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AN ANALYSIS OF THE 28 APRIL 2008 SOUTHEAST VIRGINIA TORNADO OUTBREAK

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1. INTRODUCTION

On 28 April 2008, a severe weather outbreak across southeastern Virginia produced eleven tornadoes including one strong tornado that affected the cities of Suffolk and Norfolk (Fig. 1). The tornadoes originated from both supercells and quasi-linear convective system (QLCS) cells and were associated with a variety of radar-based signatures. This event is of particular note because much of the Wakefield weather forecast office (hereafter AKQ) county warning area (CWA) had cloud ceilings 500 meters or less from the day prior to the event and through the event itself for areas along and west of I-95. The skies remained overcast across the entire area prior to convective initiation, which limited surface insolation, weakened lapse rates which narrowed the convective available potential energy (CAPE) through the column. Surface-based CAPE estimations were generally limited to values less than 1200 J kg^{-1}. The severe threat had been noted, though downplayed, from both the national and local perspectives.

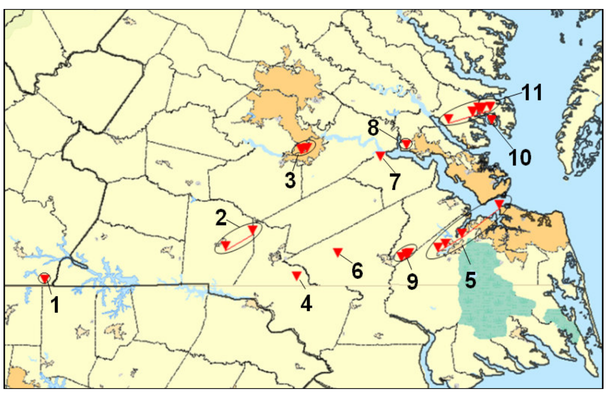

Figure 1. The confirmed tornado reports (red triangles, numbered chronologically) across southeast Virginia with red lines approximating the tornado path.

2. SYNOPTIC SETTING

A backdoor cold front pushed through eastern Virginia and into North Carolina on the morning of 27 April 2008 bringing northeast (onshore) flow and a low cloud deck across eastern Virginia with cloud ceilings generally from 250 to 400 meters. The backdoor cold front returned as a warm front early on 28 April, bringing southerly winds and slightly warmer temperatures. However, low cloud cover remained across the Virginia Piedmont and mid to high clouds remained over the Virginia Coastal Plains through the 28th. At 1200 UTC 28 April an upper trough of low pressure extended from the Hudson Bay in Canada south into the Upper Midwest (Fig. 2). This upper trough was slightly positively tilted at 1200 UTC and by 1800 UTC the embedded upper low over Wisconsin (Fig. 2) had pushed across northern Illinois, making the tilt negative. Strong southwest flow was present out ahead of the upper trough axis with 500 hPa wind speeds of 35 m s^{-1} over the Ohio Valley around 1200 UTC (Fig. 2), increasing to 38 m s^{-1} from the Appalachians to the East Coast by 2000 UTC (not shown). Through the morning hours of 28 April, a surface trough of low pressure, coincident with a strengthening cold front, had deepened along the Appalachian Mountains and slowly pushed further into the eastern US from central North Carolina to central New York State.

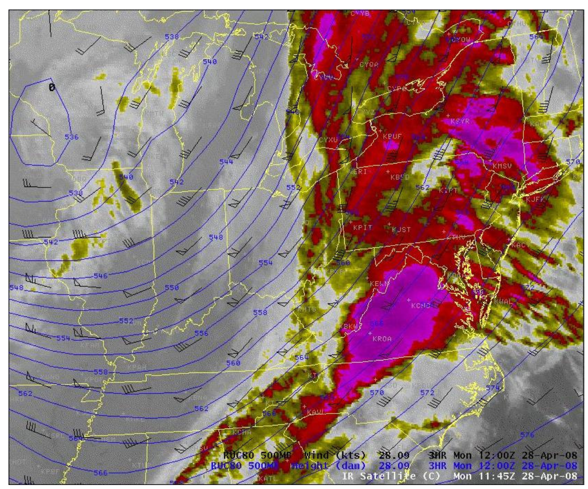
Figure 2. 1200 UTC IR Satellite and RUC80 forecast of 500 hPa height (dm) and winds (kts).

The 1200 UTC KGSO rawindsonde (Fig. 3) provides a good approximation of the environmental conditions for later in the day in eastern VA as the site is directly upstream given southwest steering flow. Notable features in the sounding include a moist profile through the column, strong speed and directional shear in the lowest levels, and the deep layer of strong southwest flow through the low- and mid-levels. Precipitation across eastern Virginia, ahead of the approaching cold front and along the warm front, served to stabilize the environment during the morning hours of 28 April 2008. Under cloudy skies, surface temperatures across southeast Virginia rose only slightly through the day, from 17°C to 19°C at 1200 UTC to 20°C to 22°C by 1800 UTC. Since

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surface insolation was greatly limited due to the cloud cover, this warming was mostly due to warm air advection from southerly surface winds ahead of the cold front and behind the warm front. At 1800 UTC, the cold front was evident along the East Coast, and was slightly arced with a southwest to northeast orientation from Charlotte, North Carolina to Washington, DC then south to north up through Syracuse, NY (not shown). A mesolow embedded in the surface trough was analyzed across north central Virginia at 1800 UTC (Fig. 4) and by 2000 UTC the center of a mesolow was near AKQ where mean sea level pressure (MSLP) had dropped from 1008.0 hPa at 1800 UTC to 1005.6 hPa at 2000 UTC.

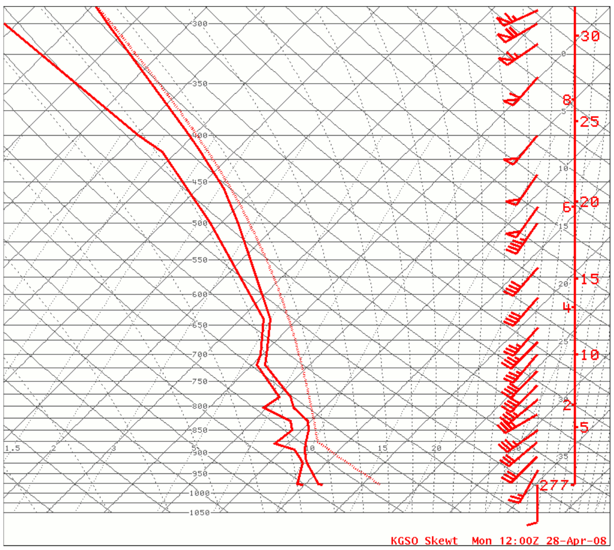

Figure 3. 1200 UTC KGSO rawindsonde sounding on 28 April 2008.

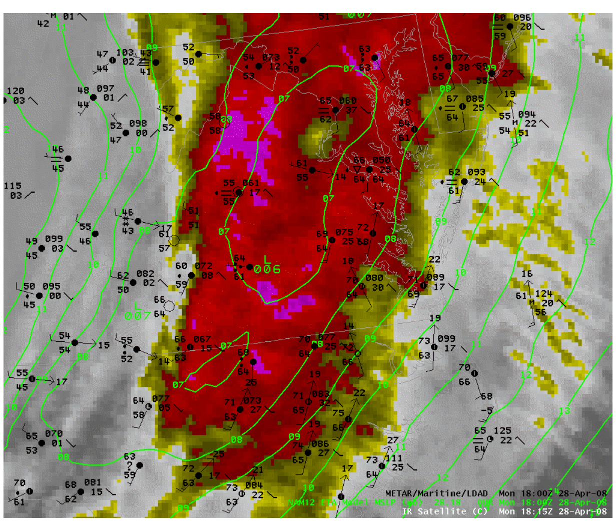

Figure 4. 1800 UTC NAM12 MSLP analysis with IR satellite and surface observations.

3. MESOSCALE SETTING

The dynamic and thermodynamic conditions varied ahead of each tornado on 28 April 2008 (Table 1). Data were collected from RUC40 initialization soundings shortly before tornadogenesis for each of the eleven tornadoes as in Reilly (2004). Clearly, this is a case of severe weather in a low lifted condensation level (LCL), high low-level shear, and limited CAPE environment. The bulk Richardson number (BRN) is a ratio of CAPE to bulk layer wind magnitude, with values generally between 10 and 40 supportive of supercellular storms (Weisman and Klemp, 1986). BRN values were held down due to limited CAPE and significant differences in wind magnitude across the bulk layer. However, higher CAPE and BRN values existed east/southeast of AKQ where the ceiling had raised to mid levels behind the warm front allowing for steeper lapse rates compared to areas with low clouds.

Low level helicity, found to be one of the most significant discriminators between tornadic and non-tornadic storms (Thompson et al. 2003), was abundant on this day (Table 1). Ahead of the cold front and embedded mesolow, low level winds backed several degrees from 1800 UTC and 2000 UTC including surface winds backing of 30 degrees at AKQ (Fig. 5) and 40 degrees at Suffolk. A major limitation of the RUC40 from this day is that its surface winds backed only to 180°. Although the exact depth of the backing beyond 180° is unknown, the AKQ velocity azimuth display wind profile (VWP) suggests the depth was less than 600 m AGL (Fig. 5). An input of the 1900 UTC KSFQ surface wind vector (160° at 4 m s^{-1}) and 180° at 13 m s^{-1} into the editable hodograph in AWIPS increased the 0-3 km storm relative helicity by from 299 m^2 s^2 to 316 m^2 s^2.

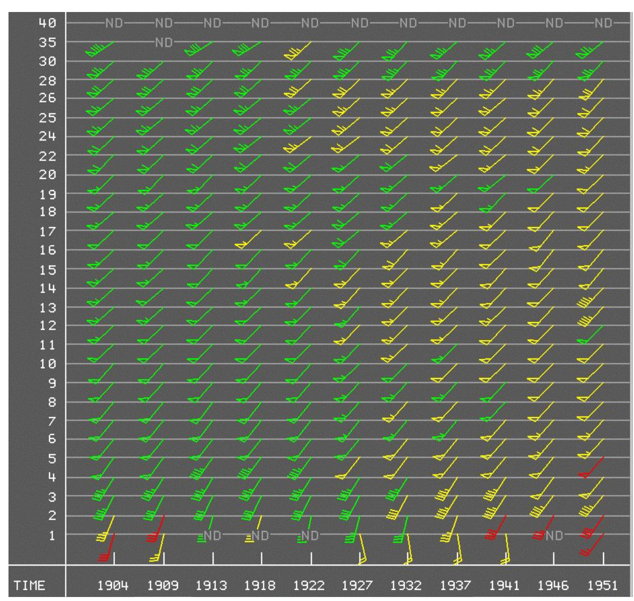

Figure 5. AKQ VWP from 1904 UTC to 1951 UTC with low level backing ahead of the storms at 1927 UTC and veering as the storms arrived at 1951 UTC.

Table 1. Select dynamic and thermodynamic parameters from RUC40 soundings shortly prior to each of the eleven tornadoes (numbered as in Figure 1) of 28 April 2008 in Virginia. CAPE is surface based and the storm motion for helicity in the RUC model is from the Bunker's storm motion technique.

Number (Fig. 1)	Time (UTC)	Tornado	Rating	LCL (m)	0-1 km shear (ms^{-1})	0-6 km shear (ms^{-1})	0-3 km helicity (m^{-2} s^{-2})	CAPE ($J\ Kg^{-1}$)	BRN
1	1710	Virgilina	EF-1	317	15	26	182	627	8.2
2	1848	Lawrenceville	EF-1	237	17	26	260	754	8.3
3	1940	Colonial Heights	EF-1	362	16	26	239	707	8.2
4	1950	Bryant's Corner	EF-1	312	17	22	299	626	6.5
5	**2005**	**Suffolk – Norfolk**	**EF-3**	**456**	**15**	**22**	**299**	**1099**	**14.1**
6	2010	Capron	EF-0	362	17	22	297	711	7.9
7	2018	Claremont	EF-1	387	17	23	260	659	9.9
8	2035	James City Co	EF-0	337	17	23	267	712	11.1
9	2040	Carrsville	EF-1	437	16	22	300	979	11.8
10	2045	Bohannon	EF-1	140	16	22	291	852	14.3
11	2055	Gloucester – Mathews	EF-0	287	17	23	281	805	13.2

Table 2. Classification of each tornado with notable reflectivity and velocity signatures.

Time (UTC)	Tornado	Rating	Reflectivity Signature	Velocity Signature	Classification
1710	Virgilina	EF-1	Broken-S	mesocyclone	QLCS
1848	Lawrenceville	EF-1	Hook, BWER	mesocyclone	Embedded Supercell
1940	Colonial Heights	EF-1	Broken-S	Non-descending mesocyclone	QLCS
1950	Bryant's Corner	EF-1	Broken-S	Non-descending mesocyclone	QLCS
2005	Suffolk – Norfolk	EF-3	Hook, BWER	Descending mesocyclone	Discrete Supercell
2010	Capron	EF-0	Broken-S	Non-descending mesocyclone	QLCS
2018	Claremont	EF-1	Broken-S	Non-descending mesocyclone	QLCS
2035	James City Co	EF-0	Broken-S	Non-descending mesocyclone	QLCS
2040	Carrsville	EF-1	Broken-S	Non-descending mesocyclone	QLCS
2045	Bohannon	EF-1	WER	Descending mesocyclone	Discrete Supercell
2055	Gloucester – Mathews	EF-0	Broken-S	Non-descending mesocyclone	QLCS

Therefore, the storm relative helicities and shear in Table 1 are likely underestimated, particularly for the cells that were ahead of the mesolow and QLCS. RUC13 data were available on that day (and were used by the AKQ forecasters) and would have likely handled the mesoscale aspects such as low level wind backing better than the RUC40. However, RUC13 data were not archived in the AKQ weather event simulator due to their large size.

The combination of high low level shear, low LCLs, and relatively limited CAPE resulted in an optimal environment for QLCS development. Higher CAPE existed east of the AKQ office where ceilings rose to 1500 m to 3000 m after morning showers. The rise in ceilings served to increase the low level lapse rates as well as provide more insolation (even if just a little) which led to temperatures about a degree Celcius higher and CAPE values around 500 J Kg^{-1} higher than locations west of Wakefield. Thus, as the QLCS, which was oriented along the surface trough, approached Wakefield there was an increase in the CAPE to shear ratio (i.e. BRN), increasing the potential for discrete supercell thunderstorms. The embedded surface low along the frontal trough increased the backing of the surface winds on the eastern flank, resulting in enhanced low level wind shear and horizontal vorticity. This horizontal vorticity could then be tilted and stretched near the surface by buoyant updrafts; likely a key aid to tornadogenesis.

4. TORNADO SUMMARIES

Radar analysis of the eleven tornadic storms allows for the classification of storm types (Table 2). Three of the eleven storms are classified as supercells with hook echoes, bounded weak echo regions (BWERs), and descending mesocyclones. Two of these supercells were discrete and ahead (east) of the QLCS in the area of enhanced CAPE across far southeast Virginia. For example, the Suffolk-Norfolk tornado had about 40% higher CAPE than the Claremont tornado at a similar time, resulting in a higher BRN (Table 1).

The other eight tornadoes were produced from storms classified as QLCS with interacting and splitting lines. At the time of touchdown, all eight QLCS storms exhibited a 'Broken-S' reflectivity signature as described in McAvoy et al. (2000). Grumm and Glazewski (2004) further the research by identifying that a Broken-S can come from both bowing line segments and rotating storms. Indeed, Broken-S signatures resulted from both bowing line segments and rotating storms on 28 April 2008 in southeastern Virginia. Descriptions of three storms that account for six of the tornadoes on 28 April 2008 follow.

a. Lawrenceville Tornado

Around 1800 UTC a supercell, embedded in the leading edge of the QLCS, entered the AKQ CWA from North Carolina and began traversing northeast across Virginia with a circulation couplet at the lowest AKQ slices (not shown). This couplet intensified and at 1848 UTC a tornado touched down, producing EF-1 damage near Lawrenceville in Brunswick County. A small BWER and hook echo are visible in the 0.5° reflectivity data at around 880 m above ground level (AGL) at 1855 UTC (circled in Fig. 6a). By 1910 UTC, the storm had produced a broken 25 km path of EF-1 damage that extended into northern Greensville County. Around 1937 UTC, this storm transitioned into a bowing, bilinear storm with a Broken-S reflectivity signature as it crossed Sussex County, Virginia (oval in Fig. 6b). Grumm and Glazewski (2004) suggest that the development of a strong rear-flank downdraft (RFD) may create the Broken-S signature in a line of rotating storms. This storm had already produced an RFD and tornado for nearly an hour, so in this case the transition was not spontaneous with the development of an RFD. A deep couplet remained with the storm as it crossed Sussex County and passed within 17 km of the AKQ radar around 2000 UTC (not shown), though no damage was found on both aerial and ground surveys. The storm continued to progress further northeast with a mesocyclone couplet along the segment break and produced a very brief touchdown with EF-1 damage just south of Claremont in Surry County, and another with EF-0 damage in rural James City County. Upon reaching the York River, this storm merged with the Colonial Heights tornado producing storm which resulted in another Broken-S in eastern Gloucester County and produced the Gloucester-Mathews tornado which had a track of EF-0 damage along a 17 km path.

b. Colonial Heights Tornado

Shortly before 1900 UTC a bowing segment of the QLCS was over Dinwiddie County, Virginia (rectangle in Fig. 6a). Around 1920 UTC, the 50+ dBZ portion of the segment split in the middle as the northern part of the segment took a more northerly track (not shown). Despite this break, no discernable couplet was visible in the SRM data, with only a broad area of weak rotation present (not shown). By 1937 UTC, the northern segment had bowed out with its southern end now west of the northern part of the southern segment forming a Broken-S signature (rectangle in Fig. 6b). At this time, a small couplet in the 0.5° SRM data became apparent over southern Colonial Heights, with gate-to-gate velocities of 5 m s^{-1} inbound 14 m s^{-1} outbound, at about 505 m AGL (Fig. 7). This couplet was coincident with the southern end of the northern segment, just west of the break in the reflectivity (Fig. 7). Around this time, a tornado touched down just west of I-95, crossed the Interstate, damaged vehicles and a shopping center, and injured about 20 people near the Southpark Mall. Coincidentally, this shopping center was built after the previous structure was destroyed in the 6 August 1993 Petersburg-Colonial Heights F4 tornado.

In the 1942 UTC 0.5° scan, the inbound portion of the couplet had doubled in strength as the tornado moved into Prince George County (not shown) where brief touchdown produced low end EF-1 damage to a home, trees, and outbuildings. The couplet soon dissipated, though the storm maintained cyclonic convergence as it pushed east-northeast into Charles City County and merged with the line that produced the Claremont and James City tornadoes mentioned above.

c. Suffolk Tornado

Around 1900 UTC a line of four discrete cells developed ahead of the QLCS in northeast North Carolina (Fig. 6a). Each of these cells, aided by the enhanced CAPE ahead of the QLCS and strong ambient shear, quickly began rotating (not shown). The northernmost and southernmost cells took a northeast track and paralleled the eastward progress of the QLCS, while the middle two cells tracked nearly due north and eventually merged with the QLCS (Fig. 6 b, c). The northernmost cell, the supercell that later produced the Suffolk EF-3 tornado, presented the most significant indicators of severe weather, producing a large hook echo, BWER, and a strong velocity couplet as it crossed Northampton and Hertford counties in North Carolina, prompting tornado warnings from AKQ. However, no damage was reported or found by NWS survey in North Carolina on this day. The cell strengthened again as it crossed the Virginia border producing a mesocyclone that descended as it crossed Suffolk city proper. Time series of SRM and reflectivity data clearly show the low level storm structure, including a descending mesocyclone and BWER, during tornadogenesis as the storm progressed northeast across the city of Suffolk. The supercell moved roughly perpendicular to the AKQ radials as it

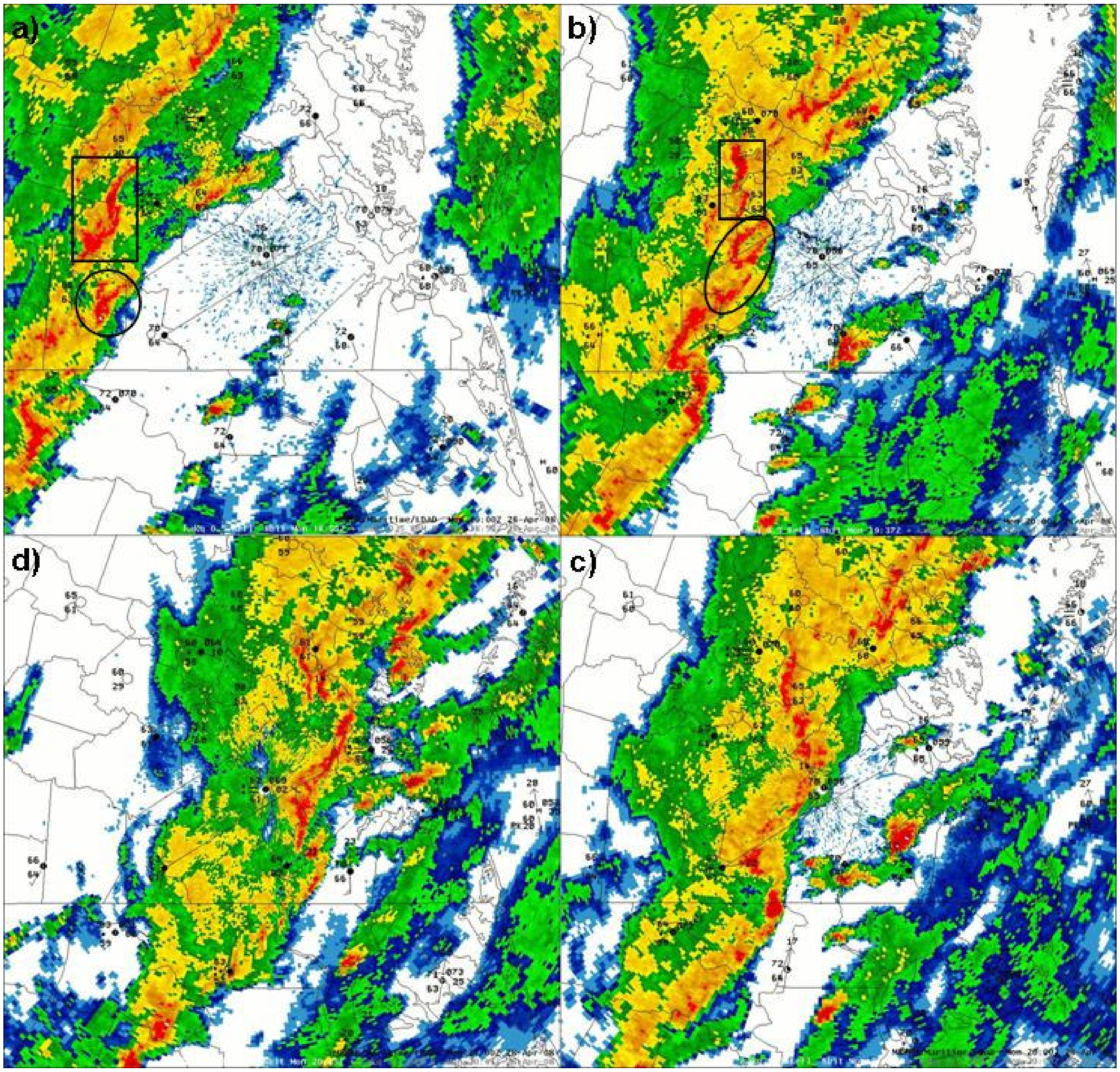

Figure 6. AKQ 0.5° reflectivity showing the QLCS and leading supercells as they progressed through the AKQ CWA at: a) 1855 UTC, b) 1937 UTC, c) 2006 UTC, and d) 2045 UTC with hourly surface METAR observations.

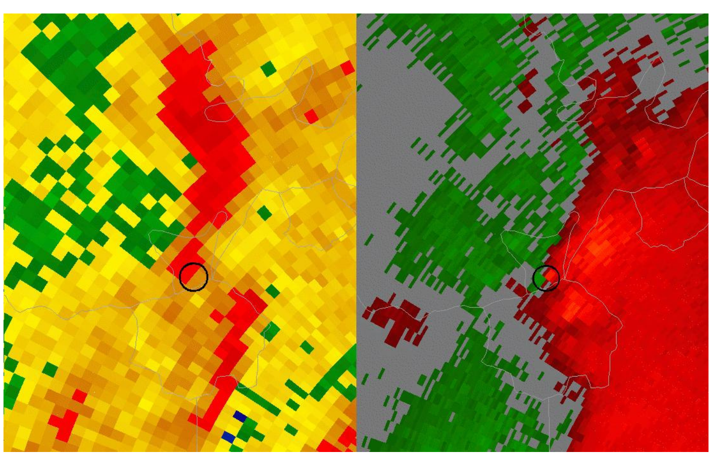

Figure 7. 1937 UTC 0.5° reflectivity (left) and SRM (right) with the rotation associated with a tornado over southern Colonial Heights circled. The AKQ radar is 46 km southeast of the circle.

crossed Suffolk, allowing for features' vertical movement to be seen over time in given elevation slices (Figs. 8, 9). At 1946 UTC cyclonic convergence is evident in the 0.5° Storm Relative Motion (SRM) data at a height of 475 m (Fig. 8a) while a developed mesocyclone, with velocities inbound of 22 m s^{-1} and outbound of 15 m s^{-1}, is visible in the 1.8° SRM data at 1380 m (Fig. 8b). Touchdown is estimated to have occurred around 2005 UTC and by the time the cell crossed just northwest of downtown Suffolk, at 2011 UTC, a couplet with velocities of 23 m s^{-1} inbound and 22 m s^{-1} outbound was present in the 0.5° slice at 520 m AGL (Fig. 8c). This was a deep circulation with the couplet evident through the 1.8° slice at 1520 m (Fig. 8d).

Analysis of reflectivity data reveals that a BWER also descended with the mesocyclone couplet as it crossed Suffolk (not shown). By 2016 UTC, the BWER had reached the 0.5° slice at 540 m AGL with a very clear hook echo (Fig. 9a) that was bounded above, at the 1.3° slice at 1180 m AGL, by 40+ dBZ reflectivity (Fig. 9c). According to the mapping features available in AWIPS, at 2016 UTC the tornado had crossed US Highway 58, which is when EF-3 damage occurred in neighborhoods east and northeast of Obici Hospital. Over one dozen homes were completely destroyed with several hundred significantly damaged. Amazingly, there were no direct fatalities with the Suffolk tornado (and for all the Virginia storms on 28 April), though an estimated 200 were injured. The total property damage of the Suffolk tornado has been estimated at $20M.

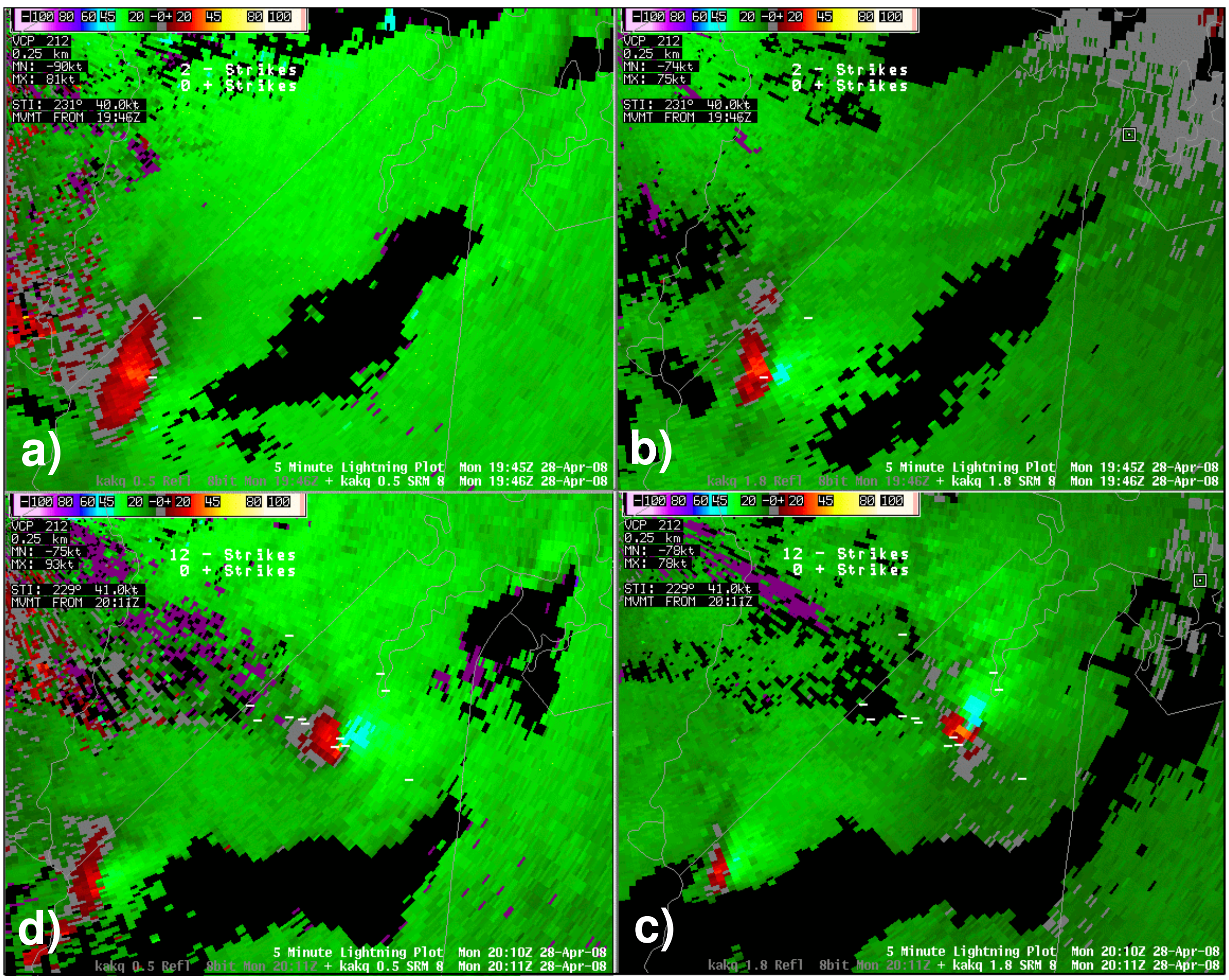

Figure 8. KAKQ SRM data zoomed in over the city of Suffolk at 1946 UTC: a) 0.5° and 1.8° b) and at 2011 UTC c) 1.8° and d) 0.5° with lightning data. The AKQ radar is located 43 km north-northwest of the couplet at 1946 UTC and 44 km northwest of the couplet at 2011 UTC.

5. COMPARISON TO PREVIOUS CASES

On 28 April 2002, a cyclic supercell developed near Charleston, West Virginia and maintained intensity as it pushed east across the northern Virginia Piedmont, the Coastal Plains of Maryland and into Wicomico County in the lower Maryland eastern shore. This supercell produced the La Plata, Maryland F4 tornado as well as an EF-3 in Dorchester County, Maryland. According to Strong and Zubrick (2004) there was a trough of low pressure over the Upper Midwest with an attendant cold front across the Ohio Valley. However, this trough was not as meridional as the setup in 2008, leaving steering winds more westerly, resulting in an eastward storm motion. Also, complete clearing of clouds ahead of the cold front in the early afternoon of the 28th allowed full solar insolation, slightly warmer temperatures, higher LCLs, and nearly twice the CAPE (near 1900 J kg^{-1} compared to near 1100 J kg^{-1}). Whereas cloud cover on 28 April 2008 limited CAPE, resulting in a mix of QLCS cells and supercells, 28 April 2002 had clearer skies, greater CAPE and mostly discrete supercells. There was little meteorological similarity between this case and the 2008 case other than the date.

During the morning of 23 September 2003, multiple tornadoes occurred in a low LCL and high low-level shear environment. According to Reilly (2004), there were a series of embedded surface lows along an approaching cold front with tornado producing line segments exhibiting Broken-S signatures. A tornado producing broken line on the north side of Richmond had a Broken-S signature with a mesocyclone coincident with the southern end of the northern segment and west of the break as with the Colonial Heights tornado. The CAPE in this case varied more than 28 April 2008 with some estimations above 2000 J kg^{-1} and low level helicity about 33% less (around 200 $m^2\ s^{-2}$ instead of 300 $m^2\ s^{-2}$). Still, eleven F0 and F1 tornadoes from QLCS cells occurred on that day, including nine in the AKQ CWA.

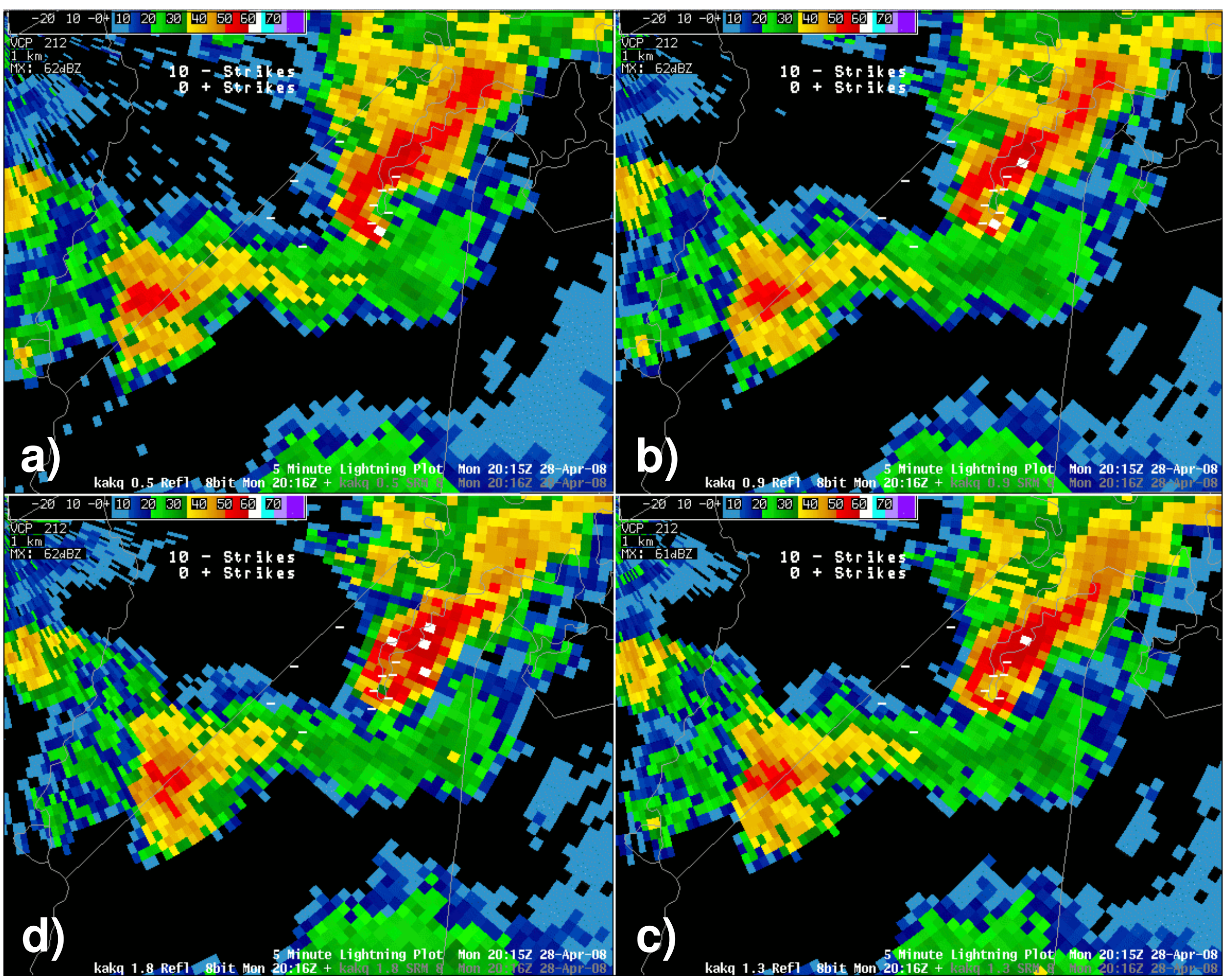

Figure 9. Same projection as Fig. 8, with 2016 UTC reflectivity over the city of Suffolk at: a) 0.5°, b) 0.9°, c) 1.3°, and d) 1.8°. The AKQ radar is located 44 km west-northwest of the hook echo/BWER.

6. CONCLUSIONS

On 28 April 2008 a warm and moist air mass ahead of a strong cold front provided a low cloud environment with low LCLs, a limited amount of CAPE, and a mesolow along the cold front provided enhanced helicity and shear which lead to the formation of QLCS thunderstorms. Ahead of this line, in far southeast Virginia, southerly winds increased low level temperature and moisture, yet cleared out the low level clouds that had persisted for over 24 hours. This created an environment where greater CAPE was present which increased the CAPE to shear ratio and allowed for discrete cell formation. The cell closest to the mesolow took advantage of the warm, moist air and backed low level winds, took on classic supercell characteristics and produced the strongest tornado in eastern Virginia in a decade.

This was an historic day for southeast Virginia with some notable extremes for the AKQ CWA. This was the first ten tornado day from a non-tropical system since the AKQ office opened in 1994. The Suffolk tornado was only the third (E)F-3 or greater tornado since AKQ's inception; an F3 in Hanover County on 01 April 1998 and the F3 damage in Wicomico County from the same cell as the La Plata, Maryland tornado on 28 April 2002. There had only been 24 (E)F-3 or greater tornadoes in the jurisdictions that make up the AKQ CWA since 1950.

High situational awareness is always key during severe weather warning decisions. In this case, several tornadoes from different convective modes occurred consecutively and concurrently. Reflectivity data displayed signatures common to QLCS tornadoes a few radar scans prior to tornado touchdown, while a combination of reflectivity and SRM data allowed for significant lead times ahead of tornado touchdown from the supercells. Also, modeled data did not fully realize the dynamic implications of a mesolow. Therefore a high awareness of the environmental conditions and ongoing activity across the region were vital to successful warning operations.

This case shows that, in opposition to the colloquial notion, the sky does not have to clear for any length of time to have a significant severe threat. In fact, greater insolation would have resulted in higher LCLs, a higher CAPE to shear ratio, and a different severe outcome.

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