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THE DENVER CYCLONE AND TORNADOES 25 YEARS LATER: THE CONTINUED CHALLENGE OF PREDICTING NONSUPERCELL TORNADOES

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1. INTRODUCTION

The year 2006 marks the 25th anniversary of the "discovery" of the Denver Cyclone, made possible after the installation of a mesonetwork of automated weather stations in 1981 by then NOAA/PROFS (Program for Regional Observing and Forecasting Services). The “PROFS mesonet” provided sufficient resolution to observe the Denver Cyclone, a zone of low-level convergence and cyclonic vorticity, formed under conditions of ambient low-level south or southeast flow (as illustrated in the schematic in Figure 1).

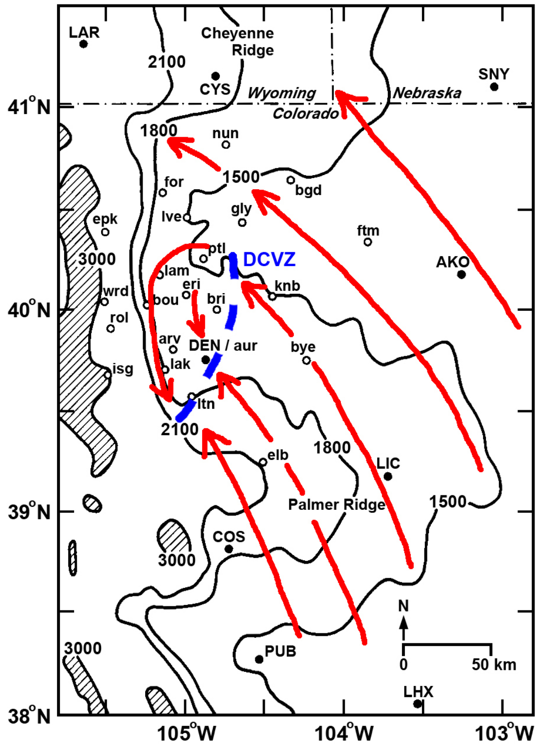

Fig. 1. Schematic of the Denver Cyclone overlaid on a topographic map (m), with the PROFS mesonet stations shown by open circles and the standard NWS stations by darkened circles.

The history of the Denver Cyclone and associated research on this feature, along with its connection to nonsupercell tornadoes, is reviewed in Section 2. The Denver Cyclone's association with tornadogenesis has been vigorously investigated. Knowledge from those studies has been shared with forecasters through workshops and other means at the local National Weather Service (NWS) Weather Forecast Office (WFO), now collocated in Boulder with NOAA/Earth System Research Laboratory (ESRL). With this knowledge, and the close proximity of the Denver Cyclone to the Denver radar (located near DEN in Fig. 1), the Boulder WFO may be one of the most experienced WFOs with respect to nonsupercell tornadoes. Nonetheless, a number of challenges remain when it comes to issuing warnings with non-negligible lead-time for these types of tornadoes. A recent case of ten reported nonsupercell tornadoes in the vicinity of the Denver International Airport (DIA) and northwards, which happened to occur during the last Severe Local Storms Conference (October of 2004), will be used to illustrate some of the issues that still can occur even when the phenomenon that produces the tornadoes is well understood.

2. A HISTORY OF THE DENVER CYCLONE

The population along the Front Range of Colorado has grown substantially in the last quarter of a century, so that tornadoes that were spotted in open country east of Denver back in the 1970s often hit what are today's eastern suburbs. While undergoing a study of one such tornado in the 1970s, Zipser and Golden (1979) speculated on the existence of a convergence zone near where the tornadoes formed, based on the sparse standard NWS surface stations. To our knowledge, this was the first documentation of the Denver Cyclone. However, it was not until a study of the 1981 tornado outbreak in Denver that the feature was named, based not only on the mesonet data for that case, but examination of two years (1981-82) worth of mesonet data as well (Szoke et al. 1984, published initially as a conference paper at the 12th Conference on Severe Local Storms (Szoke et al. 1982)). The Denver Cyclone was formally named the Denver Convergence-Vorticity Zone (DCVZ), since the

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feature often appeared as a zone of converging winds rather than a well-defined cyclonic circulation.

Interest in the DCVZ, and in particular the types of tornadoes that seemed to form along the zone, increased in the years that followed. This interest was in part fueled by observations from a prototype Doppler radar located near the old Denver Stapleton Airport and operated on an experimental basis, but available in real-time at the Denver WFO, beginning shortly after the 3 June 1981 tornadoes. In addition, there were numerous visual observations of tornadoes, sometimes from seemingly innocuous storms, by chase teams associated with forecast exercises organized by PROFS during the developmental years of early versions of what would become AWIPS (MacDonald 1985).

Other experiments were carried out in northeastern Colorado in the 1980s, in addition to the PROFS forecast exercises. A major program called CINDE (Convection Initiation and Downburst Experiment, Wilson et al. 1988) included extensive mobile soundings, additional Doppler radars, and research aircraft. A much smaller experiment using mobile soundings preceded CINDE in 1986, and captured the details of a nonsupercell tornado along the DCVZ in late July (Szoke and Brady 1989). A Doppler radar analysis of this case (Brady and Szoke 1989), with a preliminary version presented at the 15th Conference on Severe Local Storms (Brady and Szoke 1988) led to a life cycle model for a nonsupercell or "landspout" tornado (Fig. 2), along with some ideas for how forecasters might handle such events. A similar life cycle model was developed from a number of nonsupercell tornado cases that occurred during CINDE (Wakimoto and Wilson 1989). Both studies noted the importance of the boundary (often the DCVZ). It provided the source of low-level vertical vorticity for the tornado, and also a zone of deeper boundary layer moisture and low-level forcing for the convective development that stretches the incipient vertical vorticity into a tornado.

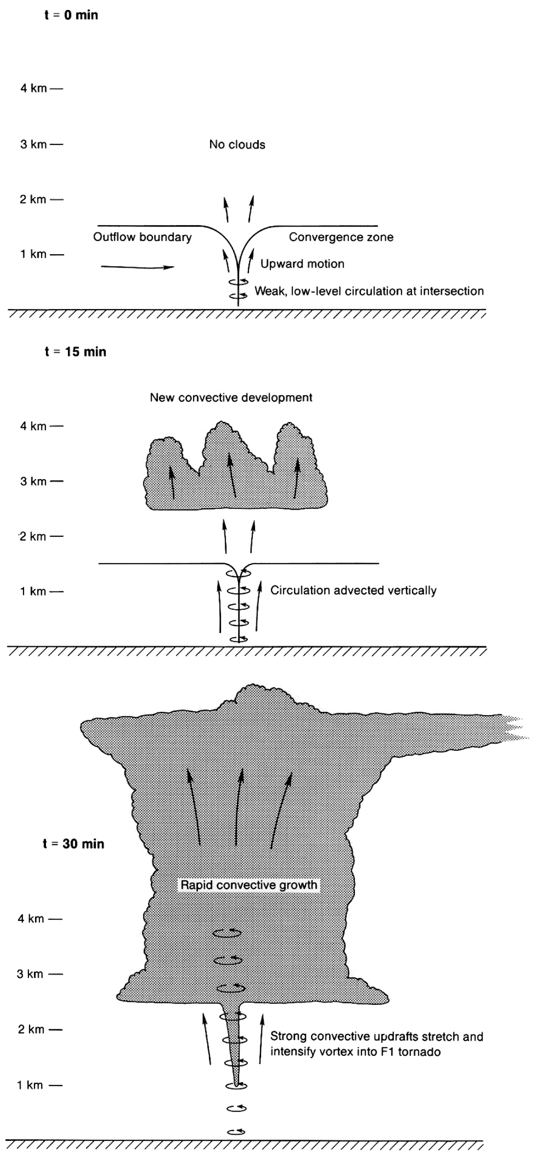

Fig. 2. Schematic illustrating the life cycle of a nonsupercell tornado (Brady and Szoke 1989).

Interest in understanding the mechanisms for the formation of the Denver Cyclone grew quickly in the mid 1980s, leading to a number of numerical modeling studies. Wilczak and Glendening (1988) successfully modeled the Denver Cyclone using a mixed-layer model, concluding that baroclinically generated vorticity caused by the ambient, south-southeast boundary layer flow over the west to east sloping Palmer Ridge (see Fig. 1) produced the Denver Cyclone. Other successful model simulations with fully three-dimensional models produced a Denver Cyclone under vastly different (stable) conditions, with baroclinic generation of horizontal vorticity as the stably stratified air flows over the Palmer Ridge, then tilting downstream to produce the circulation (Crook et al. 1990; Smolarkiewicz and Rotunno 1989). From their detailed study, Crook et al. (1990) also suggested wave breaking downstream of the Palmer Ridge as well as some blocking of the turned flow by the Front Range as additional contributing mechanisms. The virtues of these conflicting results were discussed (Dempsey and Rotunno 1988), and summarized as they applied to an interesting case made "visible" by low cloudiness (Szoke 1991). While observations do support the formation of the Denver Cyclone under more stable conditions with a low Froude number, the Denver Cyclone often persists through the day when a substantial mixed layer typically develops. It is likely that more than a single mechanism is responsible for the formation of the feature.

The second dramatic tornado event in the 1980s occurring within the Denver area and associated with the Denver Cyclone happened on 15 June 1988, when four tornadoes developed in less than an hour (Roberts and Wilson 1995). Two of the tornadoes were F2 strength, with one of these being even low-end F3 strength. The tornadoes took place within the Denver metropolitan area, with two of them close to the airport (which at that time was considerably closer to the city of Denver). Interestingly, on this day the Denver Cyclone was not a full cyclonic feature but truly a DCVZ type boundary, and the tornadoes did not develop until the boundary was intersected simultaneously by two outflows. One outflow from thunderstorms over the nearby mountains approached the ~north-south DCVZ from the west, while the other moved northward from thunderstorms to the south and approached the DCVZ from the east side. The outflows intersected the DCVZ at an angle that maximized the horizontal shear along the boundary, leading to the development of multiple shear-induced centers of vertical vorticity, some of which developed into the tornadoes. In this case, the DCVZ by itself would not have likely led to a notable event, with its role probably more important in creating a zone more favorable for convective development. The interaction that occurred over the DCVZ led to the low-level circulations and ultimately the tornadoes.

3. CLIMATOLOGY

A 2-year climatology of the DCVZ and its association with tornadoes was presented as part of the study of the 3 June 1981 tornadoes (Szoke et al. 1984). They found that ambient, south to southeast surface flow occurred over a third of the time during the summer months, and over 80% of these days had a DCVZ. Approximately 75% of the days with a DCVZ developed more of a circulation (at least a weak Denver Cyclone). A strong correlation with tornadoes was found, especially in June, typically the month with the most tornadoes, with ~40% of the DCVZ days having a tornado, and the majority of tornadoes near the usual location of the DCVZ occurring on days when a DCVZ was present. The climatology was expanded to cover the decade of the 1980s (Szoke and Augustine 1990), with the results confirming the earlier climatology. A predominance of DCVZ tornado days occurred with no other type of severe weather, which agrees with the idea of nonsupercell tornadoes developing from "ordinary" thunderstorms. The distribution of DCVZ days was spread evenly over the summer months, in agreement with the earlier climatology, but the strongest correlation with tornadoes continued to be in June. In fact, the occurrence of a DCVZ day in June was found to have a 30% chance of being a tornado day in the area in and near the convergence zone, with the chance over 60% if there was a strong Denver Cyclone (a well-developed circulation).

There is a general feeling of late, based on a perceived lack of tornadic activity in the Denver and nearby area, that the 1980s may have been an anomalous period of both tornado activity and, by correlation, DCVZ-associated tornadoes. However, there has not been a comprehensive climatological study to confirm this. It is true that the last significant tornadoes within the Denver metropolitan area occurred in 1988, although tornadoes of course have continued to occur relatively close to Denver.

A crude attempt was made to examine the numbers of tornadoes since the 1980s to determine what changes may have occurred. This is accomplished by examining the tornado numbers for the counties that could be in or near a DCVZ boundary, with no attempt made to correlate any of the tornadoes with a potential DCVZ. With these caveats, results are shown in Fig. 3, using the NOAA/NCDC tornado data-base. The numbers in Fig. 3 do appear to confirm a sizable drop in the number of tornadoes during the current decade, given that almost 70% of the current decade is accounted for. Tornado activity in Denver and areas to the south and west has also been low since 2000, and dropped off considerably during the 1990s, compared to the numbers from the 1980s. Otherwise, overall tornado numbers during the 1990s are similar to what was recorded in the 1980s. While population has grown eastward during this period, the more organized chase activities associated with the various

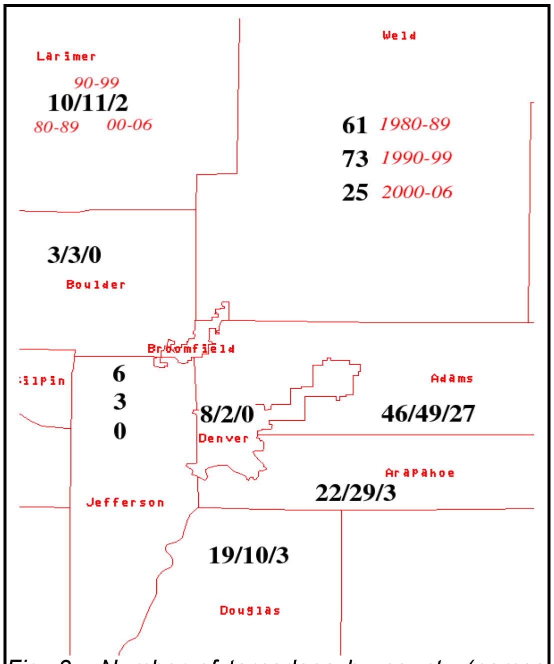

Fig. 3. Number of tornadoes by county (names shown) for the three time periods indicated. Note that no data is included for newly created Broomfield County, and the size of most of the counties extends beyond the figure (especially for Weld, Adams, and Arapahoe Counties).

experiments in the 1980s may counteract any issues in the reporting as a result of population effects. The main conclusion from Fig. 3 is that there does appear to be a downward trend in tornadoes since the 1980s, especially in and near the Denver area. One could speculate that, as a result, forecasters may have lost some of the situation awareness in regards to DCVZ-induced tornadoes that they possessed in the “wild '80s”.

4. 4 OCTOBER 2004 CASE

As the 2004 Severe Local Storms Conference was concluding its first day, an exciting late afternoon was unfolding for forecasters at the Boulder WFO. Ten nonsupercell tornadoes were reported between 2155 and 2248 UTC (1555-1648 LT) in a narrow zone from close to DIA northward about 50 km to near the town of Windsor in far western Weld County (Fig. 4). The tornadoes were rated between F0 and F1, with some property damage occurring due to a few of the tornadoes, while others remained over open areas. This case provided an opportunity to examine some of the issues that forecasters face when dealing with nonsupercell tornadoes, even for a WFO familiar with such events.

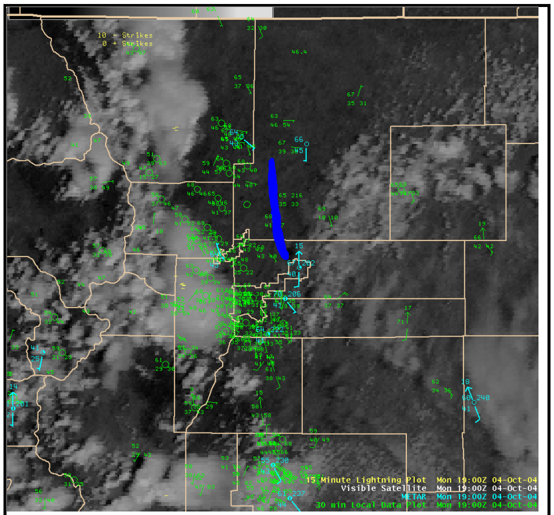

Fig. 4. Visible satellite image overlaid with METARs (cyan) and observations from a variety of non-official surface sites (yellow), and a 15-min duration lightning plot, for 1900 UTC on 4 Oct 04. Map background shows the counties. Note that the first station to the southeast of DIA is reporting an erroneous (northeasterly) wind direction. Tornadoes occurred within the blue swath.

A DCVZ boundary was present for much of the afternoon. The initial tornadoes were approximately 18 km from the radar. However, the tornadoes that occurred farther north were at least 70 km away, so the effects of distance on observing WSR-88D radar signals associated with these nonsupercell tornadoes was apparent. The time of the year for such an outbreak of tornadoes was unusual, and surface conditions were dry (Fig. 4), with dewpoints near or just under 40 °F. Using surface conditions observed close to the time of the tornadoes (a temperature of 67 °F with a dewpoint of 42 °F) with the 1200 UTC Denver sounding yields a CAPE of 900 Jkg^{-1}, with an LCL of approximately 5300 ft AGL. Note that at 1900 UTC convection was already ongoing in the foothills west of Denver.

Surface observations did not suggest a particularly strong DCVZ, although there is a lack of surface stations east of Denver and DIA. In fact, the Doppler velocity (Fig. 5) at 2000 UTC indicates a stronger south to southeast flow of about 20 kts extending westward to just west of the radar. Some light flow towards the radar is shown in the limited clear-air signal in southeast Boulder County, with KBJC reporting a 5 kt NNW wind. The stronger southeast flow is revealed at some of the METAR sites as the DCVZ continued to drift to the west, passing DIA (Fig. 6). Meanwhile, weak but more organized outflow from small storms in the foothills was increasing the flow towards the DCVZ from the west. The result was an increase in existing vertical vorticity along the DCVZ to between 0.005 and 0.010 s^{-1}, values slightly less than those favored for nonsupercell tornado development, according to guidance from the

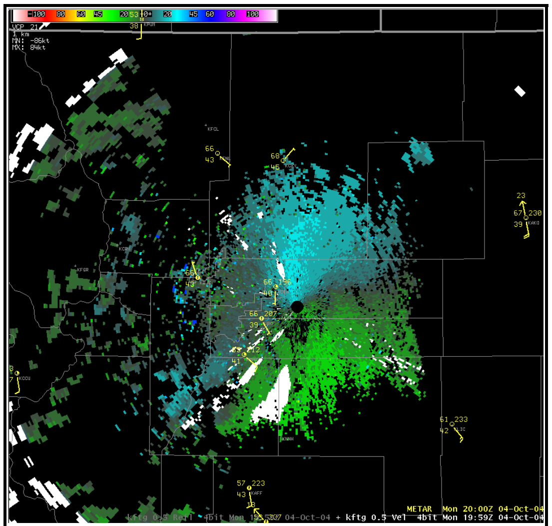

Fig. 5. Doppler velocity overlaid with METARs for 2000 UTC on 4 Oct. Scale at top is in knots.

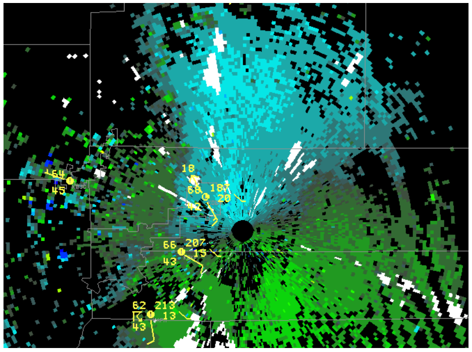

Fig. 6. As in Fig. 5, for 2130 UTC on 4 Oct.

NOAA Warning Decision Training Branch (WDTB, at http://www.wdtb.noaa.gov/index.html). Moisture convergence had increased as well, enough to generate convection directly over DIA by 2105 UTC. From past experience, initial landspout development typically occurs near these first rapidly developing storm cells. However, in this case, the first storm cell was displaced approximately 8 km east of the DCVZ, potentially far enough away to prevent the updraft from stretching the already limited vertical vorticity and thus preventing tornado development at this time. Nonetheless, outflow from this storm produced an increase in southeasterly surface flow to the northwest of DIA, further strengthening the DCVZ and associated vertical vorticity to more favorable values around 0.01 s^{-1}.

By 2145 UTC, another storm cell had quickly developed just northwest of DIA. This particular storm was only displaced about 3 km east of the DCVZ, and the first tornado developed with this circulation. While this tornado was reported at a later time to the Boulder WFO, weather spotters estimated that it occurred near 2155 UTC, followed by another tornado near 2202 UTC. Figure 7 shows the KFTG WSR-88D imagery for 2154 UTC near the time of the first reported tornado. Note the VR shear tool indicates 26 knots of shear over a distance of 0.7 nm, or existing vertical vorticity near 0.021 s^{-1}. WDTB guidance showed this to be more than sufficient for tornadogenesis. This was the first of five tornadoes in the Barr Lake and Brighton areas. Five additional, short-lived F0 to F1 intensity tornadoes which produced structural damage occurred in an eight-minute period between 2240 UTC and 2248 UTC farther north along the DCVZ in Weld County. Velocity signatures from the KFTG WSR-88D for these ensuing tornadoes were similar to the first

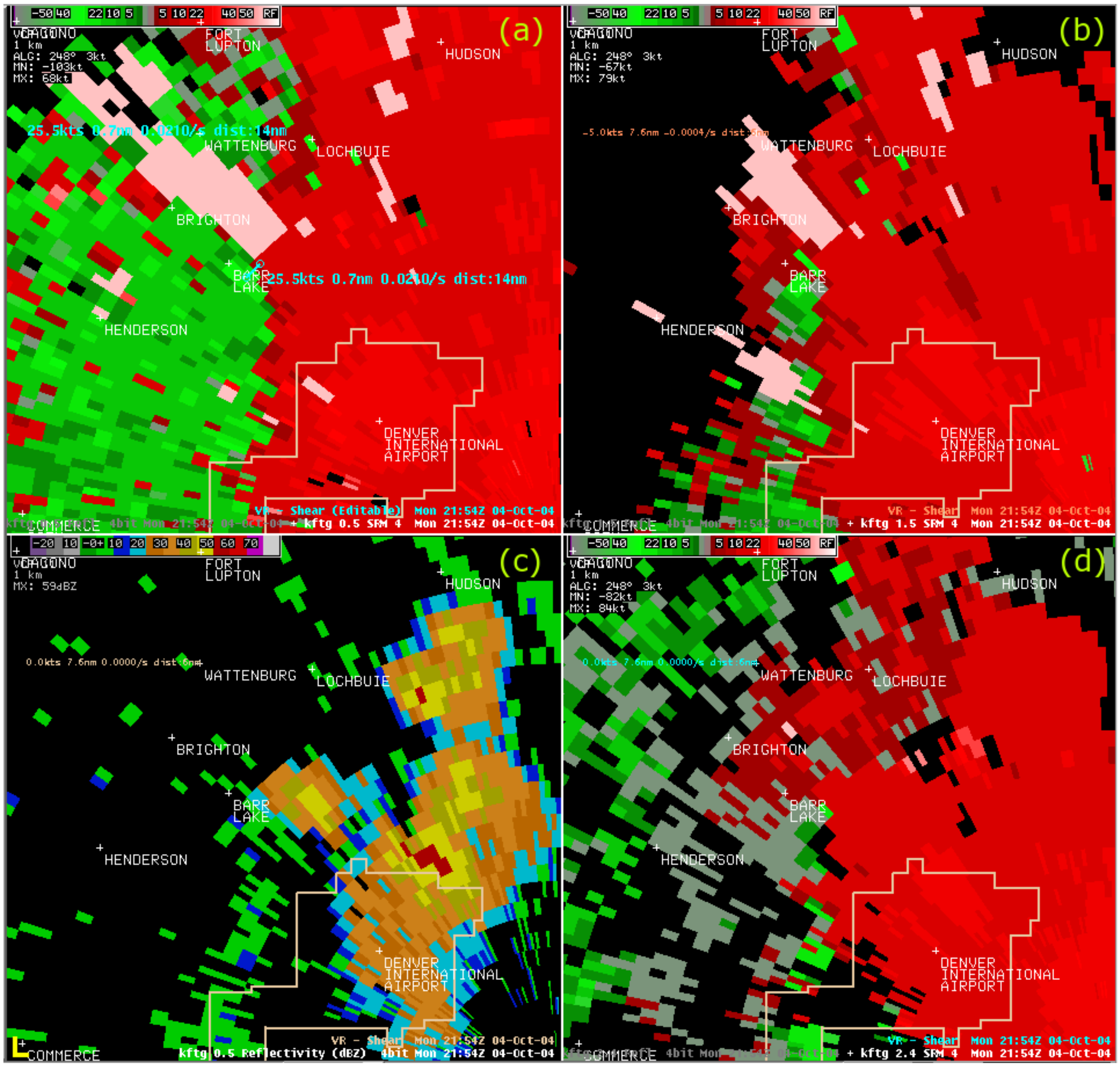

Fig. 7. A 4-panel display for 2154 UTC on 4 October showing: Doppler velocity (storm-relative motion, as in Figs. 5 and 6) at 0.5º (a), 1.5º (b), 2.4º (d), with 0.5º reflectivity (c).

signatures in some of the closer tornadoes, although the best signal was the one shown in Fig. 7. Signals were almost non-existent for the other tornadoes to the north, as these were close to 70 km from the radar, and consequently the wider range bins masked the tornado signatures.

5. CONCLUDING REMARKS

Accurately predicting the development of nonsupercell tornadoes with appreciable lead times, while concurrently minimizing false alarms, continues to be a challenge. Though the synoptic scale features that produce the DCVZ are well recognized, the intricate details that determine whether or not the day will be “active” remain less certain. Many days with a DCVZ produce nothing more than ordinary thunderstorms, while others, such as the one on 4 October 2004, are prolific producers of tornadoes. If warnings would be issued every time a storm cell initiated along the DCVZ, false alarm rates could reach excessive levels quite rapidly. However, if warnings are not issued until tornadoes are being reported, average tornado warning lead times (for all tornadoes) will decrease substantially. Perhaps further-detailed, real-time vertical vorticity analysis using the VR shear tool would aid the forecaster in determining whether or not tornadogenesis would occur, and provide some additional lead time. But even this technique could only be used within reasonable distance (~50 km) from the radar. A dense radar network could provide significantly better coverage of boundary location, interaction, and existing vertical vorticity, and thus aid the forecaster in warning decisions. Experimental technology such as infrasound (Bedard et al. 2004) may yield signals with an incipient nonsupercell tornado. Experience at the Boulder WFO with experimental infrasound data has been mixed over the last two years. Some infrasound data for this case will be shown at the conference. The challenge for forecasters will still exist, with tornadogenesis along the DCVZ under young cumulonimbi, so detailed analysis of zoomed radar data at multiple elevation angles is required on DCVZ days.

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