P10.4 EXAMINATION OF TORNADIC AND NON-TORNADIC SUPERCELLS IN SOUTHWEST VIRGINIA ON 28 APRIL 2002

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1. INTRODUCTION

Strong tornadoes spawned by supercell thunderstorms in and near the central Appalachians in the eastern U.S. are quite rare compared to some other parts of the country. This is likely due to the fact that the higher terrain typically has reduced surface temperature and moisture, a complex boundary layer with variable wind speeds and directions. Furthermore, a mid-level mixed layer with drier air aloft is much less common in the Eastern U.S. compared to the Midwest. Still, supercell thunderstorms are often an annual occurrence, often making several appearances during the spring in the central Appalachians, producing many reports of wind damage and often hail the size of golf balls or larger. Relatively weak and brief non-supercell tornadoes can occur at just about any time of year with multicellular or convective lines. Occurrences of stronger (F2 and greater) tornadoes from supercell thunderstorms are extremely rare within the mountainous terrain of southwest Virginia, but become more common with increasing distance east of the “Blue Ridge” (the eastern most chain of mountains in the Appalachians of Virginia and North Carolina). Figure 1 shows the number of F2 and greater intensity tornadoes between 1950 and 2002 in a portion of the Mid-Atlantic region that includes Virginia, West Virginia, Maryland, Delaware, and portions of surrounding states. Note the higher density and longer tracks of tornado touchdowns in eastern North Carolina and Virginia, with a clear minimum in western Virginia as well as West Virginia (mountainous areas).

While supercells approaching from lower elevations to the west are most likely to meet their demise as they move into the more stable environment of the Appalachian mountains, and other storms may first develop or intensify into supercells several tens of kilometers east of the Blue Ridge, *occasionally* long track supercells will move right through the Appalachian mountains from west to east with only minor, if any, weakening. Even so, these long lived severe storms rarely produce tornadoes until they move east of the Blue Ridge. A more detailed analysis of the climatology of supercells and strong tornadoes in this region is beyond the scope of this study, but would be worthwhile exploring in future work.

The afternoon of 28 April 2002, was one of those rare occasions when favorable conditions allowed long track isolated supercells to develop west of the Appalachians and track all the way through the mountains and eventually out into the Piedmont of eastern Virginia and central North Carolina. One supercell tracked through the mountains of northern Virginia and into Maryland south of Washington D.C., producing the well-publicized F4 La Plata tornado (the subject of a couple of studies presented at this conference). Four isolated supercells moving across the Blue Ridge of southwest Virginia were within the warning responsibility area of the National Weather Service Forecast (NWS) Office (WFO) in Blacksburg, Virginia (RNK). These supercells left swaths of wind damage and large hail in their wakes. However, only one of these supercells, the northern most, produced tornadoes within the area of study (two separate touchdowns of F1-F2 damage, resulting in 12 injuries and approximately $7 million in damage). Figure 2 shows the approximate tracks of the four supercells as defined by their mesocyclone positions (dashed lines), as well as the two tornado tracks (red solid lines) associated with mesocyclone “A”, and in relation to the terrain. Much later, the second of the four supercells

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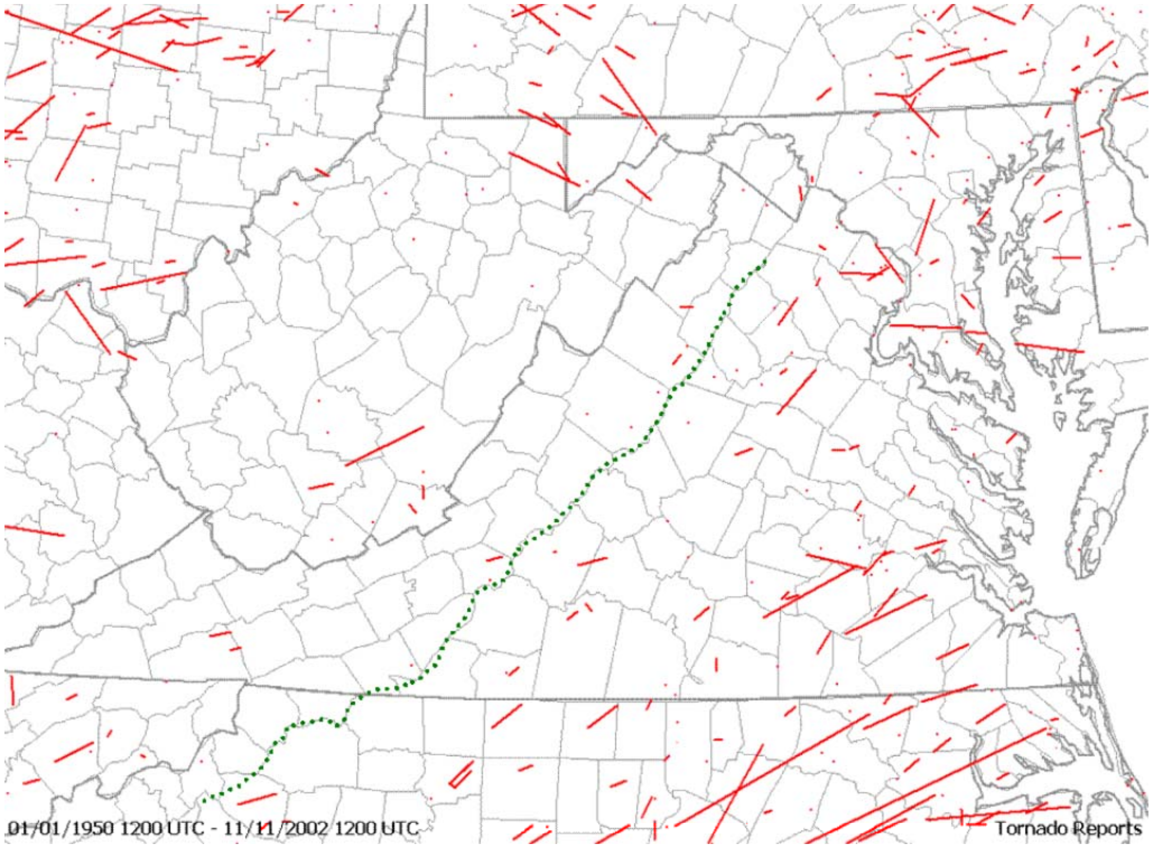

Figure 1. Tracks of strong to violent (F2 and greater) tornadoes across Virginia and surrounding areas between 1950 and 2002. The Blue Ridge is depicted by the dotted green line. Tornado data and the plotting application for Figure 1 are courtesy of the Storm Prediction Center (SPC) in Norman, Oklahoma.

(labeled "B" in Fig. 2) did produce a weak tornado in southeastern Virginia, but this was well outside the RNK WFO area of responsibility and the effective range from the Floyd County WSR-88D radar (labeled KFCX in Fig. 2), which roughly defined the area of this study.

It will be shown that differences in mesocyclone and radar reflectivity structures between the four storms were rather subtle. The depth of the tornadic supercell (as observed in satellite and radar data), and some observed *trends* in mesocyclone characteristics, may have slightly favored this northern-most storm for tornadic threat. Furthermore, objective mesoscale analyses of the environment (from the 40km Rapid Update Cycle [RUC] model) and close examination of surface observations is reviewed and suggests there were some subtle differences in several parameters previously shown to be correlated with tornadic environments including: lifted condensation level, storm-relative helicity, energy-helicity index, the vorticity generation parameter, and others (Rasmussen and Blanchard 1998). In addition, cloud-to-ground lightning behavior associated with these supercells showed similar trends to previously documented tornadic supercells (MacGorman 1993), but did not help to differentiate between the tornadic and non-tornadic storms in this case.

This study illustrates the difficulties in making operational tornado warning decisions when there are many complex factors associated with tornadogenesis to consider. Careful scrutiny of subtle differences in storm structures and trends, as well as small scale

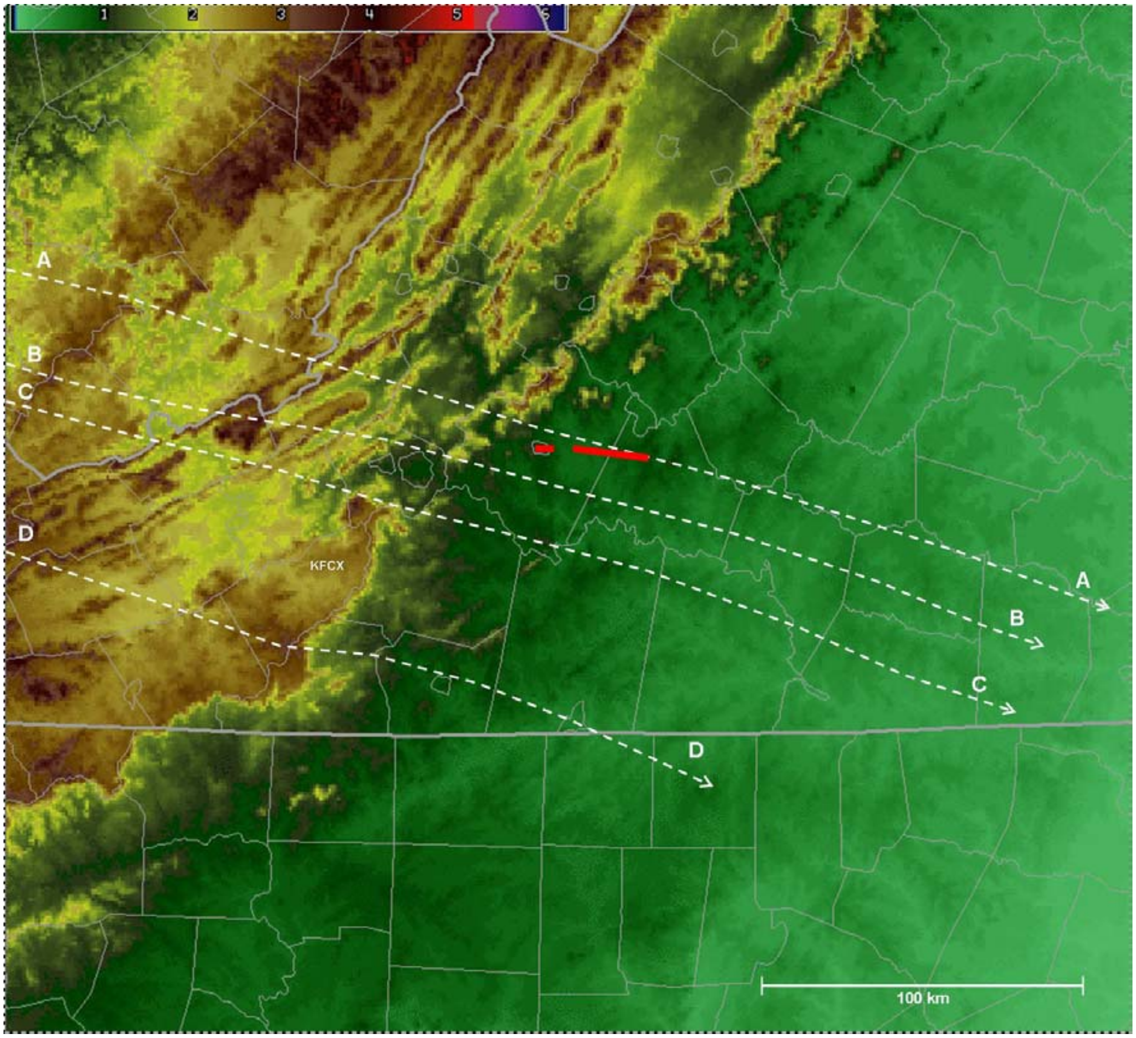

Figure 2. Tracks of mesocyclones (dashed) shown relative to terrain (shaded image) and state borders (thicker gray solid lines). Storms were moving from WNW to ESE. Two tornado tracks are shown as thick, solid red lines. Scale of terrain image is in upper left in thousands of feet (yellow is 2,000 ft and brown begins around 2,500 ft). Distance scale in lower right is 100 km.

environmental differences, is required to enable forecasters opportunity for success in future warning decisions.

2. SYNOPTIC OVERVIEW

The large scale pattern on the morning of 28 April 2004 was characterized by generally progressive flow, with a fast moving low amplitude 500 hPa trough over the Midwest U.S (not shown). A surface warm front extended across Pennsylvania and northern Virginia, and a strong surface cold front moving into the Ohio Valley was forecast to reach the western side of the Appalachians by the evening. As the day progressed, the warm front continued to move north, while the atmosphere to the south quickly destabilized. Surface dew points climbed into the mid and upper 60s (°F), and winds aloft steadily increased as the surface cold front moved closer. A special sounding was released at RNK 1800 UTC (1400 local time), in the heart of the Appalachians about 600m MSL. The sounding was modified for surface conditions just east of the Blue Ridge, and indicated Convective Potential Available Energy (CAPE) values were near 3000 Jkg^{-1}, with a nearly straight hodograph shape and 0-4 km shear values of about 30 ms^{-1} (not shown). These values of instability and shear are more than enough for supercell formation to be anticipated according to both numerical simulations and observational evidence (Weisman and Klemp 1984). In advance of the surface front across portions of Ohio, West Virginia, Kentucky, and Tennessee, many thunderstorms quickly developed into isolated supercells that generally maintained their structure and intensity as they moved across the Appalachian mountains by mid afternoon. A Tornado Watch was issued for the entire area by the SPC in Norman, Oklahoma at 1800 UTC.

3. MESOSCALE ENVIRONMENT ACROSS VIRGINIA

Hourly 40 km RUC model initial analyses from the NWS Advanced Weather Information Processing System (AWIPS) and the NOAA Forecast System Lab's (FSL) Display Two Dimension software (D2D) were the only archived data available for generating pseudo-mesoscale objective analyses of parameters previously identified to help differentiate between tornadic and non-tornadic supercell environments (Rasmussen and Blanchard 1998; Rasmussen 2003; among others). The fields examined included surface-based CAPE, 0-3 km storm-relative helicity (SRH), 0-1 km SRH, energy-helicity index (EHI), lifted condensation level (LCL), and the vorticity generation parameter (VGP). Although there are some minor differences between how these parameters are calculated from representative soundings in the referenced work and the RUC analyses from AWIPS (for example, each uses a different method for estimating the storm motion vector to calculate SRH), the AWIPS RUC values of these parameters were well into the "favorable" range for supercell tornadoes (based on Rasmussen and Blanchard 1998; Rasmussen 2003) across all of Virginia as the supercells moved east across the Blue Ridge and into the Piedmont.

In the environment just east of the Blue Ridge at the time the first and northern most supercell (its associated mesocyclone track is labeled "A" in Fig. 2) moved east of the Blue Ridge (at 2000 UTC), CAPE values ranged from 1500 Jkg^{-1} in north-central North Carolina to 2500 Jkg^{-1} in west-central Virginia. This is somewhat less than the value obtained from the 1800 UTC observed RNK sounding modified for observed surface conditions just east of the Blue Ridge. The RUC underestimate of CAPE would also result in the possible underestimation of other parameters which use CAPE in their calculation. Additional parameter values from the RUC for the area east of the Blue Ridge at 2000 UTC include: 0-3 km SRH ranged from 250 to 400 m^2s^{-2}, 0-1 km SRH ranged from 150 to 200 m^2s^{-2}, EHI ranged from 1.0 to 2.5, and LCL ranged from 1200 m down to 600 m (shown in Fig. 3 overlaid with surface observations), and the VGP ranged from 0.25 to 0.35. While all these fields suggested more than enough instability, shear and low level helicity, as well as favorable cloud base heights for tornadic potential anywhere across the region where the supercells tracked, the parameter values at this particular time generally increased (decreased in the case of LCL) from south to north, placing the northern most supercell in the most favorable environment of all four storms at this time. The temperature and dew point observations at 2000 UTC (Fig. 3) also support the RUC analysis of lower cloud bases farther to the north and east across Virginia.

Over the next one to two hours (2100 - 2200 UTC), soon after the tornado touchdown with supercell "A", and as the next three supercells were beginning to move east of the Blue Ridge along tracks just to the south of supercell A, the RUC analyses indicated that most of these parameters continued to increase across the region. As low level shear and surface dew points increased, many of these parameters became just as favorable across southern Virginia as anywhere else in the region east of the Blue Ridge. Therefore, while it is likely that conditions favoring tornadic development increased somewhat from south to north initially (at about 2000 UTC when supercell A moved east of the Blue Ridge), it is difficult to argue that the mesoscale environments were any less favorable at the times when supercells B, C, and D tracked east of the Blue Ridge (between 2100 and 2200 UTC). Despite any gradients from south to north, the overall environment in this entire region was considered favorable for tornadoes.

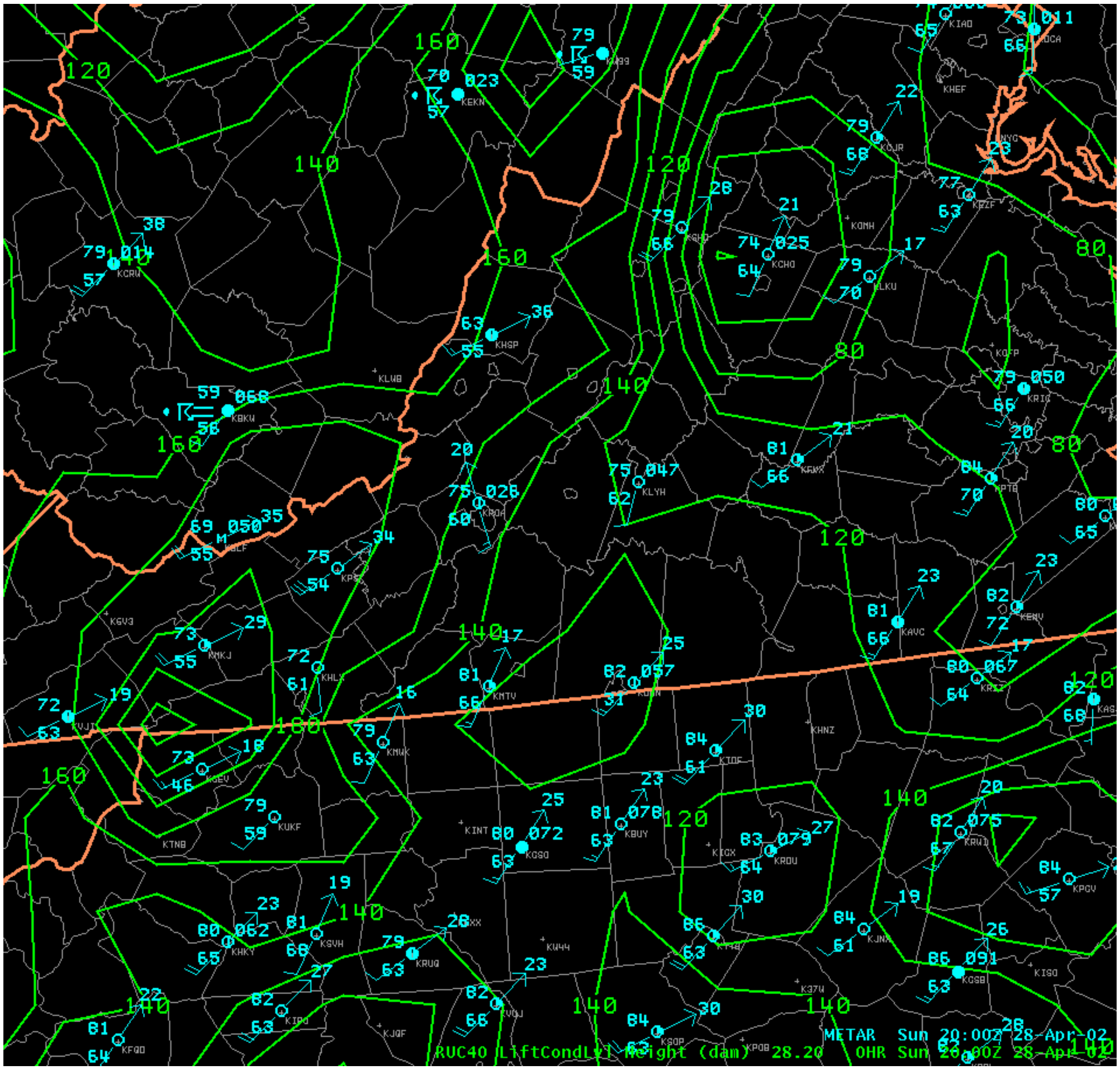

Figure 3. 40 km RUC analysis valid 28 April 2002, 2000 UTC of lifted condensation level (green) in dm, with plotted surface observations (blue) with T/T_d in °F.

Since many field intercept projects such as Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX) have shown that environments can change dramatically on the storm scale (Markowski et al. 1998), and the observational network in this region of Virginia (which is primarily NWS and Federal Aviation Administration (FAA) automated surface sensors at airports, as well as the Doppler radar wind profile) was not able to resolve any variations on this scale, some important storm scale differences in the low level environment might very well have existed. It is possible that these supercells may have altered the storm scale environment for each other. For example, outflow from supercell A may have influenced the local environment of supercell B tracking just behind it and to the south, and similarly storm B may have influenced the environment for storm C, and so on. Whether this might have altered the environment favorably or unfavorably is difficult to tell with the spacing of observations, but will be discussed briefly in Section 5.

4. SATELLITE AND LIGHTNING OBSERVATIONS

Infra Red (IR) satellite data (not shown) revealed that the tornadic supercell had the coldest tops of any storms in Virginia on 28 April, including the isolated supercell that crossed the northern part of the state and produced the devastating La Plata, Maryland tornado. However, by the time the storms were headed into central Virginia (60-90 minutes after the time of the tornado), supercells B and C were nearly as deep, while supercell D remained clearly shallower through its existence. This may be the best indication that the updraft of the tornadic storm was a little more intense that the others, since radar products only indicated subtle differences in depth, and sampling errors increased as storms moved farther from the radar.

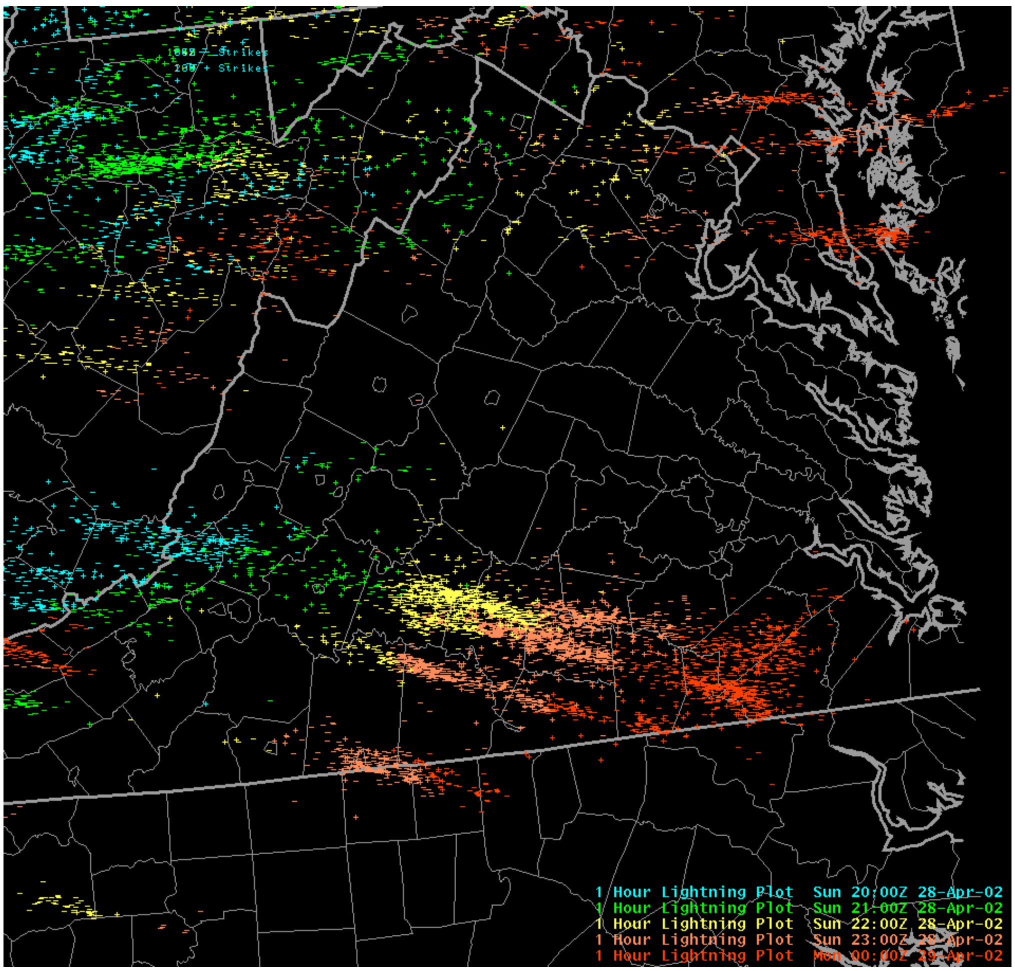

Figure 4. Cloud-to-ground lightning strikes between 1900 UTC 28 April 2002 – 0000 UTC 29 April 2002. Each hour is represented by a different color (blue first hour, red latest hour).

Cloud-to-ground (CG) lightning data showed that over the course of its existence, the tornadic supercell (A) had an overall higher flash density, perhaps due to a stronger updraft (Fig. 4). Supercells B, C and D eventually developed high CG flash rates as well. In Figure 4, as supercell A initially crossed the West Virginia/Virginia state line it actually was more active, before decreasing about one county into Virginia, which was roughly 30-45 minutes before tornadogenesis. Then, immediately after the tornado dissipated, the CG flash rate increased dramatically. This is consistent with other published observations of CG lightning in tornadic storms, where the flash rate is seen to increase dramatically either during the tornado or immediately afterward, as the intense updraft begins to collapse (see MacGorman 1993, for a good summary of some of these studies). In this case, the CG flash rates associated with supercells B, C, and D each showed dramatic increases along their tracks as well, but none were associated with tornadoes. So it appears in this case the CG flash rates are not a particularly good discriminator between the tornadic and non-tornadic supercells, other than the fact that the tornadic supercell was more active as it crossed the higher terrain, before then decreasing in activity as it crossed the Blue Ridge and produced the tornado.

5. RADAR OBSERVATIONS

All four storms exhibited classic supercell radar signatures in terms of reflectivity and mesocyclone structures. A comparison of the subtle differences between the tornadic storm and three non-tornadic storms will demonstrate potentially important characteristics that suggest a higher tornado threat.

5.1 Reflectivity Structures and Trends

As it moved east of the Blue Ridge, the tornadic supercell ("A" in Fig. 2) continued to intensify and develop very distinct supercell structures, including a bounded weak echo region (BWER) (not shown) and a text book low-level hook echo on the southwest flank, which emerged minutes before tornado touchdown (Fig. 5a). At this time there was also a strong, but rather broad low-level mesocyclone circulation associated with the updraft region (Fig. 5b), which did not tighten until after the tornado had touched down for the first time. A more detailed description of the mesocyclone characteristics and trends of all four storms is provided in Section 5.2.

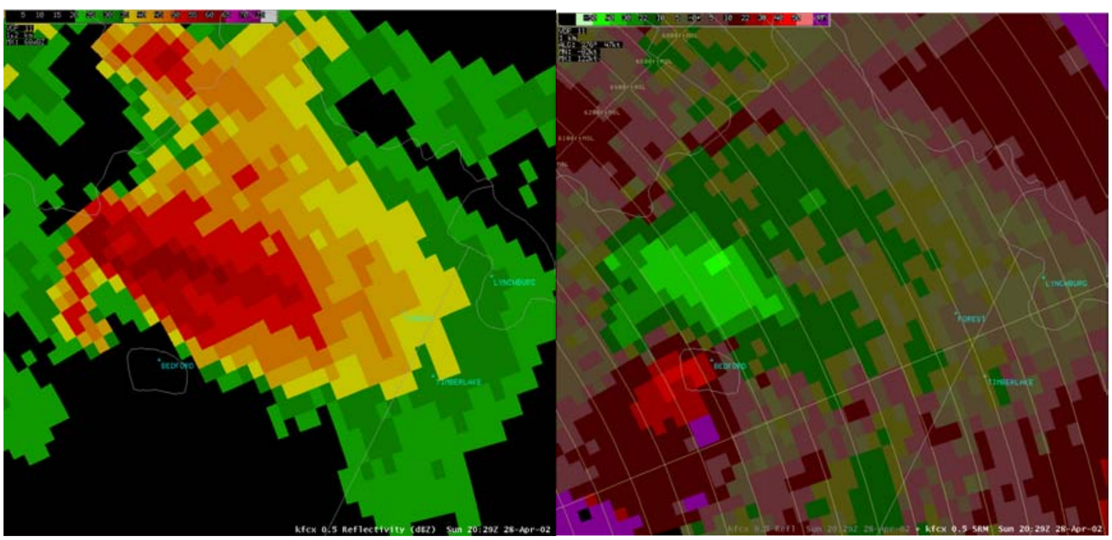

Figure 5. a) Left: KFCX WSR-88D reflectivity at 0.5° elevation slice, valid at 2029 UTC 28 April 2002, zoomed in on supercell "A" (track shown in Fig. 2) a couple of minutes before tornado touchdown. Center of image is approximately 100 km from radar site. Dark red represents 60 dBZ reflectivity. b) Right: Same as in (a) except for storm-relative velocity. Range rings are approximately 3.5 km apart, and show the radar is located toward the southwest. Red is outbound velocity, green is inbound. Strongest outbound in mesocyclone is 30-40 kts; strongest inbound is 40-50 kts.

As supercell A moved east-southeastward, the tornado eventually lifted, with supercell B following a parallel path within about 10-20 km to the south. This appeared to place supercell B in a favorable position relative to the assumed outflow location of supercell A (which could not be directly seen in surface observations or in radar data due to beam overshooting). On closer examination, a small area of light rain associated with the rear flank downdraft (RFD) region pushed south just enough to possibly stabilize the boundary layer in the path of supercell B. Supercell B also had a clear hook echo and BWER during segments of its existence (not shown), but perhaps not as distinct as supercell A as seen in Fig. 5.

There was no indication that supercell B was able to push an outflow boundary into the path of supercell C, even though supercell C was following a parallel track close behind and about 10-20 km south of supercell B's track. The updraft for supercell C was more likely to be passing over a well-mixed boundary layer for its entire life cycle compared to supercell B. Supercell C also developed a very distinct classic supercell structure, much like supercell A, but perhaps slightly smaller in horizontal extent (Fig. 7a).

Supercell D on the other hand, was 40-50 km to the south of supercell C, and even farther behind the other storms and well away from their outflow boundaries While certainly not being influenced negatively by outflows from other storms, this supercell probably was moving through a slightly less favorable mesoscale environment for tornadoes (as described in the Section 3). Supercell D was also somewhat smaller both in horizontal and vertical extent compared to the other supercells, although it definitely exhibited clear hook echo and BWER through a significant portion of its life cycle. Figure 6 shows a low-level reflectivity image of all four supercells together as they tracked across south-central Virginia. Although this is more than an hour after the tornado dissipated from supercell A, even at a substantial range from the radar (100-150 km) the hook echoes and weak echo inflow notch signatures are apparent in all four storms.

5.2 Mesocyclone Structures and Trends

While radar sampling can often mask true mesocyclone characteristics and trends, and there are always exceptions to the more commonly observed behaviors of tornado-producing mesocyclones, forecasters are trained to look for the following mesocyclone characteristics that are more likely to spawn tornadoes: persistent and relatively deep signature and getting deeper (especially developing downward), strong rotational velocities and getting stronger (strong is defined relative to range from radar), small or compact horizontal diameters and getting smaller (as measured from the maximum outbound to maximum inbound value of Doppler velocities within the signature), and a low-level convergent signature below the mesocyclone (Burgess et al. 1993). All four supercells examined in this study exhibited similar characteristics in terms of mesocyclone strength, diameter, and depth, in a general sense throughout their existence. All four mesocyclones were very persistent as well, although there were differences in how long their strongest attributes lasted. A low-level (below 3 km) convergent signature below the mesocyclone core was not observed with any of the storms. Only relatively subtle differences in the vertical structure and trends of the mesocyclones may offer some indication as to why only supercell A produced a tornado.

A full 30 to 40 minutes before the first tornado touched down, mesocyclone A was strong and deep down to about 1 km above ground level (AGL). Then it broadened and weakened substantially 15 minutes before the touchdown, not re-strengthening until 5 to 10 minutes after the second tornado touched down, and mainly only above 3 km. Figure 5b shows the broad diameter at low levels (~1.5 km AGL) between maximum outbound (red) and maximum inbound (green) velocities within minutes of tornado touchdown (and matches in time with the reflectivity image in Fig. 5a). The diameter remained rather broad (6-10 km), despite strong rotational velocities below 3 km AGL for about 90 minutes past the time the second tornado lifted. While the mesocyclone trends didn't correlate all that well with the tornado occurrences, it did have a strong and deep signature well in advance of the tornado. Mesocyclone A also showed very good vertical correlation, whereas the other mesocyclones often had some degree of tilt to them.

Mesocyclone B overall had weaker rotational velocities than A, but also generally had a smaller diameter, resulting in comparable values of shear, including below 3 km AGL (not shown). It is important to point out, however, that sampling limitations of the radar make diameter measurements less consistent from scan to scan than rotational velocity measurements. Nevertheless, these measurements of shear were not as persistent through as much of a depth compared to mesocyclone A, other than for about 10 minutes early on in its existence. As supercell B moved farther away from the radar, it developed very strong rotational velocities at the lowest elevation scan (not shown), although the diameter was very broad. Due to lack of adequate vertical sampling at this range, we can only tell that this strong rotation was sampled at about 3 km AGL, although there is some evidence from a neighboring radar to the east that it did extend a little lower.

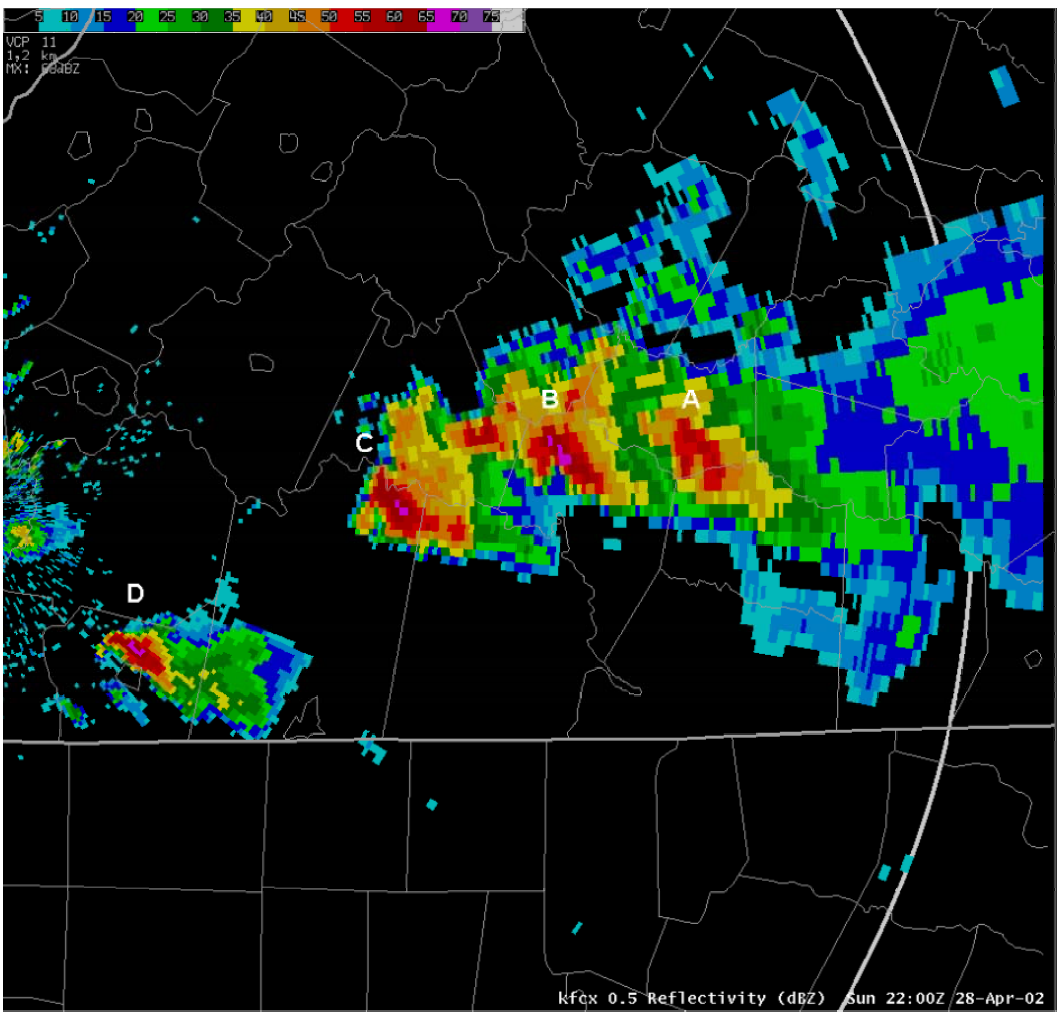

Figure 6. KFCX WSR-88D reflectivity at 0.5° elevation slice valid at 2200 UTC 28 April 2002. The supercells are labeled as they are referred to in the text. Radar is located at left edge of figure. Range ring shown is at approximately 250 km from the radar.

Mesocyclone C exhibited the strongest rotational velocities and smallest diameters (thus strongest overall shear values) in low levels (2-3 km AGL) of any of the mesocyclones, but only for about 15 minutes. However, it was rather broad above this (4-6 km AGL), and otherwise did not show much persistence in terms of the stronger signatures. The very strong low-level signatures correlated with the time of classic supercell reflectivity structures. Figure 7b shows the compact circulation coincident with the hook echo (Fig.7a). In an operational setting this supercell appeared to have as much tornadic threat as any of the four that day. In fact, 10 minutes after the image in Fig. 7, was the only volume scan where a tornado vortex signature (TVS) was detected by the algorithm on this day (adaptable parameter values for the KFCX radar product generator were set to trigger a TVS only for the most extreme signatures).

Mesocyclone D, while much smaller in diameter than the others for most of its life, had weaker rotational velocities in general. There was a period of time relatively early on when it had overall strong shear between 2-5 km AGL (and occasionally down to 1 km) for over 30 minutes, but the strong shear was due mainly to the small diameter rather than impressive rotational velocities. When stronger rotational velocities finally developed at the lowest 2-3 km, the mesocyclone was either broad, or for the one or two volume scans when it was also compact (therefore strong shear), the signature was not all that deep. Since the overall storm was not as deep as the others (as described earlier in satellite imagery), the mesocyclone still extended through a significant relative depth of the storm.

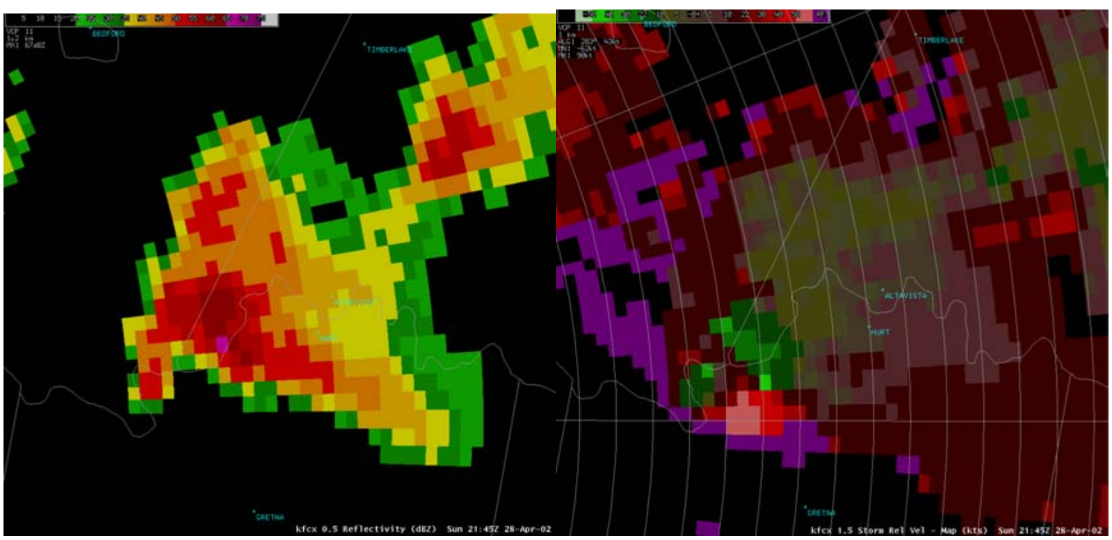

Figure 7. Same as Fig. 5, except for 2145 UTC and zoomed on supercell "C" (track shown in Fig. 2). Center of images is approximately 90 km east of the radar.

6. DISCUSSION

The differences in reflectivity and mesocyclone structures between the four storms was considered rather subtle. Supercell A was a little deeper overall, perhaps slightly larger horizontally, and exhibited the most classic supercell reflectivity structure of all the storms for one or two volume scans. While all mesocyclones were very long-lived, when comparing the longevity of the particularly strong and deep periods, mesocyclone A probably showed these characteristics for a little longer, even though this was well before the tornado touchdown. Mesocyclone C had the strongest and most persistent overall low-level signature. An argument can be made that mesocyclone B crossed the outflow boundary from the RFD of supercell A, and that supercell D was in a slightly less favorable environment for tornadoes compared with the other supercells, and was also not quite as deep and strong overall. In an operational setting where decisions have to made rapidly, it would be difficult to place substantial weight on these subtle observations, nor would it be easy to keenly observe all these subtle differences when trying to view a variety of data in a short period of time.

The degree to which the terrain may have played a role in tornadogenesis in this case is not clearly understood. Additional observations or numerically modeling these storms would assist in substantiating the role of terrain in tornadogenesis. One hypothesis is that since supercell A was already fairly intense as it crossed the Blue Ridge, the low-level circulation would be stretched vertically coming off the slope, thus intensifying and deepening the circulation through conservation of potential vorticity. The other storms became more intense well after they crossed the Blue Ridge, or did not cross where the slope was as steep, and therefore lacked one potential mechanism for vertical stretching. Local forecasters also know the Appalachians can produce a lee side convergence zone under west or northwesterly flow regimes, and which typically develops several tens of kilometers east of the Blue Ridge. This lee side convergence zone was not present on 28 April. Perhaps there were smaller scale convergent zones or regions of locally strong vertical vorticity (analogous to the Denver Cyclonic Vorticity Zone; Szoke et al. 1984) that cannot be currently resolved but are often present. In such cases, a strong updraft, especially one with a pre-existing deep mesocyclone, could spin up one of these vorticity zones into a tornadic scale circulation from the ground up.

7. CONCLUSIONS

In order to obtain longer lead times for tornado warnings, decisions to warn should be based largely on classic supercell reflectivity structures when associated with moderate to strong and persistent mesocyclones, and supported by favorable mesoscale or storm scale environments for tornadoes. The exception would be when observations *clearly* indicate the local environment is *not* favorable (e.g., usually a very stable near-surface layer preventing the rear flank downdraft from stretching and tightening the vortex down to the ground). Waiting for the tightening of the mesocyclone or strengthening of the rotational velocities in the lowest 1-2 km may result in little if any lead time, since these signatures may develop coincident with tornado formation (and with increasing range from the radar diameter measurements become less reliable).

The data shown in this study reveal subtle differences between the storm structures and mesoscale environments of the one tornadic supercell and three non-tornadic supercells. This analysis has provided some insight concerning why the northern-most supercell produced a tornado and the other supercells did not. While the careful examination of pertinent environmental parameters and storm structure characteristics suggests a higher overall tornadic threat with the northern-most supercell, they do *not* necessarily suggest that tornado warnings were *not* appropriate for the other three supercells, especially supercell C. Still, by understanding the importance of examining all potential evidence, and scrutinizing subtle differences, forecasters will be better able to make the appropriate decisions to warn earlier, or not to warn.

Less than half of all mesocyclones are associated with tornadoes in a large sample of cases from Oklahoma (Burgess 1993), and, in fact, when considering observations across the entire country this percentage may be significantly less than half. The 28 April 2002 event seems to be a good illustration of these earlier observations. There are still many unanswered questions concerning tornadogenesis mechanisms, particularly when terrain may have an important influence on the boundary layer. Storm scale modeling in locations east of the Appalachian mountains, or in other more subtle terrain features, such as the Cumberland Plateau in eastern Tennessee, the Ozarks in Arkansas, among others, would improve forecaster understanding about the possible orographic influences on low-level mesocyclones and tornadogenesis. The best hope for reducing the relatively high false alarm ratios while still maintaining high accuracy and long lead times for strong and violent supercell tornadoes, is for continued critical research into the most important local scale environmental parameters and internal storm physics that lead to tornadogenesis. This must be coupled with the deployment of observational networks and systems that can adequately detect mesoscale and storm scale environments, as well as continued forecaster training on results from research, use of new data sets, and best practices for warning decision methodologies.

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