A Multiscale Examination of the 31 May 1998 Mechanicville, New York, Tornado

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ABSTRACT

On 31 May 1998, an F3 tornado struck Mechanicville, New York, injuring 68 people and causing \$71 million in damage. The tornado was part of a widespread, severe weather outbreak across the northeast United States. The synoptic conditions that caused the outbreak and the mesoscale and storm-scale environments that produced the tornado are discussed.

The coupling of two strong upper-level jets and a very strong low-level jet, in association with an unseasonably strong surface cyclone, created a synoptic-scale environment favorable for severe weather. As the result of these jet interactions, a very warm, moist air mass was transported into the Northeast with an associated increase in the wind shear in the lower troposphere. A terrain-channeled low-level southerly flow up the Hudson Valley may have created a mesoscale environment that was especially favorable for tornadic supercell development by increasing storm-relative helicity in the low levels of the atmosphere and by transporting warm, moist air northward up the valley, leading to increased instability.

A broken line of locally severe thunderstorms moved eastward across New York several hours prior to the tornado. The storm that produced the Mechanicville tornado developed over central New York ahead of this line of storms. As the line of storms moved east, it intensified into a solid line and bowed forward down the Mohawk Valley of New York. These storms were moving faster than the isolated supercell to the east and overtook the supercell where the eastern end of the Mohawk Valley opens into the Hudson Valley. Based on limited observational evidence and the results of simulations of idealized quasi-linear convective systems reported elsewhere in the literature, it is hypothesized that backed low-level flow ahead of a bookend vortex at the northern end of the bowing line of storms over the Mohawk Valley may have contributed to the tornadogenesis process as the squall line overtook and interacted with the intensifying supercell.

1. Introduction

Tornadoes rated F3 or higher on the Fujita (1981) scale are rare in eastern New York and western New England. Since 1950, there have been only six occurrences of F3 tornadoes or stronger (Table 1), two of which were killer tornadoes. On 28 August 1973, an F4 tornado struck Columbia County, New York, and Berkshire County, Massachusetts, killing four and injuring 36. The same counties were struck again on 29 May 1995 by an F3 tornado producing three deaths and

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29 injuries. On 31 May 1998, an F3 tornado formed just west of Mechanicville, Saratoga County, New York, and traveled over 50 km before reaching southwest Vermont as an F2 tornado (Fig. 1). Since significant tornadoes have the potential to produce severe damage and great loss of life, it is incumbent on the National Weather Service (NWS) to provide as much warning as possible for these storms. Although 68 people were injured in the Mechanicville tornado, accurate and timely severe weather outlooks, tornado watches, and tornado warnings, and rapid communication of hazardous weather information likely contributed to no lives being lost. Across the entire Northeast on 31 May, there were 5 fatalities and 127 injuries, associated with 32 tornadoes, 264 reports of wind damage, and 84 reports of 3/4-in. (1.9 cm) diameter or larger hail (Fig. 2a).

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Date	Intensity	Counties affected	Deaths	Injuries	Damage (millions \$)
24 Jun 1960	F3	Schenectady, NY	0	9	25
28 Aug 1973	F4	Columbia, NY; Berkshire, MA	4	36	25
16 Jun 1974	F3	Greene, NY; Albany, NY; Saratoga, NY	0	0	2.5
10 Jul 1989	F4	Montgomery, NY; Schoharie, NY; Albany, NY; Greene, NY	0	20	100
29 May 1995	F3	Columbia, NY; Berkshire, MA	3	29	35
31 May 1998	F3	Saratoga, NY; Rensselaer, NY; Bennington, VT	0	68	71

TABLE 1. Tornadoes of F3 or greater intensity since 1950 in east-central New York and adjacent western New England.

Although severe weather in the Northeast is infrequent compared to that in the Great Plains, it does occur as is evident from climatological studies (e.g., Brooks et al. 2003) and a review of research on severe weather in the Northeast (e.g., Johns and Dorr 1996). The unique terrain of the Northeast can also influence the observed distribution of severe weather (e.g., Riley and Bosart 1987; Wasula et al. 2002). A perspective on operational severe weather forecasting in the Northeast and an operational severe weather forecasting algorithm for the NWS Albany, New York, county warning area is presented in Maglaras and LaPenta (1997).

Since tornado outbreaks of this magnitude are relatively rare in the Northeast, it is important to examine the evolution of this outbreak, and in particular the Mechanicville tornado. Carefully reviewing past storms is a key step in improving a forecaster's ability to diagnose severe weather potential and accurately forecast and warn for tornadoes and severe thunderstorms. This paper will examine the synoptic and mesoscale conditions that resulted in this widespread severe weather outbreak. Although the Mechanicville tornado developed within a synoptic-scale environment already favorable for tornadoes and severe thunderstorms, we will present some limited evidence that terrainchanneled low-level flow in north–south river valleys and the interaction of the isolated supercell responsible



FIG. 1. Map of eastern New York and western New England showing terrain features. The white arrow indicates the path of the Mechanicville tornado; KENX is the NWS radar location, and ALY is the location of the Albany NWS radiosonde site. Terrain heights (m) according to color bar in the lower right. The terrain map was obtained online from the Color Landform Atlas of North America, compiled by R. Sterner of the Johns Hopkins University Applied Physics Laboratory (http://fermi.jhuapl.edu/states/ states.html).



FIG. 2. Severe weather reported across the northern United States from (a) 1800 UTC 30 May to 0400 UTC 1 Jun 1998, (b) 0000 UTC 29 May to 0400 UTC 30 May 1998, and (c) 0000 UTC 2 Jun to 0400 UTC 3 Jun 1998 (Hart and Janish 1999). Tornadoes are indicated by black squares and lines, hail by gray squares, and severe wind reports by gray crosses. Inset in the upper left provides statistics on severe weather events plotted in (a).



FIG. 3. The 200-hPa mean (29 May–4 Jun 1998) geopotential heights (solid, every 12 dam) and height anomalies (every 6 dam and shaded according to the bar at the right). Height anomalies are defined as the 29 May–4 Jun for 1968–96 mean heights subtracted from the 29 May–4 Jun for 1998 mean heights.

for the Mechanicville tornado with an overtaking squall line may have enhanced the likelihood of tornadogenesis. The paper is organized as follows. The synoptic overview appears in section 2. The mesoscale environment is described in section 3, while the details of the Mechanicville tornado appear in section 4. Speculations about the formation of the Mechanicville tornado are presented in section 5 with a summary in section 6.

2. Synoptic overview

Severe weather was widespread from the northern plains across the Great Lakes to New England during late May and early June 1998 (Fig. 2). The 200-hPa height pattern over North America during this period was dominated by above normal heights from north of Hawaii northward across the Gulf of Alaska, eastward toward Greenland, and over much of the southern half of the United States (Fig. 3). Below normal heights were found west of California and over Canada to the south of Hudson Bay. Given the strong trough (ridge) south of Hudson Bay (over the southern United States), the pattern shown in Fig. 3 was conducive to a strong westerly jet from the northern Rockies to New England. The severe weather threat was maximized where the ascent zones associated with disturbances embedded in the jet intercepted low-level baroclinic regions and warm, moist unstable air.

A 500-hPa closed low, destined to play a significant role in the severe weather shown in Fig. 2, moved southward off the west coast of North America, turned northeastward, caused weak cyclogenesis over Nevada at 0000 UTC 29 May, and reached central Idaho by 1200 UTC 30 May (Fig. 4). A weak 500-hPa trough to the southeast of this landfalling closed low formed over western Colorado at 1200 UTC 30 May, moved to central Nebraska 12 h later, and subsequently initiated



FIG. 4. Track of selected 500-hPa disturbances (solid lines) with solid (open) circles denoting the 1200 (0000) UTC position. The dashed line indicates the path of the surface cyclone with solid (open) triangles denoting the 1200 (0000) UTC position. Bold numbers adjacent to the 1200 UTC positions indicate dates. Italicized numbers indicate the sea level central pressure in the cyclone (hPa with leading 10 or 9 omitted). Nonbold upright numbers indicate maximum 500-hPa absolute vorticity values ($\times 10^{-5} \text{ s}^{-1}$).

weak cyclogenesis over northwest Kansas at 1200 UTC 30 May (a weak lee cyclone was present over the Texas and Oklahoma panhandles during the previous 24-h period).

The key player in the eventual 31 May severe weather outbreak over the Northeast was a 500-hPa vorticity center that was located over northern Canada at 1200 UTC 29 May (Fig. 4). This disturbance moved southward and then southeastward around the western periphery of a closed low situated over Hudson Bay (not shown). During the late afternoon and evening of 30 May, it helped produce severe weather over South Dakota, where the town of Spencer was devastated by an F4 tornado (NCDC 1998). A derecho evolved from this convection and moved eastward across Minnesota, Iowa, and Wisconsin at more than 30 m s⁻¹, reaching lower Michigan by 0800 UTC 31 May. This derecho produced widespread wind damage (Fig. 2) in association with wind gusts of 30–40 m s⁻¹ (NCDC 1998).

By 1200 UTC 31 May, the above disturbance was located over the upper peninsula of Michigan, where it began to phase with the weak disturbance moving northeastward across Colorado. In response, the surface cyclone over the northern Rockies accelerated eastward and merged with the weaker cyclone moving northeastward out of Kansas. Subsequently, the 500hPa disturbance turned northeastward, stalled in the vicinity of James Bay, and was absorbed by the Hudson Bay closed low. As the associated surface cyclone moved northeastward to southeast of James Bay, it deepened 13 hPa in the 24-h period ending 0000 1 June. The severe weather over the northeastern United States on 31 May occurred in the warm sector of this deepening cyclone. Additional disturbances that rotated around the closed low also interacted with the strong upper-level jet (Fig. 3) and helped to produce two additional major severe weather outbreaks (29 May and 2 June) over the northeastern United States in addition to the 31 May storms (Figs. 2b and 2c).

A series of surface and upper-air maps were crafted from the Global Reanalysis Data produced by the National Oceanic and Aeronautics Administration's (NOAA) National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (Kalnay et al. 1996; Kistler et al. 2001) to provide a synoptic overview of this event. A surface cyclone located over South Dakota at 1200 UTC 30 May (Fig. 4) intensified as it moved eastnortheast to a position north of New York and New England by 0000 UTC 1 June (Figs. 4, 5a-c). Model-



FIG. 5. (left) Sea level pressure (solid, every 4 hPa), 1000–500-hPa thickness (dashed, every 3 dam), and 700-hPa absolute vorticity (every $4 \times 10^{-5} \text{ s}^{-1}$ beginning at $8 \times 10^{-5} \text{ s}^{-1}$ and shaded according to the grayscale) for (a) 1200 UTC 31 May, (b) 1800 UTC 31 May, and (c) 0000 UTC 1 Jun 1998. (right) The 850-hPa geopotential heights (solid, every 3 dam), temperatures (dashed, every 3°C), and θ_e (every 5 K beginning at 325 K and shaded according to the grayscale) for (d)–(f) the same times as (a)–(c).

diagnosed upward vertical motion at 700 hPa, from the Great Lakes northward into Canada at 1200 UTC 31 May, moved east across New York, New England, and Quebec during the next 12 h (Figs. 6d–f).

The observed 850-hPa winds at Detroit, Michigan

(DTX), and Wilmington, Ohio (ILN), at 1200 UTC 31 May were 33 and 23 m s⁻¹, respectively. This strong low-level flow produced significant warm-air advection across the Northeast (Figs. 5d–f). In addition, it helped to advect moisture rapidly into eastern New York dur-



FIG. 6. (left) The 700-hPa geopotential heights (solid, every 3 dam), temperature (dashed, every 3° C), and LI to 500 hPa (shaded according to the grayscale for values < -2) for (a) 1200 UTC 31 May, (b) 1800 UTC 31 May, and (c) 0000 UTC 1 Jun 1998. (right) The 700-hPa geopotential heights (solid, every 3 dam), 700-hPa relative humidity (dashed, every 10% beginning at 50%), and 700-hPa ascent (every 2×10^{-3} hPa s⁻¹ beginning at -2×10^{-3} hPa s⁻¹ and shaded according to the grayscale) for (d)–(f) the same times as (a)–(c).

ing the morning. A tongue of high equivalent potential temperature (θ_e) was drawn northeastward toward the lower Great Lakes and then New York and New England, increasing the convective available potential

energy (CAPE; Figs. 5d–f). The strong 850-hPa flow also contributed to strong shear and storm-relative helicity (SRH) in the lower troposphere (section 3). The severe storms that were initiated across the



FIG. 7. (left) The 500-hPa geopotential heights (solid, every 3 dam), temperature (dashed, every 3° C), and absolute vorticity (every $4 \times 10^{-5} \text{ s}^{-1}$ beginning at $8 \times 10^{-5} \text{ s}^{-1}$ and shaded according to the grayscale) for (a) 1200 UTC 31 May, (b) 1800 UTC 31 May, and (c) 0000 UTC 1 Jun 1998. (right) The 250-hPa geopotential heights (solid, every 12 dam), divergence (dashed, positive values only, every $1 \times 10^{-5} \text{ s}^{-1}$), and isotachs (every 10 m s⁻¹ beginning at 40 m s⁻¹ and shaded according to the grayscale) for (d)–(f) the same times as (a)–(c).

Northeast in the 6 h ending 0000 UTC 1 June occurred in a warm-sector environment of 700-hPa ascent and relatively dry air, a situation conducive to destabilization, with drier air aloft over high- θ_e air below (Figs. 6e,f). By 0000 UTC 1 June, a deepening 500-hPa trough and associated cyclonic vorticity axis had acquired a negative tilt (Figs. 7a–c). The surface cyclone had deepened to 985 hPa and had turned northward as the trailing cold front began to cross New York (Figs. 4, 5c).



FIG. 8. (a) Sounding (skew *T*-log*p* format) for DTX (72632) for 1200 UTC 31 May 1998. Winds in m s⁻¹ with one pennant, full barb, and half barb denoting 25, 5, and 2.5 m s⁻¹, respectively. (b) As in (a) except for ALY (72518) for 1200 (solid) and 1800 (dashed) UTC 31 May 1998.

At 250 hPa, a coupled jet pattern was evident across the Northeast (Figs. 7d-f). Divergence was concentrated in the left exit region of the trailing jet and the right entrance region of the leading jet, especially by 0000 UTC 1 June (Fig. 7f). The aforementioned derecho that affected the Great Lakes region originated hours earlier as isolated storms over South Dakota within the left exit region of the trailing 60 m s⁻¹ 250-hPa jet that was crossing extreme northern Colorado and southern Wyoming. This trailing jet shifted rapidly eastward to Iowa by 1200 UTC 31 May (Fig. 7a), at which time the remnant convection from the derecho over lower Michigan at 0800 UTC was situated near a region of 250hPa divergence located between two coupled jets (Fig. 7d). By 0000 UTC 1 June, the 250-hPa divergence core was spread in an arc from eastern Pennsylvania to southern Quebec between the coupled jets and above the southern part of the axis of 700-hPa ascent (Figs. 6f, 7f). The strongest warm advection and strongest ascent were well north of the severe weather areas, but nonetheless, upward motions were sufficient to enhance severe storm potential, and allow parcels to reach the level of free convection and release the instability.

3. Mesoscale environment

a. Morning destabilization

The 1200 UTC 31 May sounding from Detroit, Michigan (DTX; Fig. 8a), was taken just to the west of the derecho that crossed the Great Lakes overnight and, thus, was representative of the immediate postderecho mesoscale environment. A strong corridor of westerly winds (peak speeds $> 35 \text{ m s}^{-1}$) was found in conjunction with the deep mixed layer from 825 to 700 hPa that was possibly the signature of a descending rear-inflow jet behind the derecho (Weisman 1992). The DTX sounding also indicated that the air mass below the mixed layer had been stabilized, likely in response to rain-cooled air. Heating and moistening the low levels of the DTX sounding (Fig. 8a), to make it representative of the warmer and moister conditions observed in New York during the afternoon, would produce a very unstable air mass. Unfortunately, no representative sounding was available to confirm this hypothesis because there was no Buffalo, New York radiosonde launch for 1200 UTC 31 May, owing to equipment failure. Instead, Fig. 8b shows the 1200 and 1800 UTC 31 May soundings from Albany, New York (ALY). A stable pre-warm front environment at



FIG. 9. KALB hodographs for 1200 (gray) and 1800 UTC (black dotted) 31 May 1998. Wind components in m s⁻¹.

1200 UTC warmed and moistened considerably by 1800 UTC. During this 6-h period, the surface-based CAPE (SBCAPE) increased from 0 to more than 750 J kg⁻¹ as higher- θ_e air to the southwest began to arrive in conjunction with strengthening low-level southerly winds.

A comparison of the 1200 and 1800 UTC 31 May ALY hodographs (Fig. 9) shows that the 0–6-km above ground level (AGL) shear¹ and SRH increased (shear from 24 to 29 m s⁻¹ and SRH from about 250 to over $500 \text{ m}^2 \text{ s}^{-2}$) in response to a strengthening 25 m s⁻¹ west-southwesterly jet between 750 and 500 hPa and a strengthening of the low-level southerly flow below 850 hPa (note that the wind direction near 800 hPa in the 1800 UTC ALY sounding was likely erroneous; Fig. 8b). The end result was a hodograph indicative of favorable shear conditions for severe weather, by 1800 UTC 31 May.

Between 1500 and 2000 UTC, the air mass over New York and Pennsylvania rapidly destabilized (Figs. 10– 12). At 1500 UTC, most of the Hudson Valley region of New York and all of New England were under a south and southeasterly flow of relatively cool marine air, with surface dewpoints generally under 15°C (59°F; Fig. 10). A southwesterly flow across Pennsylvania and western-central New York marked the leading edge of the advancing warmer, more moist, and unstable air mass (Fig. 10). The eastward advance of the cloud shield across the upper Hudson Valley into western New England between 1200 and 1500 UTC and the clear area over eastern Pennsylvania, New Jersey, and the southwestern Catskills of New York at 1500 UTC show the eastward movement of the warm, humid, and unstable air mass (Figs. 10, 13a–c). Surface θ_e values exceeded 340 K by 1500 UTC across western New York and Pennsylvania, with an area in excess of 348 K over southeastern Pennsylvania, as solar heating combined with the transport of increasingly warm and moist air to destabilize the air mass [Fig. 10; surface-based lifted indexes (LIs) had decreased to -5 to -8 in this region].

Satellite visible imagery showed thick cloudiness with a large area of showers, and some embedded thunderstorms, from northern New York to northeastern Ohio by 1700 UTC (Fig. 13c). This area of clouds and precipitation was associated with the remnants of the derecho that crossed portions of the Great Lakes the previous night. As this area of convection moved eastward across New York, thunderstorms re-ignited between 1700 and 2000 UTC (Figs. 13c,d). The surface map for 1800 UTC (Fig. 11) showed the strengthened southerly flow up the Hudson Valley as higher-dewpoint air $[\sim 18^{\circ}C (64^{\circ}F)]$ reached the region. Immediately to the west in the clear region (Fig. 13b), θ_{e} values exceeded 340 K over a wide area. Surface-based LIs were between -6 and -10 in the clear air in response to continued heating and airmass destabilization.

b. Environment for supercell growth over complex terrain

As the afternoon of 31 May 1998 progressed, the atmosphere across eastern New York became increasingly favorable for severe weather. By 2000 UTC the warm and moist, unstable air had overspread the Hudson Valley and much of interior southern New England with $\theta_{\rm e}$ values > 348 K being common (Fig. 12). At Glens Falls (KGFL) and Albany (KALB), New York, sustained winds in the southerly flow in the Hudson Valley were exceeding 10 m s⁻¹. Surface temperatures in the clear air southeast of the developing thunderstorms were in the 27° - 32° C (81° - 90° F) range, with dewpoints of 18°-20°C (64°-68°F). The 1800 UTC radiosonde observation at ALY (Fig. 8b), located about 6 km south of KALB, was modified for the observed KALB surface temperature and dewpoint temperature at 2000 UTC. The SBCAPE [mean layer CAPE (MLCAPE)] increased to about 2000 J kg⁻¹ (1600 J kg^{-1}). The mean layer lifted condensation level (MLLCL, lifted condensation level based on lifting a parcel with conditions averaged over the lowest 100 hPa) was about 1200 m. Thompson et al. (2003) showed median MLLCLs for significant tornado, weak tornado, and non-tornadic supercell cases, of about 1000, 1200, and 1350 m, respectively.

¹ Shear values are based on output from the NWS SHARP workstation (Hart and Korotky 1991) and represent a summation of 500-m hodograph shear segments, from 0 to 6 km, showing clockwise curvature.



FIG. 10. Manual analysis of sea level pressure (solid contours every 2 hPa) and θ_e (dashed contours every 8 K) for 1500 UTC 31 May 1998.

The shear magnitude was 29 m s⁻¹ in the 0–6-km AGL level. Observations and modeling studies (e.g., Weisman and Rotunno 2000) indicate that vertical wind shear greater than $20-25 \text{ m s}^{-1}$ is favorable for the development of long-lived convective structures such as supercells. Based on observed storm motion of 260° at 21 m s^{-1} , the SRH was greater than $500 \text{ m}^2 \text{ s}^{-2}$. Davies-Jones et al. (1990) indicated this SRH value would be large enough to support significant (F2 and greater) tornadoes. Recent studies using Rapid Update Cycle model generated proximity soundings (Thompson et al. 2003) and observed proximity soundings (Rasmussen 2003) suggest that shear and SRH in the 0-1-km AGL layer are better at discriminating supercells that produce significant tornadoes from nontornadic supercells than deep-layer (0-6-km shear and 0-3-km SRH) measures of these parameters. The SRH (shear) in the 0-1km AGL layer was about 140 m² s⁻² (14 m s⁻²). In Thompson et al. (2003) more than 75% of the significantly tornadic supercells had 0–1-km SRH $> 75 \text{ m}^2 \text{ s}^{-2}$ while 70% of the nontornadic supercells occurred with lesser values. The 0-1-km SRH was well above the median value (89 m² s⁻²) for tornadic storms in Rasmussen (2003). Finally, based on Thompson et al. (2003) and Rasmussen (2003), the combination of MLCAPE and 0–1-km SRH pointed to the possibility of significant tornadoes.

Although conditions in the warm sector of this storm were favorable for the development of severe storms and tornadoes, terrain may have played a role in enhancing the tornadic potential in the immediate Hudson Valley. A number of significant physiographic features are present in eastern New York and western New England. To the west of the north-south-oriented Hudson Valley are the Catskill and Adirondack Mountains (Fig. 1). These two mountain ranges are separated by the east-west-oriented Mohawk Valley. To the east of the Hudson Valley in western New England are the Green (Vermont) and Berkshire (Massachusetts) Mountains. On this day, terrain channeling of the southerly low-level flow within the Hudson Valley may have enhanced the transport of warm, moist air northward. At KALB, the dewpoint increased steadily through the day, and the wind remained out of the south until convection arrived shortly after 2000 UTC (Fig. 14a). This southerly flow transported high- θ_a air



FIG. 11. As in Fig. 10 except for 1800 UTC 31 May 1998.

northward. The 1900 UTC θ_e analysis² shows an axis of higher- θ_e air extending northward up the Hudson Valley (Fig. 15). The radar reflectivity pattern has been included to help delineate areas of rain-cooled air. This pattern of higher- θ_e (instability; Fig. 16) air in the Hudson Valley with a south or southwest low-level wind flow is common, and is also seen in higher-resolution operational numerical models.

The near surface flow west of the Hudson Valley was generally out of the south-southwest. This southsouthwest flow was channeled into a more southerly direction at low levels within the immediate Hudson Valley. Binghamton, New York (KBGM), consistently had a more westerly component to the surface wind than Hudson Valley locations [KALB and Schenectady, New York (SCH); Fig. 14b]. At Utica, New York (KUCA), the surface wind was from the southeast (up the Mohawk Valley; see Fig. 1) prior to 1500 UTC. Once in the warm sector (after 1600 UTC), however,

² Analysis taken from the NWS Advanced Weather Interactive Processing System's (AWIPS) Local Analysis and Prediction System (LAPS) analysis. the wind at KUCA showed a greater westerly component than at Hudson Valley locations (Fig. 14b). The channeling of the surface wind in the Hudson Valley to a more southerly direction resulted in an increase in the shear and SRH. The channeling of a southwest flow to a southerly flow within the Hudson Valley is a common occurrence, as indicated by the wind rose for KALB in Fig. 14c taken from Wasula et al. (2002). The wind rose for KALB at 850 hPa in Wasula et al. (2002; not shown) does not show a southerly directional bias, which illustrates the decreasing influence of the terrain with height on wind direction.

Figure 17 shows estimated hodographs based on the 1800 UTC ALY sounding for a location in the Hudson Valley, and for a location west of the Hudson Valley. The lower 2 km of the observed hodograph were modified using the 1900 UTC observed surface winds at KALB and KBGM, and applying a nonlinear Ekman spiral approach to interpolate the winds between the surface and 2000 m. The channeling of the wind in the Hudson Valley hodograph resulted in an increase in 0-3-km (0-1 km) SRH from about 400 (300) to about 530 (420) m² s⁻². There was also an increase in shear in



FIG. 12. As in Fig. 10 except for 2000 UTC 31 May 1998.

the lowest kilometer. There is no way to know the actual hodographs at this time, and a different methodology for estimating the hodograph could produce a different result. To test the validity of the estimated hodographs, the 1200 UTC 31 May Eta Model soundings for 1900 UTC for KALB (in the Hudson Valley) and KBGM (west of the Hudson Valley) were compared to the estimated hodographs (Fig. 17b). At 1900 UTC, both KBGM and KALB were in the warm sector of the low pressure area, and ahead of the thunderstorms approaching from the west (Figs. 14b and 15). The winds in the two model sounding hodographs were similar at 2 and 3 km AGL, but were markedly different below. The KALB model sounding was similar to the Hudson Valley hodograph, while the KBGM sounding showed somewhat less curvature (Fig. 17a). The model sounding winds showed a more westerly component at 2 km AGL than in the observed winds. The hodographs indicate there might have been enhancement of SRH and shear due to terrain effects.

A 6-h NCEP Eta Model forecast (the model was initialized at 1500 UTC with 32-km grid spacing) of 975hPa winds valid at 2100 UTC (Fig. 18) showed evidence of terrain channeling. The winds in the Hudson Valley, especially near and just south of Mechanicville, were more southerly than in surrounding areas to the west and to the east. This helped maximize the 0–6-km shear (29 m s⁻¹) just south of Mechanicville (Fig. 18). While mesoscale conditions supported the possibility of tornadoes (e.g., Rasmussen 2003; Johns and Doswell 1992; Davies-Jones et al. 1990), a storm moving from the northern Catskills into the Hudson Valley would encounter a somewhat more unstable air mass with greater SRH and shear in the lower troposphere, due to terrain channeling.

4. Evolution of the Mechanicville tornado

a. Radar analysis

The remnants of the derecho that crossed Michigan during the early morning hours of 31 May reached western New York about 1600 UTC. The convection then intensified as it moved east, producing locally severe weather as it reached central New York by 1824 UTC (Figs. 2 and 19a), about 2 h prior to the Mechanicville tornado (2022 UTC). As the line of thunderstorms passed KUCA, it produced a 7°C (13°F) drop in temperature between 1900 and 2000 UTC. At



FIG. 13. Satellite imagery on 31 May 1998 with (a) infrared image at 1215 UTC, and visible images at (b) 1445, (c) 1745, and (d) 2002 UTC.

1824 UTC, a small cluster of isolated storms developed about 55 km to the east of the line. One of the storms in this cluster intensified by 1906 UTC as it moved east-northeast (Fig. 19b). By 1942 UTC, the advancing and intensifying line began to bow down the Mohawk Valley as it was catching up with the leading supercell storm (Fig. 19c). This leading storm, only about 30 km ahead of the line racing down the Mohawk Valley, had become severe (downed trees were reported) as it approached the Hudson Valley north of ALY (Fig. 19c).

North of the apex of the bowing squall line, there was evidence of a line echo wave pattern (LEWP; Fig. 20a). A rotational velocity couplet (13 m s⁻¹ at 1946 UTC) along the Fulton–Montgomery County line (upper circle in Fig. 20b) was found near the northern end of the advancing squall line, in a location where a northern bookend vortex would be found. A separate velocity couplet (13 m s⁻¹ at 1946 UTC) was also apparent just south of the Fulton–Montgomery County line (lower circle in Fig. 20b). Two volume scans later, at 1957 UTC, the rotational velocity associated with the mesoscale vortex had decreased (Figs. 20c,d). Just to the east, the leading supercell intensified between 1957 and 2012 UTC (see discussion below) as it approached the confluence of the Mohawk and Hudson Valleys

(Figs. 19d, 20a,c). This intensification may be related to the presence of a slightly more unstable and more highly sheared environment in the Hudson Valley and/ or the ongoing interaction of the overtaking squall line with the leading supercell (Figs. 14a, 15–18, 19d).

A tornado developed at 2022 UTC, about the time the outflow from the line of storms to the west reached the leading severe storm (Fig. 19d). This outflow was likely channeled east-southeastward down the Mohawk Valley. KENX base velocity data at 1957 UTC (25 min before tornadogenesis) indicated an area of higher winds in this storm-initiated outflow moving down the Mohawk Valley (Fig. 21). At 2002 UTC, 20 min prior to the tornado, weak convergence was indicated in the SRM data about 1 km above mean sea level (MSL) in the KENX 0.5° beam angle volume scan (not shown). Above 1 km, cyclonic rotation increased with height, reaching 21 m s⁻¹ at 3–4 km MSL. By 2012 UTC, strong rotation (21–23 m s⁻¹) had descended toward the surface, but at the lowest elevation scan (about 1 km MSL), convergent rotation was present. At that time, the outflow from the line of severe storms approaching from the west had reached the storm. At 2017 UTC, strong rotation reached the lowest elevation scan (0.5°) , but inbound and outbound velocity maxima were still



FIG. 14. (a) (top) Time series (UTC) of temperatures (solid) and dewpoint (dashed) in °C, (middle) pressure in hPa, and (bottom) wind (as in Figs. 8a,b) for KALB on 31 May 1998. KALB is located about 6 km north of the ALY radiosonde site. (b) Time series comparing wind direction at KALB and KSCH in the Hudson Valley with KUCA and KBGM located west of the Hudson Valley (see Fig. 1). (c) Wind rose for KALB for the period Mar 1993–Mar 1997 taken from Wasula et al. (2002).

separated by about 2 km. The first tornado damage occurred at 2022 UTC and, at that time, the radar showed a maximum gate-to-gate rotational velocity of 28 m s⁻¹ at 0.5° (Fig. 22a). The Weather Surveillance Radar-1988 Doppler (WSR-88D) first identified a tornado vortex signature (TVS) based on the volume scan beginning at 2022 UTC, although it should be noted that the TVS information was not available to forecasters until several minutes after the completion of the volume scan, or at about 2030 UTC.

At 2022 UTC there was strong gate-to-gate rotation at the lowest elevation scan (about 1 km MSL), which was likely indicative of the low-level tornadic mesocyclone (Fig. 22b). Also apparent is the thunderstorm mesocyclone with inbound and outbound velocity maxima separated by about 8 km. The tornado reached its greatest intensity shortly after formation in Saratoga County, New York. It moved east across northern Rensselaer County, New York, before dissipating in Bennington County, Vermont (F2 intensity), with a total pathlength of 48 km (Fig. 1).

b. Lightning analysis

Cloud-to-ground (CG) lightning flash rates and distributions were also examined to document the interaction of the overtaking squall line with the isolated supercell that eventually produced the Mechanicville tornado. Our analysis was motivated by previous CG



FIG. 15. AWIPS LAPS analysis of surface θ_e at 1900 UTC 31 May 1998. Green shaded areas represent θ_e values > 342 K. Radar reflectivity (0.5° elevation scan, greater than 20 dBZ) according to color bar at the top. Conventional plotting of surface observations except temperature and dewpoint values given in °F.

lightning studies (e.g., Kane 1991; Seimon 1993; Doswell and Brooks 1993, MacGorman and Burgess 1994; Galarneau et al. 2000; Gilmore and Wicker 2002) that suggested that some tornadic supercell thunderstorms can have distinct lightning flash rates and polarity characteristics. We used CG flash data obtained from the National Lightning Detection Network (NLDN) to construct a time series of CG flashes in the advancing squall line and the isolated supercell beginning approximately 2 h prior to tornado formation at 2022 UTC 31 May. We also mapped the storm-relative distribution of CG flashes in 10-min periods, beginning at 2002 UTC, in an effort to identify possible spatial variations in CG flash activity during the interaction of the squall line and the isolated supercell.

In order to construct Fig. 23a, CG lightning flash data obtained from the NLDN were plotted on a topographic map. These CG flashes were assigned to either the squall line or the isolated supercell. We estimate that the subjective tabulation procedure had a small margin of error (± 1 –2 flashes per count) prior to squall line and supercell merger, and a larger margin of error $(\pm 5-10 \text{ flashes per count})$ subsequently. The separation distance between the squall line and supercell was determined using the KENX Doppler radar reflectivity images and was measured from the core of the highest reflectivities in the squall line to the supercell mesocyclone. The 10-min distributions of CG lightning flashes shown in Fig. 23b were plotted onto a horizontal map relative to the position of the KENX Doppler radarindicated mesocyclone prior to tornadogenesis. The analysis domain was 70 km \times 80 km (5600 km²) and was centered on the mesocyclone (or tornado). The number of CG lightning flashes, denoted in the lowerright corner of each panel, was counted objectively. The CG flash numbers were not normalized because the relative length of the squall line within the analysis domain did not change during the 40-min period shown in Fig. 23b (i.e., the overall area of the horizontal map covered by electrically active convection changed little with time).

The results of our CG flash analysis are shown in Fig.



FIG. 16. NWS AWIPS LAPS surface-based LI (to 500 hPa) analysis for 1900 UTC, with dashed contours indicating values less than zero and solid contours values zero or greater.

23. Until about 1855 UTC, the CG flash rate in the isolated supercell remained under 10 flashes per 5 min, during which time the squall line remained 40-45 km to the west of the supercell (Fig. 23a). Subsequent to 1855 UTC, the squall line began to accelerate eastward relative to the isolated supercell, closing to within 10 km by 2005 UTC. Over this 80-min period, the supercell flash rate first increased slowly to 10-15 CG flashes per 5 min period, and then more rapidly to more than 20 CG flashes per 5 min after 1950 UTC. Beginning at 2010 UTC, the CG flash rate increased to 20 flashes per 2 min (note time interval reduction beginning at 2010 UTC) through 2014 UTC, during which time the advancing squall line reached to within 6-7 km of the supercell. A brief decrease in the CG flash rate from 2014 to 2018 UTC was followed by an increase to almost 25 flashes per 2 min by 2022 UTC. Subsequent to tornadogenesis at 2022 UTC, the CG flash rate continued to increase to more than 35 flashes per 2 min. The percentage of positive flashes generally remained under 10% (except 12% near 1905 UTC), but was briefly near zero at the time of tornadogenesis.

A clear separation can be seen between the CG

flashes in the overtaking squall line and the leading isolated supercell between 2002 and 2012 UTC (Fig. 23b). The few positive CG flashes were concentrated mostly along the northern half of the squall line. By 2022 UTC (tornado formation), the overall number of CG flashes in 10 min had increased from 253 to 461. This increase in CG flash rate occurred as the squall line overtook the supercell (it was still possible to distinguish the CG activity with each feature). Between 2022 and 2032 UTC, the overall number of CG flashes increased further to 664 but it was more difficult to distinguish between squall line- and supercell-related CG flashes, as merger of the two systems had occurred. Likewise, the number and percentage of positive CG flashes increased through 2042 UTC, particularly in close proximity (within 10-15 km) of the tornado. The CG flashes were concentrated mostly to the left of the storm track, primarily in the forward-flank downdraft region of the supercell prior to tornadogenesis (Lemon and Doswell 1979) and merger with the squall line. Subsequent to tornadogenesis and merger, the CG flashes were concentrated in the left-rear and right-rear quadrants relative to the storm track. Overall, the results



FIG. 17. (a) Hodographs based on 1800 UTC 31 May 1998 observed ALY sounding. The lower 1500 m were modified based on observed surface winds at 1900 UTC in the Hudson Valley at KALB (left curve) and to the west at KBGM (right curve). A nonlinear Ekman spiral approach was used to interpolate between the surface and 2000 m. Wind speeds are in m s⁻¹. Heights of points on the hodograph are in km AGL. The two hodographs are identical at 2000 m and higher. Using the observed storm motion of 260° at 21 m s^{-1} produces an SRH of about 530 m² s^{-2} for the Hudson Valley hodograph and 400 m² s⁻² for the hodograph west of the Hudson Valley. (b) The Eta Model 1900 UTC model sounding hodographs from 1200 UTC 31 May 1998 for KALB (left curve) and KBGM (right curve). Wind speeds are in $m s^{-1}$. Heights of points on the hodograph are in km AGL. Using the observed storm motion of 260° at 21 m s⁻¹ produces an SRH of about 580 m² s⁻² for the KALB hodograph and 210 m² s⁻² for the hodograph west of the Hudson Valley.

from Fig. 23 suggest that as the squall line bowed down the Mohawk Valley and overtook the leading supercell, there was a significant increase in the CG flash rate, which continued beyond 2022 UTC.

5. Speculations about the genesis of the Mechanicville tornado

While most supercells produce severe weather, less than half produce tornadoes (e.g., Thompson et al. 2003; Brooks et al. 1994). Several studies (e.g., Thompson et al. 2003; Rasmussen 2003; Brooks et al. 1994)



FIG. 18. NCEP Eta Model 6-h forecast 975-hPa winds and 0–6-km bulk shear (solid contours every 2 m s⁻¹ with dashed line intermediate contour) valid at 2100 UTC 31 May 1998. Full (half) barbs connote wind speeds of 5 m s⁻¹ (2.5 m s⁻¹). Insert at the bottom of figure shows a model terrain cross section with the vertical scale in hPa.

have attempted to identify meteorological conditions that differentiate environments that produce tornadic supercells and nontornadic supercells. Although atmospheric conditions on 31 May 1998 favored the development of supercells and tornadoes, the critical question is what physical mechanisms may have contributed to the actual tornadogenesis process. We have attempted to address this question through an examination of the available observations. Our results indicate terrain-channeled southerly flow existed in the Hudson Valley that was backed relative to the more southwesterly flow to the west of the valley. This contributed to increased SRH and shear in the Hudson Valley. The highest peaks of the Catskill Mountains rise to a little above 1200 m MSL, indicating the impact of the terrainchanneled flow will be most significant in the critical 0-1-km layer. Increased SRH and shear in the lowest



FIG. 19. KENX 0.5° base radar reflectivity at (a) 1824, (b) 1906, (c) 1942, and (d) 2022 UTC 31 May 1998. The dBZ scale is along the bottom of each panel.

1 km above the ground have been shown to be favorable for tornadogenesis in idealized modeling studies (e.g., Wicker 2000; Wilhelmson and Wicker 2001), and in studies using model-generated (Thompson et al 2003) and observed soundings (Rasmussen 2003) near supercells. As the supercell that produced the Mechanicville tornado reached the juxtaposition of the western edge of the Hudson Valley with the eastern end of the Mohawk Valley, it also may have been influenced by the higher- θ_e air being advected northward up the valley.

Another factor that may have played a role in tornadogenesis was the interaction of an overtaking squall line with a leading isolated supercell. The storm that produced the Mechanicville tornado developed over 50 km ahead of a line of severe storms to the west (1824 UTC). Just prior to the tornado (2022 UTC), the outflow from the line of storms to the west reached the supercell. The timing of the merger suggests the possibility that it could have contributed to the formation of the Mechanicville tornado, or at least the intensification of the supercell that produced it.

Przybylinski (1995) examined seven cases where isolated convective elements developed 50–80 km ahead of bowing lines. The lead cell intensified as the line approached and, in over half of the cases, tornadoes were observed when the merger occurred. One case produced several strong tornadoes. Goodman and Knupp (1993), Bullas and Wallace (1988), Hamilton (1969), and Cook (1961) have documented cases where tornadoes formed after this type of interaction. Good-



FIG. 20. (a) KENX reflectivity (dBZ) at 1946 UTC 31 May 1998 according to the color bar at the top. The letter S indicates the location of the supercell that produced the Mechanicville tornado. The dashed line marks the line of thunderstorms to the west with the associated LEWP. The numbers 1, 2, and 3 indicate the locations of Fulton, Montgomery, and Saratoga Counties, respectively. (b) KENX SRM (kt) at 1946 UTC according to the color bar at the top with the yellow circle indicating the location of the mesoscale vortex. The KENX radar is located near the lower-right portion of the figure. (c) KENX reflectivity at 1957 UTC as in (a). (d) KENX SRM at 1957 UTC as in (b).

man and Knupp (1993) examined the Huntsville, Alabama, tornado (F4) of 15 November 1989. The Edmonton, Alberta, Canada, tornado (F4) on 31 July 1987 developed in a similar fashion (Bullas and Wallace 1988). Hamilton (1969) summarized the work of Cook (1961) concerning cases where cells developed ahead of, and eventually merged with, a line of thunderstorms. Tornadoes occurred in 8 of 11 cases where the advance cell was intense. Other studies have also shown the importance of boundary interaction in tornado formation, although in these studies squall line-supercell interactions were not present in all cases. In a study of 86 tornadoes in the northeastern United States, La-Penta et al. (2000) indicated radar-detectable boundaries were present in about a fifth of the cases. Nearly 70% of significant tornadoes in the VORTEX-95 experiment (Markowski et al. 1998) occurred near preexisting mesoscale boundaries. It should be noted that

unlike the Mechanicville event, the VORTEX cases involved old outflow boundaries, and the air on the cool side of these boundaries had been substantially modified. All of the studies cited point to the complexities involved in the tornado formation process and indicate that boundaries can be an important source of environmental heterogeneity.

A different perspective on the possible interaction of a squall line and an isolated supercell comes from an idealized simulation of a quasi-linear convective system by Weisman and Davis (1998). In an experiment with Coriolis effects included, they showed that well-defined backed flow was prevalent at the 2-km level ahead of a northern bookend vortex 4.5 and 6 h into the simulation (their Fig. 4). This result, repeated in Weisman (2001, his Fig. 22), prompts us to ask if such a region of low-level backed flow ahead of a northern bookend vortex were to begin overtaking an isolated supercell



FIG. 21. KENX 0.5° base velocity at 1957 UTC 31 May with insert in the lower right showing the 0.5° reflectivity at the same time. Light blue line indicates the location of the Mohawk River (see Fig. 1 for topography of the Mohawk Valley and surrounding higher terrain). Base velocity (kt) and reflectivity (dBZ) scales as noted.

downstream, that the immediate supercell environment might be especially favorable for tornadogenesis? A future idealized simulation of a squall line with a northern bookend vortex overtaking a leading isolated supercell, modeled after the Mechanicville tornado case, might prove to be enlightening. A schematic synopsis of how the overtaking northern bookend vortex and squall line might have interacted with the leading isolated supercell and low-level terrain-channeled southerly flow in the Hudson Valley is offered in Fig. 24.

There are some similarities between the Mechanicville tornado event and the 29 May 1995 F3 tornado in Great Barrington, Massachusetts (GBR), as described by Bosart et al. (2004). Both events occurred on days when the environment over the northeastern United States was favorable for the development of supercells and tornadoes. In addition, both events were associated with terrain-channeled low-level flow in the northsouth-oriented Hudson Valley and external forcing may have played a role in the evolution of the tornadoes. The possible importance of external forcing on tornadogenesis in both the Mechanicville and GBR events should be tested by idealized simulations as noted above.

6. Summary

During late May and early June 1998, a large-scale circulation pattern evolved into a configuration that

was unusually favorable for widespread severe weather from the northern plains eastward across the Great Lakes into New England. A series of disturbances, embedded in a strong upper-level flow, helped to initiate episodic severe weather. On 31 May 1998, one episode resulted in 32 tornadoes over the Northeast, one of which was the F3 Mechanicville, New York, tornado and was the focus of this paper. This tornado was examined in detail because it was one of four F3 events in the Northeast, it caused significant damage and many injuries, and storms of its severity are rare in the Northeast. The 31 May disturbance was associated with a coupled jet structure at 250 hPa, with wind speeds exceeding 65 m s⁻¹. A strong low-level jet (33 m s⁻¹) advected warm, moist air into the Northeast; helped to destabilize the atmosphere (CAPE $\sim 2000 \text{ J kg}^{-1}$); and contributed to high 0–6-km shear (>25 m s⁻¹) and SRH $(>450 \text{ m}^2 \text{ s}^{-2})$. The Mechanicville event also bore some similarity to the westerly flow tornado cases defined in the Johns and Dorr (1996) study of strong and violent tornadoes in New England and eastern New York.

Forecast issues were also raised by the Mechanicville tornado event. Recognizing that synoptic-scale conditions were favorable for severe thunderstorms and tornadoes on 31 May 1998 was the first step in alerting the public to the potential for dangerous weather. The Storm Prediction Center had indicated a high risk of severe thunderstorms and tornadoes for parts of the Northeast. A local study (Maglaras and LaPenta 1997) supported the tornadic threat, and strongly worded statements were issued alerting the public to the dangerous situation. Previous research on the GBR tornado event (Bosart et al. 2004), a storm similar to the Mechanicville tornado, provided meteorologists an understanding of the potential role of terrain and mesoscale processes in supercell intensification. It also provided experience in radar-based detection of tornado formation. Being aware of the mesoscale environment, and the role terrain can play in modifying it, can be important in maximizing warning lead time. This is especially true in locations where tornadoes are infrequent. A tornado watch was issued nearly 2 h prior to the Mechanicville tornado and a tornado warning was issued with 39-min lead time. The large lead time can be attributed to a number of factors. The city of Mechanicville lies in the extreme eastern portion of Saratoga County, New York. As the storm moved east and neared the western portion of the county, about 40 km to the west of Mechanicville, a warning decision had to be made. Radar and spotter reports indicated that at least a severe thunderstorm warning was necessary. While the radar did not indicate a tornado at that time, a tornado warning was issued based on a number of



FIG. 22. (a) KENX 0.5° SRM at 2022 UTC 31 May (tornado formation time). (b) SRM cross section at 2022 UTC with distance (horizontal axis) and height (vertical axis) in km. (c) Location of cross section in (b) (yellow line), 45–50 km from the KENX radar. ALY is the location of the Albany radiosonde site.



FIG. 23. (a) Time series of CG lightning flashes (solid, scale on left axis) for 5- (2-) min periods from 1825 to 2010 (2010 to 2034) UTC 31 May 1998. Heavy solid vertical line at 2010 UTC marks the change from a 5- to a 2-min-period CG flash count. Heavy vertical dashed line at 2022 UTC marks the time of tornadogenesis. The distance between the advancing squall line and the leading isolated supercell is shown by the dashed line (scale on right axis). (b) Storm-relative CG flash distribution over four consecutive 10-min periods beginning at (left) 2002–2012 UTC and ending (right) 2032–2042 UTC. The left (right) two panels denote the pretornadic (tornadic) phase. Distance scale as indicated in the left panel. Squall line is marked by the dashed line. The X denotes the KENX Doppler radar–indicated supercell mesocyclone (tornado) in the left (right) two panels. Storm motion vector denotes direction of movement of the supercell. Blue (red) dots denote negative (positive) CG flashes. The number of positive and negative CG flashes per 10-min period is shown in the lower-right corner of each panel.



FIG. 24. Schematic illustration of the physical processes postulated to be important to the Mechanicville, NY, tornadogenesis event. Squall line bowed down the Mohawk Valley is shown in white with the L symbol marking the location of the northern bookend vortex. The light red dotted circle shows the area where low-level flow should be backed ahead of the northern bookend vortex according to the idealized quasi-linear convective system simulation performed by Weisman and Davis (1998). Channeled southerly flow up the Hudson Valley and prevailing southwesterly flow over the Catskill Mountains is shown by the yellow arrows. Position of the Mechanicville supercell to the east of the overtaking squall line is shown by a base reflectivity image at 1946 UTC 31 May 1998 (36 min prior to the start of the Mechanicville tornado).

factors. A tornado watch was in effect and the SPC had indicated a high risk of severe storms. The storm was already severe and a spotter reported a tornado about 9 km west of the Saratoga County line. The KENX radar is located at an elevation of about 550 m MSL and the radar beam can overshoot shallow features in valleys, so it was difficult to rule out this report. Also, experience and previous research (Bosart et al. 2004) indicated the storm was entering an area of somewhat increased instability and shear. The storm continued to intensify as it crossed the county line and as radar indicated the high probability of a tornado, a severe weather statement was issued refining the tornado track and indicating that a "dangerous tornado was moving across Saratoga County...." Tornadoes rated F3 or higher in upstate New York are relatively rare. Although 68 people were injured in the Mechanicville tornado, accurate and timely outlooks, tornado watches and tornado warnings, and rapid communication of hazardous weather information likely contributed to no lives being lost.

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