis. Furthermore, tornadic and non-tornadic supercells appear to be morphologically similar, at least in their general appearance and structure (Fig. 2).

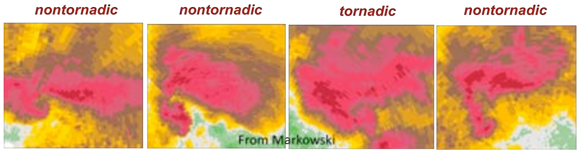


Figure 2. Reflectivity fields in three non-tornadic and one tornadic supercell. Subjectively, all four storms appear possibly tornadic, but only one produced a tornado.

The basic mechanisms for the generation and/or intensification of vorticity very near the surface also are believed to be at least partially understood. As tilting of primarily horizontal vorticity (in the absence of pre-existing near-surface vertical vorticity) by an updraft only can only produce intense vertical vorticity away from the ground, a significant role for downdrafts in instigating supercellular tornadogenesis has long been suspected (Fig. 3). For decades researchers have argued that a downdraft is a necessary condition for intense vertical vorticity generation immediately adjacent to the ground.

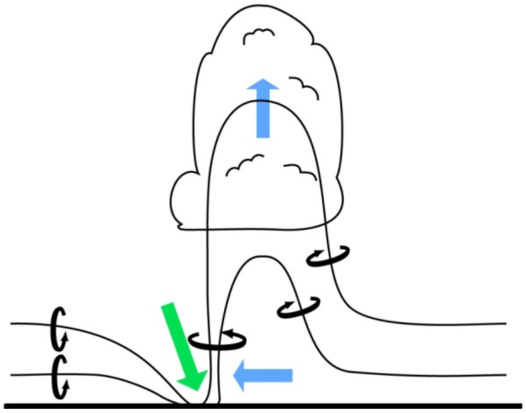


Figure 3. Schematic illustration demonstrating how a downdraft can contribute to intensification of near surface rotation.

VORTEX1 and subsequent observational experiments have reinforced this hypothesis.

Downdrafts have long been observed in the rear flanks of both tornadic and non-tornadic supercells. Trajectory analyses and numerical simulations of tornadic supercells have indicated that at least some of the air entering tornadoes first passes through the rear-flank downdraft (RFD).

Despite ample theoretical, computational, and observational evidence of the role of downdrafts in tornadogenesis, critical details remain uncertain. RFDs either form through microphysical processes and/or dynamical processes. Which of these mechanisms is responsible or dominant likely has an impact on the thermodynamic structure of the RFD, and likely plays a strong role in any potential tornadogenesis. Baroclinic forcing of RFDs was proposed long ago based on observations of low equivalent potential air at the surface in the wakes of some thunderstorms, reinforced by later observations of radar echo erosion (hydrometeor evaporation) in the mid- and upper levels in the rear flanks of supercells. Evaporation of precipitation resulting in negative buoyancy and, consequently, downward accelerations is the proposed mechanism for RFD formation. The melting of ice-phase precipitation also may contribute to the negative buoyancy. Downward-directed dynamic vertical pressure gradients also may accelerate air downwards in the RFD. Additionally, this mechanism has been suggested to be important in the potentially related, but smaller scale, occlusion downdrafts that have been observed and simulated near low-level circulation centers. Finally, precipitation loading has been proposed as a cause of downward acceleration in the RFD. Observations taken in RFDs as they impact the surface suggest that different combinations of the above mechanisms may be important in different supercells, at different locations within individual RFDs, and at different times in the same supercell. High resolution dual-Doppler observations of tornadic supercells using DOW data from ROTATE have revealed multiple gust fronts in some storms, and suggest that some of these mechanisms may be transient and that RFD air reaching the ground nearly contemporaneously from the same supercell may reach the ground with different thermodynamic properties. Multiple gust fronts also have been observed by ground-based mobile mesonets.

3.2 Low level winds in tornadoes

The violence, transience, and infrequency of tornadoes, particularly strong to violent tornadoes, greatly complicate the study of the structure and evolution of the tornado vortex.

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), most of the damage is to non-engineered structures such as one- and two-story wood-frame houses. Some recent events, however, also highlight the risk to engineered structures. For example, the Cash America International Building was heavily damaged by the tornado that struck Fort Worth on 28 March 2000 and 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 typically idealize a tornado as a vortex symmetric about a vertical axis. This axisymmetric vortex can be subdivided into five interacting regions based on the salient features of the swirling or tangential, radial, and vertical flow and the governing vortex dynamics (Figure). 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 and computer models of tornadoes have improved our understanding of complex tornado dynamics in a simplified environment. In particular, the recent large-eddy simulation (LES) results of Lewellen et al. 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. 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. 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. 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.

Model simulations with a wind engineering focus, such as those conducted by, have sought to modify traditional, straight-line wind engineering studies, including those based on wind tunnel experimentation. Preliminary results from computer model prototypes suggest that changing winds produce more damage than static wind conditions. It has been suggested that the wind speed-damage relationships implied in the Fujita scale overestimate the peak winds in tornadoes. The peak wind speed versus damage relationship has been modified with the Enhanced Fujita (EF) Scale. Recently however, based on comparisons of direct radar observations and observed damage, there is some evidence that changing wind speeds and directions, and/or the integrated effect of wind-speed moments, are as well correlated with damage as well as peak-wind-gust Fujita-scale-type metrics. Except two cases, the Spencer (1998) tornado, and one currently being analyzed from VORTEX2, 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, namely that damage is a function of the peak wind gust and not wind duration, wind direction, etc., is nearly untested in actual tornadoes. Consequently, unless the actual nature of the tornado low-level wind threat is quantified, it is difficult to design building codes to mitigate this threat.

Although observational studies of the low-level and core-flow regions are challenging, observations by radar and in situ instruments occasionally have been obtained. The most frequent observations have been by mobile radars at close range to tornadoes and occasional in situ observations. In a limited number of cases, some basic predictions of the conceptual and computational 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. Sub-vortices within large tornadoes also have been mapped infrequently, as have the vertical distribution of wind speeds, with suggestions of convergent inflow at the lowest levels being observed. 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 confidence in our ability to examine tornado dynamics in tornadoes of a various strengths and sizes 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 May1998 Spencer, South Dakota, tornado). Vertical (RHI) cross-sections obtained with X-band and W-band radars offer the promise to resolve fine-scale vertical structures in tornadoes, particularly in the corner flow region.

Given the aforementioned gaps in our understanding of the low-level wind field in tornadoes, VORTEX2 sought to answer the following questions:

- 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?

4. The VORTEX2 Field Experiment

While VORTEX1, ROTATE, and other studies have substantially increased our knowledge of tornadogenesis, evolution, and structure, key questions remain and appear not to be addressable using the observations provided by these efforts. Specifically, there is a need to observe supercell evolution prior to and during tornadogenesis as well as during the entire life cycle of the tornado with multiple observational platforms. At minimum, these observations need to span periods of 1000-2000 s in order to capture key evolutionary processes. In addition, simultaneous radar observations are required at the storm scale, covering substantial portions of the supercell up to well above the melting layer, and at the mesocyclone scale, which resolves the tornado and other kilometer-scale circulations and low level divergence and horizontal and vertical vorticity fields. Critically, simultaneous thermodynamic data are required in and below the storms, particularly in the inflow, gust fronts, and rear and forward flank downdraft regions. Finally, ultra-fine-temporal and spatial scale radar observations and in situ observations are needed in the tornado itself.

4.1 Spatial Domain and Nomadic Plan

In order to maximize the number of tornadic supercells intercepted, operations were conducted over nearly all of the High Plains (Fig 4). The domain was similar to that of the fully nomadic ROTATE. VORTEX2 would consider targeting storms anywhere from the Dakotas to southwestern Texas, as far west as New Mexico, Colorado and Wyoming, and as far east as Missouri and Iowa. Operations were avoided in urban areas, hilly and/or forested terrain, and areas with few roads. However, operations in marginal areas were considered if there were no viable alternatives. In order to operate efficiently over this large area, extending over 1700 km north-south and 1200 km east-west, over 1.2×10^6 km^2, there was no fixed home base. At the end of each operations day, VORTEX2 crews would spend the night at hotels chosen with the next day's target region in mind. Several institutions participating in VORTEX2 had home facilities at the edges of the VORTEX2 domain, including the University of Oklahoma and the National Severe Storms Laboratory in Norman, Oklahoma, Texas Tech University in Lubbock, Texas, and the National Center for Atmospheric Research, the University of Colorado, and the Center for Severe Weather Research in Boulder, Colorado. These groups had garage and maintenance facilities that were available to all participants. In addition, a large high bay garage was rented in Hays, Kansas, near the center of the operational domain during 2009.

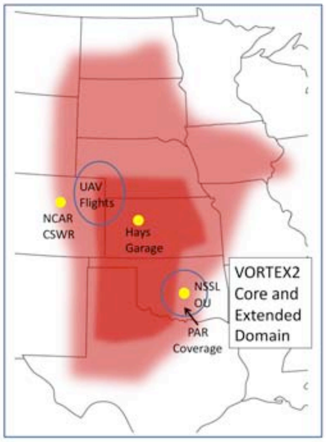


Figure 4. The core (darkly shaded) and full domain of VORTEX2. Nomadic field teams could intercept supercell thunderstorms across the High Plains. Fixed or restricted assets

VORTEX2 employed approximately 50 vehicles and was staffed by approximately 120 participants. The fully nomadic nature of the project provided unique logistical challenges. Early each afternoon it was necessary to decide where all 120 crewmembers (and additional observers and media hosted by VORTEX2, totaling upwards of 160 people in over 110 rooms) would stay that night. This made locating enough hotel rooms in the usually small cities in the High Plains difficult. We know of no precedent in any science project for lodging this large a group in different cities on such repeatedly short notice.

4.2 Duration

Tornadoes occur relatively infrequently, irregularly, are of short duration, and the geographic location of their occurrence varies significantly each year. Planning an experiment targeting such a fickle phenomenon posed special challenges. Due to limitations of funding and staffing, it was impractical to conduct a many-year study, and it was impossible to operate throughout the entire peak tornado season, which extends from March to July. The ROTATE project, having intercepted approximately 140 tornadoes over 12 field seasons from 1995-2007, provided a statistical basis for choosing the optimal field operation period, and for estimating the level of success that could be reasonably anticipated by VORTEX2. Operating over various domains and time periods, ROTATE observed tornadoes on an average of 4.9 days/season and significant tornadoes (F2 or greater), which were of the greatest interest to VORTEX2, on 1.3 days/season. Data were collected in zero significant tornadoes during four of the twelve seasons, a "failure" rate of 33%. However, these "failure" seasons were uncorrelated and were repeated only once, or 1 out of 11 possible times, a 9% rate. In order to reduce chance of failure, it was decided to spread VORTEX2 field operations over two years, focusing on the statistically most likely time for

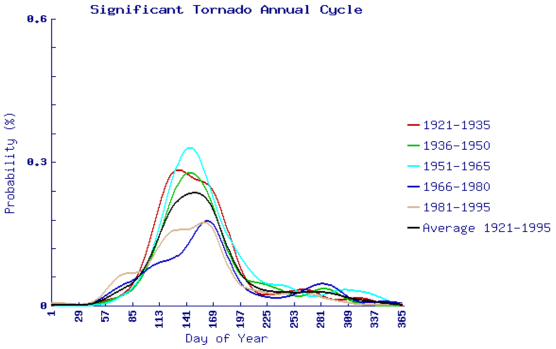


Figure 5.Frequency distribution of significant tornado occurrence in the United States. The peak in tornado occurrence occurs from roughly Day 120-175, encompassing most of May and June. (From Brooks)

tornado occurrence in the High Plains. Operations were planned for 10 May – 15 June 2009 and 01 May – 15 June 2010.

5. Observational strategies

5.1 Nesting of observational scales

One of the central and most ambitious goals of VORTEX2 was to obtain contemporaneous radar data at a multitude of scales (storm-scale, mesocyclone-scale, and tornado-scale), while in situ thermodynamic data were collected by a combination of instrumented vehicles (mobile mesonets operated by NSSL and CSWR), arrays of deployable weather stations (Sticknet operated by TTU, Tornado Pod Array operated by CSWR, Pods deployed by CU), an unmanned aerial system operated by CU and UNL, and upsondes operated by NCAR and NSSL (Fig. 6). Observations at all these scales, both at the surface and aloft, and for long durations at frequent intervals, were critical to testing many of the hypotheses related to tornadogenesis, evolution, and structure.

5.1.1 Nesting of Storm Scale and Mesoscale Radar Arrays

To accomplish these multi-scale observations, a strategy of deploying nested groups radars was used. The C-band (5.5 GHz) SMART-Radars from OU were deployed approximately 20-30 km to the south of the forecast track of a supercell thunderstorm, with a baseline of approximately 35 km. This resulted in a dual-Doppler surveillance area of approximately 1500 km^2, extending lengthwise for approximately 50 km along the storm's path. Ideally, assuming a typical storm motion of 10 m s^{-1}, dual-Doppler observations could be obtained for about 1.5 hours.

While this long term, storm-scale dual-Doppler domain was established, an array of four X-band (9.4 GHz) radars from CSWR (DOW6 and DOW7), NSSL (NOXP), and the University of Massachusetts (UMXP) would deploy in a line ~10 km to the south of the path of the hook of the supercell. An elongated region of fine-spatial-scale resolution dual-Doppler coverage would be established along the path of the mesocyclone. As the mesocyclone would pass the rearmost X-band radar, this radar would undeploy and slide forward to the head of the X-band line, ensuring continuous dual-Doppler coverage at the mesocyclone scale.

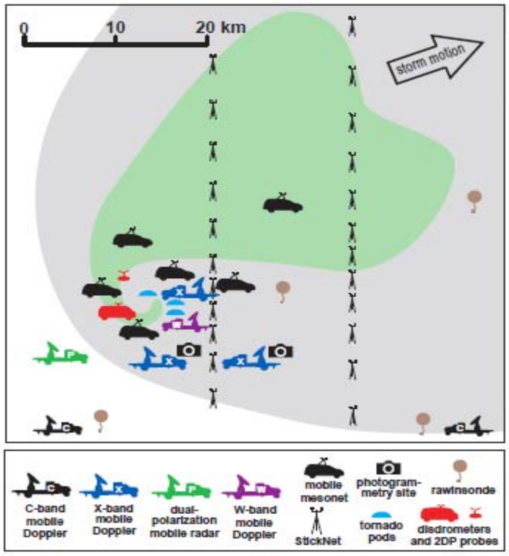
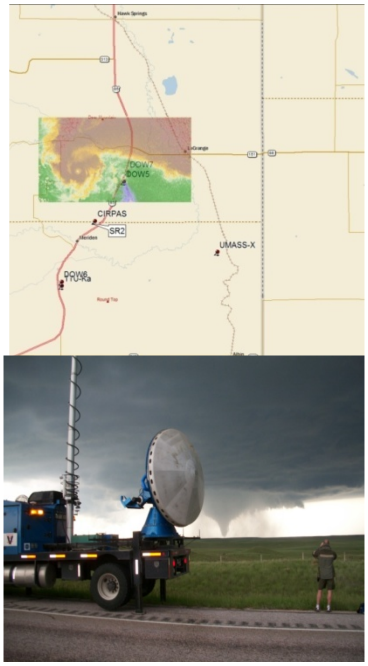


Figure 6. (above) Schematic of a nested deployment showing part of the VORTEX2 instrument array. C-band radars and mobile balloon launchers deployed away from the storm to observe the full storm and the environment. X-band radars (some dual-polarization) deployed closer to resolve mesocyclone-scale features. Mobile mesonets and the Sticknet array collect surface thermodynamic data. Disdrometers collect surface precipitation data. W-band and Rapid-Scan radars and Tornado Pods sample tornadic winds. Coordinated photographs of the tornado are provided by the photogrammetry teams. (The UAS team is not shown)

While this was the general operational plan, real-world conditions frequently precluded full realization of this strategy. For example, radars would sometimes arrive late, have difficulty finding deployment sites unblocked by trees, terrain or buildings, malfunction, or be unable to redeploy due to intense intervening precipitation, traffic, or even low clearance overpasses. However, on several occasions, nested storm-scale/mesocyclone-scale arrays were established successfully, for example on 05 June 2009 (Fig. 7).

5.1.2 Surface and airborne observations

Figure 7. (right)(top) Actual deployment of several of the VORTEX2 radars near a tornado on 05 June 2009 in Wyoming. The DOW6 and DOW7 radars are collecting dual-Doppler data. The UMASS-X and NOXP radars are deployed ahead of the storm to collect storm-scale and later mesocyclone scale data as the storm moves east. The DOW5/Rapid-Scan is collecting ultra-fine-scale data at ranges as low as 400 m. The CIRPAS phased array, The SMART-Radar 2 and TTU-Ka band are deployed south of the storm.
(bottom) DOW7, with mast extended, observing tornado.

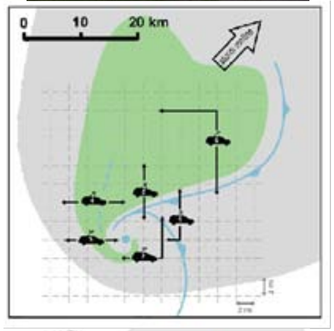


The goal of the mobile mesonet vehicles was to conduct an elaborate series of transects under various portions of the supercell, including the gust fronts and updraft regions, which were in the C-band and X-band storm/mesoscale dual-Doppler radar coverage area. Mobile mesonets contained weather instruments on racks mounted well above the chassis, measuring temperature, relative humidity, wind and pressure. Six mobile mesonets were provided by NSSL and operated by PSU and four provided/operated by CSWR. (Fig. 8). CSWR mobile mesonet vehicles also deployed Tornado Pods (see below)

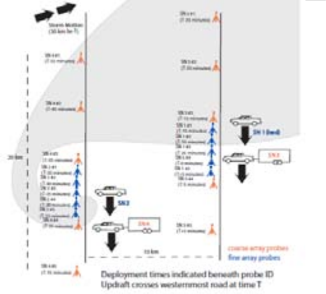
An array of 24 deployable Sticknet weather stations, was deployed in either one or multiple lines ahead of the supercell in order to provide a rake of transects in the storm-scale and mesoscale dual-Doppler coverage area. Sticknet units are tripods with weather instruments mounted at approximately 1.5 m AGL. The Sticknets were deployed in ~20 km length lines, ideally on several consecutive roads, with a spacing between the deployments of 1-5 km. One major focus of the Sticknet array was observations in the storm's main updraft, rear flank downdraft, and gust fronts (Fig. 8).

Figure 8. (top) NSSL (left) and CSWR (right) Mobile Mesonet systems.

(right) schematic of Mobile Mesonet transects of a supercell with gust fronts annotated.



(bottom) Sticknet (L) and schematic of sticknet array deployment in a supercell (R).



During the 2010 field phase, an Unmanned Aerial System (UAS), operated by the University of Colorado (CU) and the University of Nebraska (UNL), provided information about the immediate storm environment. The UASs were launched near supercells and flew patterns outside the storms, sampling the nearby environment. These measurements provided several quasi-horizontal transects through portions of the near-supercell environment, complementing the surface measurements collected by the Mobile Mesonets and Sticknets.

5.1.3 Tornado Scale Observations

Four (2009) and then six (2010) CSWR vehicles were each equipped to carry three in situ Tornado Pods. Each 1m Pod contained an ultrasonic anemometer, a RM Young anemometer, and a shielded T/RH sensor. A data logger was housed in an armored waterproof box at the base. The package weighed approximately 50 kg.

The strategy was to deploy the Pods in arrays that maximized the chance of achieving multiple transects through the core flow and surrounding regions of a tornado. The Rapid-Scan DOW, TTU K-band, and

Figure 9. (above) The Rapid-Scan DOW observing a tornado on 05 June 2009 in Wyoming during VORTEX2(left). An instrumented Tornado Pod (right).

UMASS W-band radars were deployed near and south of the tornado track, scanning over the Pod arrays, in order to provide 2D and 3D wind measurements from 15 m to 1 km AGL. The Rapid-Scan DOW could provide volumetric updates at 7 s intervals, with a 0.8 degree beam, and 25 m gates. The TTU K-band radar had a 0.5 degree beam, and the W-band radar a 0.19 degree beam, providing potentially unprecedented spatial sampling.

5.1.4 Microphysical measurements using radars and disdrometers

Testing of several hypotheses related to tornadogenesis require a knowledge of the microphysical properties of the precipitation in various portions of supercells. Several of the mobile radars had dual-polarization capability, including the SMART-Radars, UMASS-X, and NOXP. The DOW6 and DOW7 radars were upgraded for the 2010 season to dual-frequency, dual-polarization capability and could conduct double-speed dual-polarization measurements. All the dual-polarization radars had a double mission since they were critical components of the nested dual-Doppler arrays described above. On each mission day, scanning was optimized for dual-polarization objectives (scanning higher in the storm with slower updates, typically 3 minutes) or for dual-Doppler (scanning less deep, but with more rapid updates, typically 2 minutes). Several disdrometers provided by CU and the University of Florida were deployed near polarization radars.

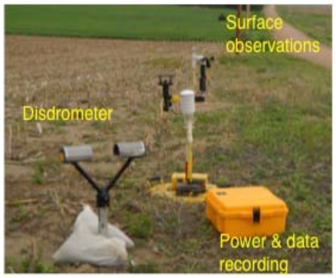


Figure 9. A laser disdrometer and a Tornado Pod in VORTEX2

5.1.5 Storm environment measurements with balloon systems

In order to diagnose the local environment in which supercells form and are maintained, vans containing MGAUS systems, operated by the National Center for Atmospheric Research (NCAR) the National Severe Storms Laboratory (NSSL), and the State University of New York at Oswego (SUNY), launched instrumented balloons at frequent intervals from a multitude of locations. These sondes were launched prior to convective initiation in order to capture changes in the local environment thought to be conducive to supercell formation. Additionally, once the supercell has formed the environment surrounding the storm was sampled. (Fig. 10)

Figure 10. Balloon launch

5.1.6 Photogrammetry at tornado and storm scale

Photogrammetry teams deployed at various ranges to the storms. Some of these teams were co-located with mesoscale radars, usually DOW6 and DOW7, so that integrated photographic-radar analysis of tornado and storm structure could be conducted. Other teams documented various other portions of the supercells. (Fig. 11)

Figure 11. Photogrammetry

5.1.7 Field Logistics

The size and mobility of VORTEX2 posed unique challenges to achieving both safe and efficient field operations.

5.1.7.1 Communications and Coordination

One of the most challenging aspects of VORTEX2 was the coordination of nearly 50 scientific vehicles. Deployment strategies were complex. In addition, the phenomena being studied posed a substantial risk. Supercell thunderstorms produce large hail, hazardous

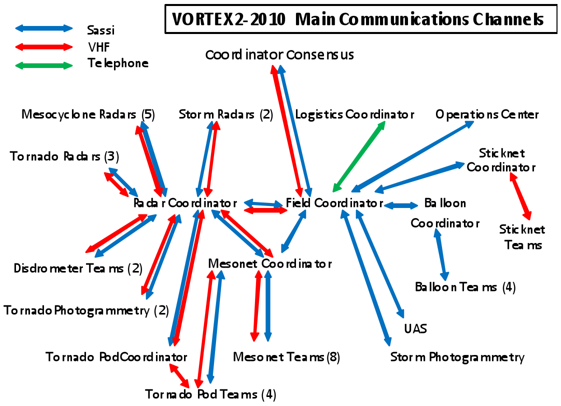


Figure 12. Main channels of communication.

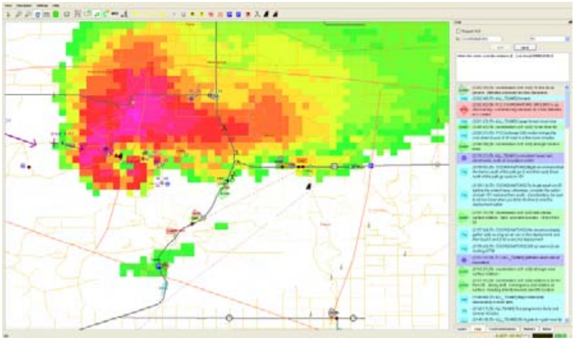


Figure 13. SASSI display

winds, frequent lightning, flash flooding, low visibility, hydroplaning risks and, of course, tornadoes with the attendant risks posed by extremely high winds and airborne debris.

Based on experiences from VORTEX1, ROTATE, and other tornado studies, it was decided that decentralized coordination was critical due to the number and variety of vehicles and platforms. Control of deployments was split among several coordinators: mobile mesonet, radar, field, UAS, balloon, etc. Overall targeting, forecasting, and logistical decisions were made through a consensus of these coordinators.

The VORTEX2 Steering Committee, with the Mission Scientist as a rotating potential tiebreaker, made mission and targeting decisions. In practice decisions were nearly always arrived at with the consensus with instrument system and other Principal Investigators.

To facilitate this decentralized control model, a high level of situational awareness among all the participants was needed. The Situational and Awareness software (SASSI) provided vehicle tracking and real time chat capabilities using cellular internet. SASSI enabled coordinators and individual crews to maintain awareness of their location relative to other platforms and the target storm. Participants could communicate via low bandwidth chat to their team leaders and others. Coordinators could annotate charts sent to all teams to provide awareness of the forecast location of the mesocyclone, future multiple-Doppler lobes, and hazards such as washed out roads or accidents.

In addition to the cell internet based SASSI, many teams operated VHF radios, some at up to 200 W. Some platforms had pneumatic masts that could be raised (DOWs up to 18 m AGL) to achieve very long VHF ranges. Communication among several of the radars, mobile mesonets, and tornado pod teams was conducted primarily via VHF. Redundant vehicle tracking system, with VHF and cell failback capability, was installed in some platforms.

5.1.7.2 Forecasting

Accurate forecasting of target regions a day out, the morning of, and during the day of a mission was critical. In 2009, members of the VORTEX2 Steering Committee rotated through morning forecast duties and in 2010 NOAA forecasters in the field provided daily briefing assistance. During mission days, a group of NSSL-based forecasters provided updated information, frequently providing experimental model forecasts to the Field Coordination team and other PI's.

5.1.7.3 Lodging, Food, Fuel

VORTEX2 had unique logistical challenges due to its fully nomadic nature, lodging in different small cities every evening, with little notice, and the large number of participants and observers, which at times exceeded 160. Over 50 vehicles were associated with VORTEX2. Many different logistical challenges were unique to a project such as this. The fueling of 50 vehicles could overwhelm local service stations and require mission-compromising lengths of time. Food service for over 100 participants and dozens of observers could result in long delays. Lavatories in small service stations could not cope with 160 simultaneous arrivals.

Several vehicles, particularly the larger radars were able to avoid in-mission fueling by carrying large amounts of fuel in auxiliary tanks. The DOW6 and DOW7 radars carried 290 gallons (850 litres) and the Rapid-Scan DOW carried 140 gallons (400 litres) resulting in 2000 km ranges. The largest individual team, from CSWR, provided in-field catering for its 30 participants and some observers. A Logistical Coordinator searched for and provided central group reservations for over 100 hotel rooms each night in order to avoid the likely chaos that would result if over a dozen VORTEX2 groups individually competed for rooms in small cities.

During 2009 the VORTEX2 fleet travelled approximately 20,000 km, with an additional 26,000 km in 2010, for a total of approximately 2,000,000 vehicle-miles. In part due to extraordinary attention to safety, there only were two relatively minor vehicle accidents that resulted in no injuries. Approximately 10,000 hotel reservations were made in about 50 different cities throughout the High Plains. It is estimated that VORTEX2 consumed over 600,000 liters of fuel.

6 Preliminary Results

2009 proved to be a very challenging year for a tornado study. In May only 15% of the normal number of tornado warnings were issued, and VORTEX2 did not achieve many of its objectives during May 2009. Fortunately weather conditions became more propitious for scientific study in June.

On 05 June 2009, a supercell thunderstorm that initiated on the Cheyenne Ridge in Wyoming moved east into the Plains, eventually creating a long-lived and moderately intense tornado. The VORTEX2 fleet targeted the supercell, deploying well in advance of tornadogenesis capturing the entire life cycle of the tornado. Multiple mobile radars, Mobile Mesonets, Tornado Pods, Disdrometers, Sticknets, and Photogrammetry teams were deployed on the storm. The duration, diversity, and detail of this integrated data set are unprecedented and realize the goals of VORTEX2.

Figure 14. (above)The DOW6 and DOW7 dual-Doppler lobe during the genesis, intensification, and dissipation of the 5 June 2009 tornado. The rapid-scan DOW captured high-resolution data during tornado intensification and demise.

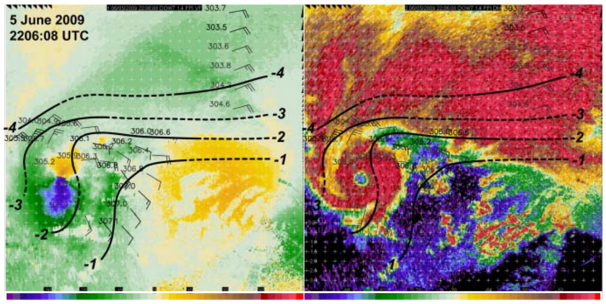
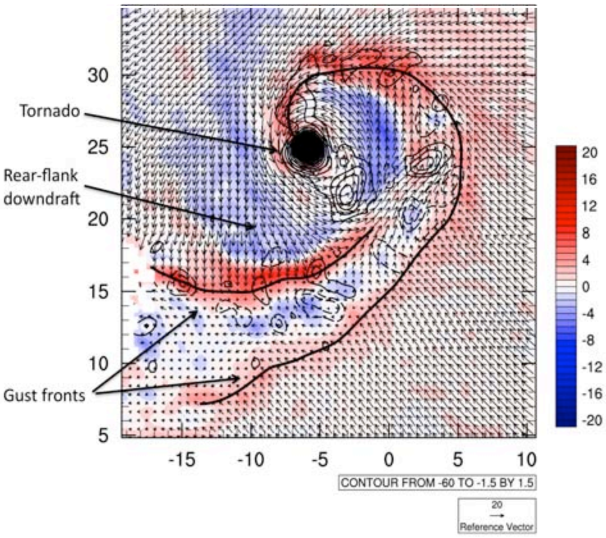


Figure 15. (above)Preliminary analysis of surface winds and temperatures, as measured by the mobile mesonets, overlaid on DOW7 velocity and reflectivity at 2206 on 5 June 2009.

The analyses of the data are ongoing and will be published elsewhere. Examples of mesonet (Fig. 15), dual-Doppler (Fig. 16) and radar-photogrammetry (Fig. 17) analyses are shown here to illustrate the richness and detail in the collected data. This combined knowledge is necessary to fully document the evolving dynamics linked to tornadogenesis, intensification and demise.

Figure 16.(below) Dual-Doppler at 2202 UTC 05 June 2009 depicting the rear flank downdraft, primary and secondary gust fronts and the tornado. Convergence (red), Divergence (blue), and Vertical Vorticity (black contours).



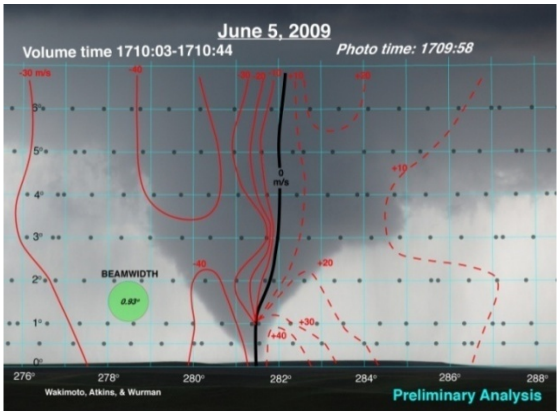


Figure 17. Preliminary integrated radar-photogrammetric analysis of the 05 June 2009 tornado. Red contours depict the Doppler velocities. (From Wakimoto et al. 2010)

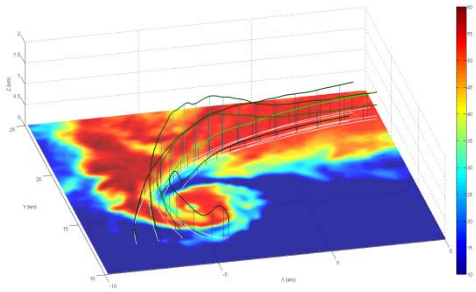


Figure 18. An example trajectory analysis of the 05 June 2009 supercell. The lines indicate the path of the parcels that comprise the secondary convergence line.

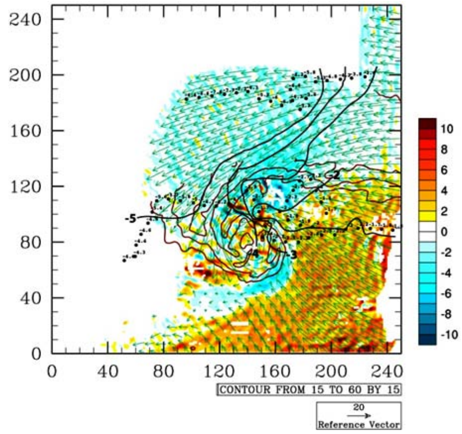


Figure 19. (above) An example buoyancy analysis of the 05 June 2009 tornado. Oranges/reds indicate relatively buoyant air while blues indicate regions of lower/negative buoyancy. Mobile mesonet-derived buoyancy values plotted in black.

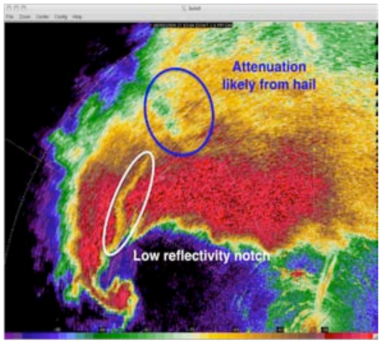


Figure 20. Low reflectivity notch on 05 June 2009.

The high-resolution, dual-Doppler observations have allowed researchers to diagnose the evolution of the rear flank gust front and the subsequent development of a secondary convergent line in relation to tornadogenesis and intensification (Fig. 16). Preliminary results indicate that the secondary convergent line exhibited microburst-like characteristics, with a ring vortex interacting with the primary RFD convergence zone, thus generating cyclonic vertical vorticity proximal to the main updraft. It is thought that generation of vertical vorticity by this mechanism was critical to tornadogenesis.

Trajectory analysis revealed that downdraft parcels entered the tornado circulation. The downdraft parcels originated from several hundred meters aloft and to the north and east of the main updraft (Fig. 18). As the source region of the parcels showed no temporal evolution, it is speculated that the thermodynamic characteristics of the primary and secondary downdrafts change in time. Indeed buoyancy retrievals from the dual-Doppler data and surface mesonet observations reveal an increase in theta-V of the secondary convergence line, in particular, as a function of time (Fig. 19).

Preliminary analyses indicate that cause and subsequent evolution of the secondary convergent line likely is due to precipitation loading and increased evaporation in the rear flank of the storm. Interestingly, a low reflectivity notch develops between the forward flank and the rear flank of the storm (Fig. 20). The intensity of this notch fluctuates in time. The microphysical and/or dynamical causes of this notch currently are under investigation.

Several other days in 2009, most notably 07, 09, and 11 June, yielded data in non-tornadic and weakly tornadic supercell thunderstorms. Investigating why these storms did not produce significant and/or long-tracked tornadoes is underway.
During 2010, data were obtained in over a dozen tornadic supercells. Particular events of interest include 10 May in east-central Oklahoma, 12 May in north-central Oklahoma, 19 May in west-central

Oklahoma, 7 June in eastern Colorado and 11 June on the Texas/Oklahoma border. Interestingly on 11 June 2010, the tornadic supercell north of Booker, Texas exhibited a low-reflectivity notch similar to the 05 June 2009 tornadic supercell. (Fig 21.)

Figure 22 provides a preliminary pictorial summary of the location and type of supercell and quality of intercept in various data sets collected during the 2009 and 2010 field phases of VORTEX2. Analysis of data collected in 2010 is in its very early stages.

References

Markowski, P. M., and Y. P. Richardson, 2009: Tornadogenesis: Our current understanding, forecasting considerations, and questions to guide future research. *Atmospheric Research*, **93**, 3-10.

http://www.vortex2.org

(Scientific Program Overview SPO, Experimental Design Overview EDO, and Operations Plan)

http://www.eol.ucar.edu/projects/vortex2
(data archives, other documents)

Acknowledgments

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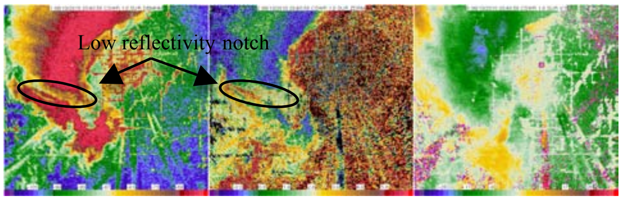

Figure 21. (above) uncalibrated reflectivity (left), differential reflectivity (center) and Doppler velocity(right).

Figure 22. Summary of VORTEX2 intercepts.