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TERRAIN-INFLUENCED TORNADOGENESIS IN THE NORTHEASTERN UNITED STATES: AN EXAMINATION OF THE 29 MAY 1995 GREAT BARRINGTON, MASSACHUSETTS, TORNADO

by

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1. INTRODUCTION:

On 29 May 1995, a supercell thunderstorm traveling a corridor across prominent topographic landforms in the northeastern United States (US) produced an almost continuous 50 km track tornado that caused damage of up to F3 intensity (Grazulus 1997). The damage swath ranged up to 1 km in width, with severe forest destruction and structural damage reported. Maximum impact was felt in Great Barrington (GBR), Massachusetts, where widespread structural damage occurred and 3 people were killed when a vehicle was thrown more than 500 m by the tornado (Storm Data, 1995). The purpose of this paper is to conduct a detailed examination of the evolution of the GBR storm and its interaction with the complex terrain. A terrain and station/county location map with the GBR tornado track superimposed appears in Fig. 1.

In its size, intensity, longevity, and most significantly, its occurrence over complex terrain, the GBR tornado represents a rare event, though it is far from unique. On occasion, tornadic storms will form over relatively flat terrain but then propagate into hilly or mountainous regions with their tornadic circulations remaining intact. Examples include the long-track Adirondack tornado in New York State in 1845 (Ludlam 1970), the Shinnston, West Virginia tornado that killed 103 during an outbreak on 23 June 1944 (Brotzman 1944; Grazulis 1993), and several tornadoes of the 31 May 1985 outbreak that propagated from eastern Ohio into the hilly terrain of northwest Pennsylvania (Storm Data, 1985; Farrell and Carlson 1989).

The GBR tornado occurred over a topographic environment of comparable relief to reported Rocky Mountain tornado events (e.g., Evans and Johns 1996), although at lower overall elevations. Terrain in the Appalachian mountain system of the northeastern United States averages ~2 km lower than the Rockies; however, the magnitude of terrain variations is often comparable, especially where deeply incised river valleys are located. The hilly, forested environments that characterize most of the northeastern US interior probably determine to a large degree why, despite an abundance of intense warm season convection, relatively few tornadoes are known to occur compared to the Midwest and Great Lakes at comparable latitudes further to the west.

The GBR storm was fortuitous in being observed with Doppler radar (WSR-88D) during both supercell development and the subsequent tornadic phase over complex terrain, thus providing for the opportunity to study tornadogenesis in the context of a supercell's underlying topography. Our analysis

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reveals compelling evidence supporting a hypothesis that terrain influences play a deterministic role in significant mountain tornado occurrence. We find that tornadogenesis in the GBR storm was supported by, if not actually attributable to, orogenic modifications of boundary-layer storm inflow and outflow as the parent supercell traversed a series of prominent topographic landforms.

2. RESULTS:

The case study analysis of the GBR tornado has shown that the GBR supercell possessed a midlevel mesocyclone while it was located to the west of the Catskill Mountains and well before tornadogenesis. Our analysis revealed that the aforementioned mesocyclone intensified as it moved off the eastern end of the Catskill escarpment and entered the Hudson Valley. Our analysis further revealed that mesocyclone intensification also coincided with the serendipitous arrival of an accelerated terrain-channeled cold surge, triggered by additional convection to the north of the GBR supercell, down the topographic trough that marked the Catskill Creek and into the Hudson Valley. The eastward-moving GBR supercell intercepted the southeastward-moving cold surge down the Catskill Creek as the leading edge of the surge encountered the terrain-channeled southerly flow up the Hudson Valley (Fig. 2). Subsequently, the mesocyclone weakened as it moved upslope over the Taconic Range and into western Massachusetts before it intensified again as it moved downslope into the Housatonic Valley where it was associated with the GBR tornado.

We show in Fig. 3 modified hodographs for the Hudson Valley and the higher terrain to the west of the Hudson Valley based upon the observed 1200Z/29 May sounding from Albany, New York, and the observed midafternoon surface winds. The two hodographs are identical above 1.5 km. In the Hudson Valley the terrain-channeled south-southeasterly flow in the lowest few hundred meters gradually veers to southwest and west-southwest above 500 m. In the higher terrain to the west of the Hudson Valley where there is no terrain channeling of the low-level southerly flow and the overall length of the hodograph is shorter. Based upon a radar-determined GBR tornadic supercell storm motion of 272° at 13 m s^{-1}, the corresponding estimated storm-relative helicity values are 324 (252) m^2 s^{-2} for the Hudson Valley (higher terrain) hodograph.

In an effort to better assess the observed change in structure of the GBR supercell as it moved off the higher elevations of the Catskills into the lower elevations of the Hudson Valley we show in Fig. 4 the combined KENX 0.5° base reflectivity, composite reflectivity and base velocity for 2211Z, 2216Z, and 2221Z/29. The 50 dBZ threshold is used for the base and composite reflectivities. At issue is whether the >18 m s^{-1} inbound velocity maximum seen near the southern edge of the storm at 2211Z/29 (Fig. 4a) is a manifestation of terrain-channeled southerly flow up the Hudson valley and/or is a reflection of storm-induced inflow. Note that as the GBR supercell propagates across the Hudson River the inbound velocity maximum tends to remain in the same storm-relative position, suggestive that it is responding to the storm updraft (Fig. 4). However, there is also evidence for both updraft-related acceleration and flow channeling. At 2211Z/29 (Fig. 4) the inbound velocity contour > 13 m s^{-1} subtends an area extending to the west-southwest and east-northeast of the inferred updraft location. A pixel (yellow) of > 18 m s^{-1} inflow identifies the inbound velocity maximum close to where one might guess the updraft core to be situated based on the 50 dBZ composite and base reflectivity contours (at the observed distance of the GBR supercell from KENX the inbound velocity components are representative of ~1 km above the surface). The location of the inbound velocity maximum in Fig. 4a appears to be slightly upshear of the updraft, consistent with parcel motion shifting from horizontal to mostly vertical as air enters the storm tower.

The observed elongation of the inbound velocity maximum relative to the size of the storm updraft (rarely more than 5 km), especially at 2211Z and 2216Z/29 (Figs. 4a,b), suggests that other physical processes in addition to supercell dynamics are important to storm evolution at these times. The significant observed inbound velocity components behind the mesocyclone at 2211Z/29 (Fig. 4a) would be difficult to reconcile with the observed radar-derived wind field in the wake of an individual supercell. It is hypothesized instead that the observed east-west elongation of this inbound velocity maximum is primarily orogenic. It is also hypothesized that the peak updraft core likely propagates through the elongated inbound velocity maximum in response to the intensifying updraft. In response, as the GBR supercell crosses the Hudson Valley and intensifies, the ~1 km wind field adjusts and shuts off the flow channeling in the Hudson Valley as the flow weakens and/or veers behind the storm (Fig. 4c).

The eastward elongation of the inbound velocity maximum at 2211Z/29 (Fig. 4a) is also noteworthy since it parallels the downshear anvil precipitation immediately to its north. This is a traditional domain of the forward-flank downdraft and likely identifies the establishment of a strong boundary where inflow meets outflow, a rich source of vorticity to be ingested into the approaching mesocyclone. Again, this storm behavior is typical of supercells observed elsewhere. (e.g., Weisman and Rotunno 2000; Davies-Jones et al. 2001; Wilhelmson and Wicker 2001).

We next show in Fig. 5 a manually prepared cross section through the GBR supercell as it moved into the Hudson Valley at 2216Z/29. Base reflectivity values above 45 dBZ are highlighted in Fig. 5 as are storm relative inbound and outbound velocity components. The cross section is oriented along the 160° radial with north-northwest (south-southeast) to the left (right) according to the insert shown in Fig. 5. With inbound velocities > 20 m s^{-1} computed below 2 km just ahead of the reflectivity tower and outbound velocities > 5 m s^{-1} below 1.5 km in the core of the reflectivity tower, very strong convergence is indicated at the front of the intensifying GBR supercell as it crosses the Hudson valley at 2216Z/29 (recall also Fig. 4b). It is also apparent from Fig. 5 that the implied updraft core tilts to the north-northwest above the storm.

Based upon the evidence presented in Figs. 4 and 5, we hypothesize that the observed inbound velocity acceleration as the GBR supercell descends the eastern slopes of the Catskills into the Hudson Valley is a product of the supercell interacting with the Catskill escarpment, not just one or the other. Similarly, the outbound velocity maximum that develops along the Catskill Creek is hypothesized to be produced by channeling of outflow from the reflectivity core down the topographic trough and isallobaric acceleration in response to pressure falls associated with supercell. The behavior of both of these flows and the resultant tornadogenesis is probably predicated by the chance propagation of the GBR supercell across the complex, but highly defined, topographic domain represented by the Catskill Mountains-Hudson Valley landscape.

To summarize the results of this section, we show in Fig. 6 a time series of the inbound-outbound shear across the GBR mesocyclone as derived from an average over the three lowest elevations scans (0.5°, 1.5° and 2.4°) of the KENX radar along the disturbance track. For reference purposes, the underlying terrain height is included in Fig. 6. Note that immediately after 2200Z/29 that there is a rapid decrease in terrain height from ~800 m to < 200 m as the GBR supercell reaches the Hudson Valley. After a lag of 15-20 min, the slow increase in inbound-outbound average shear increases dramatically from 0.005 s^{-1} to 0.05 s^{-1} as the mesocyclone intensifies. The increase in average inbound-outbound shear corresponds to the first tornadic phase of the GBR supercell as the storm crosses Columbia County, New York, immediately to the east of the Hudson River.

As the line of thunderstorms containing the GBR supercell became better organized a new thunderstorm developed behind the inferred cold outflow boundary 15-20 km to the northeast of the GBR supercell. This second storm also maintained its identity as it moved eastward across the northern Catskills. Although this second (northern) storm was secondary to the GBR supercell, it was important because an analysis of radar-derived base velocity fields showed that it was responsible for triggering a cold outflow boundary that surged eastward across Schoharie and southern Albany Counties in New York. When this outflow surge reached the headwaters of the Catskill Creek over the Heidelberg escarpment north of the high Catskills it accelerated and was channeled southeastward by the configuration of the Catskill Creek**;** this behavior might also involve the refraction of the outflow gust front around the barrier represented by the high Catskills.

An analysis of the KENX base velocity data showed that the outflow surge down the Catskill Creek reached the Hudson Valley at about the time the GBR supercell was encountering the outflow on its northern side. This occurred as the GBR supercell entered the Hudson Valley after traversing the steep escarpment marking the eastern edge of the Catskills. The significance of the serendipitous arrival of the Catskill Creek outflow surge into the Hudson Valley, where it could be intercepted by the eastward-moving GBR supercell, was that the distance between the inbound and outbound velocity maxima associated with the supercell mesocyclone decreased from 10-15 km to 5-6 km, resulting in a strengthening of the mesocyclone.

3. CONCLUSIONS:

Tornadogenesis in the Hudson Valley appeared to be related to a combination of terrain-channeled (below 1 km) southerly flow up the Hudson Valley and mesocyclone updraft-induced acceleration associated with the Catskill Creek cold surge. We conclude that that the behavior of the terrain-channeled flows down the topographic troughs marking the Catskill Creek and up the Hudson Valley, respectively, and the resultant tornadogenesis, is predicated by the chance propagation of the Great Barrington supercell across the complex, but highly defined, topographic domain of the Catskill Mountains-Hudson Valley region. Subsequent terrain-channeled flow interaction with the mesocyclone likely occurred in the Housatonic Valley prior to tornado reformation in Great Barrington, Massachusetts, where F3 damage and 3 fatalities were observed.

LaPenta et al. (2004) have analyzed the severe weather outbreak over the northeastern US on 31 May 1998 with particular emphasis on the F3 tornado that occurred in Mechanicville, New York. Like the GBR storm, the Mechanicville storm occurred on a day when the environmental conditions were favorable for severe weather over the Northeast (tornadoes occurred elsewhere in the Northeast that day). As occurred with the GBR storm, terrain-channeled low-level southerly flow up the

Hudson Valley appeared to be an extra ingredient that increased the length and clockwise turning of the hodograph in the Hudson Valley relative to the higher terrain of the Catskills to the west. The resulting increase in low-level shear and enhanced moisture transport in the boundary layer may have created especially favorable conditions for tornadogenesis as the Mechanicville supercell moved down the Mohawk Valley toward the Hudson Valley.

Lastly, just as storm splitting and an associated cold surge down the topographic trough marking the Catskill Creek appeared to be an important external factor on tornadogenesis for the GBR storm, the Mechanicville supercell appeared to intensify just prior to tornadogenesis as it was overtaken by, and interacted with, a squall line moving down the Mohawk Valley. This interaction appeared to be focused in the region of an apparent northern book-end vortex. Weisman and Davis (1998) and Weisman (2001) conducted idealized simulations of quasi-linear convective systems. Their results suggested the existence of backed low-level (~ 2 km) flow ahead of a book-end vortex to the north of the apex of a bowed squall line. A future simulation might profitably be directed toward the interaction of an idealized squall line overtaking an isolated supercell to test whether backed low-level flow ahead of a northern book-end vortex could provide an extra ingredient to assist the tornadogenesis process in these situations.

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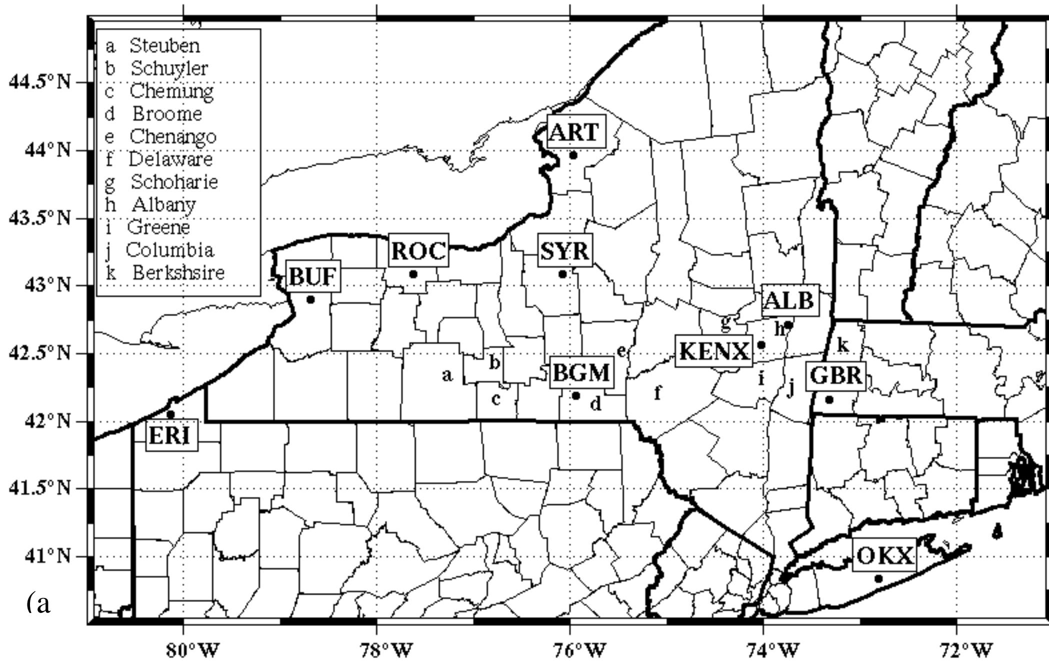
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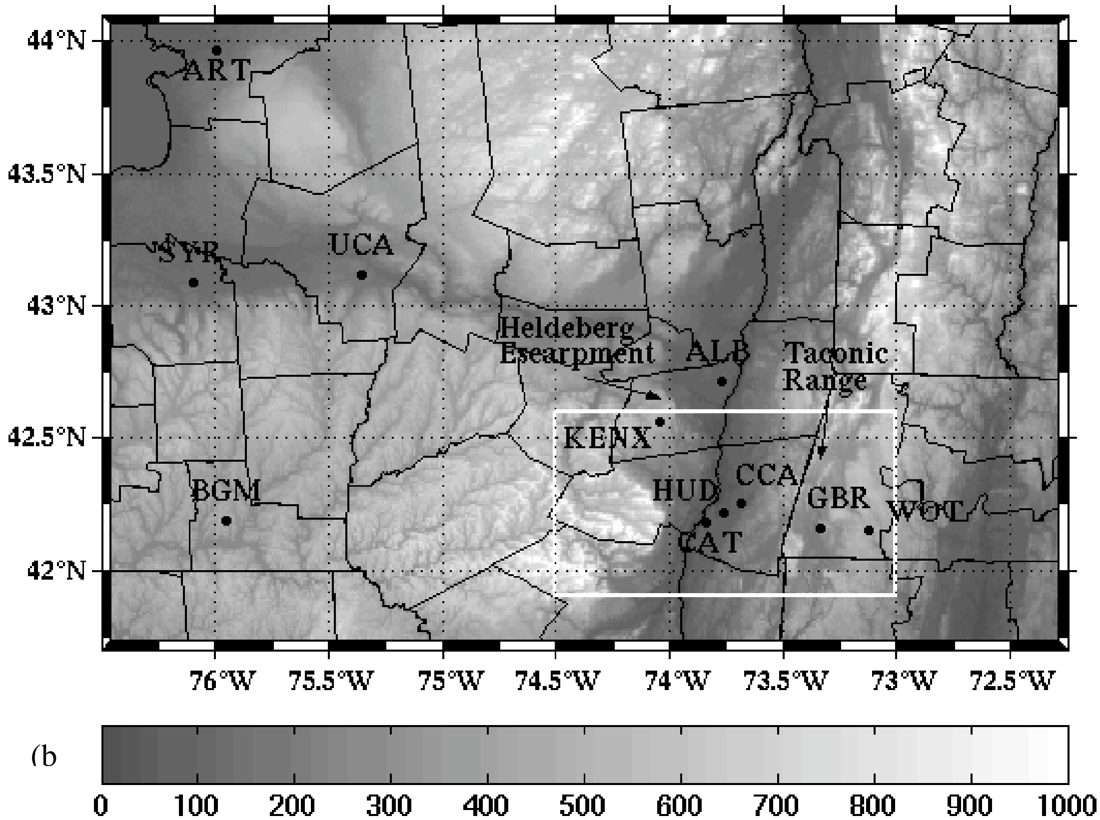
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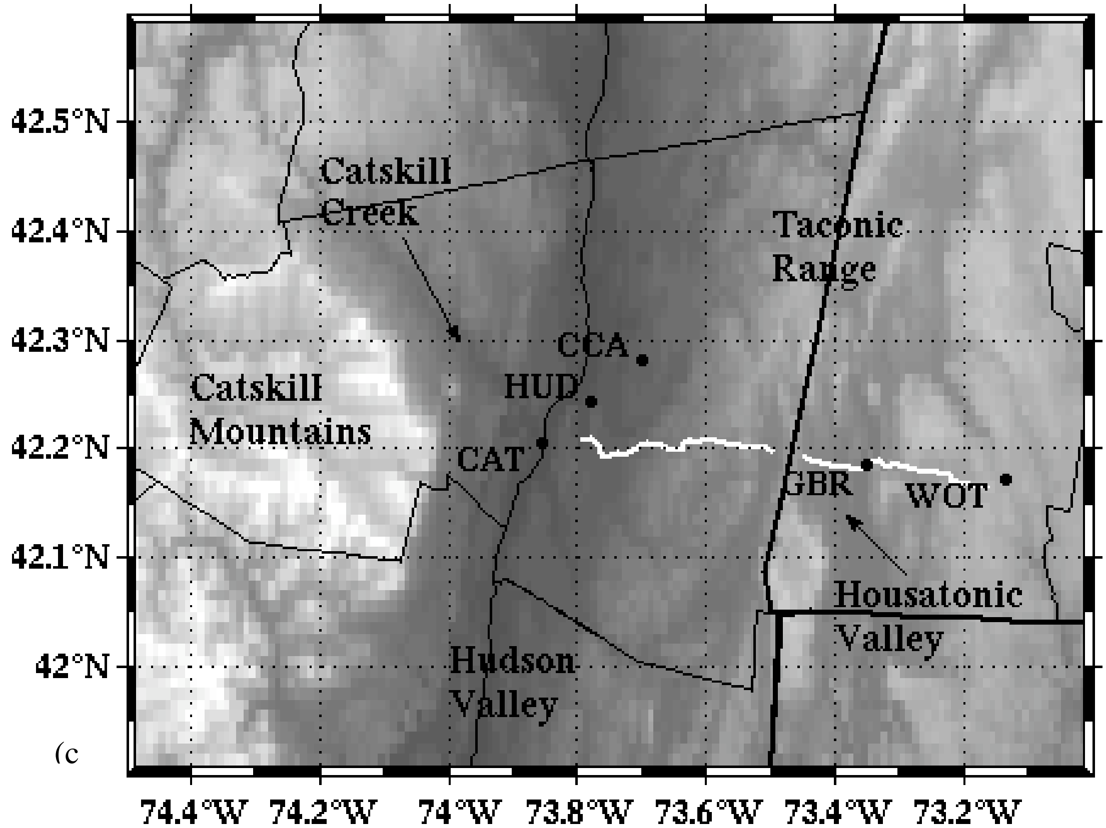

Figure 1: (a) Station and county identifier map, lower-case letters identify the following counties: a-Stueben, b-Schuyler, c-Chemung, d-Broome, e-Chenango, f-Delaware. (b) Station identifiers with terrain height shaded according to the color bar below. Bold outlined box marks the area shown in part c. (c) Close-up view of topography and station identifiers along with approximate tornado damage path (white line). Several key counties are labeled. CAT=Catskill, HUD=Hudson, CCA=Columbia County Airport, and WOT=West Otis.

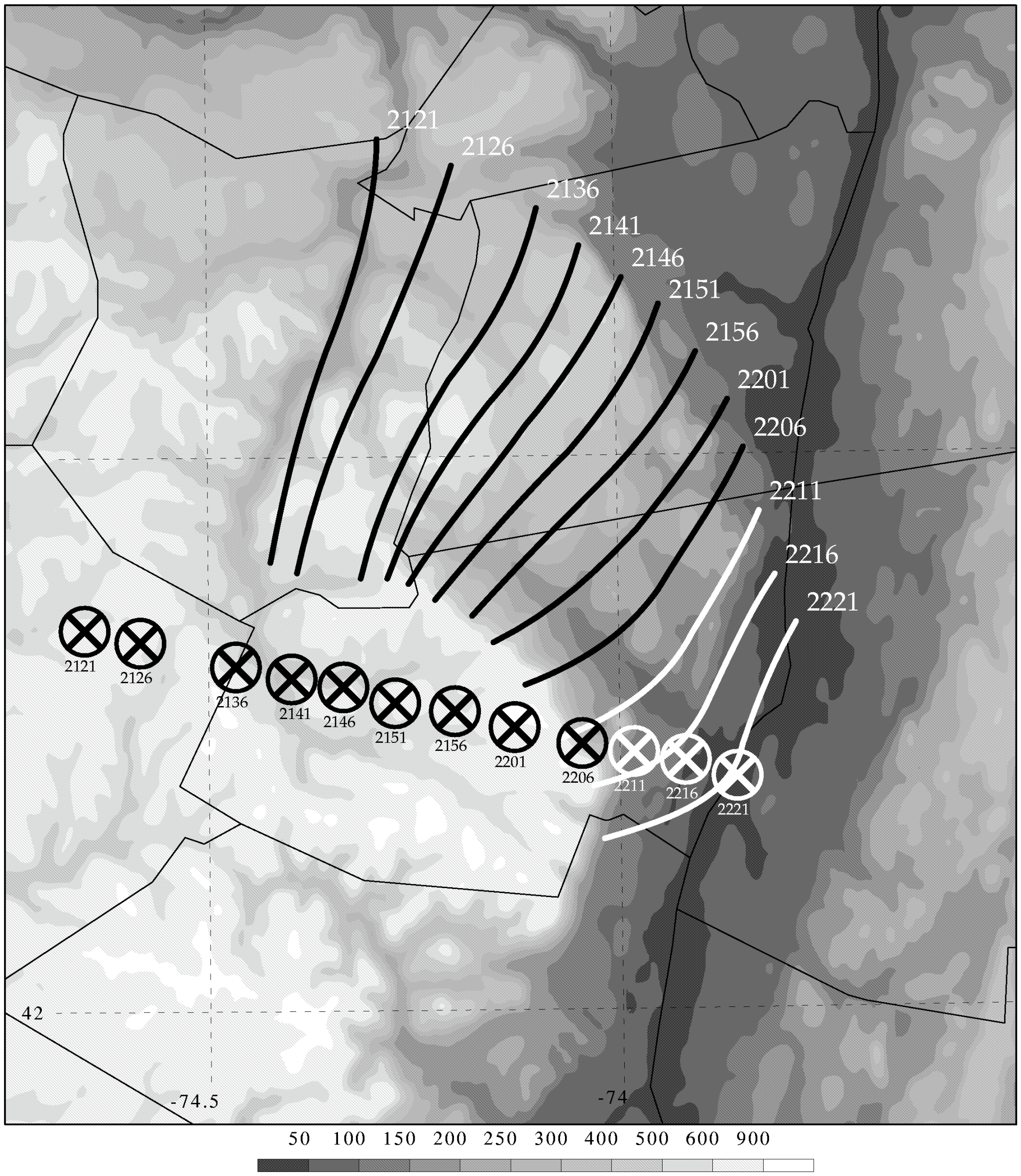

Figure 2: Isochrones of the leading edge of the Catskill Creek outflow boundary surge and position of the reflectivity core of the GBR storm on 29 May 1995 (marked by circle with ‘x’ at its center) for UTC times given. Note that the outflow boundary is far more extensive than the Catskill Creek Valley.

MSL(m)	Dir/Spd
89	170/8 (215/8)
500	185/14 (215/14)
1000	215/16 (225/16)
1500	242/20
2000	245/20
2500	247/21
3000	246/22
3500	246/22
4000	247/22
4500	245/23
5000	245/24
5500	245/24
6000	250/27
6500	249/26
7000	247/26

Winds at 89 m, 500 m and 1000 m over high terrain to the west of the Hudson Valley in parenthees

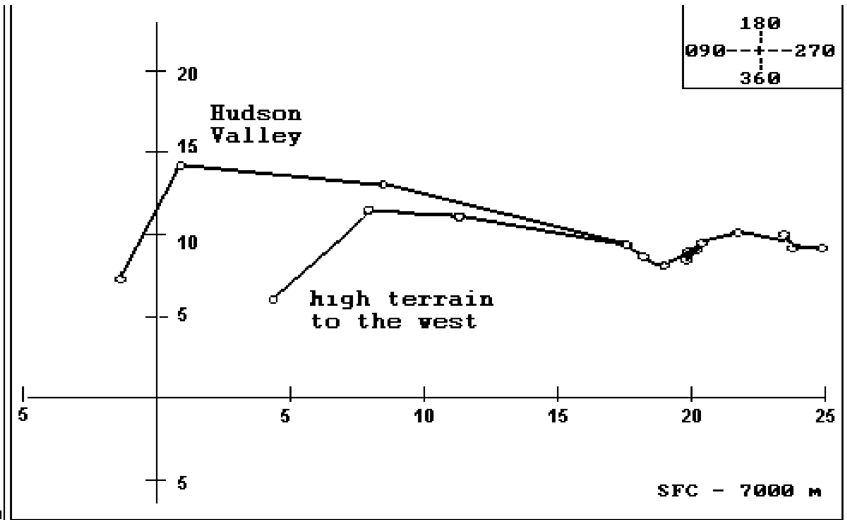

Figure 3: Representative hodographs for the Hudson Valley and the higher terrain to the west over the Catskills valid approximately 2000 UTC 29 May 1995 just prior to tornado development. Winds in the lowest 1 km were modified based on the observed surface winds in the Hudson Valley and over the higher terrain of the Catskills to the west. Winds above 1 km represent are based on the 1200 UTC 29 May 1995 ALB sounding.

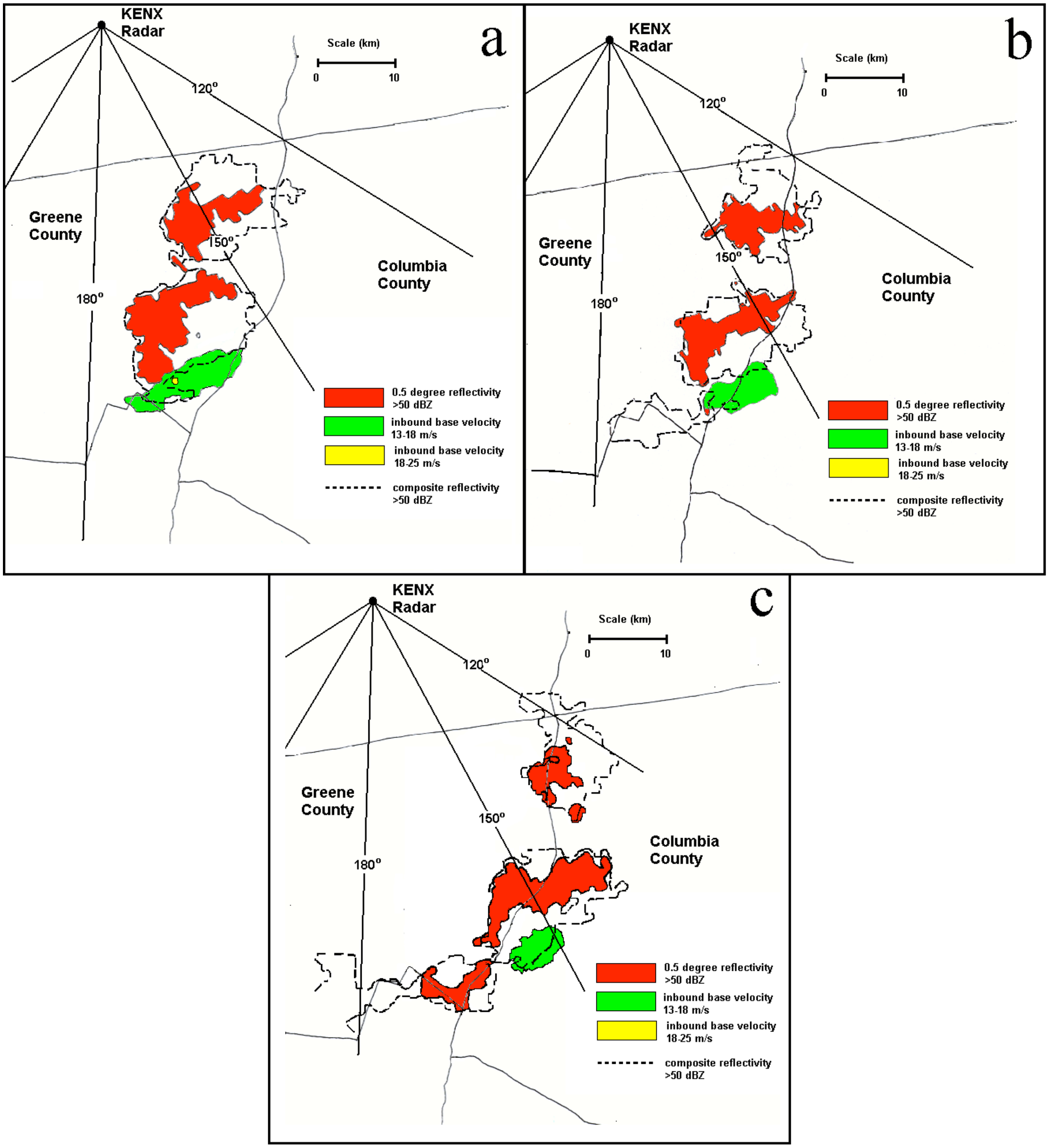

Figure 4: Combined KENX 0.5° base reflectivity, composite reflectivity, and base velocity on 29 May 1995 for 2211 UTC (upper left), 2216 UTC (upper right) and 2221 UTC (lower middle). Red-shaded areas indicate base reflectivity values > 50 dBZ. Black dashed lines enclose areas of composite reflectivity > 50 dBZ. Green (yellow) shading denotes areas of inbound velocities of 13-18 m s^{-1} (18-25 m s^{-1}). The KENX radar is located in the upper portion of each image. The Hudson River runs along the border of Greene and Columbia Counties.

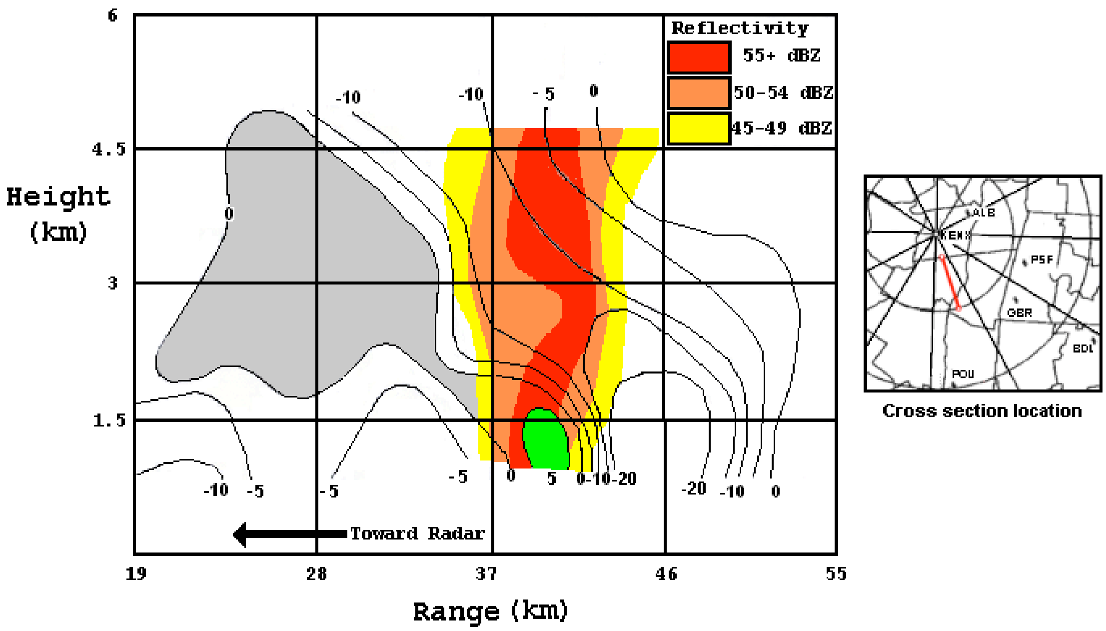

Figure 5: Manually constructed cross section of the Great Barrington storm at 2216 UTC 29 May 1995 as the storm moved into the Hudson Valley as derived from the KENX radar base reflectivity and storm-relative velocity observations. Red, orange and yellow shading denote base reflectivities >55 dBZ, 50-54 dBZ and 45-49 dBZ, respectively. Solid lines indicate storm-relative velocity values with negative (positive) values toward (away) from the radar. Outbound storm-relative velocities > 5 m s^{-1} (0-5 m s^{-1}) are shaded green (gray).

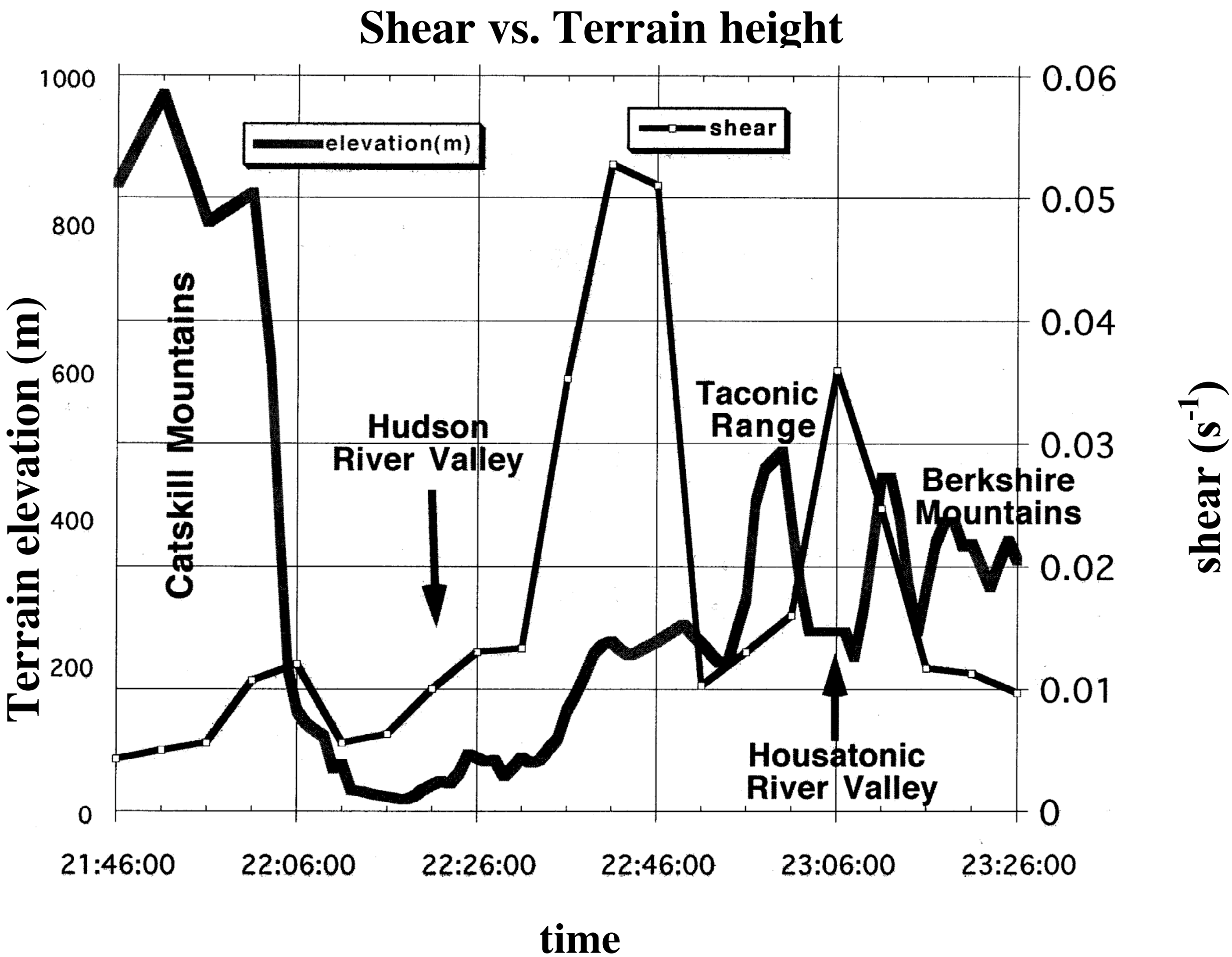

Figure 6: Inbound/outbound shear (s^{-1}; solid) derived from KENX WSR-88D volume scans averaged over the lowest three elevation scans (0.5, 1.5 and 2.4 degrees) along the disturbance path from 2146-2326 UTC 29 May 1995. Terrain elevation (m) given in solid (thick gray) with key topographic landforms labeled.