11A.1A AN OBSERVATIONAL ANALYSIS OF POTENTIAL TERRAIN INFLUENCES ON TORNADO BEHAVIOR

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1. INTRODUCTION

Terrain effects on tornado behavior have long been a source of lore in the United States. Common myths about tornado behavior include that certain areas are more prone to tornadoes, tornadoes will not form in mountainous areas, and tornadoes will not cross valleys, among others. Several cases of tornadoes in mountainous areas not obeying these commonly-held myths can been documented (e.g. Fujita 1989, Forbes 1998). However, only limited work has been done to determine the role of terrain in severe storm and tornado behavior. Much of this work has been completed on individual cases (e.g. Fujita 1989, LaPenta et al. 2005, Bosart et al. 2006, Karstens et al. 2013) or a very limited number of cases (e.g. Gaffin 2012, Shamburger 2012). In addition to these cases, some limited work has been done on interactions of severe storms and tornadoes with significant topography, including the effects of terrain on gust fronts (Frame and Markowski 2006), modeling of supercells moving over various terrain features (Markowski and Dotzek 2011), and large-eddy simulation (LES) of tornado-like vortices moving over significant topography (Lewellen 2012).

One important step to understanding the role that terrain may play in tornado evolution is to document behaviors in tornado events that appear to be linked to the underlying terrain. Through this process, the emphasis must be on patterns that are seen repeatedly so as to lessen the potential for considering coincidental behavior as being linked to the underlying terrain. This paper highlights four cases in which terrain appears to have played a significant role: the Huntsville, Alabama EF1 tornadoes of 11 April 2013, the Pisgah, Alabama EF4 tornado of 27 April 2011, the Ohatchee, Alabama EF4 tornado of 27 April 2011, and the Rainsville, Alabama EF5 tornado of 27 April 2011. These four cases are then placed in the context of behavioral modes that have been observed across 75 total cases. Implications for future research are discussed.

2. DATA COLLECTION AND METHODOLOGY

Data were gathered from numerous sources for this paper. Doppler radar analyses from the Hytop, Alabama WSR-88D radar (KHTX) where utilized in the Pisgah tornado case, while data from the University of Alabama in Huntsville's Advanced Radar for Meteorological and Operational Research (ARMOR; Peterson et al. 2005) was utilized for the 11 April 2013 case. Data from both radars was dealiased manually in the NCAR SOLOii software (Oye et al. 1995). For the ARMOR data, an attenuation correction was applied following the procedure from Bringi et al. (2001). In both cases, single-Doppler analyses of rotational velocity (VROT) and axisymmetric vertical vorticity (AVV) were used to evaluate changes in the intensity and size of the circulation detected on each sweep. These findings were then plotted with the underlying land surface terrain to evaluate changes in intensity of the tornado or parent circulation as the storm crosses the terrain.

For all four cases, storm surveys were a vital source of information for documentation. Much of the survey data used is provided by the National Weather Service Damage Assessment Toolkit (DAT; NWS 2014) or the National Climate Data Center (NCDC) Storm Events database (NCDC 2014). The DAT data is particularly useful because it provides exact damage locations and intensity along a true track instead of the straight-line paths provided by NCDC. In addition to NWS surveys, UAH Severe Weather Institute and Radar & Lightning Laboratories (SWIRLL) researchers often augment survey information by performing ground surveys for important events. The lead author conducted one such survey for the 11 April 2013 Huntsville tornadoes. Aerial imagery, including NOAA response imagery from the 27 April 2011 outbreak (National Geodetic Survey, 2014) as well as photography supplied to UAH SWIRLL from other sources is also used in this paper.

3. 11 APRIL 2013: HUNTSVILLE, ALABAMA

A severe quasi-linear convective system (QLCS) impacted the Tennessee Valley during the afternoon hours of 11 April 2013. One mesovortex formed along the Tennessee River on Redstone Arsenal and quickly produced an EF1 tornado. This tornado moved northeast across the southeastern end of Redstone Arsenal and the southern end of Huntsville. Upon reaching Huntsville Mountain, a 250-m vertical relief over the Tennessee Valley floor, the tornado dissipated, only to reform on the east side of the mountain (Fig. 1; NWS 2014, NCDC 2014).

The favorable location of the tornadoes to ARMOR (within 12 to 25 km of the radar for the entire event evolution) and the frequent 0.7°-2.0° scan strategy (60-80 sec. volume time) lent to the ability to perform a detailed low-level radar analysis of the circulation. Figure 2 shows the beginning of the first tornado from ARMOR's perspective. Of note are the classic radar indicators of a tornado circulation, including an intense velocity couplet, a dual-polarimetric tornado debris signature (TDS; e.g. Ryzhkov et al. 2005), and a differential reflectivity (Z_{DR}) arc (Kumjian and Ryzhkov 2008). In contrast to the first

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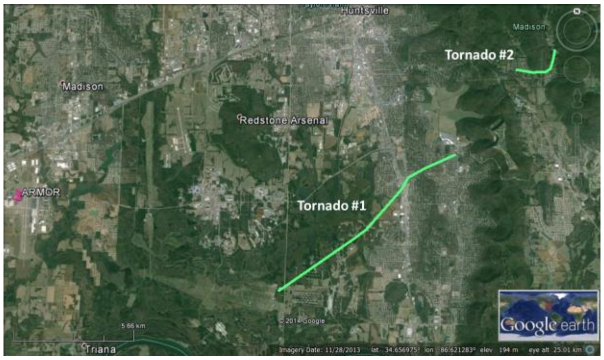

Figure 1: Overview of the two Huntsville EF1 tornadoes tracks from 11 April 2013, showing the two tornado tracks separated by Huntsville Mountain as well as the location of ARMOR relative to the tornadoes. Paths synthesized from NWS DAT and UAH survey data.

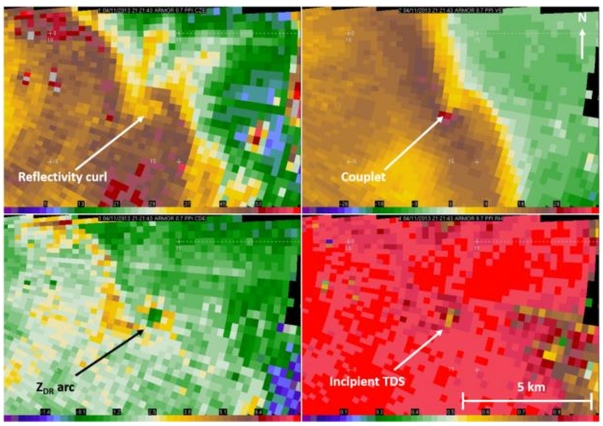

Figure 2: ARMOR four-panel plan position indicator (PPI) plot of attenuation-corrected equivalent reflectivity factor (Z_e, upper-left), dealiased base velocity (V_r, upper-right), attenuation-corrected differential reflectivity (Z_{DR}, lower-left), and cross-correlation coefficient (ρ_{hv}, lower-right) at 21:21:43 UTC 11 April 2013. Note the typical dual-polarimetric and Doppler velocity signatures for a tornado event.

tornado, however, the second tornado did not feature a Z_{DR} arc or TDS (Fig. 3), and the velocity couplet was not as intense (Figs. 4 and 5). This observation is notable, especially given that the second tornado produced slightly more impressive damage than the first tornado as judged by both the NWS and UAH surveys.

The most important observations from the Huntsville tornadoes are related to the rapid dissipation and regeneration around Huntsville Mountain, which seems to be closely tied to the terrain in this case. Additionally, it is important to note that the second tornado's reintensification appeared to be largely confined to near the surface, owing to the lack of lofting of debris, size-sorting due to increased shear at radar beam height, and lower V_{ROT} and AVV values. The key behavior of dissipation on an upslope and genesis on a downslope will be addressed in broader context in Section 7.

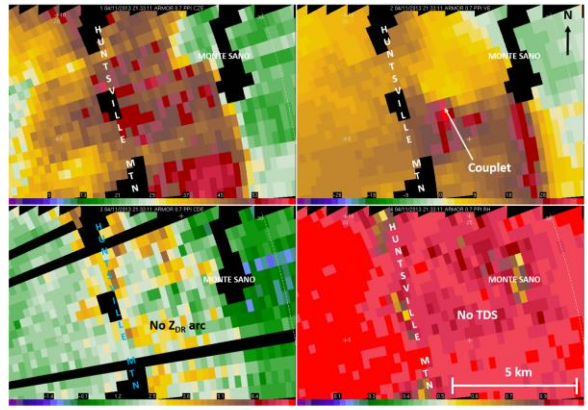

Figure 3: As in Fig. 2 at 21:33:11 UTC 11 April 2013. Note the lack of the dual-polarimetric signatures observed with the second tornado, which was ongoing at this time. The velocity couplet is also slightly weaker than with the first tornado.

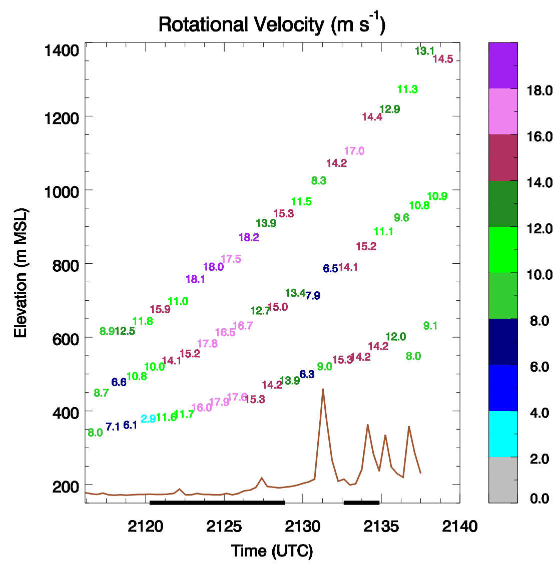

Figure 4: Time-height plot of V_{ROT} (numbers), underlying land surface elevation (brown), and Storm Data official tornado times (bold black) for the 11 April 2013 tornadoes. Note the marked weakening as the circulation reaches Huntsville Mountain and the muted reintensification upon descent.

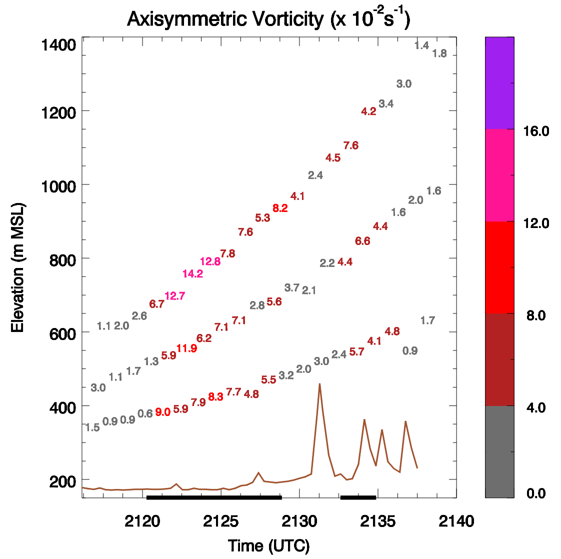

Figure 5: Time-height plot of AVV (numbers), underlying land surface elevation (brown), and Storm Data official tornado times (bold black) for the 11 April 2013 tornadoes. Note the marked weakening as the circulation reaches Huntsville Mountain and the muted reintensification upon descent, as was observed with V_{ROT}.

4. 27 APRIL 2011: PISGAH, ALABAMA

A violent tornado impacted portions of Jackson and DeKalb Counties in Alabama and Dade and Walker Counties in northwestern Georgia as part of the historic 27 April 2011 tornado outbreak. This high-end EF4 tornado traveled 75.0 km and reached 1600 m in width. Along its track, 14 people were killed, 12 in Alabama and 2 in Georgia (NCDC 2014).

Numerous intriguing behaviors were noted with the Pisgah EF4 tornado during the course of its lifespan. Figure 6 shows that the tornado formed along the northwestern slope of the Sand Mountain plateau, moved across the plateau, crossed the Wills Valley, and crossed Lookout Mountain before dissipating south of Chattanooga, Tennessee.

The genesis of the tornado was extremely rapid as the mesocyclone crossed onto Sand Mountain. Figure 7 illustrates the radar evolution of the genesis of the tornado, which went from incipient circulation to violent tornado in less than 10 minutes. This rapid intensification is also captured in the plotting of VROT as the circulation moves atop the plateau (Fig. 8). The tornado caused near-EF5 damage across Sand Mountain before starting to weaken near the eastern edge of the plateau. As the tornado descended into the Wills Valley in northwestern Georgia, it momentarily weakened before intensifying to a local maximum of high-EF3 damage in the town of Trenton, where the 2 Georgia fatalities occurred. As the circulation moved over the valley, AVV decreased dramatically to a low-level minimum, and as it moved back atop Lookout

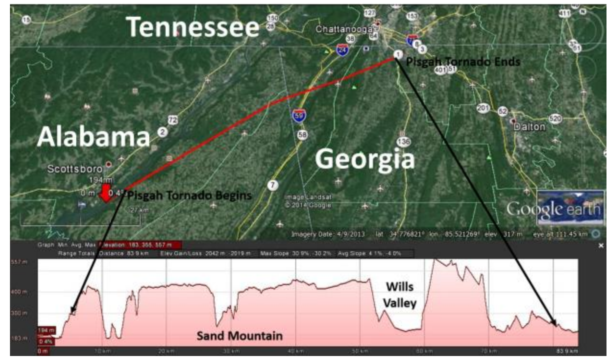

Figure 6: Overview map of the Pisgah, Alabama EF4 tornado of 27 April 2011, with a Google Earth profile of underlying land surface elevation for the tornado path. The arrows indicate the start and end points of the tornado.

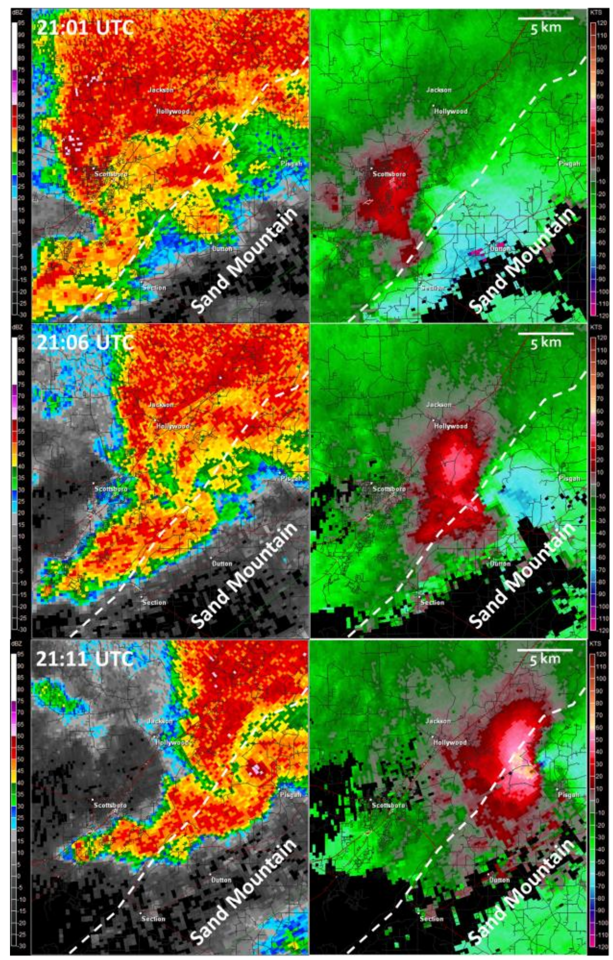

Figure 7: Two-panel PPI of Z_e (left) and V_r (right) from KHTX of the Pisgah, Alabama EF4 tornado of 27 April 2011 at 2101 UTC (top), 2106 UTC (middle), and 2111 UTC (bottom), showing the rapid evolution of the tornadic circulation as it moves atop Sand Mountain.

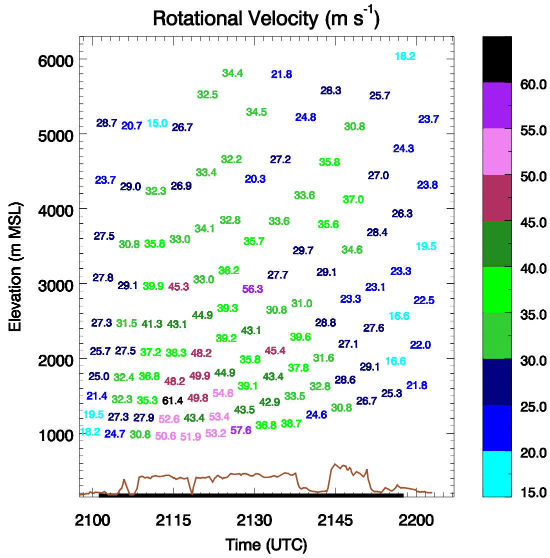

Figure 8: As in Fig. 4 for the Pisgah, Alabama EF4 tornado of 27 April 2011. Note the rapid intensification as the circulation moves atop Sand Mountain.

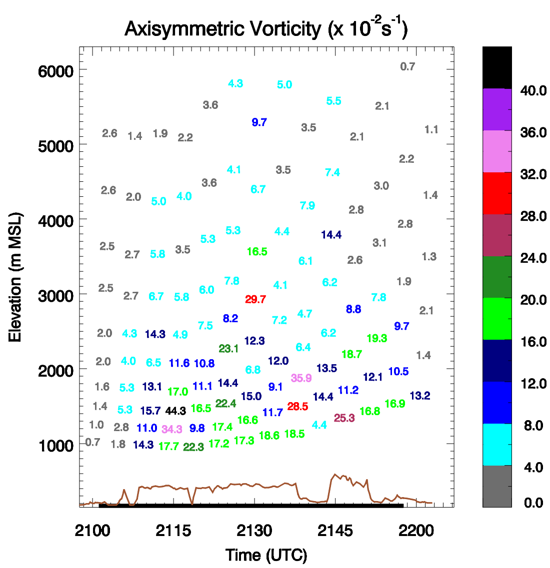

Figure 9: As in Fig. 5 for the Pisgah, Alabama EF4 tornado of 27 April 2011. Note the rapid intensification as the circulation moves atop Sand Mountain, a dramatic drop in vorticity as the circulation moves over the Wills Valley, and the rapid increase in vorticity in the lowest tilt as the tornado moves atop Lookout Mountain.

Mountain, the 0.5° AVV reached the absolute maximum value observed during the entire tornado (Fig. 9). Once the tornado moved off of Lookout Mountain, it steadily weakened until it dissipated.

The rapid intensification of the tornado and its parent circulation as the storm moved atop Sand Mountain, and subsequent weakening near the other end of the plateau, is important to note. This behavior has been noted in other cases and is placed in a broader context in Section 7. Additionally, the behavior of intensification in the valley near the surface with a corresponding weaker low-level circulation is similar to the second 11 April 2013 tornado.

5. 27 APRIL 2011: OHATCHEE, ALABAMA

The Ohatchee, Alabama tornado of 27 April 2011 was the second tornado produced by the Tuscaloosa-Birmingham supercell. This violent EF4 tornado killed 22 people along a 156.64 km path that was up to 1600 m wide across east-central Alabama into northwestern Georgia (Fig. 10; NCDC 2014, NWS 2014)

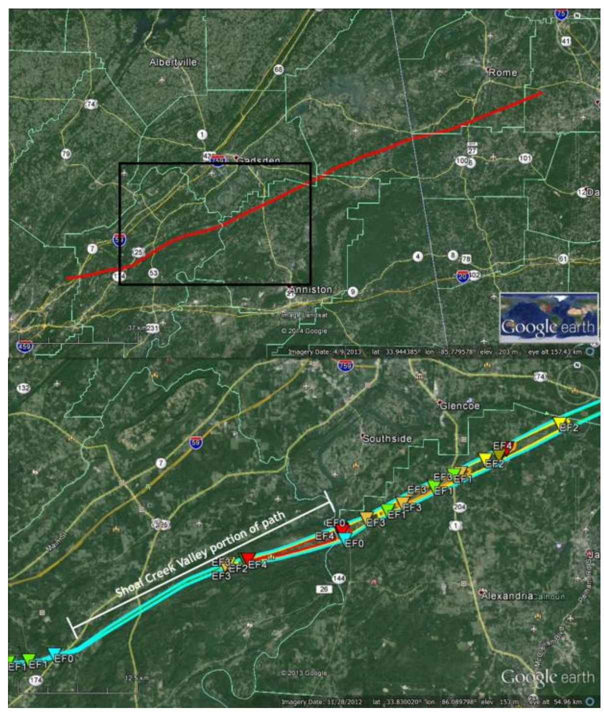

Figure 10: Overview map of the Ohatchee, Alabama EF4 tornado (top) with a zoomed-in focus on the Shoal Creek portion of the tornado path (bottom). Bottom polygons extracted from the DAT (2014).

The most notable portion of this tornado path was early in its lifecycle across St. Clair County, Alabama (Fig. 10). The tornado formed just east of the suburbs of Birmingham and moved east-northeast into St. Clair County. The tornado reached the Shoal Creek valley, a valley that feeds to the east-northeast toward Neely Henry Lake, at EF1 intensity (Fig. 11a). The tornado continued to follow the valley while intensifying to EF4

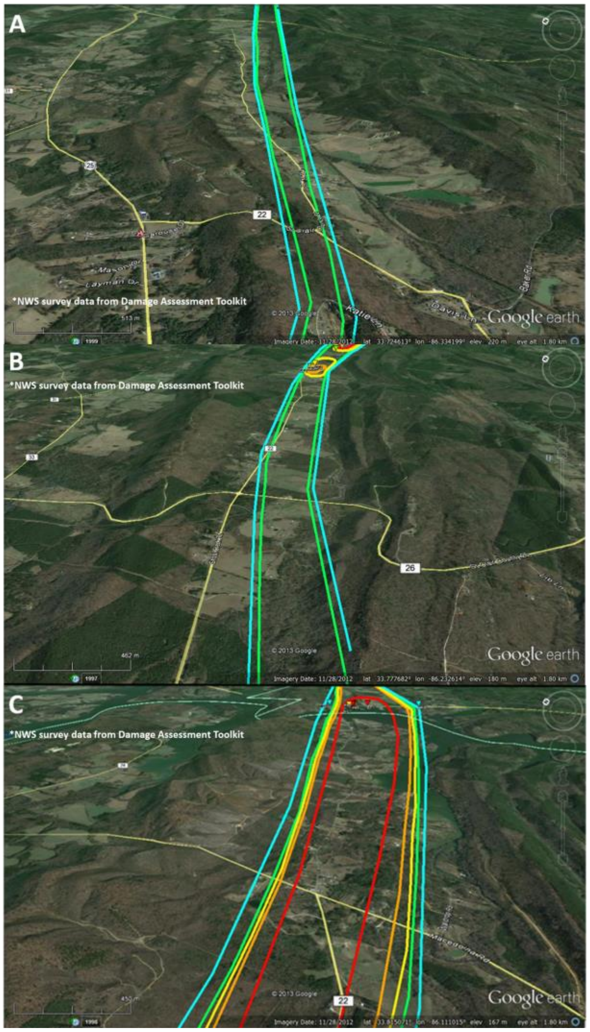

Figure 11: Down-track views of the Ohatchee EF4 tornado from when it entered the Shoal Creek Valley (A) to where it reached Neely Henry Lake (C). The tornado track clearly follows the shape of the valley as it intensifies from EF1 to EF4 intensity. Polygons extracted the DAT (2014).

intensity until it reached Neely Henry Lake and continued east-northeastward (Figs. 11c and 11c). The behavior of tornado tracks following valleys has also been documented in a number of past events and will be placed in a broader context in Section 7.

6. 27 APRIL 2011: RAINSVILLE, ALABAMA

An extremely violent tornado impacted portions of DeKalb County, Alabama, and Dade County, Georgia, during the late afternoon hours of 27 April 2011. This tornado, the second tornado produced by a supercell that also produced violent tornadoes at Cordova, Alabama, and Ringgold, Georgia, reached EF5 intensity in the town of Rainsville. In all, the tornado traveled 58.89 km, was up to 1200-m wide, and was responsible for 25 fatalities (NCDC 2014).

One notable aspect of the Rainsville tornado was its mean motion. As shown in Fig. 12, the Rainsville tornado featured a greater northerly component of mean motion than the other violent tornadoes in eastern Alabama that evening. The mean motion of the Rainsville tornado was 225°, while the mean motions of the three other violent tornadoes shown ranged from 230°-250°. Approximately the last two-thirds of the Rainsville tornado featured a mean motion of 220°, which is roughly parallel to the southeastern edge of Sand Mountain.

Figure 12: Overview map of four of the violent tornadoes that impacted eastern Alabama on 27 April 2011, illustrating the deviant motion of the Rainsville EF5 versus the other tornadoes.

The Rainsville EF5 tornado remained atop Sand Mountain as it approached the Georgia border. As it approached the border, it interacted with a local peak on Sand Mountain, with an elevation of 590 m MSL, compared to 300-400 m MSL elevation of the surrounding areas of the plateau. Figure 13 shows a distinct minimum in damage atop this peak on the plateau, followed by an intensification burst on the downslope of the local peak. As the tornado continued northeast, the Wills Valley curved to the north, which led to the tornado crossing into the valley. The tornado rapidly weakened as it moved off of Sand Mountain, lifting just northeast of Rising Fawn, Georgia.

The motion of the Rainsville EF5 tornado parallel to the edge of Sand Mountain is a behavior that has been documented in other cases. This behavior will be placed in a broader context in Section 7. Additionally, the weakening of the tornado on the local peak of the plateau and subsequent rapid intensification bears strong similarities to the 11 April 2013 Huntsville circulation's behavior as it crossed Huntsville Mountain, as well as the 27 April 2011 Pisgah EF4 tornado as it reintensified in Trenton, Georgia. Finally, the rapid dissipation of the tornado as it moved off of Sand Mountain is the corollary of the intensification of the Pisgah EF4 tornado as it moved atop Sand Mountain. The implications of all these documented behaviors and how they relate to other documented cases will be discussed in Section 7.

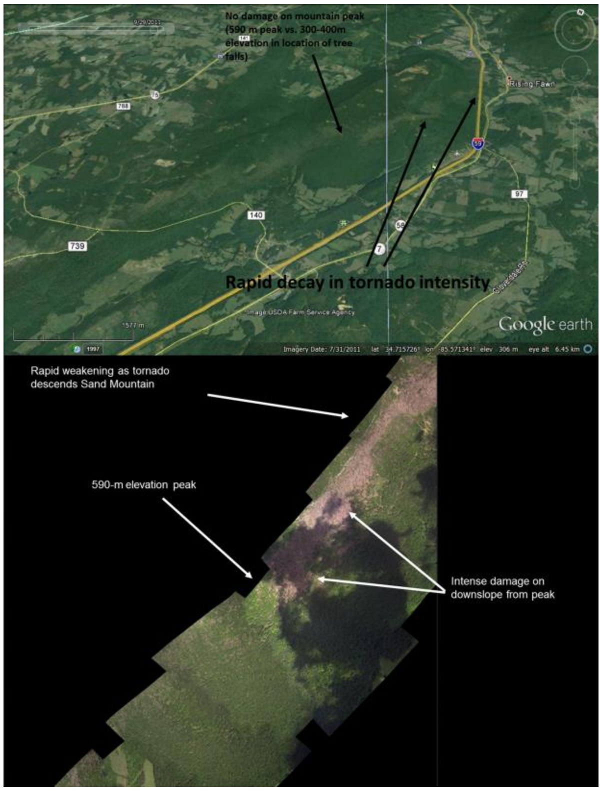

Figure 13: Top: Google Earth satellite image along the Alabama-Georgia border northeast of Rainsville, Alabama, taken 31 July 2011, showing the tornado scar Bottom: National Geodetic Survey (2014) aerial image of the weakness on the mountain peak shown in the Google Earth image. Both images show the weakness on the peak, a local maximum in damage on the downslope of the mountain peak, and weakening of the tornado as it moves off of Sand Mountain.

7. SUMMARY AND FUTURE WORK

The Huntsville, Pisgah, Ohatchee, and Rainsville tornado cases display a range of behaviors that appear to be potentially linked to the underlying terrain. Four of these behaviors can also be applied to other cases to form a baseline of repeated behaviors of tornadoes in the presence of significant terrain (Table 1). These four modes of behavior are as follows:

1) Mode I: Weakening or dissipation of tornadoes on the upslopes of hills/mountains and strengthening or dissipation of tornadoes on the downslopes of hills/ mountains (e.g. Pisgah 2011, Rainsville 2011, Huntsville 2013),
2) Mode II: Intensification of a circulation as it crosses onto a plateau or weakening of a circulation as it moves off a plateau (e.g. Pisgah 2011, Rainsville 2011),
3) Mode III: Tracks that deviate slightly to follow valleys (e.g. Ohatchee 2011),
4) Mode IV: Deviation to follow the edge of a plateau (e.g. Rainsville 2011).

Table 1: Overview of cases for each mode of tornado behavior, including number of tornadoes of each rating, storm mode (S – supercell, Q – QLCS, U – unknown), and total number of tornadoes for each mode.

Mode	EF0	EF1	EF2	EF3	EF4	EF5	S	Q	U	Total
I	0	14	7	6	6	2	21	14	0	35
II	3	12	4	6	5	1	17	14	0	31
III	0	7	3	2	3	0	4	9	2	15
IV	0	3	1	0	0	1	4	1	0	5

Table 1 shows that each mode has numerous cases, with modes I and II containing the most cases. Each mode has samples of weak, strong, and violent tornadoes, as well as supercell and QLCS tornadoes. Note: for additional examples cases, see poster P.120 of these proceedings for examples of mode II, III, and IV behavior exhibited during the 28-29 April 2014 tornado outbreak.

This work establishes an a posteriori knowledge of behaviors exhibited by tornadoes in the presence of significant terrain. Future work will focus on transition from a purely a posteriori knowledge to a physical understanding of this behavior. A main goal of this work will be to separate and/or exclude the effects of other influences on storm behavior from terrain influences, including wave interactions, internal processes, differential surface roughness, and cell mergers. This work will include a focus on better understanding flows around terrain features in different environments, differential profiling of thermodynamic and kinematic characteristics around the terrain, additional in-depth analyses of possible terrain-influenced events, and investigation of numerical modeling to attempt to verify these apparent modes of behavior in the presence of terrain.

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