2.6 ENVIRONMENTAL CONDITIONS ASSOCIATED WITH WEAK TORNADOES ACROSS SOUTHERN VIRGINIA AND NORTHEAST NORTH CAROLINA IN 2003 AND 2004

Daniel H. Reilly*
NOAA/National Weather Service, Wakefield, VA

1. INTRODUCTION

During 2003 and the first half of 2004, 36 tornadoes occurred within the National Weather Service (NWS) Weather Forecast Office (WFO) Wakefield, Virginia (AKQ) county warning area (CWA), which includes southeast Virginia, northeast North Carolina, and the lower Maryland and Virginia Eastern Shore. The tornadoes occurred on 18 different days. All were classified as weak, with ratings of F0 or F1 on the Fujita scale. Some of the tornadoes developed out of supercell storms, characterized by persistent and vertically correlated mesocyclones, and well-known reflectivity signatures such as hook echoes, bounded weak echo regions, echo overhangs, etc. However, most of the tornadic storms were not supercells, but had generally weaker or smaller scale circulations, with shallower and more transient radar velocity and reflectivity signatures.

In this study, the storm environments and radar signatures of all of these tornado cases, plus 2 in a county bordering the AKQ CWA, were studied. Radar, satellite, upper air, and surface observations were analyzed, as well as RUC-2 model soundings. Many of these events were not well anticipated by the Storm Prediction Center (SPC), or WFO AKQ.

It was found that tornadoes developed out of various environments, but certain patterns and environmental characteristics were common. On four days, tornadoes developed from supercells, which moved along northwest to southeast oriented thermal boundaries or fronts. Most of the other tornadic storms developed out of warm, humid air masses, characterized by relatively high surface dew points, low surface dew point depressions, and relatively low lifted condensation levels (LCLs). Given a low LCL environment, tornadoes were found in a variety of vertical shear environments, some characterized by large zero to 1 km shear, and others characterized by relatively weak low-level shear. Thermal boundaries, or cyclonic wind shift lines, and surface mesolows, were found near or at the points of tornado development in many cases.

In the following, the data used in this study will be described. Common shear and thermodynamic environments for these tornadic storms will be identified. Radar signatures of the tornadic storms for the various environments will be shown. Finally, the implications of this study for the warning forecaster will be given.

2. DATA

Surface, upper air, satellite, radar and model data were loaded into the Weather Event Simulator (WES), a software package that enables the replaying of archived meteorological data (Ferree 2002). Soundings from the initialization of the Rapid Update Cycle (RUC-2) model on a 40 km horizontally-spaced grid were analyzed at the points of tornado development for each case in the dataset, at the nearest hour prior to tornadogenesis. When adequate surface data were available, the surface parcel used in the RUC sounding was modified based on observations representative of the storm inflow. In addition, wind difference fields were computed between the RUC-2 surface level, and the 1 km and 6 km levels, to gauge the vertical wind shear in the environment. Various thermodynamic and shear parameters from the model soundings and shear fields were entered into a spreadsheet and further analyzed. RUC-2 data were unavailable for 3 cases, so they were not included. Surface, upper air, satellite and radar data were also studied using the WES for further assessment of storm environment and to identify any precursor radar

* Daniel H. Reilly, NOAA/NWS Wakefield, Wakefield, VA 23888-2742; email: Dan.Reilly@noaa.gov

signatures which might be useful in warning for these storms.

Information about the tornadoes, including intensity rating and time of occurrence, were taken from Storm Data from the National Climatic Data Center (NCDC). Data plots and analyses were also taken from the storm events, and mesoscale analysis archives from Storm Prediction Center (SPC) web site, and the online surface and upper air data archive from Plymouth State University.

3. RESULTS

3.1 *Analysis of the dataset*

Several recent studies have shown the importance of LCL height in discriminating tornadic versus non-tornadic environments (e.g. Craven 2002a; Edwards 2000; Rasmussen 1998; Thompson 2003). A scatter diagram, showing values of convective available potential energy (CAPE) versus LCL for the storm environments in this dataset, is shown in Fig. 1. Immediately apparent is the clustering of events at low LCLs, with greater than 85% of the cases occurring with values at or below 620 m, and nearly 60% of the cases below 420 m. There were also a handful of cases with higher LCLs, at or above 900 m, with higher CAPEs. These LCL values are considerably lower than the LCL values found in Rasmussen (1998), for observed soundings in the proximity of tornadoes rated F2 or greater (Fig. 2). They are also lower than the mean-layer LCL (MLLCL) values found in RUC soundings taken near F0 and F1 tornado-producing supercells in Thompson (2003), although results are not directly comparable as MLLCL is typically higher than LCL (Craven 2002b).

Looking more closely at the low LCL cases, the zero to 1 km and zero to 6 km shear values are plotted for those cases with LCLs less than 620 m, with the results presented in Fig. 3. It should be noted that shear values have a potential rounding error of ± 1.3 ms^{-1} as they were taken from a vector shear field that was displayed rounded to the nearest 2.6 ms^{-1} (5 knots). This rounding also explains the number of events with apparently identical shear values. Note that tornadoes

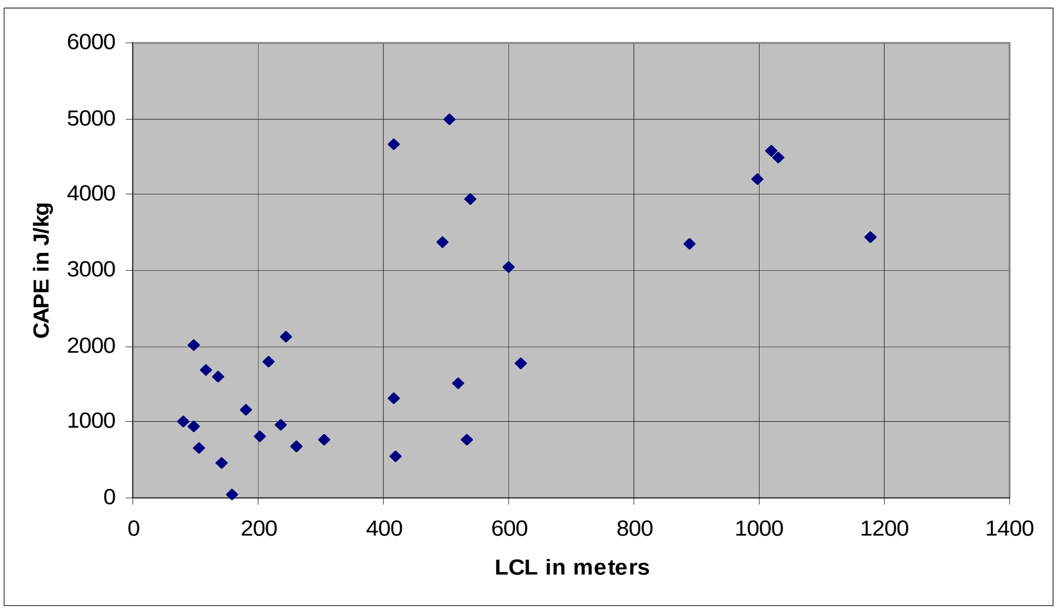

Fig. 1. Convective available potential energy (CAPE) versus lifted condensation level (LCL) for the tornadic thunderstorm environments in this study. Values taken from RUC-2 soundings.

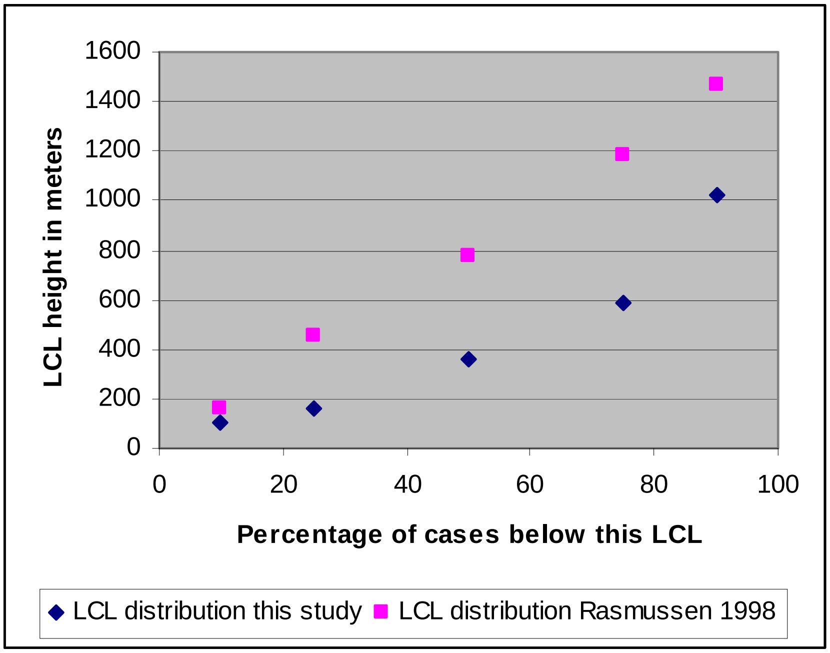

Fig. 2. Comparison of LCL distribution for this dataset with that from Rasmussen 1998. X-axis shows the 10th, 25th, 50th, 75th, and 90th percentile values for each dataset.

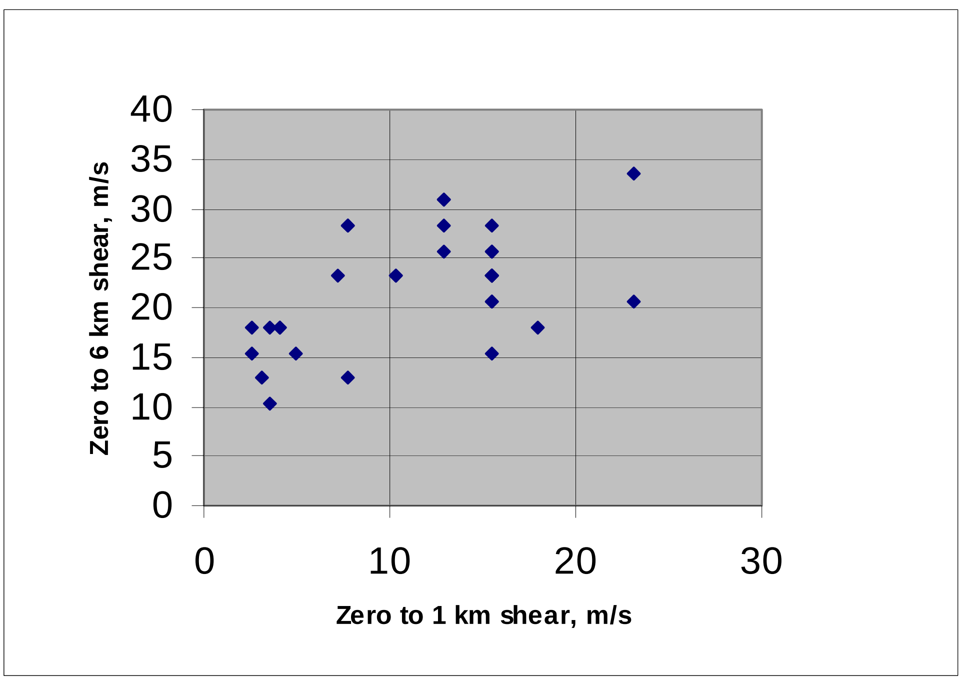

Fig. 3. Deep layer (zero to 6 km) versus zero to 1 km shear for low-LCL cases (LCL less than 620 m).

Table 1. Shear and instability parameters from RUC soundings just prior to tornado development for supercell storms near boundary. CAPE is surface based. Data missing for 8 May 2003 case.

Date	Time (UTC)	Tornado	Rating	LCL (m)	0-1 km shear (ms^{-1})	0-6 km shear (ms^{-1})	0-3km helicity (m^2s^{-2})	CAPE	BRN
5/8/2003	1915	Tappahannock, VA	F0						
5/9/2003	1850	Antioch, VA	F0	506	13	31	364	4992	31.3
5/9/2003	1935	Amelia C.H., VA	F1	538	13	31	372	3941	25.6
5/9/2003	2035	Jarratt, VA	F0	1020	8	28	231	4574	45
5/9/2003	2050	Drewryville, VA	F0	1020	8	28	231	4574	45
5/9/2003	2110	Severn, NC	F0	1178	13	28	146	3442	47
5/9/2003	2120	Murfeesboro, NC	F1	1178	13	26	146	3442	47
5/9/2003	2150	Colerain, NC	F0	997	10	23	156	4200	59
5/9/2003	2200	Rockyhock, NC	F0	1030	10	23	140	4500	67
8/26/2003	2330	Newland, VA	F0	888	5	15	162	3345	39.7
6/12/2004	0200	Rockyhock, NC	F1	216	7	23	223	1797	21

formed in a variety of shear environments for the low-LCL cases, with a cluster of events with zero to 1 km shear less than 5 ms^{-1}, and others with values greater than 15 ms^{-1}.

In what follows, we will present examples of both the higher CAPE and relatively higher LCL events, which turned out to be supercells, as well as the more common lower CAPE, low-LCL cases. The low-LCL events will be divided between relatively high zero to 1 km shear environments, and relatively low shear environments based on the distribution seen in Fig. 3.

3.2 *Supercells Moving Along a Thermal Boundary*

On 4 different days, supercell thunderstorms developed in environments with moderate to strong deep layer (zero to 6 km) shear, with northwest flow aloft. The cells would propagate southeastward along northwest to southeast oriented thermal boundaries. The RUC-2 sounding parameters for these cases are listed in Table 1. Note each of the 5 cases with LCL greater than 800 m is represented in this type of event (Fig. 1).

On 9 May 2003 two primary supercells developed and tracked across Virginia and North Carolina, one producing 10 tornadoes over a 6 hour period, with 8 in the AKQ warning area (Fig. 4). Storms formed early in the afternoon at the southern periphery of a mesoscale convective complex (MCC), which had passed across western Pennsylvania and western Maryland earlier in the day. The line of convection became elevated and weakened as it crossed the Appalachian mountains, except on its southern end, near a back-door cold front which extended from northwest to southeast across Virginia. The tornadic supercell moved southeast along the front, with the front dropping southward during the afternoon. Surface observations and RUC analyses of temperature and pressure are shown in Fig.5 for 1900 UTC, about 10 minutes after it had

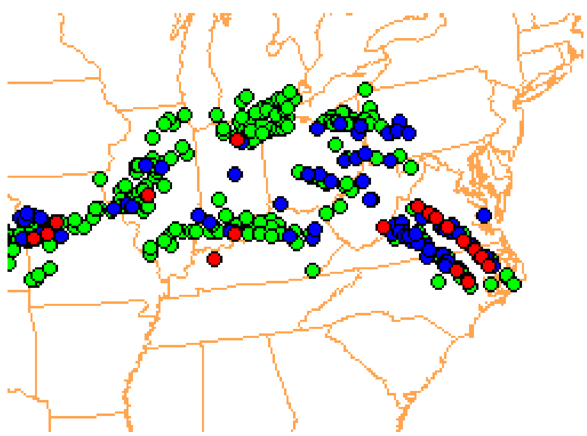

Fig. 4. Preliminary storm reports from SPC for 5 May 2003 where red indicate locations of tornadoes, blue reports of wind damage, and green hail.

produced a tornado (Table 1). Note the pronounced temperature contrast across the front, with temperatures around 30 C (in the mid 80s F) over south-central Virginia,, but only around 20 C (in 60s to the lower 70s F) to the north. Over the subsequent 4 hours, the storm continued southeastward along the front, with several brief tornado touchdowns reported. Tornado damage was relatively minor, mostly rating F0 with some F1 on the Fujita scale. Also noteworthy, the storm produced softball-sized hail on three occasions. The storm exhibited the reflectivity structure of a classic supercell at times, with hook echoes (Fig. 6), bounded weak echo regions, and pronounced echo overhangs all apparent.

The cases of 8 May 2003 and 24 June 2004 were similar to 9 May 2003, with a weakening MCS, with associated stratiform rain, passing to the north of the warning area, and with supercell thunderstorms developing along the southern periphery of the MCS, along a northwest to southeast oriented back-door cold front. In each case, the rain and cloud cover associated with the decaying MCS increased the temperature contrast, by inhibiting solar heating and through evaporative cooling to the north of the surface front. In the case of 26 August 2003, there was no pre-existing back door cold front, but an MCS that passed over Pennsylvania, Maryland and northern Virginia earlier in the day effectively created one with its rain-cooled outflow, with observed temperature contrasts similar to the other cases. Fig. 7 shows the base reflectivity and storm relative motion of the 26 August storm just as it is about to produce an F0 tornado. Fig. 8 again shows that the development occurred along a well-defined thermal boundary (compare with Fig. 5), in this case a temperature contrast due to rain-cooled outflow from an earlier MCS to the north.

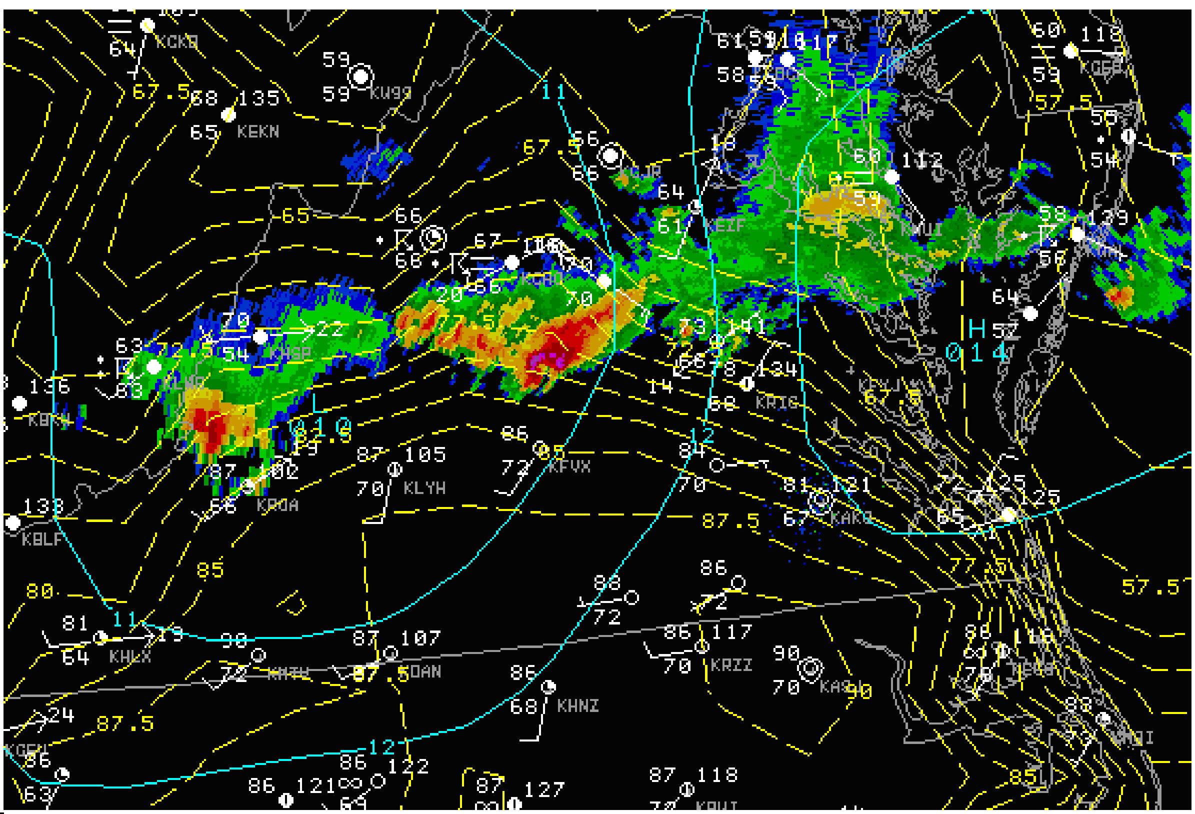

Fig. 5. Surface observations, and RUC initialization fields of temperature (dashed) and mean sea level pressure for 1900 UTC, 9 May 2003.

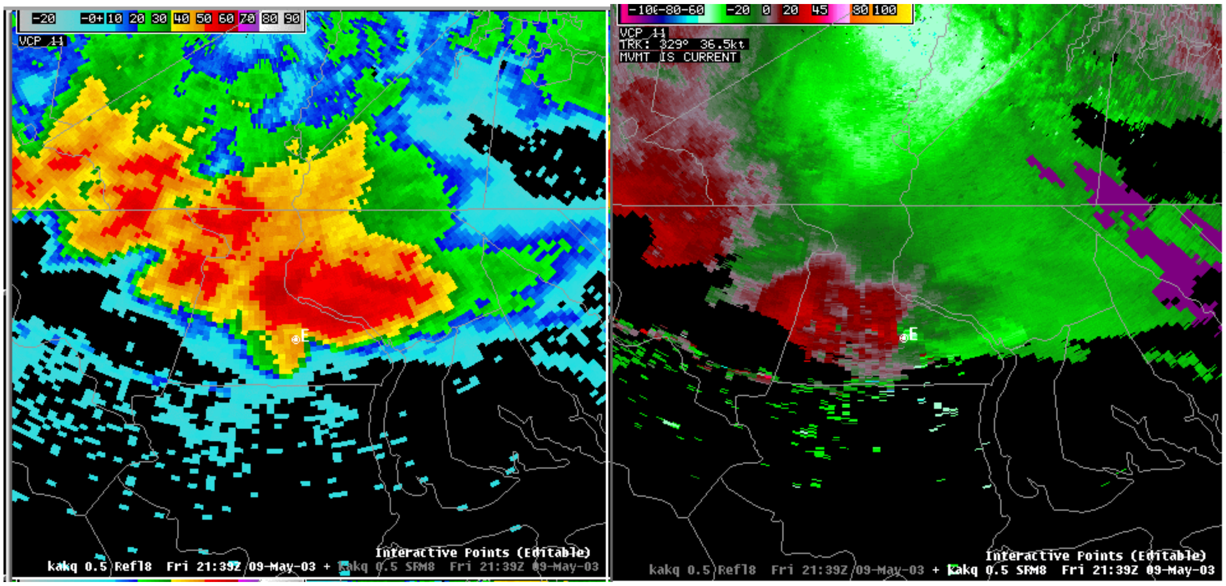

Fig. 6. Base reflectivity and storm relative motion of tornadic supercell, showing hook feature and low-level mesocyclone. Time of image 2139 UTC 9 May 2003. The AKQ radar is located 75 km to the north-northwest of the mesocyclone.

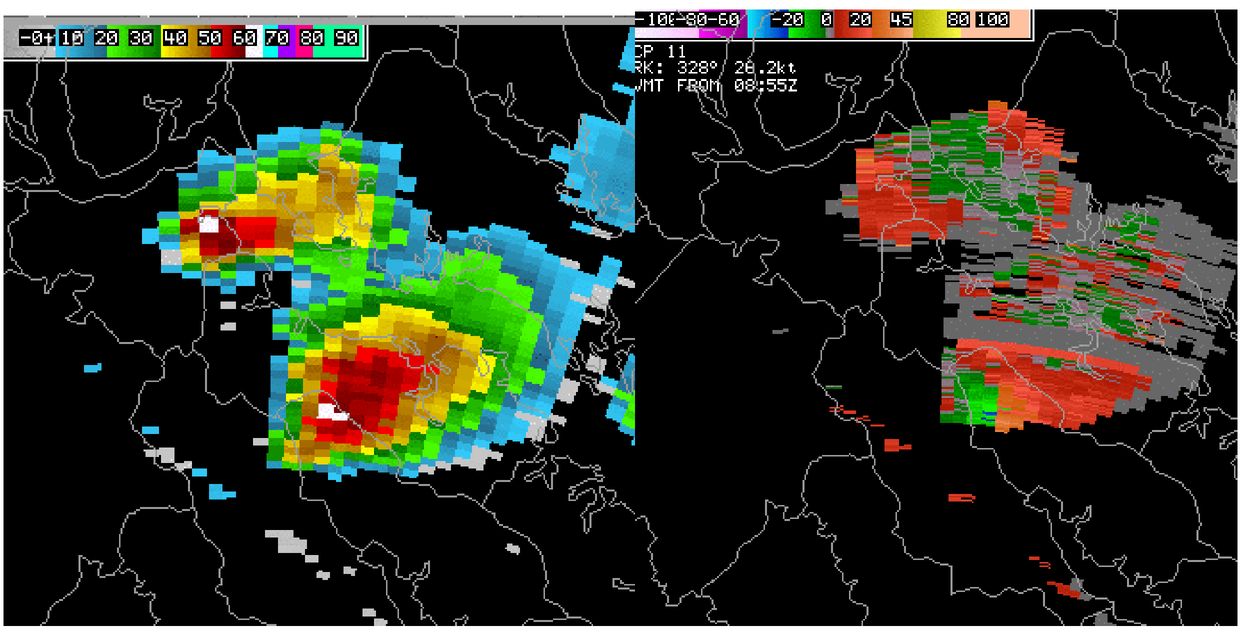

Fig. 7. Reflectivity and SRM from Newland, Virginia tornadic supercell at 2330 UTC, 26 August 2003. The AKQ radar is located 119 km to the south of the tornadic cell.

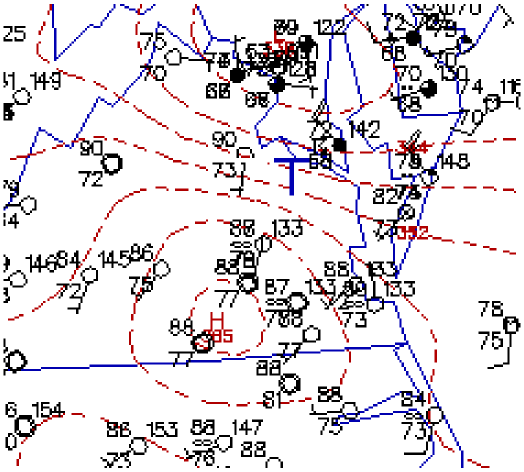

Fig. 8. Surface observations and objective surface equivalent potential temperature analysis for 2300 UTC 26 August 2003. Tornado location at 2330 UTC indicated by the blue "T."

The apparent importance of external thermal boundaries on tornado formation has been suggested in a number of studies (e.g. Maddox 1980; Markowski, 1998; Rasmussen 2000). In these cases, with storm motion along the surface boundary, the storm would, in its inflow, ingest air parcels with horizontal vorticity generated baroclinically along the frontal zone, thus providing an important source of low-level vorticity for these storms. This low-level horizontal vorticity would then be tilted and stretched by the updraft.

3.3 *Low LCL, high low-level shear cases*

Another type of environment found to be favorable for tornadoes was characterized by a warm, humid, near saturated boundary layer, with associated low LCLs, coupled with strong vertical wind shear in lower levels. For the purpose of grouping cases with similar environments, we will define this group as being characterized by LCLs less than 500 m, and with zero to 1 km shears greater than 15 ms^{-1}. Tornadoes formed on 4 different days meeting these criteria (see Table 2). In comparing Tables 1 and 2, we see that CAPEs, LCLs, and zero to 6 km shear were mostly lower than with the supercell cases, but the zero to 1 km shear was much greater. With the vertical wind shear concentrated in the lowest levels, it is not surprising that the convection in these cases took the form of lines and bows, as opposed to more discrete rotating supercells.

In the case of 8 June 2003, a band of rain with embedded convection developed on the southern flank of a short wave that was passing by to the north. The southwesterly low-level flow was warm and humid, with temperatures and dewpoints in the lower to middle 20s C. Transient gate-to-gate circulations were observed within the embedded convection during the few hours prior to tornado

Table 2. As in Table 1, but for low-LCL, high zero to 1 km shear cases.

Date	Time (UTC)	Tornado	Rating	LCL (m)	0-1 km shear (ms^{-1})	0-6km shear (ms^{-1})	0-3km helicity (m^{2}s^{-2})	CAPE	BRN
6/8/2003	0055	Moyock, NC	F0	237	15	15	211	963	26
9/22/2003	0428	Crystal Hill, VA	F1	420	15	21	211	553	9.6
9/22/2003	0438	4 e Halifax, VA	F1	306	15	21	223	774	12.3
9/23/2003	0837	Rubermount, VA	F0	136	15	23	173	1606	23.6
9/23/2003	0850	Crewe, VA	F0	117	15	23	175	1694	25.1
9/23/2003	0912	4 S Amelia C.H.	F1	98	15	23	171	2007	27
9/23/2003	0945	Chesterfield, VA	F0	180	15	23	198	1159	16.9
9/23/2003	1004	Lakeside/Richmond, VA	F1	79	15	23	129	1014	13
9/23/2003	1005	Azalea/Richmond, VA	F1	79	15	23	129	1014	13
9/23/2003	1022	Studley, VA	F1	96	15	23	154	947	12
9/23/2003	1230	Fruitland, MD	F0	261	15	26	227	680	8.8
9/23/2003	1245	2E Fruitland, MD	F0	261	15	26	227	680	8.8
5/3/2004	0233	King and Queen C.H., VA	F1	106	18	18	245	663	20.3

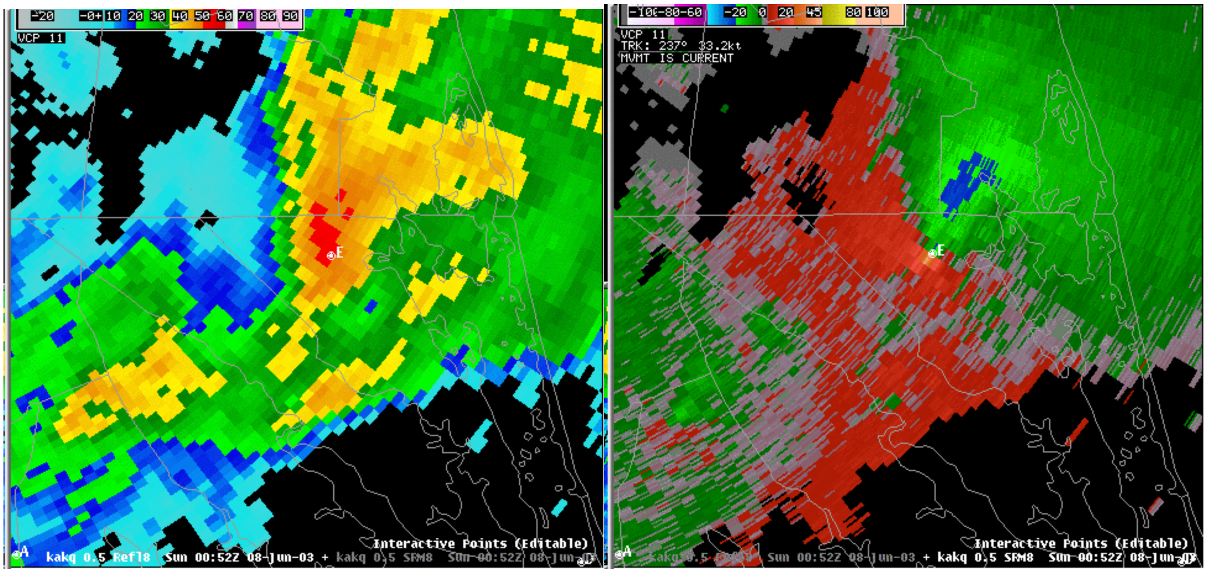

Fig. 9. Base reflectivity and storm relative motion for 0052 UTC 8 June 2003 just prior to tornado touchdown. The AKQ radar is located 93 km to the northwest. Location of tornado near point E.

development. One cell developed a somewhat broader, deeper circulation as it neared the coast. Fig. 9 shows the reflectivity and velocity signatures of this cell just prior to it producing a tornado. Note the flared-S shape to the reflectivity pattern, with tornado development just north of the apex in the lower portion of the "S." This type of reflectivity pattern was observed often with tornadic developments in this low LCL, high shear regime. Note also the well-defined mesocyclone, with gate to gate rotational velocities of 19 ms^{-1}, or 35 kts. RUC-2 soundings around the time of tornadogenesis in this case showed a strong low-level jet, with wind speeds of 20 ms^{-1}, beginning 1 to 2 km above the surface. This type of wind profile was typical for the cases discussed in this section.

Another series of tornadoes occurred during the early morning hours of 23 September 2003. Eleven tornado touchdowns occurred between 0400 UTC and 1300 UTC 23 September, as verified by storm surveys. Once again, the low level shear was strong, but so was the zero to 6 km shear in this case (see Table 2). LCLs were extremely low, within a few hundred meters of the ground.

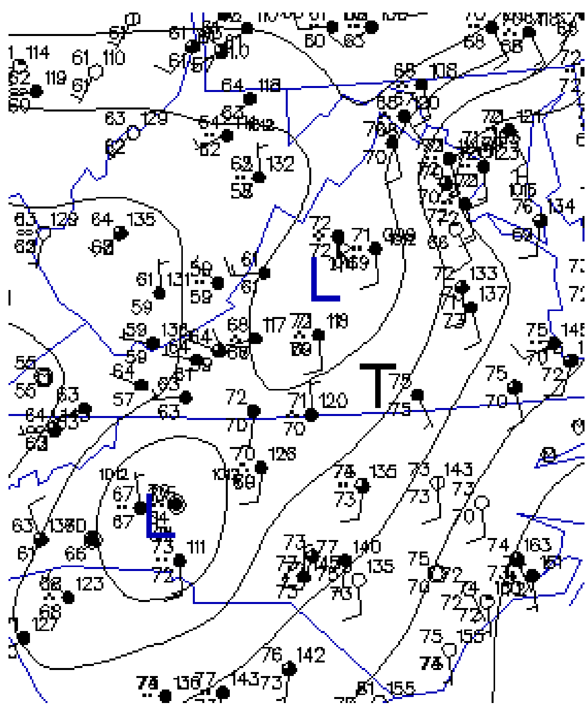

Figure 10. Surface observations and MSLP analysis from 0400 UTC 23 September 2003. Position of tornado development around 0430 UTC is indicated by black "T".

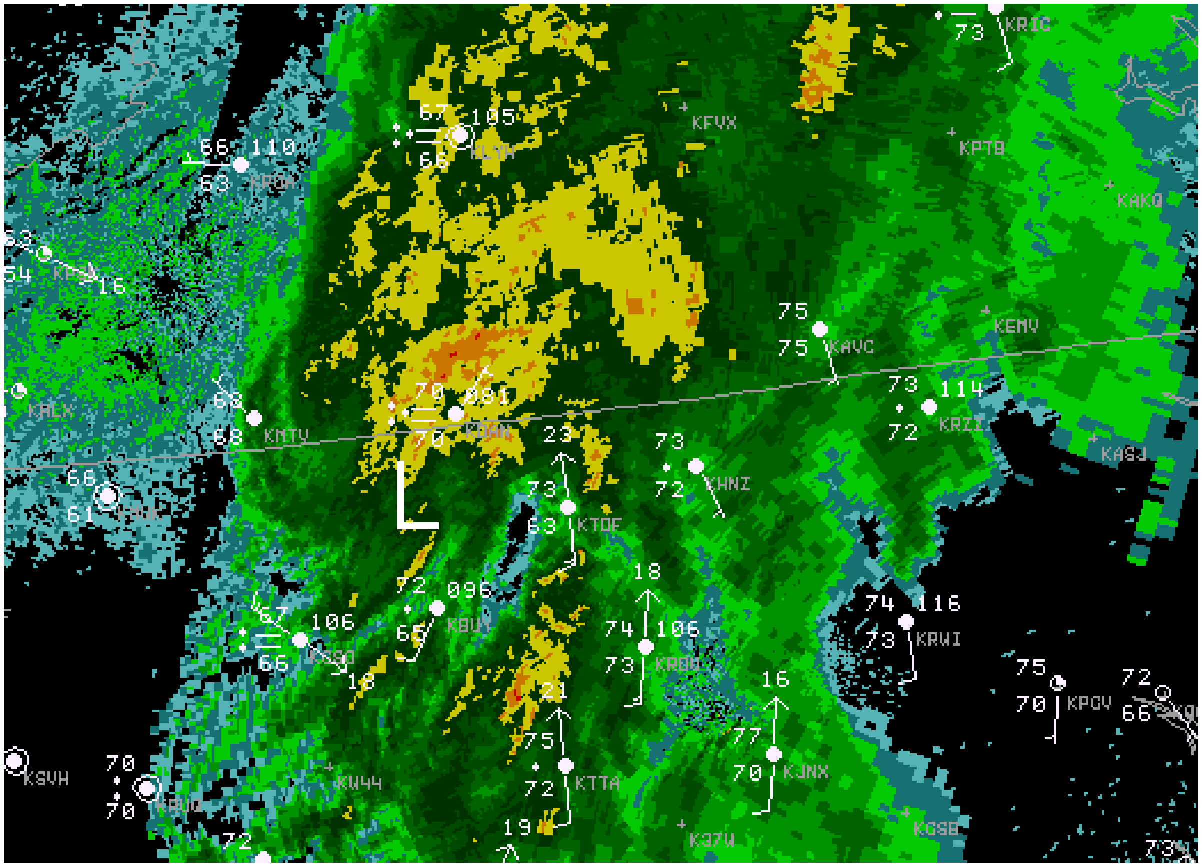

Fig. 11. Surface observations and radar composite from 0700 UTC 23 September 2003 Position of frontal low indicated by L.

RUC soundings also revealed between 1000 and 2000 J/kg of surfaced based CAPE for the majority of cases, with little or no cap despite the time of night. The first tornadoes developed around 0430 UTC in Halifax County, Virginia, just outside the AKQ CWA. Fig. 10 shows a surface analysis at 0400 UTC. Note the waves of low pressure along a cold front. The low over western North Carolina at 0400 UTC would later play an important role in tornado development across south-central Virginia as it moved northeastward along the front. In Fig. 11, the radar composite and surface observations are shown 3 hours later, with the position of the low center now analyzed over north-central North Carolina, approaching the Virginia border. The frontal wave is also clearly evident in the reflectivity pattern. As this low continued north, a slightly-bowing line segment developed just to the northeast of the low center. It was this convective element that would drop the first of a series of tornadoes at 0830 UTC, exhibiting a slight S-shape pattern (not shown). This convective element would then evolve into a broken-line or "broken-S" pattern, with a tightening mesocyclone located just north of the break in the line (see Fig. 12). This type of signature has been shown to be associated with tornadogenesis in other studies (McAvoy 2000). By this time, the mesocyclone was very close to the center of the synoptic-scale cyclone, or frontal low.

The role of the frontal low in this case was likely to both enhance vertical wind shear by backing the surface winds on its northeast flank, and also to provide ambient vertical vorticity. This horizontal and vertical vorticity could then be stretched near the surface by the buoyant updrafts, presumably beginning near the LCL at the level of free convection (LFC) within a few hundred meters of the ground.

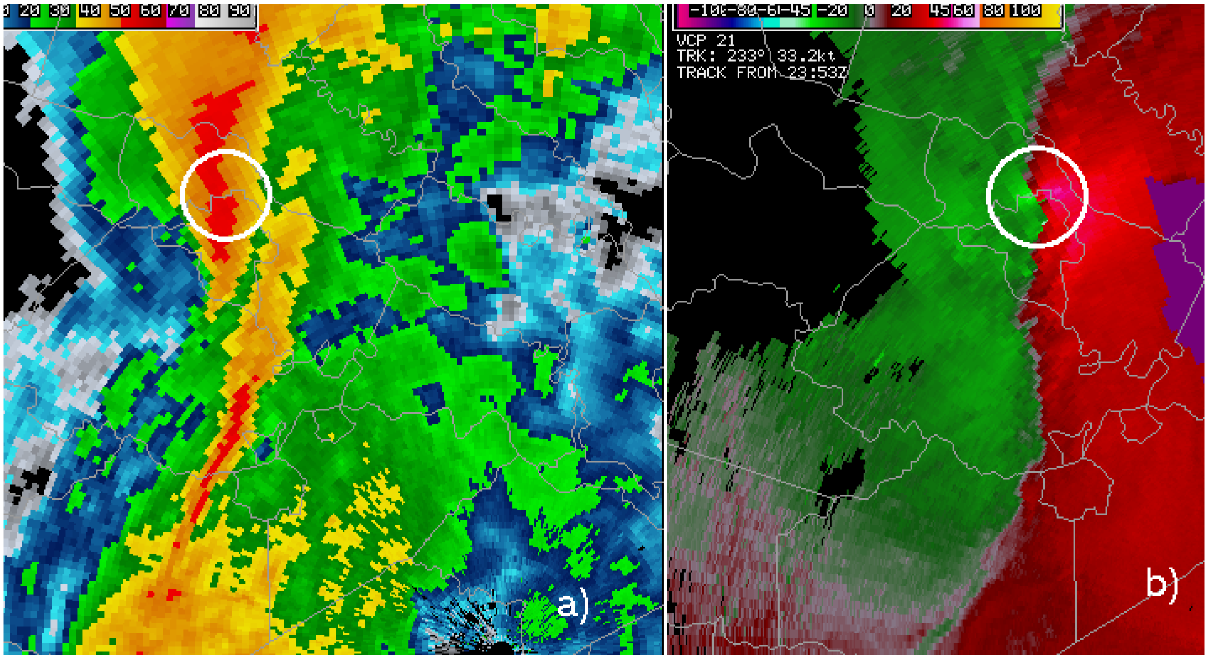

Fig. 12. Base reflectivity (a) and storm relative motion (b) for 1000 UTC on 23 September 2003 around the time F1 tornadoes were touching down on the north side of Richmond, VA. AKQ radar located 81 km southeast of the mesocyclone.

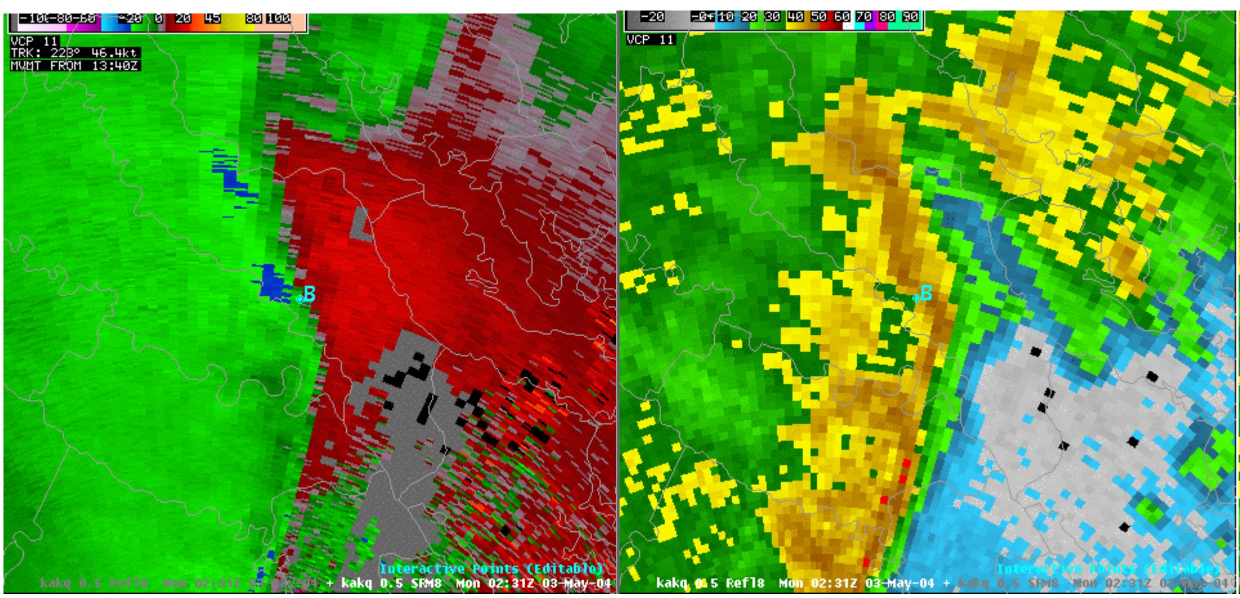

Fig. 13. Base reflectivity and storm relative motion for 0231 UTC 3 May 2004 around the time of tornado touchdown at point B. AKQ radar located 96 km south of the tornado.

Another similar case occurred on 3 May 2004, with the environment characterized by an LCL of just a few hundred meters, and a zero to 1 km wind shear of 18 ms^{-1} (see Table 2). In this case an isolated tornado touchdown occurred when a small circulation developed just north of the apex of a low-amplitude bow in the line (Fig. 13). Note again the S-shape in the reflectivity pattern.

With these type of low-LCL, high low-level shear tornadoes, it is likely that the high horizontal vorticity in the storm environment, associated with large zero to 1 km shear values, plays an important role in the near-surface circulations. Just as with the baroclinically generated horizontal vorticity of the previous section, this environmental horizontal vorticity might be ingested into the storms, then stretched near the surface by parcel accelerations due to buoyancy, beginning near the LCL at the LFC.

These type of tornadoes have been found at AKQ to be more difficult to warn for than the supercell-type previously discussed, as the associated circulations appear to develop more quickly, are smaller-scale, shallower, and tend to build from the ground up. By contrast, supercells often tend to possess a more persistent, broader, deeper parent mesocyclone. As a result, radar beam-resolution, and over-shooting limitations come into play more often with these cases.

3.4 *Low LCL and low shear cases*

As shown in Fig. 3, there were several cases of tornado development from low-LCL environments with relatively weak vertical shear in lower levels. For this group, all cases with LCLs less than 500 m, and zero to 1 km shears less than 5 ms^{-1} were selected. The results are shown in Table 3. Note the tremendous difference in zero to 1 km shear values between the cases described in Tables 2 and 3.

For the 4 June 2004 case, although zero to 1 km shear was relatively weak, the zero to 6 km shear was strong enough, 18 ms^{-1}, to allow for the development of a supercell. Fig. 14 shows a cell as of 1600 UTC, that had developed a hook echo, while positioned northeast of a mesolow and on the southern edge of a more stratiform rain area. Locally, a temperature contrast of about 5C can be seen to the north and south of the storm. Both of the mesolow and north-south temperature gradient might be sources of low-level vorticity, as previously discussed for other cases. The storm maintained its supercell appearance, and by 1634 UTC, the hook echo was seen to wrap-up (Fig. 15) as an F1 tornado was produced near Dolphin, VA. (Table 3).

Another interesting low shear case occurred on 7 August 2003, when a tornadic storm developed on the northeast flank of a surface mesolow, as the storm crossed a surface trough or wind shift line, which extended northeast of the low center (Fig. 16). The isolated tornado occurred as the cell developed weak rotation in the southerly flow east of the mesolow, which tightened up as it crossed the surface trough axis. In this case, it appears that the cell may have derived low-level rotation from the ambient vertical vorticity associated with the cyclonic wind shift line. In addition, the mesolow may have enhanced the vertical shear more than indicated in the RUC-2 soundings. At the time of tornadogenesis, the cell took on the appearance of a broken S-shape (Fig. 17), with a weak mesocyclone located to the left of the break of this northward moving cell. The tornadic cell was low-topped, with echo tops only around 5 km, and did not contain any lightning during its lifetime, as with many of the other lower CAPE low-LCL cases in this study.

Table 3. As in Table 1, but for tornadic development with low-LCL and weak zero-to-1 km shear.

Date	Time (UTC)	Tornado	Rating	LCL(m)	0-1 km shear (ms^{-1})	0-6km shear (ms^{-1})	0-3km helicity (m^2s^{-2})	CAPE	BRN
7/14/2003	1311	Crisfield, MD	F0	141	4	10	21	463	16.7
8/7/2003	1551	Tabb, VA	F1	202	3	15.	47	819	41.1
8/8/2003	1848	Va. Beach, VA	F0	245	3	13	27	2128	134
6/25/2004	1630	Dolphin, VA	F1	415	3	18	57	4668	141
6/25/2004	1905	Suffolk, VA	F0	495	4	18	129	3367	69

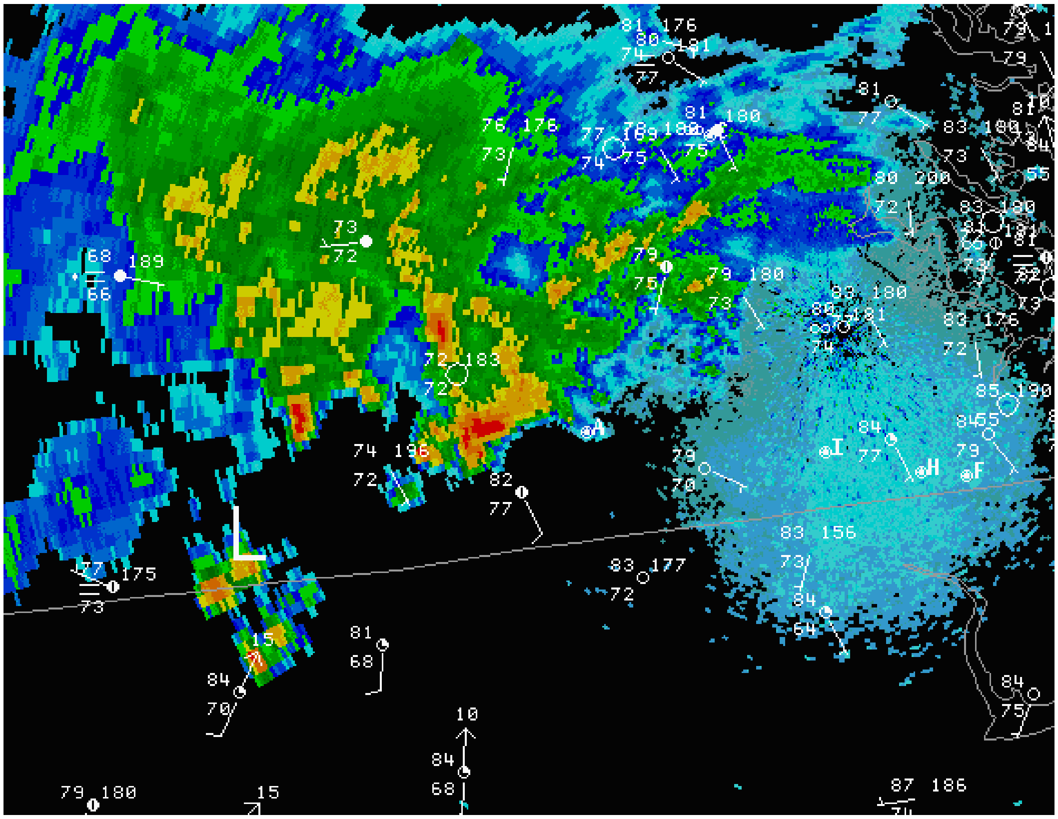

Fig. 14. Radar reflectivity an surface observations, showing initial development of a supercell thunderstorm at 1600 UTC 25 June 2004. Position of a mesolow is also indicated by a white L.

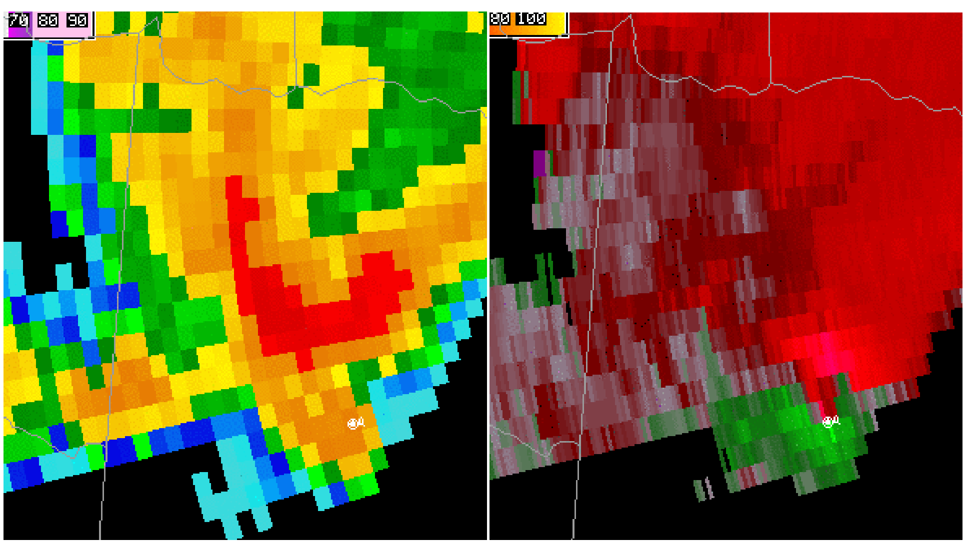

Fig. 15. Base reflectivity and storm relative motion, 1634Z 25 June 2004. Note the wrapped up hook in the reflectivity pattern. Storm was producing F1 tornado at this time. AKQ radar located 76 km east-southeast of tornado.

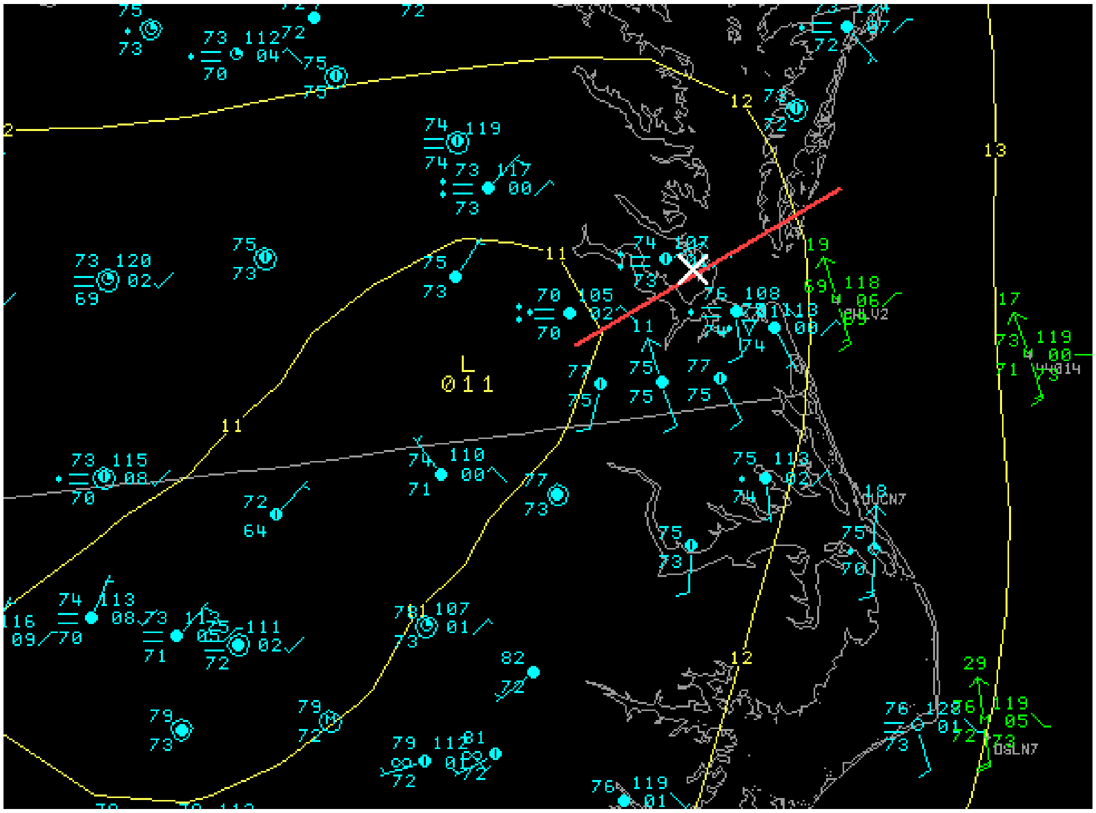

Fig. 16. Surface observations from 1500 UTC 7 August 2003. Position of surface trough denoted by red line. Cell became tornadic at point X at 1557 UTC.

4. SUMMARY AND CONCLUSIONS

In this study of tornadoes across the AKQ CWA that occurred in the last eighteen months, it was found that tornadoes developed from generally two types of environments. One was characterized by moderate to strong deep layer (zero-to-6 km) shear and northwest flow aloft, as well as the presence of a northwest to southeast oriented back-door cold front or outflow boundary. The fronts were a result of, or enhanced by precipitation associated with an MCS passing by to the north. This strong deep-layer shear environment favored the development of supercells, which became tornadic as the storm motion followed the fronts or boundaries. The radar signatures for these cases were the familiar deep, persistent mesocyclone in the velocity fields, and hook echoes, bounded weak echo regions, pronounced echo overhangs in the reflectivity data.

The other type of environment was characterized by a warm and humid air mass, with generally high surface dew points, mainly in the 22 to 25 C range, low dew point depressions, and low LCLs, often below 600 m (Fig. 1). These low-LCL cases occurred with varying degrees of vertical shear. The reflectivity patterns in the high zero to 1 km shear, low-LCL cases were characterized by lines or line segments evolving into bows, S-shaped echoes or broken lines. The tornadoes were observed just left of the apexes of the bows, and north of the breaks in the lines. In these cases, it is likely that the horizontal vorticity in the environment may be a source for low-level vertical vorticity, once tilted by the convective updrafts. Several tornadoes also developed in low-LCL, and relatively low low-level shear environments, including a few

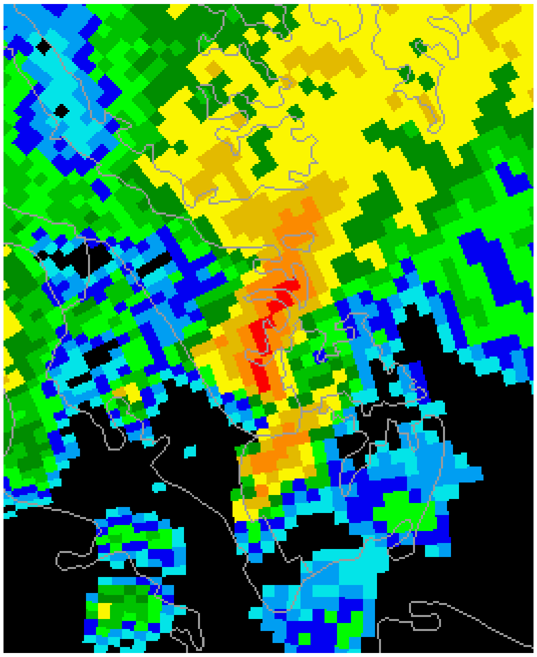

Fig. 17. Base reflectivity for 1551 UTC 7 August 2003

supercell events. In these cases, it appears that the necessary vorticity to spawn the tornadoes was derived from either baroclinic production of horizontal vorticity, as air flowed into the storms along paths with horizontal temperature gradients, or from pre-existing ambient vertical vorticity near the centers of mesolows or wind shift lines.

Based on these results, a forecaster might take an ingredients approach to anticipating tornadoes on a given day. One might expect the possibility of tornadoes given two general environments. If deep layer shear is sufficient to produce supercells, and thermal boundaries or fronts are present in the warning area, tornadoes would be possible, with special attention needed to be given to cells propagating along fronts or boundaries. Alternatively, tornadoes might be considered possible given an environment characterized by a warm, moist boundary layer, with low LCLs, and any potential source of near surface vorticity combined with positive surface-based CAPE. Sources of low-level vorticity would include any cyclonic wind shift lines or mesolows, surface thermal boundaries, or a strong low level jet within 1 to 2 km of the ground. Special attention should be given to cells near boundaries and mesolows.

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