SUPERCELLS OVER COMPLEX TERRAIN:
THE GREAT BARRINGTON TORNADO OF 29 MAY'95

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1. INTRODUCTION

A supercell thunderstorm spawned a F2/F3 tornado over the Hudson Valley region of New York State late on the afternoon of 29 May 1995. The tornado moved eastward into Massachusetts and was responsible for the deaths of three people in the vicinity of Great Barrington (GBR) and injuries to more than a dozen others. On the basis of aerial and ground damage surveys by permutations of the authors and time fixes from electric utility companies and schools in the affected region, it was determined that the tornado first touched down at 2231 UTC 29 May in Columbia County, NY, approximately 2-3 km east of the Hudson River. The tornado remained on the ground quasicontinuously until 2257 UTC. After skipping across the Taconic Range the tornado touched down two minutes later at 2259 UTC just west of GBR and remained on the ground quasicontinuously until 2324 UTC. The damage track of the GBR storm (~ 50 km in length and 50-500 m in width and corresponding to a tornado on the ground for ~ 50 minutes) is mapped based on GPS coordinates in Fig. 1 for reference.

The GBR storm was noteworthy in that the configuration of the regional mountains and valleys across interior eastern New York and western New England appeared to be a crucial factor in mesocyclone organization and tornadogenesis. A similar conclusion as to the importance of terrain influences on tornadogenesis was reached by Seimon and Fitzjarrald (1994) in their study of the 10 July 1989 tornado outbreak in eastern New York and western New England. In this regard the GBR storm appears to depart from the model of tornado development from a classic preexisting Great Plains supercell of the type described by, e.g., Doswell and Burgess (1993) and Brooks et al. (1994). Although, the thunderstorm complex that spawns the GBR storm may have been associated with a previous mesocyclone, renewed mesocyclone formation and organization occurs when the storm complex reaches the Hudson Valley. A terrain-channeled, warm, moist southerly inflow up the Hudson Valley provides the directional shear necessary for supercell development and mesocyclone intensification in an otherwise favorable environment for deep convection.

The important physiographic features in the region include the north-south oriented Hudson Valley (average elevation < 100 meters) with the Catskill Mountains to the west (average height 1000-1200 meters) and the Berkshire Mountains to the east (average height 500-800 meters). The Housatonic Valley, also oriented north-south, cuts through the Berkshires and opens up on its poleward side in the vicinity of GBR. Terrain heights average 300-400 meters (400-600 meters) to the west (east) of the Housatonic Valley. A prominent escarpment, containing several northwest-southeast oriented cuts, lines the eastern margin of the Catskills.

2. DATA/METHODOLOGY

Our analysis consists of all available surface and upper air observations across eastern New York and western New England. We were also able to recover supplementary AWOS observations from the Columbia County Airport in Hudson, NY. The large-scale flow structure was derived from the National Centers for Environmental Prediction (NCEP) Eta-model (Black 1994) gridded initialized and forecast fields using GEMPAK (Koch et al. 1983). Velocity and reflectivity observations were obtained from the National Weather Service
3. SCIENTIFIC HYPOTHESIS

The scientific hypothesis to be tested is that terrain channeling by north-south oriented river valleys in extreme eastern New York and western New England in conjunction with downslope-aided vortex-tube stretching creates an unusually favorable situation for severe weather development when the synoptic scale conditions are favorable for deep convection. The hypothesis rests on the idea that terrain channeling ensures the presence of a strong southerly flow of warm moist air poleward beneath increasing southwesterly flow aloft in advance of an approaching synoptic-scale trough. The end result is the creation of a right-turning (cyclonic) wind hodograph as the low-level flow is constrained to remain southerly by the orientation of the river valleys, a situation known to be favorable for supercell development. Moreover, the terrain channeling also ensures a relatively strong southerly flow at low levels in the atmosphere so that higher equivalent potential temperature \( \theta_e \) values equatorward of the region can be transported poleward beneath the strengthening southwesterly flow aloft, a situation favorable for air mass destabilization. For any supercells that form in this environment mesoscale organization is further favored by vortex-tube stretching to the lee of significant escarpments lining the western sides of north-south oriented river valleys.

4. RESULTS

4.1 Large-scale Environmental Structure

The synoptic pattern at 1200 UTC 29 May 1995 featured a positively tilted 500 hPa trough situated over the western Great Lakes. This trough moved eastward during the day and was associated with 5-10 dam height falls over eastern New York and western New England by 0000 UTC 30 May. Temperatures at 500 hPa cooled a few degrees to -14° C by 0000 UTC 30 May in the storm region. At 850 hPa a tongue of warm, moist air flowed northeastward across the Ohio Valley toward New England at 1200 UTC 29 May. Temperatures (dew point temperatures) in this tongue of warm, moist air generally averaged 14-18°C (5-12°C). At 200 hPa a 30-45 m s\(^{-1}\) west-southwesterly jet settled southeastward across the region during the day accompanied by height falls in the 5-15 dam range. These results and a sounding analysis (not shown) reveal that the synoptic-scale flow pattern was favorable for deep convection and possible supercell development over the Hudson Valley, given the existence of CAPE values of 2000-3000 J kg\(^{-1}\), the presence of a lifting mechanism associated with the approaching trough, and helicity values of ~300 J kg\(^{-1}\).

The large-scale surface pattern featured the passage of a trough through the mid-Hudson Valley region during the 2100-2300 UTC 29 May period. The apex of a thermal ridge, defined by the 564 dam 1000-500 hPa thickness contour, crossed the lower Hudson Valley during the 12 h period ending 0000 UTC 30 May. A regional map of surface winds and \( \theta_e \) valid 2100 UTC 29 May, approximately 90 minutes prior to tornado touchdown, is presented in Fig. 2. Note the tongue of relatively high \( \theta_e \) with values in the 335-340 K range that is situated over the Hudson Valley area. This air is representative of the ambient air that is being channeled up the Hudson Valley (and other nearby north-south oriented valleys) by 5-15 m s\(^{-1}\) surface winds.

4.2 88D-Derived Shear Versus Terrain Profiles

The antecedent disturbance, as measured by differential inbound/outbound flow (shear) from the KENX 88D observations, was relatively weak as it tracked eastward across the northern Catskills. In Fig. 3a we map the observed shear associated with the antecedent disturbance averaged through the lowest three 88D volume scans (0.5, 1.5 and 2.4 degrees) beginning 1913 UTC 29 May and continuing through the end of the tornado life cycle. In Fig. 3b we present an enlarged view of the shear versus terrain elevation during the pre-tornadic and tornadic phases of the GBR storm. Here terrain elevation is considered the average elevation of the terrain for ~8-10 km on the inflow (equatorward) side of the storm.

Our analysis suggests that a supercell forms out of a thunderstorm complex (which may have contained a poorly organized mesocyclone) as the complex moves off the Catskill Mountains and into the Hudson Valley. As the antecedent disturbance crosses the eastern Catskills and approaches the extreme western side of the Hudson Valley it is intercepted by an accelerating northwesterly outflow (~15 m s\(^{-1}\)) that is observed to form in the Catskill Creek in response to earlier thunderstorms over the northern Catskills. The rapidly accelerating Catskill Creek outflow expands into the western Hudson Valley where it meets the terrain-channeled southerly flow (5-15 m s\(^{-1}\)) transporting warm, humid air up the valley, a situation favorable for cyclonic vorticity production. Subsequent to the Catskill Creek outflow surge and additional cyclonic vorticity
production by vortex-tube stretching, the antecedent seeding rapidly intensifies. (Fig. 3b).

The supercell continues to intensify as it crosses the Hudson River into Columbia County and is followed by tornado development in the southwest portion of the mesocyclone where a very tight rotational inbound/outbound couplet across a distance of ~1 km is observed to form. No obvious tornado vortex signature can be detected above 3 km prior to tornado touchdown. The comparatively few sightings of the tornado suggest it was rain-wrapped and/or ensnared by low clouds. Given that the automated surface observation reports from the Columbia County Airport, situated poleward of the eastward track of the tornadic mesocyclone, indicate a continuous terrain-channeled southerly flow until the arrival of the main squall line, we consider it unlikely that the mesocyclone intensified along any preexisting outflow boundary in the eastern Hudson Valley.

The tornadic mesocyclone, after reaching peak intensity in the vicinity of the Taconic Parkway, is observed to weaken as it crosses the Taconic Range along the New York-Massachusetts border. The reintensification of the tornadic mesocyclone as it approaches GBR occurs as the disturbance reaches the poleward opening of the north-south oriented Housatonic River Valley, again suggestive of a possible important role for terrain channeling and vortex-tube stretching on storm development.

5. CONCLUSIONS

A NWS Doppler radar-based analysis of the Great Barrington, MA F2/F3 tornado of 29 May 1995 suggests that terrain-channeled southerly flow up the primarily north-south oriented river valleys in eastern New York and western Massachusetts provides the necessary directional shear to sustain tornadic supercell development, given an otherwise favorable large-scale thermodynamic environment for deep convection and the presence of a lifting mechanism associated with an approaching trough aloft. Vortex-tube stretching to the lee of the Catskill escarpment in the Hudson Valley likely also contributes to mesocyclone intensification and tornadogenesis. Mesoscale cyclonic vorticity is produced by a combination of vortex-tube stretching to the lee of the escarpment and lateral cyclonic shear created where the northwesterly outflow surge from the Catskill Creek encounters the terrain-channeled southerly flow in the Hudson Valley.

6. ACKNOWLEDGEMENT

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7. REFERENCES


8. FIGURES

Figure 1: Locator map and superimposed tornado track.
Figure 2: Manual analysis of $\theta_e$ (solid contours, every 5K) for 2100 UTC 29 May 1995. Surface winds plotted conventionally with one pennant, full barb and half barb denoting 25 m s$^{-1}$, 5 m s$^{-1}$ and 2.5 m s$^{-1}$, respectively.

Figure 3: Left (a): Inbound/outbound shear (solid, s$^{-1}$) derived from KENX SSD volume scans averaged over the lowest three elevation scans (0.5, 1.5 and 2.4 degrees) along the disturbance path from 1913-2338 UTC 29 May 1995. Right (b): As in (a) except for 2203-2328 UTC 29 May 1995. Terrain elevation (meters) given by the dashed lines (see text).

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1. Introduction

A strong-violent tornado struck Great Barrington (GBR), Massachusetts (MA) shortly after 2300 UTC on 29 May 1995 (Memorial Day) injuring two dozen people and killing three others when their car was lifted more than 100 m into the air and dropped into a wooded hillside (Storm Data 1995). The storm cut a discontinuous path of destruction that began in New York (NY) near the town of Catskill (CAT;Fig 1) and stretched ~50km eastward to West Otis, MA (WOT) with damage along the 50-500 m wide path (Fig. 1) ranging as high as F3/F4 intensity. Damage estimates totaled as high as $35 million (1995 dollars) with the bulk of the damage occurring in Berkshire County, MA. Eastern NY and western New England very infrequently experience tornadoes of such strong intensity and tornadoes in general are rarely observed over such rugged terrain.

An interesting aspect of the GBR tornado was that Doppler radar data showed low-level mesocyclone intensity and perhaps tornadogenesis were linked to terrain height changes and topographic landforms beneath the storm. Important physiographic features in the region (Fig. 1) include the north-south oriented Hudson Valley (average elevation <100 m) with the Catskill Mountains to the west (average height 500-800 m). A prominent escarpment, containing several northwest-southeast oriented cuts, lines the eastern margin of the Catskills

The Housatonic Valley, also oriented north-south, cuts through the Berkshire Mountains and opens up on its poleward side in the vicinity of GBR. Terrain heights average 300-400 m (400-600 m) to the west (east) of the Housatonic Valley.

This paper will try to show that changes in topography beneath the storm and processes related to topographic landforms may have played a role in low-level mesocyclone intensification and tornadogenesis.

2. Data and Methodology

All available surface and upper air observations across eastern NY and western New England, plus supplemental observations from the Columbia County Airport (CCA) AWOS near Hudson, NY (HUD) were used in the analysis of this event (Fig. 1). The large-scale flow structure was derived from the National Centers for Environmental Prediction (NCEP) Eta-model (Black 1994) gridded initialized and forecast fields using GEMPAK (Koch et al. 1983). Radar data were obtained from the National Weather Service Weather Surveillance Radar-1988 Doppler (WSR-88D) radar sites in Berne, NY (KENX) and Binghamton, NY (KBGM).

3. Synoptic Scale Environment

The synoptic scale flow over NY and New England was not favorable for an extensive outbreak of severe weather on 29 May, but was favorable for isolated supercells. The synoptic pattern at 29/1200 (hereafter date and time will use the format dd/hhmm,
where dd is day of month and hhmm is UTC time with month and year assumed to be May 1995) featured a positively tilted 500 hPa trough over the western Great Lakes. This trough moved eastward during the day and was associated with 5-10 dam height falls over eastern NY and western New England by 30/0000. Temperatures at 500 hPa cooled to -14°C by 30/0000 in the storm region.

At 850 hPa a tongue of warm, moist air flowed northeastward across the Ohio Valley toward New England at 29/1200. Temperatures (dew point temperatures) in this tongue of warm, moist air generally averaged 14-18°C (5-12°C). At 200 hPa a 30-45 m s⁻¹ west-southwesterly jet settled southeastward across the region during the day, accompanied by height falls in the 5-15 dam range. These results and a sounding analysis (not shown) reveal that the synoptic-scale flow pattern favored the development of isolated supercells over the NY, given the existence of CAPE values of 2000-3000 J Kg⁻¹, and storm-relative helicity values of -300 J kg⁻¹.

4. Mesoscale and Storm Scale Environment

In the hours leading up to tornadogenesis a supercell formed over western NY and moved into the Catskill Mountain Range. About 1/2 hour prior to tornadogenesis (estimated to be about 29/2225-2230) the supercell was located over the highest peaks of the Catskill Mountains (Fig. 2). Radial velocity data from the 0.5⁰ scan of the KENX radar at 29/2102 showed two moderately strong larger-scale regions of inbound velocity (> 25 m s⁻¹) to the west of the radar entering western Schoharie County, NY (not shown) moving toward the radar site. It is hypothesized that these two regions of strong inbound flow represent air surging outwards behind the gust front associated with a second storm to the north of the GBR storm. As the surge behind the gust front in Schoharie County moved east toward the radar site it began to encounter higher terrain (Fig. 2). At 29/2141 the gust front was just about at the KENX radar site and about to move downslope into the Catskill Creek and Hudson River Valley (Fig 2).

It is over the next 15 minutes that topographic landforms such as the Catskill Creek Valley become especially important in the life cycle of the GBR storm. The northwest end of the Catskill Creek Valley begins in the high terrain of the Catskill Mountains and drops in elevation at its southeast end into the north-south oriented Hudson River Valley (Fig. 1). The terrain around the Catskill Creek Valley is particularly steep to its west and south along the Catskill Escarpment and is more gently sloping to the north and relatively flat to the east (Fig 1). Between 29/2146-2201 the gust front associated with the second storm moved downslope out of the Catskill Range and entered the northern end of the Catskill Creek Valley (Fig. 2). Between 29/2206-2211 the GBR storm began to move off the mountains and across the steep Catskill Escarpment into the Hudson River Valley (Fig 2). At the same time the surge from the second storm likely began to propagate southeast down the Catskill Creek Valley toward the Hudson River Valley (Fig. 2). By 29/2216 the GBR storm was located in the Hudson Valley near the southern end of the Catskill Creek Valley at an elevation of < 200 m resulting in a net terrain reduction of > 700 m beneath the storm in 15 minutes. Extrapolation of the movement of the surge down the Catskill Creek would position the gust front at the southern end of the Catskill Creek Valley at 29/2216, the same time the GBR storm arrives there (Fig. 2).

Radial velocity data during the tornadic phase shows an interesting relationship between the GBR storm’s mesocyclone and terrain height beneath the storm. Inbound/outbound shear across the mesocyclone, derived from KENX WSR-88D volume scans averaged over the lowest three elevation scans (0.5, 1.5, and 2.4 degrees) along the disturbance path, and terrain height are plotted against time in Fig. 3. Immediately after 29/2200 terrain height beneath the GBR storm begins to fall (Fig. 3). This drop in terrain height is then followed by a rapid and dramatic increase in average shear associated with the mesocyclone, indicating a strengthening of the mesocyclone. Subsequently, as the terrain height beneath the GBR storm begins to increase, on the east side of the Hudson River Valley, the shear associated with the mesocyclone decreases, indicating a weakening of the mesocyclone (Fig. 3). It is hypothesized that the observed changes in low-level mesocyclone strength may be caused in-part by vortex tube stretching (shrinkage) as the terrain height beneath the storm decreases (increases).

After 29/2231 the GBR storm and tornado began to move out of the Hudson River Valley and into the Taconic Range. Immediately after starting upslope at 29/2241 the low-level mesocyclone began to weaken (Fig. 3). By 29/2251 the low-level mesocyclone had weakened considerably (Fig. 3). This weakening coincided with a termination in the tornado’s damage path just before it reached the highest terrain of the Taconic Range west of Great Barrington, MA (Fig. 1). As the storm moved downslope out of the Taconic Range toward the Housatonic Valley at 29/2256 the low-level
mesocyclone began to intensify again (Fig. 3). A second damage path began just east of the MA-NY border and curved slightly south and then eastward toward the south side of GBR (Fig. 1). After 29/2311 the low-level mesocyclone weakened as the storm again moved upslope this time into the Berkshire Mountains (Fig. 3). Damage associated with the tornado ceased near West Otis, MA at about 29/2325. The storm continued moving east through MA, but never produced another tornado.

5. Discussion and Conclusions

During its life cycle the GBR storm moved over terrain of highly variable height. During most of that time both the KBGM and KENX WSR-88D radars indicated the storm possessed a mid-level mesocyclone. Fortunately, during the tornadic phase of the GBR storm it was located within 25-75 km of the KENX radar thereby permitting some surveillance of the low-level mesocyclone. The most interesting period in the GBR storm's life cycle occurs as it moves off the Catskill Mountains and into the Hudson River Valley. This period begins with the supercell perched atop a mountain range more than 1 km above mean sea-level. Then over a time span of 20 minutes the supercell splits and moves over a steep escarpment into the Hudson River Valley to an elevation of about 50 m. Coincident with this -1 km fall in terrain height beneath the supercell is a dramatic increase in the strength of the low-level mesocyclone (Fig. 3) and very shortly thereafter tornadogenesis. The cause of this dramatic change in the low-level mesocyclone is not known but several different processes and/or mechanisms may play a role in the intensification:

1) Doppler data from KENX indicated that the low-level mesocyclone intensified (weakened) as it moved downslope (upslope), perhaps indicating that vortex tube stretching (shrinking) might be a cause of low-level mesocyclone intensity change.

2) Just prior to tornadogenesis inferred convergence and horizontal shear beneath the storm increased due to the meeting of a northwesterly surge in the Catskill Creek Valley and a poleward-channeled flow in the Hudson River Valley. The increase in shear may have triggered a shearing instability which lead to the formation of a low-level cyclonic disturbance that intensified in an updraft due to vortex tube stretching (Wakimoto and Wilson 1989).

3) Channeled flow in the Hudson River Valley likely increased the storm-relative helicity in the lowest layers of the atmosphere. Backing of the wind from southwesterly outside the Valley to southerly in the Valley may have helped intensify the low-level mesocyclone (Wicker 1996).

Although this discussion has not positively identified any single mechanism or process as the primary cause of low-level mesocyclone intensification or tornadogenesis associated with the GBR storm, it has identified some areas where additional research needs to be done. Our current understanding on how supercells interact with the terrain they move across is very limited. Much more work needs to be done with numerical modeling experiments and observationally before the most important processes or mechanisms are identified.

This study has shown a direct relationship between low-level mesocyclone intensity and terrain changes beneath the mesocyclone. When the low-level mesocyclone associated with the GBR storm moved downslope it intensified and tornadogenesis followed. When the low-level mesocyclone moved upslope, it weakened and the tornado dissipated. The close correspondence between low-level mesocyclone intensity change and terrain changes suggests vertical vortex tube stretching might be playing a significant role in low-level mesocyclone intensity change during this event. Whether or not this relationship will hold for other rotating storms over complex terrain needs to be examined further.

6. Acknowledgements

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7. References


FIG 1. Terrain height (in meters, shaded according to scale at left of figure) with key locations (e.g., Albany, NY (ALB), Berno, NY WSR-88D radar site (KEND), Calo, NY (CRO), Tamworth, NY (TAN), Columbia County Airport, NY (CCA), Hudson, NY (HUD), Catskill, NY (CAT), Great Barrington, MA (GBR), and West Ota, MA (WOT)) and county names labeled. For reference, CRO is located in the Catskill Creek Valley, HUD and CAT are both located in the Hudson River Valley, and GBR is located at the northern end of the Housatonic River Valley. Path of destruction caused by the tornado is marked by a thick dashed line.

FIG 2. Terrain as in Fig. 1 with location of GBR storm at given time shown by circle with 'x' in the center (all times on the figure are UTC on 29 May) and isochrones of the approximate location of the leading edge of the surge from the second storm (diagnosed by Doppler velocity data from KENX and extrapolation where data was unavailable). Latitude and longitude lines every 0.5 degree.

FIG 3. Inbound/outbound shear (dashed, s⁻¹) vs. terrain height (solid, m) along the GBR storm's path from 2146-2326 UTC 29 May. Shear is computed from the average Doppler velocity over the 0.5, 1.5, and 2.6° scans of the KENX radar.
Large-Scale Conditions Associated with the Northwesterly Flow Intense Derecho Events of 14-15 July 1995 in the Northeastern United States

1. Introduction:

During the period 13-15 July 1995 a series of exceptionally strong derechos (e.g., Johns and Hirt 1987; Przybylinski 1995) affected portions of southern Canada and the northern United States from the Dakotas eastward to New York and western New England. A companion paper elsewhere in this volume, Cannon et al. (1998), reports on the mesoscale aspects of one of the derechos that hit New York. The purpose of this paper is to document the large-scale derecho environment.

2. Data and Methodology:

Analyses have been prepared using all available surface and upper air observations and satellite imagery. Computations were made using GEMPAK with grids from the European Centre for Medium-Range Weather Forecasts. A dynamical tropopause (DT) perspective is adopted for the large-scale overview (defined by 1.5 potential vorticity (PV) units; see, e.g., Bosart and Lackmann 1995).

3. Results:

Selected soundings are shown in Fig. 1. At 00Z/15 soundings from GRB and SSM show a warm and unstable airmass situated on the anticyclonic shear side of a jet over southern Canada (Figs. 1a,b). The ALB sounding for 12Z/15 was taken ~1 h after the derecho passed (Fig. 1c). The NW winds of 60-65 kt in the 850-700 hPa layer are representative of the observed sustained surface winds over a wide area at the height of the storm. The 09,12,15Z/15 soundings from CHH (Figs. 1d,e,f) illustrate the passage of the derecho in its dying phase. These soundings show vertical shear and instability profiles favorable for the development of long-lived bow echoes (derechos).

DT and 850 hPa maps for key time periods are presented in Fig. 2. Exceptionally warm air (T>25°C) is observed at 850 hPa on the poleward periphery of a massive anticyclone. The DT maps show individual mesoscale PV anomalies (defined by relative minima (maxima) in potential temperature (pressure) on the DT) rotating around the anticyclone. The PV anomalies appear to originate by fracture from the equatorward end of the trough along the Atlantic coast. The PV anomalies move westward along the Gulf coast, turn poleward just east of the Rockies, and then turn eastward along the equatorward flank of a jet-entrance region over southern Canada. Warm air advection is intensified in a very unstable air mass ahead of the mesoscale PV anomalies and is the source of lift that helps to create an environment favorable for convection that organizes into severe derechos. The anticyclonic trajectories of the individual PV anomalies constitutes a deep convective "ring of fire".

4. Conclusions:

A multiday severe derecho outbreak during 13-15 July 1995 was favored by extreme instability (CAPE > 3000 J/kg), high low-level moisture...
FIG. 1. Selected soundings for dates and times shown. Green Bay, WI (GRB), Sault Ste. Marie, MI (SSM), Albany, NY (ALB), and Chatham, MA (CHH).