The Impact of Terrain on Three Cases of Tornadogenesis in the

Great Tennessee Valley

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ABSTRACT

The Great Tennessee Valley of East Tennessee has experienced significantly fewer tornadoes in comparison to West and Middle Tennessee. This discrepancy can partly be explained by the complex terrain of the Great Tennessee Valley. The general orientation of the valley is southwest to northeast, which is typically not conducive to low level backing of the near-surface flow to a south or southeasterly direction. However, within the larger valley there are smaller geographical features that can lead to localized enhancement of storm-relative helicity for climatologically favored eastward-moving convective systems. This study examines three tornado events that occurred in the Great Tennessee Valley to determine the impact of topography on tornadogenesis. In one or more of the examined cases, the potential for tornadogenesis appears to have been enhanced by 1) the orientation of smaller valleys relative to the prevailing flow causing the channeling and backing of near-surface winds, resulting in locally enhanced storm-relative helicity; 2) vertical stretching of vorticity increasing mesocyclone strength when storms move from higher terrain to lower terrain; 3) upslope flow leading to intensification of storm updrafts and a strengthening mesocyclone; 4) mountain barriers acting as a boundary, with a more favorable tornado environment north of the boundary.

1. Introduction

The Great Tennessee Valley is oriented southwest-to-northeast, covering most of East Tennessee, stretching from northern Georgia to southwest Virginia. It ranges from 65 km wide in the southern end to about 130 km wide at the northern end, bounded by the Southern Appalachian Mountains (around 450–2000 m [1500–6500 ft] MSL) to the east and the Cumberland Plateau (around 450–1000 m [1500–3500 ft] MSL) to the west. Within the Valley there are many smaller topographical features that create a complex terrain (Fig. 1).
East Tennessee experiences fewer total tornadoes and fewer intense tornadoes than West or Middle Tennessee (Fig. 2). It is commonly thought that the lower frequency of tornadoes in East Tennessee is mainly due to the complex terrain of the southern Appalachian region (Gaffin and Parker 2006). The terrain features of the southern Appalachian region are generally oriented from southwest to northeast, and thus backing of near-surface winds necessary for the generation of low level storm-relative helicity for west-to-east moving storms is often difficult to achieve when the predominant surface flow is southerly. Though the orientation of the Valley as a whole may generally decrease tornado frequency, there are other terrain features on a smaller scale that may enhance the potential for tornadogenesis if certain meteorological conditions are met. This study will examine three tornado events and the impact that terrain features may have had on tornadogenesis.

2. Previous research

Idealized modeling studies (Wicker et al. 1996; Wicker 2000; Wilhelmson and Wicker 2001) have shown that a veering wind profile in the lowest 1 km and increased storm-relative helicity favor low-level mesocyclone development and tornadogenesis, assuming the large-scale environment is favorable for supercell formation. The backing of near-surface winds, due to the orientation of a valley, can help to create a veering wind profile and increase storm-relative helicity (Wicker 1996).

Observational studies have investigated the impact of terrain on tornadogenesis in other locations of the United States. Evans and Johns (1996) investigated tornado events in the Big Horn Mountains of Wyoming, and speculated that the orientation of the complex terrain contributed to tornadogenesis by increasing low level moisture and storm-relative helicity in a
favorably oriented valley. Bosart et al. (2006) studied the Great Barrington, Massachusetts tornado, and found that terrain-channeled low-level (0–1 km) southerly flow in the Hudson Valley was the most important factor in the ensuing tornadogenesis. The investigation of the Mechanicville tornado by LaPenta et al. (2005) found that terrain-channeled southerly flow existed in the Hudson Valley, which contributed to increased storm-relative helicity and advection of higher theta-E air in the Hudson Valley. The relative infrequency of tornadoes in areas of rough terrain, such as the Hudson Valley and the Great Tennessee Valley regions, compared to the Great Plains (Fig. 3) may partly be explained by the disruptive influence of surface friction. A mesoscale environment may be supportive of supercell development, but tornadogenesis is unlikely to follow unless local modifications to the low-level wind field are present to increase the vorticity and convergence at spatial scales similar to that of the supercell. Topographic configurations can provide the local enhancements of wind shear and static stability that are necessary for tornadogenesis (Bosart et al. 2006).

Topographic features may also play an indirect role in tornadogenesis by acting as a barrier to boundaries and surface cold pools, or by creating localized areas of enhanced surface wind convergence. Rotunno and Klemp (1985) showed that surface cold pools can play an important role in tornadogenesis by generating horizontal baroclinic vorticity, which may be tilted vertically and amplified in the presence of a strong updraft. Cold pools may be blocked by an orographic barrier, similar to the cold air damming phenomenon east of the Appalachians (Bailey et al. 2003). Should a supercell move from higher to lower terrain and cross the orographic barrier, vertical tilting of baroclinic vorticity may occur. Convergence of low level winds along terrain features was found to play an important role in severe storm development and tornadogenesis by Brown and LaDochy (2001) and Small et al. (2002).

a. Event summary

The city of Tazewell, TN is located in central Claiborne County in northeast Tennessee. It is east of the Cumberland Mountains, which are oriented mainly southwest to northeast. An exception to this orientation is an eastward bulge that extends into Anderson County. The peaks in this mountain bulge extend up to 1000 m (3500 ft) MSL.

Around 2350 UTC (750 pm EDT) on 26 April 2007, an EF1 tornado moved through Tazewell, tracking from southwest to northeast. Surface observations and objective analyses from that afternoon suggest that a pre-existing boundary was located across the Tennessee Valley. Locations north of the boundary had extensive cloud cover through the morning and afternoon, and light rain had fallen in this area earlier in the day. Locations south of the boundary had scattered clouds and greater surface heating, resulting in a more unstable air mass (Fig. 4). Objective surface and upper air analyses indicated 0-3 km CAPE on the order of 500 Jkg$^{-1}$ south of the boundary, and less than 100 Jkg$^{-1}$ north (Fig. 5). On the north side of the boundary, LCL heights were 500-800 m with a local minimum over Tazewell (Fig. 6), and 0-1 storm-relative helicity values were around 200 m$^2$s$^{-2}$ (Fig. 7).

A loop of composite reflectivity from the KMRX radar is shown in Fig. 8, along with surface METAR observations. Thunderstorms developed in the afternoon over Middle Tennessee and the southern Cumberland Plateau, and moved northeast. One of these storms moved directly over the bulge in the Cumberland Mountains, and at the same time, it quickly intensified. As seen in Fig. 8, an observation from KOQT (Oak Ridge, TN) at 2300 UTC showed a gusty south wind with an upslope component when the storm was located over the higher
terrain. As it continued northeast, the rotational velocity (as measured by the KMRX radar) strengthened, and the storm began to develop supercell characteristics as seen by radar reflectivity and storm-relative radial velocity (Fig. 9).

b. Impact of terrain

Lack of direct observations in the region prevents definitive conclusions; however the processes that intensified the storm and led to tornadogenesis can be inferred based on the limited data. The terrain of the Cumberland Mountains appears to have impacted storm evolution and resulting tornadogenesis in several ways.

First, the timing of the intensification of the storm as it moved over the Cumberland Mountain bulge suggests that the terrain aided in strengthening the storm’s updraft. A southerly flow of relatively warm and unstable air was advected northward through the Tennessee Valley, and encountered the Cumberland Mountain bulge. This likely created a zone of low level convergence and upslope flow. As a result, the ascent rate of the unstable air was enhanced near the mountains, feeding greater amounts of unstable air into the storm.

Second, the L-shape of the Cumberland Mountains, along with the pre-existing boundary that extended southeast from the bulge, likely created an effective localized barrier to the northeasterly flow and trapped low level moisture. This may have aided in the generation of horizontal baroclinic vorticity and provided a moist near-surface layer with low LCL heights. As the storm moved off the higher elevations of the Cumberland Mountain bulge, the horizontal vorticity generated by the cold pool may have been tilted and stretched vertically by the intensifying updraft, and the storm did experience an increase in low level rotational velocity at this time. The trend of low level rotational velocity as measured by the KMRX mesocyclone
detection algorithm is shown in Fig. 10. The tilting and stretching of the pre-existing low level vorticity as the strengthening updraft moved off the higher elevations of the Cumberland Mountain bulge likely led to the formation of the Tazewell tornado.


a. Event summary

The city of Big Stone Gap, Virginia is located in the Powell River Valley, a narrow (about 1200 m wide) valley at an elevation of 450 m (1500 feet) MSL. Figure 11 shows the topography of this area. On 4 March 2008, a line of storms stretched from southeast Kentucky through East Tennessee, moving toward the northeast. As the line moved through Big Stone Gap, an EF1 tornado developed at 2155 UTC (1755 EST). The motion of the tornado was determined to be from the southeast to northwest, at about a 60 degree angle to the track of the convective line. The tornado track as determined by a NWS storm survey team is shown in Fig. 11, and a loop of 0.5 degree reflectivity is shown in Fig. 12. A mesocyclone with a rotational velocity of around 18 ms$^{-1}$ (35 kts) was indicated by the KMRX radar near the time of tornado touchdown. A loop of 0.5 degree storm-relative radial velocity is shown in Fig. 13.

The storm environment was characterized by high shear and low instability. RUC model analysis of 0-1 km storm-relative helicity at 2000 UTC showed values around 800 m$^2$s$^{-2}$ (Fig. 14). The highest 0-3 km CAPE values across the area were only around 100 Jkg$^{-1}$ (Fig. 15). Light rain had moved across the area in the morning, with some breaks in the clouds allowing surface heating in the early afternoon.
b. Impact of terrain

The spacial and temporal scales of the tornado, which are smaller than available observed data scales, prevent definitive conclusions about the causes of tornadogenesis. However, it can be inferred that the terrain surrounding the town of Big Stone Gap had a significant impact on the location and path length of the tornado, possibly in multiple ways.

A plot of surface observations across southwest Virginia (Fig. 15) shortly before the tornado occurred shows a prevailing easterly surface wind, while RUC soundings in the vicinity (Fig. 16) showed winds veering to southerly and increasing rapidly above the surface. The RUC analysis of 0-1 km storm-relative helicity (Fig. 14) shows a local maximum over southwest Virginia, likely as a result of the easterly surface flow. The northeast-to-southwest orientation of the Powell River Valley may have additionally backed surface winds to northeasterly on a local scale to enhance the storm-relative helicity. The approach of the storm from the southwest may have also caused localized pressure falls, which could have further helped to channel winds through the narrow valley in a northeasterly direction.

In the case of the Big Stone Gap tornado, the damage path of the tornado began around an elevation of 550 m MSL (1800 feet MSL) on the southeast mountain, and continued down through the valley at 460 m MSL (1500 ft MSL), as shown in Fig. 11. The end of the damage path of the Big Stone Gap tornado was near 520 m MSL (1700 ft MSL) on the northwest mountain. Since the parent storm and mesocyclone moved from southwest to northeast while the tornado track was from southeast to northwest (nearly perpendicular), it seems logical to conclude that the terrain had a complex influence on tornadic scale processes. However, beyond a simple argument of vortex stretching/shrinking contributing to intensification then weakening
as the tornado moved downslope and then back upslope, there is not enough evidence in the available data to speculate beyond that.


a. Event summary

A prominent feature of the southern Tennessee Valley region is the Sequatchie Valley, which is oriented southwest-to-northeast (Fig. 17). There are smaller valleys that branch off from the Sequatchie Valley. In southwest Marion County lies a southeast-to-northwest oriented valley (referred to as the Kimball Valley in this paper). The town of Kimball is located near the mouth of this valley. In the late afternoon hours of November 14, a long-track supercell moved across Middle Tennessee, just north of the Tennessee and Alabama state line. It briefly produced an EF1 tornado in Lincoln County in southern Middle Tennessee. The storm maintained supercell characteristics as it moved east across Franklin County, but did not produce a tornado until it moved into Marion County. Rotational velocity increased dramatically over Marion County, and the storm showed a distinct hook. A loop of reflectivity from the KHTX radar is shown in Fig. 18, and a loop of storm-relative radial velocity is shown in Fig. 19. A tornado rated as an EF2 touched down just west of Kimball, and tracked east-southeast between approximately 0100 UTC and 0110 UTC November 15.

The storm environment over Middle Tennessee was favorable for supercells and tornadoes, but became less favorable to the east over the Great Tennessee Valley. A nearby aircraft sounding shows a moist near-surface layer and winds that increase rapidly and veer slightly with height (Fig. 20). LCL heights were on the order of 750 m with 0-1 km storm relative helicity around 200 m^2 s^{-2} (Fig. 21). An objective analysis of surface theta-E (Fig. 22)
show a ridge (with maximum values of 330°K to 335 °K) over southern Middle Tennessee and northern Alabama, with the eastern edge of the maximum theta-E values near Marion County.

**b. Impact of terrain**

Although direct measurements are not available, it can be inferred that local topography played a significant role in the formation of the Kimball tornado. The predominant surface flow over southeast Tennessee, northeast Alabama, and northwest Georgia was from the southwest. This is directly in line with the Sequatchie Valley, and the flow was likely channeled up the valley. The channeled southwesterly flow likely reduced or limited the storm-relative helicity on a local scale, as surface winds in the narrow Sequatchie Valley would not have been able to back to the south or southeast. However, the mouth of the Kimball Valley is nearly orthogonal to the Sequatchie Valley. The southeast-to-northwest orientation of this valley suggests that surface winds would have been able to back, increasing storm-relative helicity on a local scale. As the supercell approached, localized pressure falls in advance of the storm likely occurred over western Marion County. Although no direct observations are available in the Kimball Valley, the observation at KCHA is located approximately 45 km (28 miles) to the east, and can be used to infer what may have occurred at Kimball. Observations from KCHA ahead of the storm showed falling pressure (from 1010.8 mb at 0000 UTC to 1008.4 mb at 0200 UTC) and backing winds (from 210° at 2000 UTC to 180° at 0200 UTC). Dewpoints were also increasing through the day at KCHA, from 12 °C (54 °F) at 1300 UTC to 18 °C (64 °F) at 2300 UTC, indicating low level moisture advection into the area. Falling pressures and backing winds would have the effect of channeling the surface winds through the Kimball Valley, which would have locally increased the storm-relative helicity. As the supercell encountered the locally backed winds through the
Kimball Valley, it is inferred that the strong mesocyclone and updraft may have coupled with the enhanced storm-relative helicity to help generate a tornado.

6. Conclusions

The complex terrain of the Great Tennessee Valley region provides a significant challenge for anticipating tornadogenesis. The southwest-to-northeast orientation of the valley is typically not conducive to low level backing of the near-surface flow, and the rugged terrain of the Cumberland Plateau and the Southern Appalachian Mountains increase surface friction. However, finer terrain features may increase the potential for tornadogenesis, as inferred from the events in this study. A more in-depth study, including cloud-scale modeling of tornadogenesis in complex terrain, would be needed to make more definitive conclusions on the processes that are inferred in this study.

A variety of topographic configurations may provide the local enhancement of low level wind shear and instability that are needed for tornadogenesis. Whether a terrain feature will enhance or diminish the potential for tornadogenesis will depend on numerous factors, including the orientation and structure of the terrain feature itself, the mesoscale environment, the structural characteristics of the storms within the environment, and the movement of the storms relative to the topographic feature. Forecasters should be alert for rotating storms that move from higher to lower terrain, which may result in vertical stretching of vorticity. Storms that move across valleys that can channel winds into a more favorable orientation for enhanced storm-relative helicity should also be closely monitored. In general, forecasters should have an intimate knowledge of the terrain in their warning area, and they must have a high level of awareness of the storm environment in order to properly anticipate tornadogenesis in areas of complex terrain.
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REFERENCES


Figure 1. Topographic image of the Southern Appalachian Mountains, the Great Tennessee Valley, the Sequatchie Valley, and the Cumberland Plateau. The locations of the radars that were used in this study are labeled by the stars. The locations of the tornadoes that are referenced in this study are labeled by the white circles, with town names labeled. The locations of the major airports are labeled by the airplanes. Color scale of terrain in thousands of feet.
Figure 2. Plot of tornado paths across Tennessee from 1950 to 2007. A white path is F0; gray is F1; yellow is F2, orange is F3, brown is F4, black is F5. From http://www.tornadohistoryproject.com/index.php

Figure 3. Tornado days per year (1980-1999). Note the minimum of tornado days located from eastern West Virginia through East Tennessee and the Southern Appalachians. From http://www.nssl.noaa.gov/hazard/totalthreat.html
Figure 4. Visible satellite image at surface METARs at 2200 UTC 26 April 2007. The location of Tazewell is marked by the white circle, and the approximate location of a surface boundary is shown by the blue line. A southerly flow with gusty winds, scattered cloud cover, and temperatures in the 70s were observed over the southern portion of the Great Tennessee Valley, while northeast Tennessee had overcast skies, light rain, and a northeast wind.
Figure 5. Topographic image and LAPS objective analysis of 0-3 km CAPE (light blue contours, units are in Jkg\(^{-1}\)) at 2200 UTC 26 Apr 2007. The location of Tazewell is marked by the white circle, and the approximate location of a surface boundary is shown by the blue line. Color scale of terrain in thousands of feet.
Figure 6. Topographic image and LAPS objective analysis of LCL height (units are tens of meters, shown by white dotted contours) at 2200 UTC 26 Apr 2007. Note that the minimum of LCL heights was over Tazewell. The location of Tazewell is marked by the white circle, and the approximate location of a surface boundary is shown by the blue line. Color scale of terrain in thousands of feet.
Figure 7. Topographic image and LAPS objective analysis of 0-1 km storm-relative helicity (shown by yellow contours, units are in m²s⁻²) and surface wind barbs at 2200 UTC 26 Apr 2007. The location of Tazewell is marked by the white circle, and the approximate location of a surface boundary is shown by the blue line. Color scale of terrain in thousands of feet.
Figure 8. Topographic image, composite reflectivity loop (CLICK HERE FOR LOOP) from KMRX between 2217 UTC and 2355 UTC 26 April 2007 (showing every other volume scan), and surface METAR observations during that time. Reflectivity values lower than 40 dBZ have been filtered out. The white circle highlights the location of the tornado. When the storm moved over the Cumberland Mountain bulge, it intensified, likely due to the southerly upslope flow of warm moist air, as seen in the KOQT observation (located immediately south of the bulge). After the storm moved off the higher terrain of the Cumberland Mountain bulge, the storm evolved supercell characteristics such as a hook echo and a bounded weak echo region.
Figure 9. Storm-relative radial velocity loop (CLICK HERE FOR LOOP) from KMRX between 2213 UTC and 2355 UTC 26 April 2007 (showing every other volume scan). The white circle highlights the location of the tornado. A tornado was reported on the ground at 2355 UTC in Tazewell (last frame of the loop). The low level rotational velocity at this time, computed by the KMRX Mesocyclone Detection Algorithm, was 12.4 m$^{-1}$. 
Figure 10. Time series plot of low level rotational velocity as calculated by the KMRX Mesocyclone Detection Algorithm. When the storm was over the Cumberland Mountain bulge, the low level rotational velocity as measured by the KMRX mesocyclone detection algorithm was 5.4 m\textsuperscript{s}\textsuperscript{−1} at 2238 UTC. Once the storm moved off the higher elevations of the Cumberland Mountain bulge at 2300 UTC and encountered higher 0-1 km storm-relative helicity, the low level rotational velocity increased. The low level rotational velocity peaked at 12.4 m\textsuperscript{s}\textsuperscript{−1} when the tornado was located near Tazewell between 2350 and 2359 UTC.
Figure 11. Topographic image of the Powell River Valley and the town of Big Stone Gap, with north being at the top of the image. The red line is the approximate center of the tornado track as determined by a NWS storm survey team. The topographical cross section in the lower portion of the image is taken approximately along the tornado track, with the left side of the cross section being north-northwest. The storm survey found that the tornado path began halfway up the slope of the mountain on the southeast side of Big Stone Gap, tracked through the town, and ended near the base of the mountain on the northwest side of town. All elevations are in feet MSL. Images ©2007 DeLorme (www.delorme.com) TOPO USA ®.
Figure 12. KMRX 0.5 degree reflectivity loop (CLICK HERE FOR LOOP) between 2128 UTC and 2210 UTC 4 March 2008 (showing every other volume scan) and a topographic image. Reflectivity values below 40 dBZ are filtered out. The white circle highlights the location of the tornado. The storm motion was southwest to northeast, but the tornado track was southeast to northwest.
Figure 13. KMRX 0.5 degree storm-relative velocity loop (CLICK HERE FOR LOOP) between 2128 UTC and 2210 UTC 4 March 2008 (showing every other volume scan). The white circle highlights the location of the tornado. The mesocyclone can be seen briefly at 2153 UTC. This was the approximate time of Big Stone Gap tornado.
Figure 14. RUC model mesoanalysis from the Storm Prediction Center at 2000 UTC 4 Mar 2008 showing high 0-1 km storm-relative helicity over SW VA before the Big Stone Gap tornado. Units are in m²s⁻².
Figure 15. Topographic image, surface observations plot, and LAPS objective analysis of 0-3 km CAPE (yellow contours, units are in Jkg\(^{-1}\)) at 2100 UTC 4 Mar 2008. The location of Tazewell is marked by the red circle. Color scale of terrain in thousands of feet.
Figure 16. RUC model sounding at 2000 UTC 4 Mar 2008 in the vicinity of Big Stone Gap, VA. Note the rapid increase in wind speed and veering just above the surface.
Figure 17. Topographic image of the southern Cumberland Plateau and Tennessee Valley. The Sequatchie Valley (cyan line), the location of Kimball (white circle), and the approximate track of the tornado through Kimball Valley (red line) are shown.
Figure 18. Loop of KHTX 0.5 degree reflectivity (CLICK HERE FOR LOOP) between 0030 UTC and 0116 UTC 15 Nov 2007 with a topographic image. Reflectivity values below 40 dBZ are filtered out. The white circle highlights the location of the tornado. The tornado was reported in Kimball at the 0102 UTC image.
Figure 19. Loop of KHTX 0.5 degree storm-relative radial velocity ([CLICK HERE FOR LOOP](#)) between 0030 UTC and 0116 UTC 15 Nov 2007. The white circle highlights the location of the tornado. The tornado was reported in Kimball at the 0102 UTC image.
Figure 20. Aircraft sounding from CHA at 2248Z 14 November 2007. The location of CHA is shown in Fig. 17. A vertical profile of wind speed is on the right. A moist near-surface layer and vertical wind shear likely enhanced the tornado potential, although low level lapse rates were not very steep.
Figure 21. RUC model mesoanalysis from the Storm Prediction Center at 0000 UTC 15 Nov 2007. Blue contours are 0-1 storm-relative helicity (units are in m$^2$s$^{-2}$), and green and tan contours are LCL height (units are in meters), with values below 1000 m shaded in green.
Figure 22. LAPS objective analysis of theta-E (units are degrees K) at 0100 UTC 15 Nov 2007. A theta-E ridge was located across northern Alabama, and extended into Marion County Tennessee. The white circle indicates the location of Kimball.