April 7, 2006 Tornado Outbreak across the Tennessee Valley

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Abstract

A tornado outbreak struck the Tennessee Valley during the late morning and afternoon hours April 7th, 2006. Strong mid and upper level jet streaks nosing into the region associated with the southern edge of a deep low pressure system over the central plains advected a cool, dry airmass over the southeastern United States. Intense low level flow fields advected moist air from the Gulf northward. Above average high temperatures and the low level moisture in the boundary layer coupled with the upper level dynamics to form an atmosphere primed for severe weather. Extreme 0-3km wind shear promoted supercell and tornado development. This paper examines these synoptic and mesoscale characteristics to prove where and why convection developed. A specific cell along the leading edge of a line of supercells will be explored in depth to discuss mesoscale interactions between cells, as well as to correlate tornado formation within the supercell life cycle. Finally, future research is proposed that will lead to a more specific and complete understanding of the severe weather events that occurred on this day, as well as enhance current understanding of supercell line formation.

Introduction

Central Tennessee weather began ominously April 7th, 2006, as a lone elevated storm propagated eastward during the early morning hours. Robust low-level moisture streaming northward from the Gulf of Mexico and dry mid-level air pushing northeast out of the southwestern United States combined with favorable upper dynamics to produce an atmosphere primed for severe weather. Surface based convection began at 14:00Z in eastern Arkansas. A single cell (hereafter referred to as “Cell A”) initiated at 15:10Z the 7th in eastern Arkansas, propagated across the entire state of Tennessee, and finally dissipated at 04:47Z the 8th in western Virginia. An environment characterized by strong deep shear may allow a squall line to be comprised primarily of tornadoes. The environment across the Tennessee Valley on April 7th certainly fit this standard. Cell A remained intact for 13 hours, constantly fed by the aforementioned synoptic scale features along the leading edge of a 300 mile long line of thunderstorms, many supercellular. Nine tornadoes were produced by Cell A along its path—two each in Henderson and Cannon Counties, and one in each Lewis, Maury, Rutherford, Warren, and Cumberland Counties. National Weather Service Personnel officially surveyed five of the nine tornadoes. Two fatalities were directly linked to the Warren County tornado, rated an F1. The southeast United States as a whole received reports of ninety-one tornadoes. Two hundred and fifteen severe wind reports blanketed the southeastern United States, and five hundred sixteen hail reports were relayed to local National Weather Service offices.

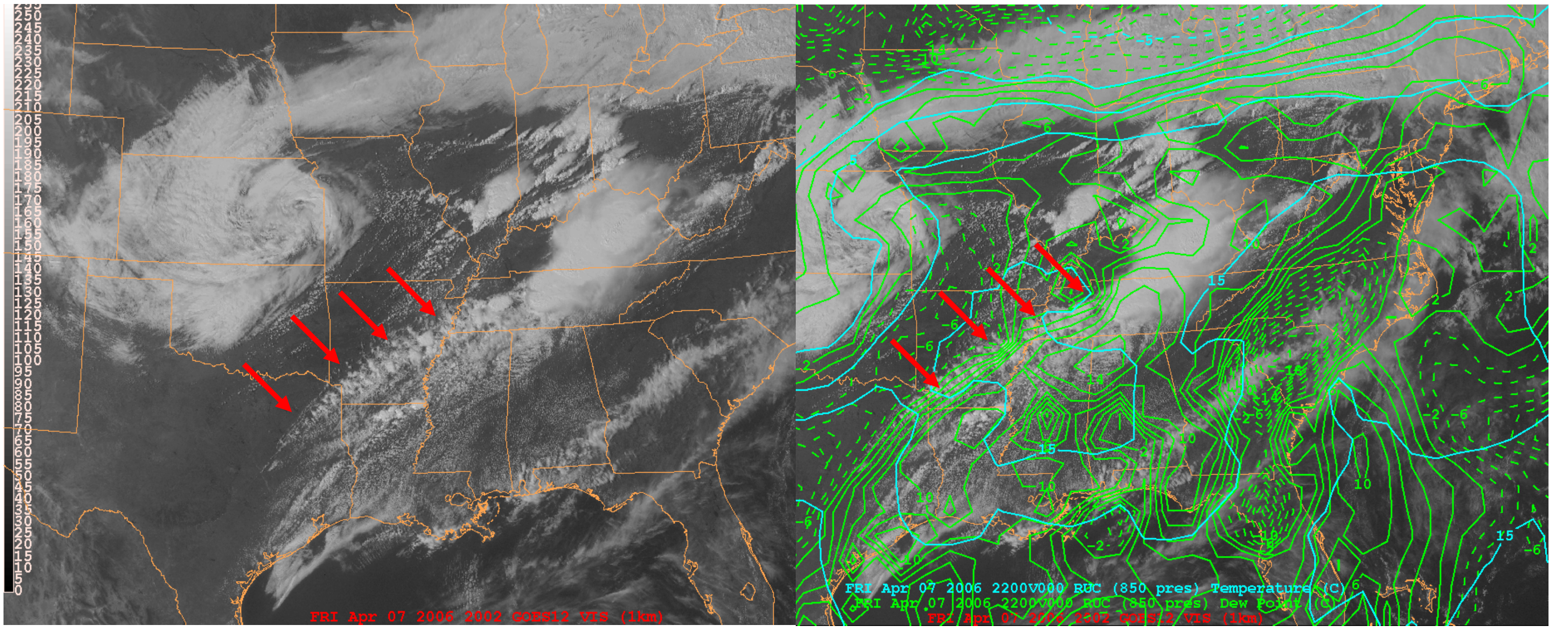

Figure 1*: At right: 20Z GOES-12 visible satellite image. At left: 20 GOES-12 satellite image overlayed with 20Z RUC analysis of 850hPa temperature (blue) and dewpoint (green). Red arrows in each point to main cloud band. At right, note that the main cloud band lies along the axis of greatest 850hPa moisture, just ahead of a tight dewpoint gradient.*

A few aspects of this weather event made it stand apart from others of its kind. First, satellite data seen in Figure 1 depicted cloud streets parallel to the mean low-level flow along which convection initiated, intensified, and eventually dissipated. The main cloud street lay coincident with the axis of the 850hPa moisture gradient positioned southwest to northeast across the Tennessee Valley, also shown in Figure 1. Second, Cell A maintained its strength for such a long duration because it was able to tap into the instability ahead of the mean flow of the system. The cells trailing Cell A were sustained by the dynamical mean flow parameters mentioned previously, just as Cell A fed off low-level moisture and midlevel dry air constantly ingested into the system. The trailing cells were also supplemented by the ingestion of the rear flank downdraft of the cell that propagated ahead of each. In essence, the cells along the line fed off one another's downdrafts to supplement the already robust environment in place. This made for long lasting, devastating supercellular storms. The severe weather event April 7, 2006 featured the main dynamic parameters that combine for a major outbreak. Distinguishing features like the 850hPa moisture gradient and multiple means for sustaining convection, made this event, and Cell A, storms to remember.

Data

Data analysis began with visible and water vapor satellite data provided by GOES-12 between 00Z the 7th through 00Z the 8th. Cloud and moisture trends were examined. Next, observational sounding data was used to develop temperature and moisture profiles for the Tennessee Valley region at 12Z and 18Z the 7th and 00Z the 8th. Convective threat, including such parameters as CAPE, LFC, and wind shear were assessed utilizing sounding data across the southeastern United States. GARP and GEMPAK were each used to plot upper level observations at sounding stations for contoured analysis maps. Model data was also examined. The 12Z

(00 to 12 hour forecast times) NAM and RUC (00Z model forecasts run 18Z the 7th through 00Z the 8th) offered severe weather parameter analysis, as well as temperature and dewpoint forecast data throughout the atmosphere. Base reflectivity and velocity data was gathered from the Nashville, TN, Paducah, KY, and Hopkinton, KY WSR-88d Doppler radars between 15Z the 7th and 04Z the 8th. Nashville radar data was missing between 1922Z and 2049Z. This may have occurred for many (speculated) reasons including a power strike at the station, storm damage, or the local data file may have been corrupt. The cell of interest spanned the length of Tennessee, and multiple radars needed to be used to follow the storm in a useful, logical manner. Southeastern United States composite maps were also used to maintain a large scale "situational awareness" of the event as a whole between 15Z and 04Z, while still focusing on the leading edge of the system. The Storm Prediction Center in Norman, OK was the source of storm reports and conceptual model characteristics. The National Weather Service Offices in Memphis and Nashville, TN provided damage surveys and detailed storm data for analysis.

Synoptic Overview

The early morning hours of April 7th, 2006 laid out a synoptically classic weather pattern conducive to severe weather development. An upper level low-pressure system was evident over Hudson Bay. A trough extended from this low southwest into the Dakotas. A second strong 300hPa low pressure system settled across eastern Kansas and Nebraska, just downstream of the Hudson Bay trough axis. A weak upper level ridge of high pressure nudged between these two systems, extending from North Carolina to Lake Michigan. The leading edge of an intense jet streak, depicted as the purple arrow in Figure 2, wrapped around the southern end of the low and pushed directly into western Kentucky and Tennessee. Winds blowing north-

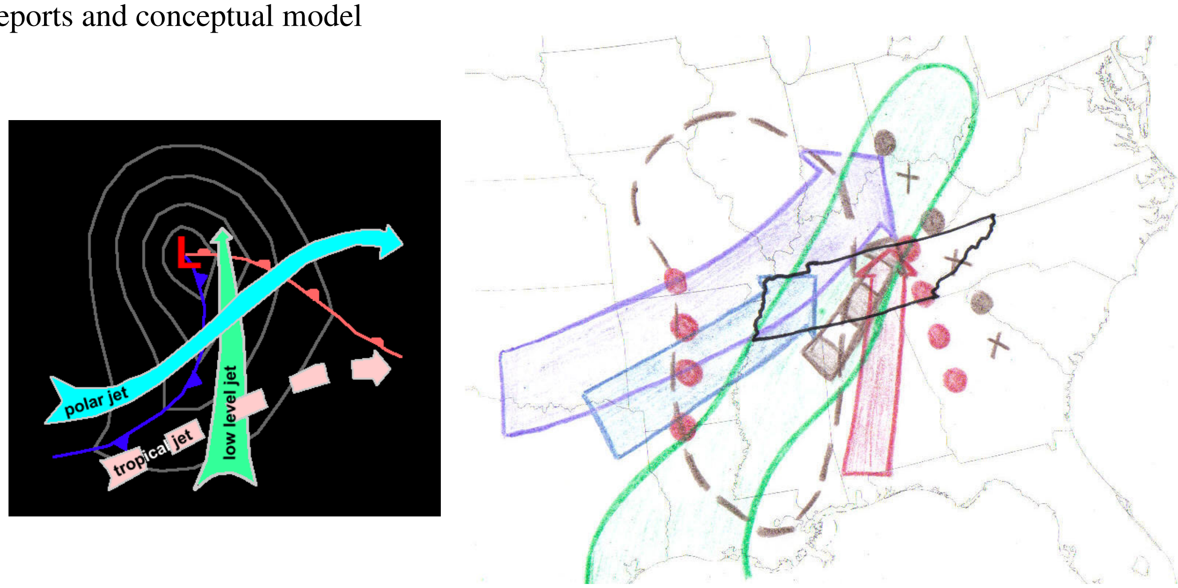

Figure 2: *Right: 18Z Miller Diagram across the SE United States. Purple arrow denotes 300hPa jet streak. Blue arrow denoted 500hPa jet. Brown/white arrows depict 700hPa jet steaks. Brown dashed area is 700hPa dry slot. Brown "x-o" line lies along 700hPa thermal ridge. Red arrow denotes 850hPa jet. Red dots indicate 850hPa thermal ridges. Green region depicts 850hPa moisture plume from the Gulf of Mexico. Tennessee outlined in black. Left denotes conceptual image of environment primed for severe weather.*

northeastward into Indiana increased in speed between 12Z the 7th and 00Z the 8th up to 105kts. Strong diffluence was evident at the nose of the jet, which was positioned midmorning just southwest of the Tennessee Valley.

The 500hPa profile depicted a strong mid-level jet, shown as the blue arrow in Figure 2, which also wound around the southern portion of the Great Plains low-pressure system. Diffluence at the nose of this jet similarly forced winds northeastward into northern Kentucky, and eastward into South Carolina promoting enhanced upward vertical motion in the Tennessee Valley. Extremely dry dewpoint temperatures were measured ahead of the low-pressure trough, downstream of the Tennessee Valley, and were forecast to progress eastward with the rest of the system. Steep mid-level lapse rates were evident on the 12Z NAM analysis across the Mississippi River Valley. The intense midlevel winds advected these lapse rates into the Tennessee/Kentucky region during the midmorning hours, forcing rapid destabilization at the midlevels. A warm temperature ridge also extended from the Gulf through the Ohio River Valley ahead of the cold front.

The 700hPa level depicted a low-pressure system across the border of Nebraska and Kansas. A jet streak was evident south of the low depicted by the brown arrow in Figure 2. Maximum mid-level wind speeds of 55kts were evident across Oklahoma and Arkansas, placing western Kentucky and Tennessee at the nose of the mid-level jet, promoting weak divergence in this region. A distinct temperature ridge extended from the Florida panhandle through western North Carolina, to Lake Michigan. Southeasterly winds were forced into this ridge axis, promoting moderate isentropic ascent in addition to the already robust upper-level diffluence at work. Cooler air upstream of the ridge axis, noted by the brown dashed region in Figure 2, was cold advecting into the Tennessee/Kentucky region. Mid-level cooling associated with this cold air advection weakened the convective inhibition, promoting atmospheric overturning and convective development. Steep lapse rates across Arkansas and Oklahoma were forecast to advect eastward as the day progressed, mixing out the mid-level atmosphere, promoting enhanced destabilization. A dry slot from northern Louisiana through Virginia was event not only in model and observational prognostics, but also on the GOES-12 water vapor image between 1800Z and 2000Z. Strong southwesterly winds continually urged mid-level dry air into the Tennessee Valley, supporting a prolonged thunderstorm system.

The 850hPa level featured the same closed low pattern across the Plains States evident at upper level. The Tennessee Valley was centered beneath a robust 850hPa jet streak extended from Alabama through Kentucky, with wind speed up to 50kts. A warm front extended from the low eastward across central Iowa and northern Illinois to Lake Ontario. A weak cold front extended from across the Texas/Oklahoma panhandles into New Mexico. The Tennessee Valley, therefore, was left in the warm moist sector ahead of the approaching system, seen in green on Figure 2. GOES-12 satellite imagery, in combination with a mid-afternoon RUC analysis seen in Figure 1, showed convection along the 850hPa moisture gradient. The darker regions surrounding the convection depict the 700hPa dry slot extending from Louisiana to Ohio, overspreading the Tennessee Valley.

The surface analysis for the southeastern United States at 13Z on April 7th, 2006 featured a 993hPa low-pressure center across the tri-state intersection of Nebraska, Kansas, and Missouri. A warm front extended from the low northeastward to Lake Huron, lying somewhat coincident with a cold front extending from the low-pressure system across Judson Bay. A cold front trailed the Plains system, extending southward across central Texas. Strong southerly winds from the Gulf of Mexico promoted a boundary layer temperature increase as the day progressed, as well as substantial moistening of the lowest atmospheric layers. Dewpoints climbed into the mid 60s and overspread the southeastern United States as seen in Figure 3. 12Z streamlines also show confluent winds to the west of Tennessee, and diffluent winds to the north of the region. The GFS and NAM models forecast a south-southeastward movement of the warm front the late morning and afternoon hours of the 7th. The cold front was forecast to continue to push eastward. The combination of frontal movement trapped and focused pooling low-level moisture over the southeast United States. This provided a constant supply of low-level moisture available for convective development. The cold front also provided a trigger to initiate convection.

Figure 3: *18Z Surface streamlines (Black) and surface dewpoint temperatures greater than 60ºF. Tennessee outlined in blue.*

The National Weather Service offices across Kentucky and Tennessee and well as the Storm Prediction Center expected convection to initiate later in the day than actually occurred. This was the case for a few reasons. First, southerly surface wind flow was stronger than had been forecast by either the GFS or NAM. Also, the midlevel jet streaks were under forecast by both models. As a result, midlevel cooling began earlier in the day. Second, the Tennessee Valley reached unseasonably warm, and under-forecasted, surface temperatures by late morning. The high temperature in Nashville (Davidson County) was 8ºF above normal, and Crossville (Cumberland County) saw temperatures 10Fº above normal. Also of note, the forecaster at the National Weather Service Office at Nashville wrote in his forecast discussion at 2:19am LST the 7th that, "A weak, pre-frontal surface trough will push across the mid state this morning, but then we actually dry out for several hours later on today. Therefore, am not expecting significant severe storms today."[1] Just a few hours later, an updated discussion at 9:15am featured the note, "SPC already talking about possible watch with supercell development already taking place in [Memphis] area." The increasing midlevel jet streaks and associated cold air advection and drying across Kentucky and Tennessee primed the upper atmosphere for convective development. Above average low level heating and abundant moisture primed the boundary layer for convection. Once midlevel cooling eliminated the "cap", the warm moist boundary layer quickly spurred overturning. Significant convective development resulted earlier in the day than anticipated. Incredibly strong diffluent winds at 300hPa already in place by late morning helped to initiate and sustain early convection providing upper level divergence and subsequent upward vertical motions over the Tennessee Valley. Finally, strong southwesterly mid-level winds continuously advected dry air into the region, and southerly low-level winds pumped moisture from the Gulf northward early and throughout the duration of the event. A continuous supply of favorable airmass composition at each the mid and low-levels fueled a long duration events across the Tennessee Valley. A vertical sounding analysis for the morning and early afternoon hours on April 7th depicted an atmosphere primed for severe weather. The Little Rock, AK sounding from 12Z the 7th (Figure 4a) best depicts the environment moving into the Tennessee Valley during the late morning and afternoon hours because the location lies upstream of the mean flow. The sounding offered 55kts of directional shear between 750hPa and the surface, and speed shear of nearly 40kts over the same layer at 12Z the 7th. These values are indicative of severe weather development, potentially supercells. The special 18Z sounding from Nashville (Figure 4b) offered 67kts of speed shear between 0 and 6km across an exceptionally veering profile over the same layer. Helicity values derived from the hodograph in Figure 4c over that same 0-3km layer reached $226 m^2/s^2$, again favorable for supercell development. Morning NAM model soundings did not grasp the extent of mid-level cooling and drying observed during the afternoon hours. Likely, the extremely strong (up to 80kt) 500hPa jet strengthened with the tightening curvature of the low-pressure system, and enhanced cold air advection resulted. Convectively derived parameters also set the stage for convective development. Early morning CAPE values, evident on the 12Z Nashville sounding (not pictured) registered next to nothing. The 12Z Little Rock sounding initialized at a more substantial 1500 J/kg. Each location saw increased values throughout the day as the moist low-level flow and dry upper level flow pushed into the

[1] Information gathered from www.srh.noaa.gov/ohx

region. Most unstable CAPE values across the southeastern United States grew to 2000 to 3000 J/kg through the morning hours. Modest convective Inhibition (CIN) during the morning hours allowed substantial low-level heat and moisture to build. A weak cap evident on the Little Rock sounding was quickly eroded as surface heating that reached seasonally high values, and midlevel cold air advection overran the region. Once the cap broke, widespread long-duration supercells resulted.

The 18Z sounding from Nashville, again Figure 4b, also helped to derive other convective parameters in the local area. The surface based Lifted Condensation Level (LCL) heights were just above 1km, the Level of Free Convection just 300m above that, and the equilibrium level was located at 38km. An LFC that is found lower than 2km is typically favorable for tornado development. Similarly, the smaller the difference between the LFC and LCL measured, the greater the potential for deep convection. Each case presents favorable parameters for deep, rotating supercell development. NAM forecasted parameters for the afternoon hours the 7th included a Sweat Index greater than 300 across the Tennessee Valley, Total Totals greater than 50, Lifted Indices dropping to –5 to –10, and 0-3km helicity values greater than 300. Nearly every parameter used to measure convective potential in the United States registered favorable values for the development of severe weather. The difference between this case and so many others is the distinctive moisture gradient along which thunderstorms developed, propagated, and were consistently fed.

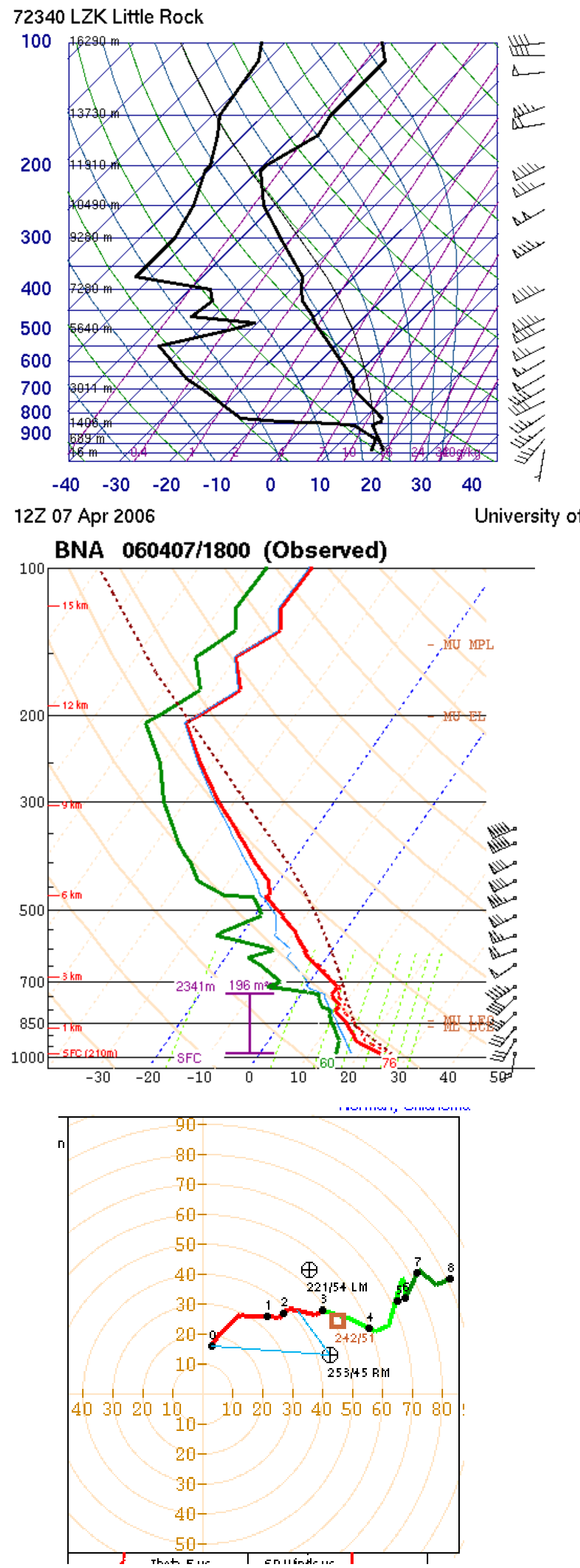

Figure 4: ***a****) Top: 12Z sounding from Little Rock, AK.* ***b****) Middle: 18Z sounding from Nashville, TN.* ***c****) Bottom: 18Z derived hodograph from Nashville, TN.*

Needless to say, the strong synoptic parameters in place on April 7th, 2006 needed only a small trigger mechanism to promote explosive atmospheric overturning. Significant cold air advection effectively weakened the cap. Upper level divergence, strong mid-level wind speeds and thermal cooling provided the necessary synoptic setup for a thunderstorm outbreak across the Tennessee Valley. Weak surface heating in combination with an extremely moist boundary layer provided the spark to induce extremely potent, surface based convection to develop. An extremely favorable shear profile promoted the development of tornadoes across Tennessee. This was well forecast by meteorologists at the Storm Prediction Center (SPC) who forecast a 60% chance that a tornado would occur within 25miles of a point within the probabilistic region just south of the Tennessee Valley (Figure 5).

Mesoscale Overview

A lone thunderstorm began to push northeastward through eastern Tennessee just after 7am on April 7th. Multiple cells depicting weak maximum on the composite reflectivity image began to pop up around 15:10Z. Cell A developed in Phillips County, AR just west of the Mississippi River. The cell propagated to the northeast and crossed the Mississippi River by 16:11Z. A low-level velocity maximum of 26kt inbound winds was observed on the Memphis 0.5° elevation cut. The cell pulsed at 16:21Z and grew what appeared to be an appendage off its northern end depicted in Figure 6. The following two reflectivity images, though, made clear that the cell actually split into individual cells that propagated in the same general northeasterly direction. The "right-moving" Cell A pulsed again along the southern edge of the Shelby/Fayette County line.

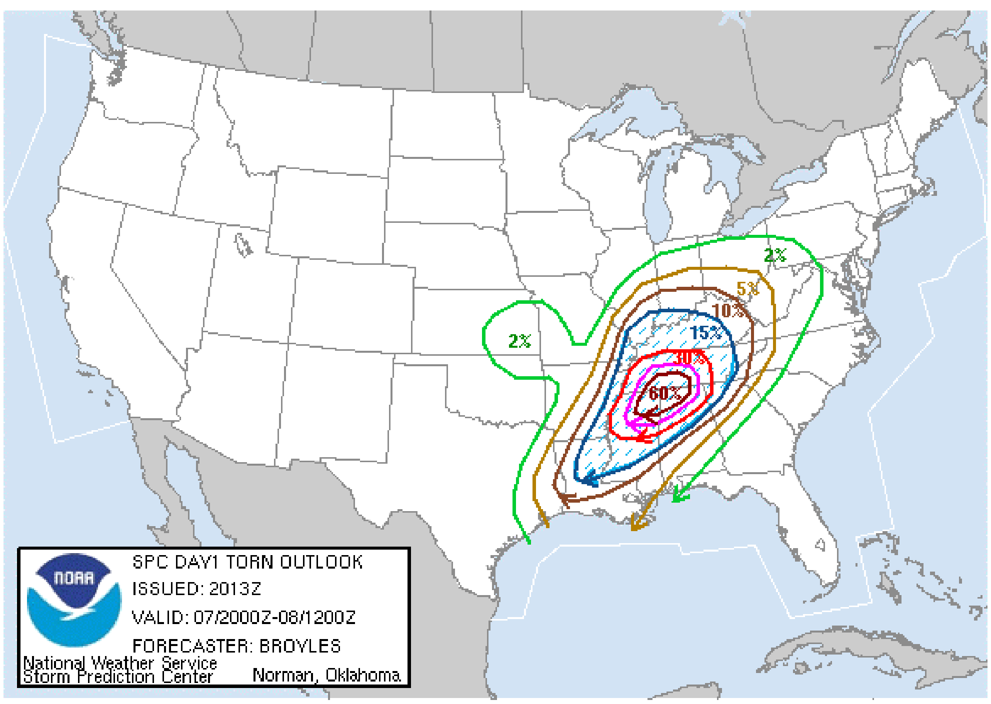

Figure 5: *SPC Day 1 Outlook for the afternoon hours of April 7th, 2006.*

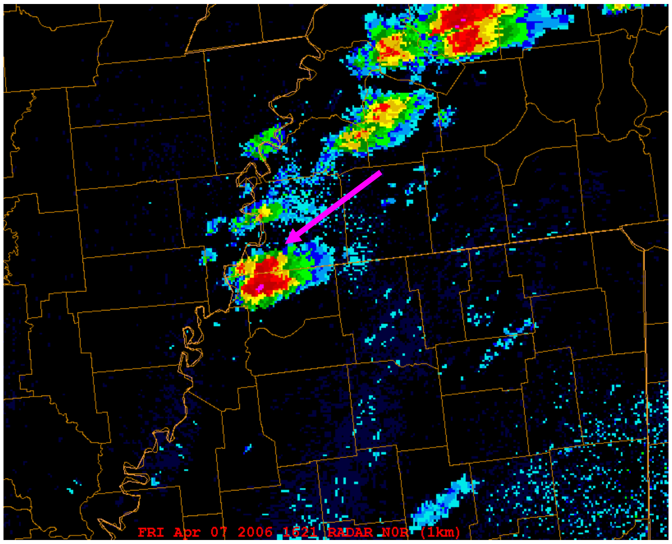

Figure 6: *16:21Z composite radar reflectivity image. Pink arrow points to the appendage.*

This time was also when a weak low-level cyclonic vorticity signature became evident on the NGA velocity image. The cell weakened over the next hour as it pushed through Hardeman and Chester Counties in southwestern Tennessee, but maintained a somewhat ambiguous couplet of coincident inbound and outbound air parcels. The cell re-intensified at the eastern edge of Chester County around 18:30Z. The first tornado report associated with Cell A came from Henderson County at 18:30Z. "Purple haze" errors off the Nashville and Memphis radars, as well as missing base data from Nashville during this time period made velocity signatures between 18:30Z and 20:49Z virtually useless. The Paducah radar, albeit a long distance (approximately 100mi) from the storm cell, featured the best rotational signature of Cell A beginning at 18:33Z, coincident with storm re-intensification. Likely, the PAH radar captured the mid-level mesocyclone occurring within the storm, but ground truth reports of a second tornado in Henderson County at 18:40Z proved that midlevel rotation was stretching down to the surface. Shortly thereafter, at 18:50Z, the cell lost its strongest reflectivity signatures but developed a hook-like echo along the southwesterly edge. The hook was heavily weighted toward the tail end, forcing the cell to take on the appearance of a kidney bean at 19:15Z. The PAH radar continued to show mid-level rotation associated with the storm, evident in Figure 7. The cell pulsed again at 19:29Z, minutes before a

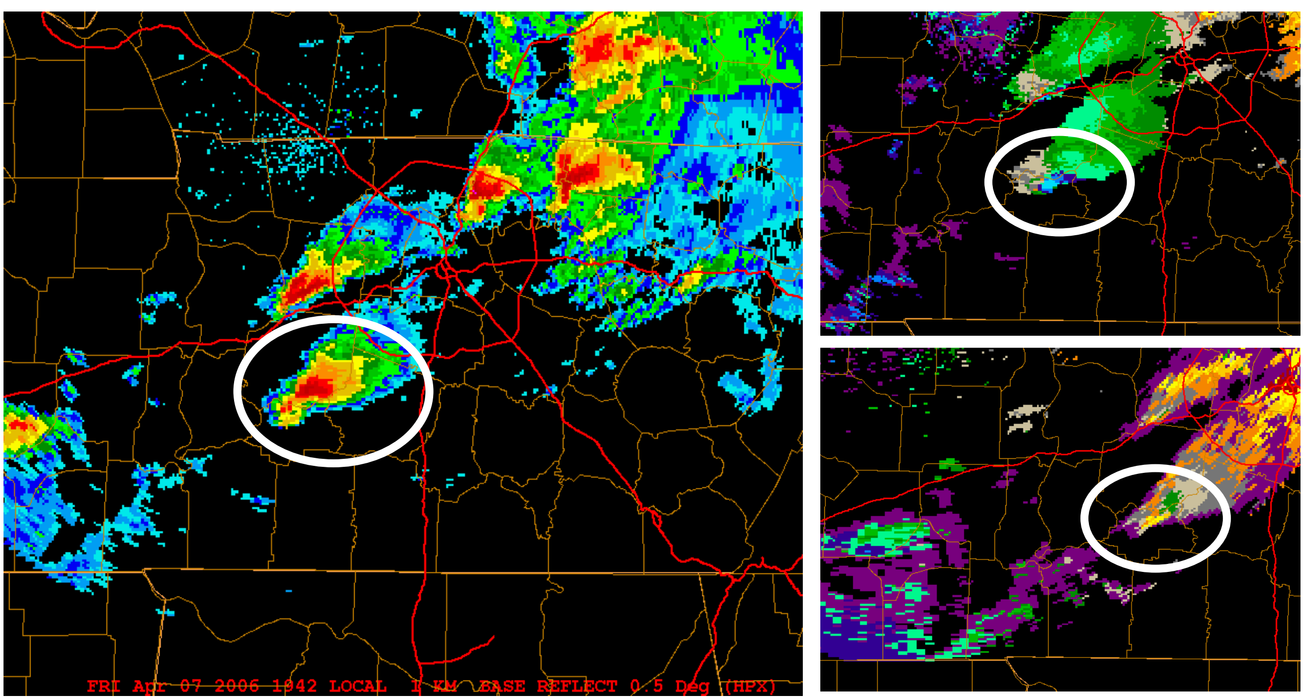

Figure 7: *Left: 19:42Z Hopkinton 0.5º base reflectivity image just before the Lewis County tornado. Upper right: 19:42Z Hopkinton 0.5º base velocity image. Bottom Right: 19:43Z Paducah 0.5º base velocity image.*

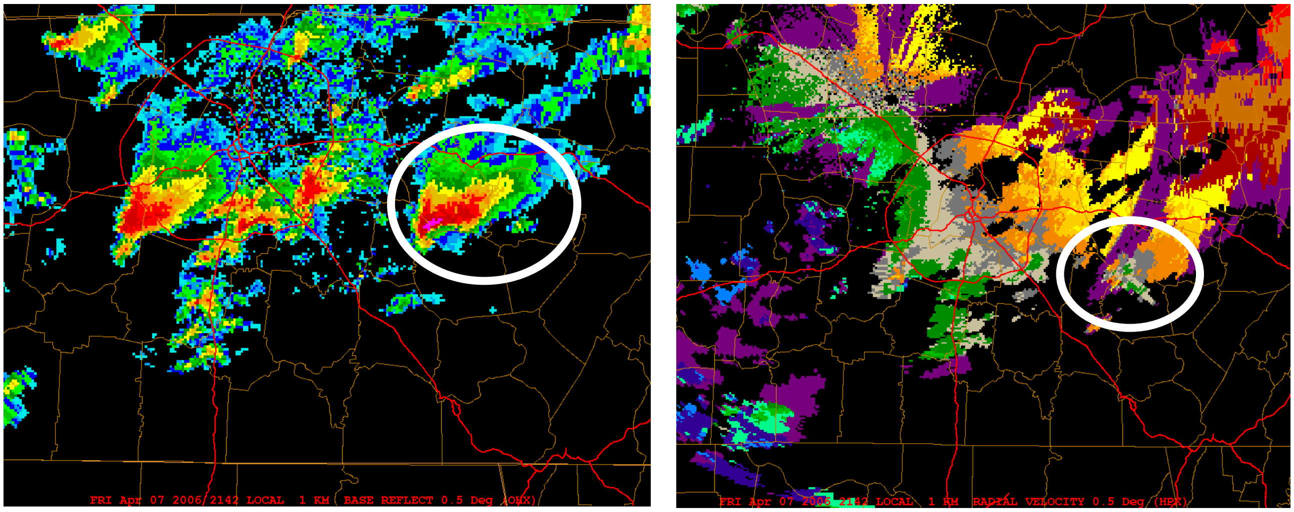

Figure 8*: Left: 21:42Z Hopkinton 0.5º base reflectivity image. White circle encapsulates storm of interest. Right: 21:42Z Hopkinton 0.5º base velocity image. White circle encapsulates storm of interest.*

tornado was reported in Lewis County at 19:43Z, the third produced by Cell A. The tornado was documented as an F0 that briefly touched down 3.0mi northeast of Hohenwald in Lewis County. A few trees were snapped in half, and no other tornado damage was reported.

The cell continued to push to the northeast. A relatively intense anticyclonic couplet was evident on the Hopkinton radar from the time of the Lewis tornado through 21:08Z when the cell unfortunately pushed out of radar range. The fourth and strongest tornado formed by Cell A rated an F2 was reported at 20:16Z in Maury County. The Nashville radar, located much closer to the storm cell, also picked up on the rotational signature particularly evident once radar data flow was reestablished at 20:49Z. The fifth tornado report came at 21:00Z from Rutherford County. The reflectivity signature from the Nashville radar at this time featured what looked to be a debris ball off the southeastern edge of the hook echo on the Williamson/ Bedford County line. The hook echo remained evident on the radar through a pulse at 21:15Z when the sixth and seventh tornadoes were reported by Cannon County, weakening at 21:26Z, and reintensification at 21:42Z. A tornado was spotted at 21:45 in extreme northwestern Warren County by a trained spotter, and lasted approximately 15 minutes. The F1 rated tornado made this supercell a killer, taking two lives along Foster Road in Warren County. The hook echo continued to be evident through 22:32Z till the storm took on a more circular appearance, based on the composite reflectivity image. Comparing the base reflectivity image with the composite, there was still a strong reflectivity core aloft, tilted ahead of the storm, in the direction of the mean wind. The ninth and final tornado report associated with Cell A came at 23:03Z from Cumberland County. The cell began to significantly decrease in intensity at 00:31Z at the head of the line of convective cells in Anderson County. The storm finally dissipated at 4:47Z in Wythe County, VA.

Cell A propagated along the leading edge of the convective line and was able to tap into the dynamically favorable environment ahead of the system to sustain convection. Additionally, cool dry midlevel air and warm moist low-level air advecting into the system helped to sustain convection. Figure 9 depicts the composite reflectivity image of this training line of cells. The cells that trailed Cell A, though, had an additional feed of instability to tap. Supercells emit both a front flank downdraft and a rear flank downdraft as depicted in Figure 10.

feeding into the already robust cell, forcing a convective feedback loop that helps sustain convection. Arrows denote RFD interaction between the cells. **Figure 11,** a vertical cross-section of theta and theta-e values in the vicinity of Cell A, depicts the air mass redistribution created by the FFD and RFD. Tornado formation is also provoked by the interaction of the FFD and RFD, and their respective density currents which force mesoscale

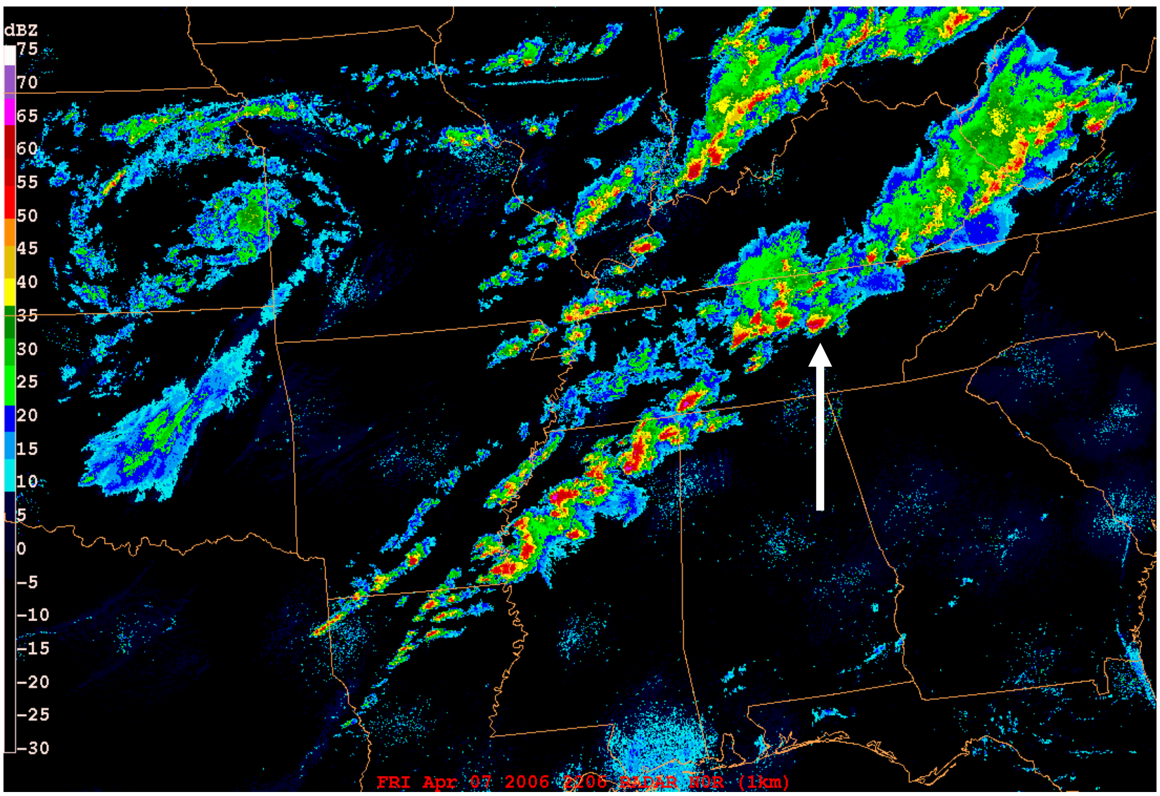

Figure 9*: 22:06 Composite reflectivity image. White arrow points to Cell A. Note low pressure system to the left of the graphic. Also note line stretching from northern Louisiana to West Virginia.*

The front flank downdraft (FFD) is characterized by the relatively cool, moist air it expels. The rear flank downdraft (RFD), on the other hand, is characterized by the relatively warm dry air it expels. This warm, dry, low density air on the trailing edge of the cell is made available to the next cell of the line. The air is primed for ascent, circulations. This is reflected in the high helicity values evident on the 18Z Nashville sounding generated by horizontal vorticity. The FFD and RFD not only assisted in sustaining convection in neighboring cells for an extended duration, but also helped to generate the low-level circulation responsible for 91 tornado reports across the southeastern United States April 7th, 2006.

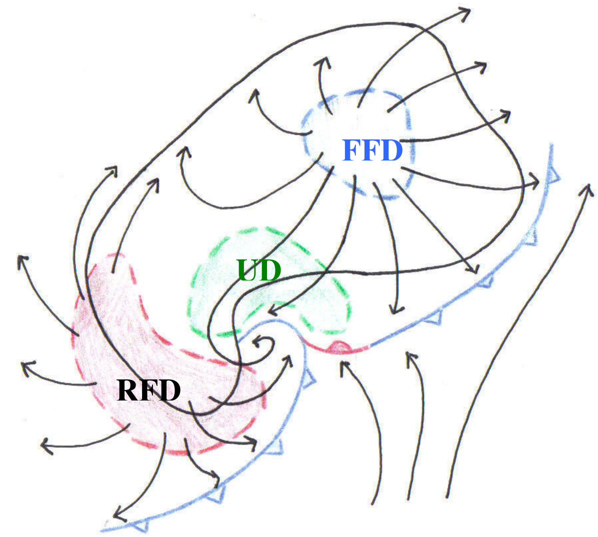

Figure 10: *Conceptual model of supercell thunderstorm airflow. Front Flank Downdraft (FFD) in blue, Updraft (UD) in green, and Rear Flank Downdraft (RFD) in red. Black lines represent streamlines.*

Conclusion

Synoptic and mesoscale interactions throughout the atmosphere across the southeastern United States led to the severe weather event that occurred April 7th, 2006. Particularly, cool dry air aloft in combination with above normal low-level daytime temperatures and abundant moisture interacted to violently overturn the atmosphere, initiating severe convection across Tennessee. This particular event was characterized by a line of convection coincident with an 850hPa moisture gradient stretched across the Tennessee Valley, and combination of mechanisms that helped to sustain convection. The first such mechanism was constant inflow of dry, cool midlevel air from the southwest, and warm, moist boundary layer air from the Gulf of Mexico. The second involved interaction between individual cells and their respective Rear Flank Downdrafts, which also helped to enhance low-level vorticity necessary for tornado development. Cell A led a line of supercells that traversed the length of the state of Tennessee, and produced 9 tornadoes, dozens of hail reports that reached up to 4.25" in diameter, and scattered downburst wind damage itself. The rest of the line contributed a significant amount of damage reports as well.

Research on the severe weather event of April 7th, 2006 is by no means near completion. Future work can and is encouraged to be performed over a plethora of fields. First, modeling of the complex interaction between individual supercells along the line could provide additional information on the convective structure of such events. Next, an area of focus could also be on the secondary line that formed to the north of the primary line—particularly on the questions of why and how this feature developed. Third, research could focus on the hail that occurred with Cell A. After initiation, Cell A consistently dropped 0.75" to 1.5" hail along its path.

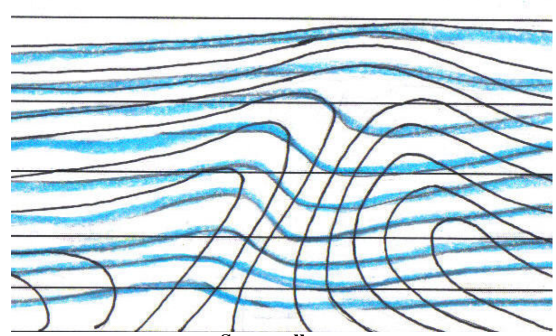

Figure 11: *A cross-section through Cell A at 21:00Z. Black lines depict constant theta-e. Note the updraft at center. This represents the supercell that just minutes later produced a tornado. Small thermal trough of warm air at left depicting the RFD. Blue lines depict constant theta. Note warmer air in the updraft of the cell, and cooler air in the tilted downdraft, particularly ahead of the cell associated with the FFD.*

One particular pulse resulted in 4.25" hail falling to the ground. After the first tornado formed, hail reports ceased. Similarly, few strong wind reports were associated with this event. The lack of each could be examined. Finally, the effect of population density on severe weather reports could be analyzed. Cell A was obviously tornadic throughout its life-cycle, but only nine tornadoes were reported and only five surveyed by the National Weather Service. This paper on the severe weather event to strike the Tennessee Valley April 7th, 2006 is by no means an exhaustive recollection of the plethora of atmospheric interactions that took place to form convection. Instead, it should be revered for its assertions regarding the cause of the sustained convective line, and the mesoscale interactions that induced tornadic development. The interaction between above average surface temperatures, boundary layer moisture, intense mid and upper level wind fields as well as cool dry mid-levels all hold their place in the events of April 7th, 2006.

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