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VORTEX: Preliminary Findings and Implications

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1. INTRODUCTION

The **V**erification of the **O**rigins of **R**otation in **T**ornadoes **EX**periment (VORTEX) has been an exciting project in which to be involved, for a number of reasons. This project (described broadly in Rasmussen et al. 1994; more detailed project information is available on the World Wide Web at:

<http://antietam.nssl.uoknor.edu/ mosaic_files/vortex.html>)

differs from most previous field programs in some important ways. Foremost among these is that the experimental design was predicated on entering the field phase with some very specific *testable hypotheses*. The hypotheses were the basis for designing the field observational strategies and the measuring systems used in the field. Thus, rather than simply going out and collecting whatever data could be collected and hoping that it would suffice to "do science," the object was to seek data sets to *invalidate* the hypotheses; that is, to collect data with the idea of giving the hypotheses a stringent test. This notion is a reflection of the philosophy of science most closely connected to Karl Popper (see, e.g., Popper 1962); viz., that empiricism cannot *prove* some scientific hypothesis but it can *refute* it. The power of a scientific hypothesis, in Popper's view, is in accordance with its ability to be tested as rigorously as pos-sible. If the data do not refute the hypothesis, this does not constitute "proof" but it certainly is a noteworthy event in the "life cycle" of a scientific idea when it is not disproved by a well-conceived rigorous test.

Another exciting aspect of the program is that it really is the first (and so is the largest, by default) scientific field project aimed solely at tornadoes and tornadic storms. Most field work associated with tornadoes, notably that of Fujita and collaborators, has been ad hoc to the extent that it only happens when tornadoes are observed. One of our fundamental operating philosophies was that in order to give our ideas a stringent test, we had to collect data on significant storms, preferably supercells, that did *not* produce tornadoes. Data collected from non-tornadic events was to be comparable in every way to that collected on a tornadic storm, at least in the ideal. In a sense, it is criti-cal to our hypothesis testing to be able to distinguish tornadic from non-tornadic events.

In fact, that very concern is yet another positive aspect of VORTEX, since it relates directly to important questions in the *operational* application of the ideas to come from the experiment. There were several explicit goals of the project that had direct and significant potential impact on operational forecasting and warning issues. A number of operational forecasters were involved in the project, especially within the forecasting support effort (see Brooks et al. 1996).

2. HYPOTHESES

A complete listing of the VORTEX hy-potheses would occupy too much space here; the details can be found at the World Wide Web URL provided above. What we realistically can hope to do here is to consider how a few of the hypotheses fared, as best we can tell from the preliminary results we have available. Any conclusions that one might be tempted to draw should be tempered with the fact that much analysis of the data remains to be done. We want to emphasize the *preliminary* nature of these "findings" and observe that a careful analysis of the field observations will almost certainly require many years.

a. <u>In the region of supercell initiation, horizontal inhomogeneities in the warm sector environment are so insignificant that they would cause no appreciable difference in simulated supercell structure and evolution.</u>

For this hypothesis, one condition for refutation was: *Even without performing numerical simulations, based on established sensitivities of simulated supercell storms to sounding-derived parameters (e.g. CAPE, shear, helicity, etc.), it can be established that the pre-storm environment is not horizontally homogeneous to the degree described in the hypothesis*. In most, if not all VORTEX cases, the near-storm environment was decidedly not homogeneous (Brooks et al. 1996). Observations with the special soundings revealed considerable structure in and around the vicinity of the storms, but we are pretty confident that the data gathered during VORTEX was insufficient to *resolve* those structures.

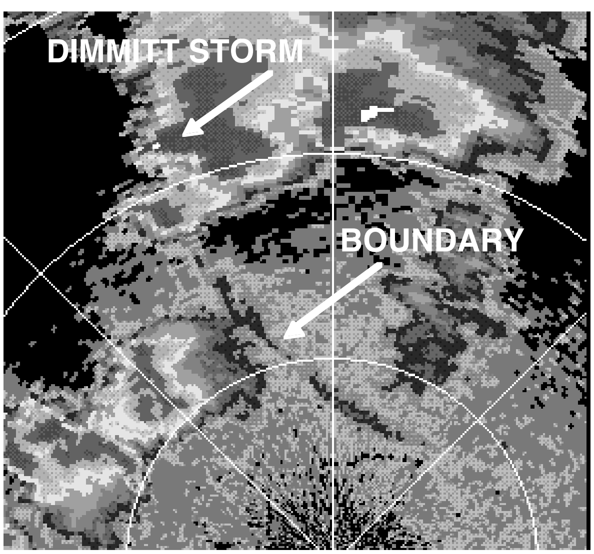

Figure 1. WSR-88D image from Lubbock, TX on 02 June 1995, at 0107 UTC, with the Dimmitt, TX tornadic storm and the boundary annotated. The large hook-shaped echo was a tornadic storm near Tulia, TX.

In every tornadic storm case examined to date, a significant low-level boundary has been found near the updraft, usually displaced a few km to the right of the updraft. These boundaries appear to be related to the occurrence of earlier convection in every case (e.g., Fig. 1). The wind and thermodynamic profiles on either side of these boundaries are so dif-ferent that it is virtually certain that num-erically simulated supercell structure and evolution must depend to some extent on the existence and structure of these boundaries.

b. <u>Low-level mesocyclone intensification is due to near-ground horizontal vorticity, generated through forward-flank baroclinity, being reoriented into vertical vorticity and stretched in the low-level updraft. Tornadogenesis results from the abrupt tilting, in the boundary layer, of this horizontal vorticity due to the movement of the RFD-associated gust front into the area below the updraft.</u>

This hypothesis has been refuted for at least one case, and preliminary analyses suggest that it will be refuted generally. It now appears that there is very large near-ground horizontal vorticity, but it is probably contained in a layer which slopes upward from a boundary several kilometers to the right of the storm, and into the storm near cloud base. It does seem to be this horizontal vorticity, generated through low-level baroclinity, that is being tilted and stretched to produces the low-level mesocyclone. However, the baroclinity and associated horizontal vorticity are not located in the boundary layer just ahead of the mesocyclone and RFD, and thus the hypothesized "abrupt tilting process" cannot occur. Preliminary analyses suggest that it is the RFD itself that contains the circulation which "feeds" the tornado.

c. Tornadoes are located in strong equivalent potential temperature gradients on the cool side of the storm outflow boundary; solenoidal generation of streamwise vorticity is significant for tornadogenesis.

This is an example of a hypothesis which seemed to be well-crafted when first posed, and indeed served to focus the data collection, but turns out to be a bit more difficult to evaluate in light of the data that were gathered. In the Dimmitt tornadic storm of 02 June 1995, there is clear evidence that the tornado is on the cool side of an outflow boundary (not generated by the storm itself). How-ever, the large gradients of equivalent poten-tial temperature were displaced from the tor-nado by at least several km, and the tornado itself was in a region of rather uniformly low equivalent potential temperature (Rasmussen and Straka 1996). It was not until the tornado began to dissipate that it was found in a large gradient of equivalent potential temperature; i.e., even colder outflow appeared on the left rear side of the tornado and eventually engulfed it as it dissipated. Preliminary evidence suggests that solenoidal generation of streamwise vorticity may be quite significant for low-level mesocyclone genesis, and this feature may be required for tornadogenesis. Thus, though the process could be more indirect than thought when the hypothesis was defined, it appears that this hypothesis may not yet be refuted.

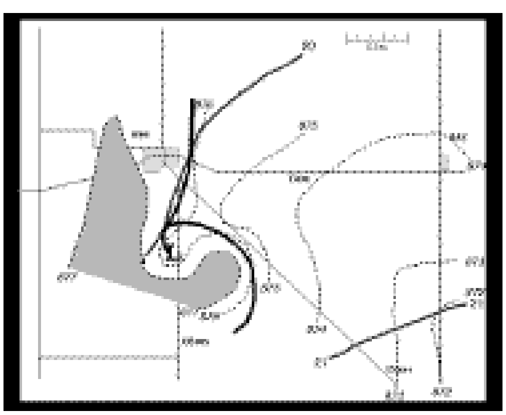

Figure 2. Analysis of mobile mesonet observations at 0100 UTC, during the intensification of the tornado, with isotherms as bold lines (20 and 21 C in this figure); isobars (hPa) as thin dashed lines. The shaded region has pressures > 877 hPa. (From Rasmussen and Straka 1996)

3. TORNADO CASES

The project was designed from the start as a two-year project to allow for the natural variability in tornado events and to provide us with a chance to "shake down" some of the new and innovative field observing systems that were used. This turned out to be a prescient decision, because 1994 was a pretty sparse year for tornadoes within the field operations area during the operational period (01 April to 15 June 1994). Nevertheless, tornadic storms were sampled on 6, 25, and 29 May. From the outset, it became clear that we were going to be seeing remarkable things. The most interesting and reasonably well-sampled event was 29 May, with a significant tornado sampled by the airborne Doppler radar on the NOAA P-3 research aircraft. An early paper on this event has been published by Wakimoto and Atkins (1996). While the VORTEX armada was sampling a strong, well-organized mesocyclone, another updraft developed rapidly about 10 km to the rear of the target supercell. It was *this* updraft, located quite near to the trailing outflow boundary of the supercell, that developed intense rotation through a column about 6 km deep in a matter of minutes, and subsequently produced the tornado. Despite the strength of this second mesocyclone, its small size made it nearly undetectable on WSR-88D radar. A general, preliminary im-pression from VORTEX is that the small, strong mesocyclones are more likely to pro-duce significant tornadoes than broad, weak ones.

The second year of the project was characterized by some refinements to the field operational strategies and some notable additions to the field observational capabilities: specifically, the mobile Doppler radar system (see Wurman et al. 1996) for direct sampling of tornadoes and mesocyclones in close with a narrow-beam, scanning, pulsed Doppler radar. Fortuitously, 1995 had many more tornadic events to work with than 1994, with tornadic events sampled on 17 April, 16 May, 02 June, and 08 June. The events on 02 and 08 June included violent tornadoes in the

Texas Panhandle that are destined to be-come benchmark tornado cases. In fact, Sufificient data were collected by 08 June that the 1995 field exercise could be terminated a week before its official closing date on 15 June.

Some events, such as tornadoes on 22 May, 05 June, and 08 June, were not worked by the VORTEX teams but some limited data are available for analysis. For example, the storm VORTEX worked on 22 May was not tornadic, but an earlier storm nearby did produce tornadoes that were documented. Radar structure comparisons are possible with the non-tornadic storm on which VORTEX collected substantial data. Also, a tornadic storm on 08 June away from the VORTEX armada was documented thoroughly with video by citizens and private storm chasers and should be amenable to extensive photo-grammetric analysis. These and other cases are of interest to the VORTEX project even though they were not specifically the objects of the full VORTEX observational armada. VORTEX is interested in collaborations with anyone studying any of the storms that occurred in the operations area during the time of VORTEX operations.

4. NON-TORNADO CASES

Given that the intentions of the project were to collect data on non-tornadic supercells, it was assumed that simply operating on what appeared to be likely target storms was almost certain to yield high-quality datasets on non-tornadic storms. This proved to be a valid assumption, and some benchmark data sets were collected on 24, 26, and 29 May in 1994 and 29 April, 12 May, and 22 May in 1995. Already, some efforts are underway to do direct compari-sons between tornadic and non-tornadic supercells (e.g., see Trapp et al. 1996). Al-though there is considerably less glamour associated with looking at non-tornadic storms, there is considerable good science that must be done to provide appropriate tests of the scientific hypotheses related to tornadogenesis. At this time, we are focusing on the similarities and differences in the origin, structure, and strength of the RFD and the associated character of the low-level boun-daries and outflow.

5. IMPLICATIONS

In our opinion, the execution of the field phase of VORTEX has been a remarkable success in most aspects. Certainly, there will be grist for considerable science in years to come. What follows are our thoughts on what all this might mean for our science and for the operational application of that science. A more extensive elaboration of these first thoughts can be found on the World Wide Web at

<http://www.nssl.uoknor.edu/~doswell/Tornadostuff.html>

As with the material already presented, we want to emphasize the preliminary nature of these thoughts; subsequent detailed analyses of the data may invalidate some or all of what we have suggested. Having given the obligatory disclaimer (these opinions are our own and don't necessarily reflect those of NSSL, the VORTEX team, NOAA, etc.), let us move on to our musings.

From our perspective, there are several interesting aspects of the VORTEX observations. Without putting them in any particular order:

1. Tornadoes can form very rapidly (5 min or perhaps less) with no clear precursors even on WSR-88D radar depiction. This might be associated with the resolution limits of the operational radars, because we are seeing fairly distinct mesocyclone signatures in the airborne Doppler radar data for at least 10 minutes prior to tornado formation (i.e., at least one Lagrangian updraft time scale). Since we don't know how tornadogenesis occurs, we might not know a precursor if we saw one!

2. It appears that many tornadoes are be the product of storms interacting with external processes (boundaries, "miso-scale" pre-existing vortices, etc).

3. A lot of things of importance to tornadogenesis may be happening below the radar horizon or outside of a fairly small radius around a radar site. It is our hope that signatures for these processes could be found on those scales resolvable at greater ranges, but there is not yet evidence that this will be the case.

4. The ratio of *tornadic* supercells to the entire class of supercells may be much smaller than we thought. Alternatively, there may be a lot more supercells out there than we thought.

5. The "cascade" paradigm (mesocyclone aloft → mesocyclone at low levels → TVS aloft → tornado at the surface) may be descriptive of only one class of events, and that class might represent only a minority of tornadoes. Or, it may be that 1) we need to refine our definitions of these phenomena based on new observations, and/or 2) we just do not have the required radar resolution (temporal, spatial) to identify the signatures correctly that are more directly associated with the processes of tornadogenesis.

Within the confines of this paper, it is difficult to give this the really thorough discussion it deserves, but we think the most important implication we can offer from these observations is that *it may well be difficult to make significant progress in operational detection and warning for tornadoes much beyond where we are at present*. Whereas it appeared that Doppler radar was going to offer a considerably higher standard in operational detection and warning for tornadoes, this may be an overly optimistic view. There can be no doubt that Doppler radar is quite proficient at detecting supercells, and this is by no means a trivial contribution, but the separation of tornadic from non-tornadic supercells may be rather more of a problem. We believe it is premature to put out to pasture all those non-radar methods that exist for enhancing tornado preparedness (spotter networks, monitoring power line breaks, etc.) simply because of the deployment of Doppler radar. If anything, we assert that it is critical to continue to *enhance* these non-radar methods even as we deploy the WSR-88D radars.

If it is found from subsequent analyses that the tornadic supercells usually are the ones interacting with boundaries, *and* the non-tornadic supercells typically are those not interacting with boundaries, then the ability of satellite and radar to detect the boundaries could make a really important contribution to short-range tornado warnings for supercells. On the basis of a preliminary look at the VORTEX data, we presently find it hard to refute the hypothesis that *all* significant tornadoes are the result of supercell/boundary interactions. In fact, we believe it would be much harder to refute that MOST are the result of such interactions. A potential fly in the ointment, of course, is that not all such interactions produce tornadoes, so we need to find out why many tornadoes result from such interactions, and yet many such interactions do not result in tornadoes.

6. DISCUSSION

With fiscal hard times ahead into the foreseeable future, it is difficult to imagine when we in the scienfitic community will once again have a chance to do a comparable field project on tornadoes and tornadic storms. Certainly, there will be chances to engage storms again on an ad hoc basis, and perhaps a small version of some parts of this project can be redone in the future. But it is unlikely that a project of this magnitude will be done again, soon (barring the unforeseen). It is our hope, however, that the style of this effort will be repeated in other field programs, wherein testable hypotheses will form the foundation for the observational strategies. We are virtually assured of being able to give many of our hypotheses some reasonably stringent tests and it appears that at least some of the ideas put forth before the field observations will be refuted. Far from being a negative result, this allows our science to continue the search for understanding in more productive ways than stuggling to choose among a host of untested ideas. Moreover, we believe that the discussions that ultimately led to the original suite of hypotheses were very productive for the scientists who parti-cipated. The debates clarified the nature of the differences of opinion and made the field observations more likely to obtain data for rigorous tests.

If any of the implications we have suggested from our preliminary review of the VORTEX experience hold up to further, more rigorous investigation, then there are some unpleasant realities to confront. While the value of Doppler radars may in fact be huge in the overall scheme of things, having a Doppler radar is not necessarily going to usher in an era where all tornadoes are warned for with 30 min lead times and no false alarms are issued. More importantly, the gains in tor-nado warning verification attributable clearly to Doppler radar might not even prove to be all that dramatic. We want to take some pains to point out that some recently published work (Polger et al. 1994) that claims to show huge improvements from installing Doppler radars has major flaws: the specific instances to which they refer *cannot* be attributed solely to the installation of the radars. We are going to assert that real gains in the issuance of tornado warnings are not simply going to follow the nationwide deployment of Doppler radars. Much more remains to be done to take advantage of the real gains that a Doppler radar offers.

The work of VORTEX is only beginning with the completion of the field phase. Much remains to be done in order to obtain the real results of the project: (a) new gains in scientific understanding and (b) the operational applications that flow from that understanding. Thus, do not look for "instant gratification" with regard to this experiment. It is also inevitable that new hypotheses will evolve from the ashes of the old, refuted ones. At some point in the future, it may become necessary to conduct another VORTEX-like project in order to test the new hypotheses. It is our wish that the new project be blessed with as much enthusiasm and dedication as we had in VORTEX.

Acknowledgments. We would like to express our gratitude to all those people involved with VORTEX who gave so unselfishly of their time and labors to make the field phase of the project a success. They are too numerous to list here, but that does not diminish the value of what they contributed.

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