Examining Terrain Effects on Upstate New York Tornado Events Utilizing High-Resolution Model Simulations

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Examining Terrain Effects on Upstate New York Tornado Events Utilizing High-Resolution Model Simulations

An honors thesis presented to the Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York in partial fulfillment of the requirements for graduation with Honors in Atmospheric Science and graduation from the Honors College

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Abstract

The region at the intersection of the Mohawk and Hudson valleys of New York is characterized by complex terrain. It has been hypothesized that this complex terrain may have an impact on the development and evolution of severe convection in the region. Specifically, previous research has hypothesized that terrain-channeled flow in the Hudson and Mohawk valleys contributed to increased low-level wind shear and instability in the valleys during past severe weather outbreaks. However, a lack of observations in the region prevented this hypothesis from being robustly tested.

The goal of this study is to further examine this hypothesis and complement existing observations by utilizing the Weather Research and Forecasting (WRF) model. High-resolution simulations were developed for a widespread severe weather outbreak that occurred on 31 May 1998. On this date, a strong (F3) tornado struck Mechanicville, New York, resulting in major damage. Results from the simulations suggest that terrain-channeled flow resulted in the formation of a robust moisture gradient at the intersection of the Mohawk and Hudson valleys during this case. East of this boundary, the environment was characterized by extreme low-level wind shear, and enhanced low-level moisture and instability, supporting tornadogenesis. A simulated supercell intensified after crossing the boundary.

These results suggest that terrain can drive mesoscale inhomogeneities that impact the evolution of severe convection. However, there remains a forecast challenge in anticipating the significance of terrain in advance of a given severe weather event. Identifying additional cases when terrain played an important role may be useful in improving the prediction of severe weather events in upstate New York.
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1. Introduction

Tornadoes rated category 3 or higher on the Fujita/enhanced Fujita scales (F/EF3) are very rare in the northeastern United States. In the period from 1950-2019, only 21 tornadoes rated F/EF3 or higher occurred in New York, and only four of those tornadoes occurred in the 30-year period from 1990-2019 (NOAA 2019). However, despite the rare nature of tornadoes in the region, tornadoes in the northeastern United States can have substantial impacts. Several notable high-impact tornadoes and tornado outbreaks have occurred in the region. On 3 October 1979, a destructive F4 tornado impacted Windsor Locks, Connecticut, resulting in three fatalities and over $200 million (1979 dollars) in damage (Riley and Bosart 1987). On 29 May 1995, a large F3 tornado tracked nearly continuously along a 50-km path in New York and Massachusetts and impacted Great Barrington, Massachusetts, resulting in three fatalities and widespread structural damage (Bosart et al. 2006). On 31 May 1998, an F3 tornado traveled over 50 km across New York and southern Vermont, impacting the city of Mechanicville, New York. This tornado resulted in 68 injuries and produced major damage (LaPenta et al. 2005). More recently, an EF3 tornado impacted Duanesburg, New York on 22 May 2014 (Tang et al. 2016).

The occurrence of severe weather in the northeastern United States is complicated by the complex terrain of the region. Figure 1 shows a topographic map of a subset of the northeastern United States including eastern New York and western New England that will be the focus of this study. The important topographical features in this region include the north–south-oriented Hudson Valley and the west–east-oriented Mohawk Valley, which intersect near Schenectady (KSCH) and Albany (KALB), New York. The Adirondack Mountains lie north of the Mohawk Valley and west of the Hudson Valley, and the Catskill Mountains are located south of the Mohawk Valley.
The complex terrain in the northeastern United States has been found to impact the occurrence of thunderstorms in the region. Wasula et al. (2002) determined that the spatial distributions of lightning and severe weather reports in the region are sensitive to the orientation of the synoptic-scale flow relative to these underlying terrain features. It was found that in cases with southwest flow, thunderstorms and severe weather reports are favored in the Mohawk Valley northward into the southern Adirondacks. In cases with northwest flow, thunderstorms and severe weather reports are most common in the southern Berkshire Mountains and Litchfield Hills of Connecticut. Katona et al. (2016) found that the Hudson Valley is climatologically slightly more favorable for the occurrence of severe thunderstorms and tornadoes than the surrounding mountain regions, although the precise impact of terrain is again sensitive to the synoptic-scale wind direction.

One major mechanism through which terrain can influence the occurrence of severe weather is flow channeling. Terrain channeling occurs when terrain features such as river valleys act to change the local wind direction. The characteristics of the Mohawk and Hudson valleys have been found to be supportive of terrain channeling in the cool season (Augustyniak 2008). Additionally, it has been hypothesized that terrain channeling has played a role in tornado events. LaPenta et al. (2005) hypothesized that terrain-channeled flow in the Hudson Valley contributed to increased low-level wind shear and instability in the region where the 31 May 1998 Mechanicville tornado occurred. Similarly, Bosart et al. (2006) found that terrain-channeled southerly flow was again present in the Hudson Valley on 29 May 1995 in the region where the Great Barrington tornado developed. They hypothesized that terrain channeling resulted in increased storm-relative helicity (SRH) and shear in the valley, supporting tornadogenesis. Bosart et al. (2006) further proposed that significant tornadogenesis is unlikely to occur in regions of
complex terrain unless favorable local modifications to the low-level wind field are present. Tang et al. (2016) determined that channeled flow in the Hudson Valley supported moisture convergence and enhanced instability in the region where the 22 May 2014 Duanesburg tornado developed.

Previous research on severe weather events in the northeastern United States has been limited by the sparse observational network in the region prior to the installation of the New York State Mesonet, which became fully operational in 2018. Studies such as LaPenta et al. (2005) and Bosart et al. (2006) relied on observational sources, including radar data, satellite data, upper-air soundings, and surface observations to assess hypotheses about the role of terrain in tornado cases. Surface observations were particularly important in establishing the presence of channeled flow in the Hudson Valley for these cases. However, there were no surface observations available in the Catskill Mountains or in the central and eastern Mohawk Valley. Observations in these regions would have allowed for a more complete analysis of the role of terrain in modulating the environment for thunderstorms.

This study attempts to address the limitations of these previous studies by utilizing high-resolution modeling. Computer modeling is one methodology that can assist in filling in the gaps in observations. Model-based studies to date on the impact of terrain on severe weather (e.g., Markowski and Dotzek 2011) have typically featured idealized storms and idealized terrain, as discussed in Katona et al. (2016). These studies are very useful in understanding the mechanisms through which terrain can modify the environments for severe weather. However, the use of real terrain in computer model simulations of tornado events has the potential to allow for a better understanding of how specific terrain features can impact the environment for severe convection. This methodology has been applied to severe weather events in different parts of the world. Geerts et al. (2009) utilized the Weather Research and Forecasting (WRF) model to analyze the role of
terrain on an unusual tornadic mesocyclone that occurred in the high terrain of southeastern Wyoming. Homar et al. (2003) utilized the MM5 model to analyze a tornado event over northeastern Spain.

Understanding the role of terrain on severe thunderstorms and tornadoes has applications beyond the northeastern United States. Tornadoes have been documented in several regions of complex topography in the United States, including the Rocky Mountains in Colorado (Bluestein et al. 2000; Nuss 1986), the Southern Cumberland System in Alabama, Georgia, and Tennessee (Lyza and Knupp 2018; Lyza et al. 2020), the Sacramento Valley in California (Braun and Monteverdi 1991), and the Teton-Yellowstone Wilderness in Wyoming (Fujita 1989). In the southeastern United States, there is considerable overlap between regions of substantial tornado risk and regions of complex topography (Coleman and Dixon 2014). Therefore, mechanisms through which terrain can modulate the potential for severe convection in one region, such as the northeastern United States, may be applicable to severe thunderstorm events in multiple different regions.

This study will focus on the 31 May 1998 case, as observations of this event are well documented in literature (LaPenta et al. 2005). A description of the model setup and verification of the model performance is provided in section 2. A review of the synoptic characteristics of the 31 May 1998 event is provided in section 3. Section 4 focuses on the mesoscale characteristics of the event, including the impact of terrain, and section 5 discusses the impact of the mesoscale environment on storm-scale processes. A discussion of the event characteristics is presented in section 6, and conclusions are provided in section 7.
2. Methodology

The Advanced Research WRF (WRF-ARW) model version 3.9.1.1 (Skamarock et al. 2008) was utilized to simulate the 31 May 1998 severe weather event. The simulation employed four two-way nested domains (Figure 2). The horizontal resolutions of the domains varied from 27 km in the outermost domain to 1 km for the innermost domain. The outermost domain covered much of the eastern United States, southern Canada, and the western Atlantic, and was utilized to analyze the synoptic characteristics of the severe weather event. The innermost domain only covered a small region, including eastern New York and western New England, and was used to examine the impact of terrain. The parameterization schemes utilized by the WRF model simulation were selected to be similar to the operational High-Resolution Rapid Refresh (HRRR) model and are provided in Table 1. The model was initialized at 1500 UTC 31 May, and the North American Regional Reanalysis (NARR) dataset (Mesinger et al. 2006) provided the initial and boundary conditions for the simulation. The initialization time is around five hours before the occurrence of the tornado event. A variety of different combinations of initialization times and data sources were tested, and it was determined that this configuration resulted in a simulation that most closely matched observations of the thermodynamic and kinematic environment (not shown). One possible reason that an initialization time close to the event time best captured the event evolution is that the severe weather event on 31 May 1998 was sensitive to the evolution of convection that formed on the previous day. The remnants of a long-lived convective system that developed over South Dakota on 30 May progressed into New York by 1700 UTC 31 May, and convection reignited in the region of remnant clouds and precipitation (LaPenta et al. 2005). It is possible that the effects of this convection were better captured in reanalysis data temporally close to the event. A validation of the model against surface observations and upper-air soundings will
be presented later in this section. Finally, the Lagrangian Analysis Tool (LAGRANTO) model version 2.2 (Sprenger and Wernli 2015) was utilized on 1-minute WRF output to calculate parcel trajectories. The integration timestep utilized by LAGRANTO was 6 seconds.

The resulting simulation did not produce a supercell that closely matched the observed path of the Mechanicville supercell. This deficiency is not surprising, as it is unreasonable to expect a short-term simulation to perfectly match the observed storm evolution. However, one goal of this study is to examine the storm-scale interactions between supercells and the complex terrain of upstate New York. To address this deficiency, a warm bubble was inserted into the model at 1700 UTC (two hours into the simulation and approximately three hours before the Mechanicville tornado began) to trigger the development of a thunderstorm that followed closely the observed track of the Mechanicville supercell. The location of the warm bubble was determined by extrapolating the path of the true Mechanicville supercell backwards to 1700 UTC. The maximum potential temperature perturbation in the warm bubble was +8 K, and the potential temperature perturbation decayed linearly outward to a radius of 15 km. The bubble was centered at 8 model levels above the surface [844 hPa, 1157 m above ground level (AGL)], which was the approximate height of the top of the boundary layer. The vertical radius was 6 model levels (952 hPa to 624 hPa, 97 m AGL to 3685 m AGL). Compared to previous idealized studies that have utilized a warm bubble to trigger convection (e.g. Nowotarski et al. 2011, French and Parker 2014), the magnitude of the maximum potential temperature perturbation used here is large. However, these previous studies utilized warm bubbles in an idealized framework. Sensitivity testing revealed that 8 K was the magnitude necessary to produce a sustained supercell in this simulation (not shown). The insertion of the warm bubble did not have any discernible effect on the near-storm
environment. The resulting supercell closely followed the observed track of the true Mechanicville supercell, as will be discussed in the following section.

\( a. \) **Model verification**

The resulting simulation is in close agreement with the sparse available observations, supporting the use of this simulation to fill in observation gaps. Figure 3 shows a comparison between Hudson Valley observations from KSCH, KALB, and Glens Falls (KGFL) and model output at the closest grid point. Additionally, the observations from Binghamton (KBGM) will be discussed as well, as they are the observations that best reflect the non-channeled flow over higher terrain in central New York. In general, the model compared well to observations. In particular, the model closely matched observations in the immediate pre-convective environment at 1900 UTC (shaded region on Figure 3). At 1900 UTC, the KALB, KSCH, and KGFL temperature errors were all small. At KALB, the model was too warm by 1.0°C (Figure 3a). The dewpoint temperature errors were also small. At KALB, the model was too moist by 0.9°C. The largest dewpoint errors were at KSCH, where the modeled dewpoint temperature was consistently 2–3°C too high (Figure 3b). It is possible that this is due to a systematic instrument error, given the accuracy of the model at the other Hudson Valley locations. A comparison between the KSCH and KALB dewpoint observations on the days preceding the outbreak indicated that the KSCH observations were consistently lower than observations at KALB, despite the proximity of the stations (not shown). The simulated winds at these locations were also very similar to observations, indicating that the model likely accurately captured the channeled flow within the Hudson Valley. Outside of the valley at KBGM (Figure 3d), the model similarly performed well. At 1900 UTC, the magnitudes of the temperature and dewpoint errors were both less than 1°C at KBGM. The simulated wind direction was also similar to the observed wind direction, although there were
differences in wind speed. Overall, the low errors at 1900 UTC suggest that the model did a good job at simulating the critical period in the pre-storm environment.

Additionally, the model forecast fields can be verified against the observed 1800 UTC 31 May upper-air sounding from Albany, New York. Figure 4 shows a comparison between the observed 1800 UTC sounding and simulated vertical profile at Albany, New York. The comparison indicates that the simulation accurately depicted the overall vertical structure of the temperature, dewpoint, and winds (Figure 4a). Below 700 hPa, the simulation adequately captured the low-level temperature and wind profiles (Figure 4b). The observed sounding contained a pronounced stable layer at 900 hPa, and this is reflected as a layer of greater stability in the simulated profile, although not to the same magnitude. The simulated wind profile closely matched the observed wind profile below 900 hPa, although the simulated winds were more southwesterly near 925 hPa in the simulation than in observations. This difference is possibly associated with differences in the depth of the stable layer between observations and the simulation, as the southerly flow was confined beneath the stable layer at 925 hPa in the simulation and 900 hPa in the observations. The similarities between the simulation and observations below 900 hPa are important, as this is the layer where terrain channeling would likely manifest. There are also some differences between the observed and simulated winds between 850 hPa and 775 hPa. The observed winds in this layer were southerly, while the simulated winds were southwesterly. LaPenta et al. (2005) hypothesized that these observed southerly winds were erroneous, as they are inconsistent with the advancing southwesterly low-level jet. It is possible, however, that these winds are real and reflect a transient mesoscale feature. A comparison between the observed and simulated hodographs, with the questionable winds omitted, is presented in Figure 4c. The hodographs are similar and contain strong curvature in the lowest 1 km. Overall, this comparison
suggests that the simulation did an adequate job representing the pre-storm environment, including both the vertical profile and the surface conditions. Therefore, we have confidence that results from the simulation can represent and be used to study real atmospheric features.

The supercell initiated by the warm bubble progressed through the southern Saratoga County (and the Mechanicville region) between 2000 UTC and 2030 UTC. The spatial and temporal characteristics of the simulated supercell closely match the evolution of the true Mechanicville supercell (Figure 5). There are some differences between the observed and simulated supercells. The primary difference is that the observed supercell underwent a storm merger near the time of tornadogenesis. A discussion of the possible role of this merger will be presented in Section 6. A second difference between the simulated and observed supercell is that the simulated supercell tracked slightly more quickly to the east. Overall, this difference is small, and both the simulated and observed supercells were crucially in a similar location at 1930–2000 UTC, when the supercell entered the Hudson Valley.

3. Synoptic overview

A full synoptic overview of this event is presented in LaPenta et al. (2005). Therefore, only a brief discussion of the important synoptic features is presented here to provide background on the event and to further verify the performance of the model simulation. The reader is referred to LaPenta et al. (2005) for a more thorough discussion.

The severe weather outbreak on 31 May 1998, including the Mechanicville tornado, occurred in the warm sector of a rapidly deepening surface cyclone (Figure 6). At 2100 UTC 31 May, this surface cyclone was positioned over western Quebec, with a minimum central pressure in the simulation of 984 hPa (Figure 6a). This is in agreement with archived analyses from the Weather Prediction Center, which analyzed the surface low at 984 hPa at 1800 UTC and 987 hPa
at 0000 UTC 1 June (WPC 2019). To the south of the surface cyclone, a strong low-level jet was located over the northeastern United States (Figure 6b). Winds in excess of 25 m s\(^{-1}\) (50 knots) in this low-level jet contributed to the advection of a moist, unstable air mass into New York. A large region of moderate instability was present extending from New York south and west (Figure 6a). The warm front of the cyclone was located over New England at the time of the severe weather. The cold front extended through the Great Lakes southwestward through Ohio, Indiana, and Illinois.

The surface cyclone was in a region of strong forcing for vertical motion. At 500 hPa, a shortwave trough was moving through Ontario at 2100 UTC 31 May (Figure 6c). Positive vorticity advection was occurring over the low-level cyclone, supporting upward vertical motion by quasi-geostrophic dynamics (Trenberth 1978). At 300 hPa, a strong, coupled jet streak was present over the region. The first jet streak was located over Atlantic Canada, with maximum winds in excess of 60 m s\(^{-1}\) in the jet core. The equatorward entrance region of this jet streak was located over eastern Quebec. The second jet streak was located over the Great Lakes region, where strong westerly winds in excess of 50 m s\(^{-1}\) were present. The poleward exit region of the jet streak was located over southwestern Quebec, in the vicinity of the surface low. The overlap between the poleward exit region of this Great Lakes jet streak with the equatorward entrance region of the Atlantic Canada jet streak provided forcing for strong vertical motion in the vicinity of the surface low.

In addition to providing forcing for ascent, the strong upper-level jet streak over the Great Lakes also contributed to the strongly sheared environment over the northeastern United States. Winds at both 300 hPa and 500 hPa were in excess of 25 m s\(^{-1}\) over Albany, New York at 1800 UTC, as sampled by the 1800 UTC sounding (Figure 4). The overlap between the strongly unstable
environment and strong wind shear resulted in an environment that was very favorable for severe weather across New York. Consistent with the volatile environment in place, the Storm Prediction Center issued a High Risk for severe thunderstorms and tornadoes for much of New York and Pennsylvania.

4. Mesoscale characteristics

The modeled mesoscale environment evolved rapidly after the passage of the synoptic-scale warm front in the morning hours of 31 May 1998. Distinct from this warm front, a sharp mesoscale boundary, characterized at the surface by a distinct wind shift and moisture gradient, developed at the intersection of the Hudson and Mohawk valleys in the WRF simulation. This boundary was not possible to observe in real time, due to the sparse observational network in the region in 1998. It is important to emphasize again that the simulation closely matched available observations, as presented in Section 2. Therefore, the presence of this boundary is consistent with the observations. The remainder of this section will focus on the development and characteristics of this boundary. Section 5 will focus on the evolution of the simulated supercell interacting with this boundary.

a. Boundary development

This boundary developed rapidly in the wake of the synoptic-scale warm front that progressed through the region. At 1600 UTC, the presence of this warm front is apparent in the model simulation as a gradient in surface equivalent potential temperature (theta-e) across the region (Figure 7a). Values of theta-e in excess of 338 K were present over the elevated terrain of the Catskill Mountains, as the warm-sector air was advected into the region by strengthening southwesterly flow. However, the theta-e within the Hudson and Mohawk valleys remained comparatively lower. Additionally, a clear signal of terrain channeling was apparent within both
valleys. East-southeasterly winds in the Mohawk Valley and south-southeasterly flow in the Hudson Valley limited the advection of higher theta-e air into valley locations (Figure 7a). Dewpoints within the Hudson Valley were relatively low at this time, between 17°C and 18°C near KALB (Figure 7b).

At 1700 UTC, the boundary began to develop at the intersection of the Mohawk and Hudson valleys. A strong wind shift remained between the Catskill Mountains and the terrain-channeled southerly flow within the Hudson Valley, and this wind shift extended northward into the lower elevations of the Mohawk Valley (Figure 8a). Moisture convergence and near-surface frontogenesis were occurring along the incipient boundary (Figure 8b), supporting the pooling of moisture along and east of the boundary. The southern portion of the frontogenesis axis closely follows the 500 m elevation contour, suggesting an association between terrain features and the initial position of the boundary. Additionally, at 1700 UTC, a reservoir of high-moisture air began to surge into the southern Hudson Valley. In the simulation, dewpoints in excess of 20°C rapidly moved into southern portions of the Hudson Valley and were advected northward in strong southerly terrain-channeled flow (Figure 8b). Observations support the occurrence of this moisture surge. Surface observations from 1700 UTC indicate that dewpoints increasing above 20°C were observed in Poughkeepsie, New York and across northern New Jersey (not shown). Due to this moisture surge, theta-e values began to increase within the Hudson Valley, although theta-e values remained higher farther west in the higher terrain where the boundary layer was warmer.

At 1800 UTC, the surge of moisture up the Hudson Valley continued, with dewpoint values above 20°C reaching as far north as Saratoga County (Figure 9b). This surge of moisture was driven by strong southerly and south-southeasterly terrain-channeled surface winds within the Hudson Valley (Figure 9a). As moisture increased within the Hudson Valley, the moisture gradient
became better established at the intersection of the Hudson and Mohawk valleys. In response to the increase in moisture along and east of the boundary, a local maximum in theta-e began to develop along and east of the surface wind shift. Theta-e values over 344 K were present in northwestern Albany County and Schenectady County (Figure 9a).

These trends continued through 1900 UTC, which represented the immediate pre-storm environment. At 1900 UTC, the boundary was more defined and characterized by a robust moisture gradient at the intersection of the Mohawk and Hudson valleys (Figure 10b). Within the Hudson Valley, dewpoints were in excess of 20–21°C in strong southerly terrain-channeled flow. Farther west in the Mohawk Valley, dewpoints were around 18–19°C in southwesterly flow. These values were lower than the previous hour, suggesting that mixing of drier air from aloft to the surface to the west of the boundary was contributing to the increased gradient of moisture across the boundary.

To better understand the development and intensification of this boundary, back trajectories were calculated surrounding the boundary location utilizing LAGRANTO. Thirty-minute back trajectories from 1930 UTC were calculated for parcels within a box surrounding the boundary at the intersection of the Hudson and Mohawk valleys. The trajectories were all located at 500 m above mean sea level (MSL) at 1930 UTC to capture flow within the boundary layer. The back trajectories clearly indicate the different source regions of air parcels to the west and east of the boundary. To the east of the boundary, high theta-e air parcels tracked towards the boundary from the south-southeast, especially in the low elevations near the intersection of the Mohawk and Hudson valleys. To the west of the boundary, lower theta-e air parcels tracked towards the boundary from the southwest. These trajectories imply the presence of downsloping to the west of the boundary, as many of the trajectories originated over terrain elevations exceeding 500 m. It is
interesting to note that some of the high theta-e air parcels along the southern end of the boundary originated over higher terrain as well. The confluent trajectories in the wake of the higher terrain features supported the tightening of the theta-e gradient farther north.

b. Boundary characteristics

The surface and near-surface characteristics of the boundary discussed above do not fully capture the full character of the boundary. The vertical structure of the boundary is important to consider as well. Figure 12 presents vertical cross sections across the boundary at two different locations along the boundary at 1900 UTC, when the boundary was well developed and not yet disturbed by convection. These locations are denoted in Figure 10b by the lines. As will be discussed below, the supercell that was triggered by the warm bubble interacted with the boundary between 1930 UTC and 2000 UTC. Therefore, the characteristics of the boundary at 1900 UTC capture the state of the boundary immediately preceding the interaction of the supercell with the boundary.

The cross sections in Figure 12 highlight several important aspects of the structure of the boundary. First, the boundary is characterized by a horizontal gradient in potential temperature in the lowest 1 km. This potential temperature gradient is strongest in the northern cross section, to the west of Mechanicville (Figure 12a), although the gradient is still present in the southern cross section. The presence of this strong northern potential temperature gradient implies that there were processes acting to strengthen the portion of the boundary west of Mechanicville. The back trajectories presented in Figure 11 suggest that confluence in the wake of the higher terrain features in the Catskill Mountains supported the strengthening of the gradient in the northern portion of the boundary. Second, the boundary is characterized by a pronounced wind shift in the lowest 1 km. This pronounced wind shift is more defined along the northern end of the boundary, where strong
south-southeasterly flow was present on the cool and moist side of the boundary below 500 m (Figure 12a). The presence of south-southeasterly low-level flow in the lowest 1 km MSL strongly supports the role of terrain channeling, because most of the Catskill Mountain region is below 1 km in elevation. Third, there is a clear gradient in stability across the boundary, with deep mixing to around 2 km to the west of the boundary, and a stable layer near 0.5–1 km east of the boundary (Figure 12a, b). This stable layer was sampled by the Albany 1800 UTC sounding discussed in section 2. Finally, there is ascent along the boundary in both cross sections.

This boundary structure resulted in a large difference in severe parameters across the boundary, and the region immediately east of the boundary (near Mechanicville) was characterized by an extremely volatile environment for severe weather and tornadogenesis. At 1900 UTC, in the immediate pre-storm environment, convective available potential energy for parcels at the lowest model level (hereafter, SBCAPE) was maximized along and east of the boundary (Figure 13d), where SBCAPE exceeded 2500 J kg\(^{-1}\). This axis of high SBCAPE corresponded with the axis of high surface theta-e air in excess of 345 K (Figure 10a). Additionally, the increase in moisture to the east of the boundary contributed to a lower lifting condensation level (LCL). The LCL height to the east of the boundary was lower (> 50 hPa higher in pressure) than LCL height to the west of the boundary (Figure 13b). Lower LCL heights (higher LCL pressures) have been found to be a favorable factor for significant tornadoes (Thompson et al. 2003). Kinematically, the south-southeasterly winds present within the Hudson Valley east of the boundary contributed to dramatically increased low-level wind shear to the east of the boundary. The 0–1-km SRH west of the boundary was approximately 300 m\(^2\) s\(^{-2}\), while the 0–1-km SRH east of the boundary was in excess of 450 m\(^2\) s\(^{-2}\) (Figure 13c). This difference in 0–1-km SRH can be seen in the difference between hodographs west and east of the boundary (Figure 14). There is much more hodograph
curvature in the lowest 1 km AGL to the east of the boundary. The values of 0–1-km SRH within
the Hudson Valley are above the 90th percentile of model proximity soundings in advance of
significant tornadic supercells analyzed in Thompson et al. (2003), highlighting the extreme nature
of the wind shear within the Hudson Valley. The environment east of the boundary continued to
grow more volatile with time as the simulated supercell approached the boundary. At 2000 UTC,
when the supercell was just east of the boundary, SBCAPE values in excess of 3000 J kg\(^{-1}\) were
present in the inflow region of the supercell (Figure 15d). Additionally, 0–1-km SRH values in
excess of 600 m\(^2\) s\(^{-2}\) were present in the inflow region of the supercell Figure 15c), highlighting
the remarkable low-level wind shear and inferred streamwise vorticity east of the boundary. The
impact of this environment on the intensity evolution of the simulated supercell is discussed in the
following section.

5. Storm-scale characteristics

The simulated supercell interacted with the boundary between 1930 UTC and 2000 UTC
and underwent dramatic changes during and after this time period, as is summarized in Figure 16.
Recall the warm bubble was inserted into the model at 1700 UTC. Therefore, the supercell had
about two hours to develop prior to the period analyzed here, and it was in a quasi-steady state by
1900 UTC. This quasi-steady state is captured in Figure 16d, prior to 1930 UTC. Before the
supercell approached the boundary from the west, the maximum 1-km updraft speed, maximum
5-km updraft speed, maximum 1-km absolute vorticity, and maximum 5-km absolute vorticity,
while variable, did not show any large, overall trend. The supercell began to interact with the
boundary at approximately 1937 UTC, when the low-level updraft began to overlap with the axis
of instability and southeasterly flow to the east of the boundary (Figure 17). Beginning at 1950
UTC, the maximum updraft speed and maximum absolute vorticity at both 1 and 5 km increased,
indicative of the intensification of the supercell. The most dramatic increase occurred in the 5-km absolute vorticity, suggesting that the mid-level mesocyclone strengthened rapidly after crossing the boundary (Figure 17d). The radar presentation of the supercell also improved after the supercell interacted with the boundary, as the cell increased in size, featured higher reflectivity, and was characterized by better defined hook echo (Figure 16a-c). In the simulation, the maximum 5-km absolute vorticity decreased between 2010 UTC and 2020 UTC, as the mesocyclone occluded (not shown). The mechanisms supporting the cycling of the simulated supercell are beyond the scope of this study.

To confirm the role of the boundary in the intensification of the supercell, back trajectories were calculated utilizing LAGRANTO for parcels seeded at both 5 km and 2 km height within the updraft core (w > 10 m s\(^{-1}\) at 5 km, w > 5 m s\(^{-1}\) at 2 km) at 1945 UTC and 2000 UTC (Figure 18). These back trajectories all terminated at 1900 UTC. Only trajectories with starting elevations less than 2000 m MSL are discussed here, as they represent the boundary layer inflow. A substantial number of trajectories originated at 1900 UTC above this level. It is possible that these trajectories are not physical, and that the time step used (1-minute WRF output, 6-second integration timestep) was not sufficient to capture the large accelerations present within supercells. A smaller integration time step was tested, however, and the results were similar. It is also possible that these trajectories represent mid-level air that was entrained into the supercell. The low-level trajectories ending in both the mid- and low-level updrafts at 1945 UTC indicate that the source region of air in the updraft at that time was primarily from west of the boundary. A small number of trajectories ending in the low-level updraft at 1945 UTC did originate from the low elevations in Schenectady and Albany County at 1900 UTC. These parcel locations are east of the boundary, suggesting the boundary interaction had just started at this time. The trajectories ending in the updrafts at 2000
UTC suggest a change in predominate source region. In both the mid- and low-level updrafts, a substantial number of trajectories originated east of the boundary. This change suggests that, at 2000 UTC, the inflow into the supercell was characterized by an increase in SBCAPE and 0–1-km SRH, associated with the more volatile environment east of the boundary.

To isolate changes in the low-level inflow, Figure 19 depicts the 1900 UTC height and theta-e of parcels that ended up in the 5-km updraft core. This figure only focuses on trajectories that were located below 2 km MSL at 1900 UTC, for the reasons discussed above. At 1945 UTC, the parcels that entered the updraft and originated at 1900 UTC between 800 m and 1400 m MSL had theta-e values near 340 K. At 2000 UTC, inflow parcels originating at 1900 UTC between 800 m and 1400 m MSL had theta-e values near 342 K. This difference captures the increase in low-level theta-e, and inferred low-level buoyancy, in the supercell updraft as the supercell moved across the boundary.

6. Discussion

The results suggest that terrain channeling can result in the formation of a boundary at the intersection of the Mohawk and Hudson valleys, and that this boundary can have an impact on the occurrence of severe weather. Markowski et al. (1998) found that nearly 70% of significant tornadoes in the VORTEX field campaign were associated with boundaries, and therefore hypothesized that boundaries may play a role in tornadogenesis in certain cases. The results discussed above support this hypothesis, although this study does not explicitly simulate tornadogenesis.

Interestingly, the boundary documented here has properties that are consistent with drylines. The vertical structure of the boundary closely matches the conceptual model of dryline structure (Parsons et al. 1991), with a steep leading edge to the cool, moist air mass and a narrow
updraft on the warm, dry side of the boundary. There are, however, distinctions between the boundary documented here and typical synoptic-scale drylines. The movement of synoptic-scale drylines is typically governed by the diurnal processes in the boundary layer along with the slope of terrain (Parsons et al. 1991). The possibility exists that these processes also played a role in the development of the boundary in this case. However, in this case, the location of the boundary is hypothesized to have been linked to smaller-scale terrain features. The formation mechanism for the boundary here was different from the typical synoptic-scale dryline. The critical role of mesoscale terrain channeling in this case is unique.

Similar boundaries have been observed in additional cases in upstate New York. Tang et al. (2016) documented that a north–south oriented boundary developed in the Hudson Valley on 22 May 2014. This boundary separated a maritime air mass to the east from a more unstable air mass to the west and was maintained by differential surface heating. The Duanesburg tornado developed as a supercell crossed this boundary into an environment characterized by strong 0–1-km wind shear, low LCLs, and large values of streamwise vorticity. A similar boundary occurred on 31 May 2017. In that case, a strong moisture gradient and wind shift was directly observed at the intersection of the Mohawk and Hudson valleys by the New York State Mesonet (Figure 20). That boundary was even more distinct than the 31 May 1998 simulated boundary, with surface dewpoint differences exceeding 6°C across the boundary within the Mohawk Valley. A cluster of thunderstorms rapidly intensified after interacting with the boundary and resulted in a concentration of severe wind and hail reports east of the boundary.

While the results here suggest that this terrain-driven boundary played an important role in the formation of the Mechanicville tornado, other additional complicating factors may have played a role as well. Primarily, it is possible that storm mergers played a role in tornadogenesis. As
presented in LaPenta et al. (2005), the storm that produced the Mechanicville tornado developed over 50 km ahead of a squall line to the west. Just prior to tornadogenesis, this squall line began to merge with the leading supercell. The reader is referred to LaPenta et al. (2005) for a more thorough description and radar analysis of the supercell-squall line merger. This merger was not present in the simulation in order to focus on the role of terrain and the supercell-boundary interaction. However, it is entirely possible that the supercell-squall line merger may have contributed to the formation of the Mechanicville tornado. French and Parker (2012) analyzed a set of 21 cases in which isolated supercells merged with squall lines and found that storm mergers may in some way serve as instigators for tornado formation in environments favorable for tornado formation. However, for strongly forced events like the 31 May 1998 event, they interestingly found that tornadoes were less common during and after the merger. Additionally, it was found that tornadoes that occurred after the merger were generally weaker and had shorter path lengths than those that occurred with isolated supercells. Therefore, the Mechanicville tornado may potentially be an unusually strong, long-lived, post-merger tornado.

7. Conclusions

The Mechanicville tornado of 31 May 1998 was a rare, high-impact tornado that occurred in the northeastern United States. Simulations of the 31 May 1998 event suggest that a robust boundary developed at the intersections of the Hudson and Mohawk valleys. The properties of the boundary closely match those of a dryline. The boundary was characterized by a moisture gradient, with dewpoint values in excess of 20–21°C to the east of the boundary within the Hudson Valley. Additionally, consistent with dryline structure, there was a layer of enhanced stability around 1 km AGL to the east of the boundary. A similar stable layer was observed by the 1800 UTC Albany upper-air sounding. Finally, there were strong, south-southeasterly winds near the surface to the
east of the boundary within the Hudson Valley, while winds to the west within the Mohawk Valley were southwesterly. The depth of the south-southeasterly flow supports the hypothesis that terrain channeling played a crucial role in the development of this boundary. Trajectories indicate that confluence in the wake of the high terrain features in the Catskill Mountains supported the tightening of the boundary in the region at the intersection of the Mohawk and Hudson valleys.

The region along and east of the boundary, in the vicinity of Mechanicville, was characterized by enhanced instability and extreme wind shear. The southerly and south-southeasterly surface winds in the Hudson Valley resulted in substantial hodograph curvature in the lowest 1 km AGL, supporting 0–1-km SRH above the 90th percentile of model proximity soundings (Thompson et al. 2003). As a result, the storm environment in this region was extremely volatile and favorable for tornadogenesis. A simulated supercell intensified within 20 minutes after crossing the boundary and entering the volatile environment within the Hudson Valley. Trajectories indicate that the period of intensification occurred as high theta-e air was ingested into the supercell updraft from the region to the east of the boundary.

The presence of similar boundaries in several severe thunderstorm cases suggests that mesoscale boundaries that develop as a result of terrain channeling may play an important role in modulating the local severe thunderstorm environment of the region at the intersection of the Mohawk and Hudson valleys, and potentially at the intersection of other major river valleys. Prior to the installation of the New York State Mesonet, such boundaries were difficult to directly observe due to the sparse observational network. New observation capabilities available through the New York State Mesonet will allow these boundaries to be observed in real time. The recognition of these boundaries in advance may be useful in increasing situational awareness of where the risk of severe weather may be locally higher during high-impact severe weather events.
References


NOAA, 2019: Storm events database. [Available online at https://www.ncdc.noaa.gov/stormevents/]


### Tables

Table 1: Model parameters utilized in the WRF model

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Option used</th>
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<tbody>
<tr>
<td>Model core</td>
<td>ARW</td>
</tr>
<tr>
<td>Horizontal grid resolution</td>
<td>27 km/9 km/3 km/1 km</td>
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<tr>
<td>Initial/boundary conditions</td>
<td>NARR</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>36, 100 hPa model top</td>
</tr>
<tr>
<td>Cumulus parameterization scheme</td>
<td>3 – Grell-Freitas ensemble scheme (outer only)</td>
</tr>
<tr>
<td>Microphysics scheme</td>
<td>28 – Aerosol-aware Thompson scheme</td>
</tr>
<tr>
<td>Planetary boundary layer scheme</td>
<td>5 – MYNN 2.5 level TKE scheme</td>
</tr>
<tr>
<td>Land surface scheme</td>
<td>2 – Unified Noah land-surface model</td>
</tr>
<tr>
<td>Radiation</td>
<td>4 – RRTMG scheme (for both SW and LW)</td>
</tr>
<tr>
<td>Surface-layer option</td>
<td>5 – MYNN surface layer</td>
</tr>
</tbody>
</table>
Figure 1: Terrain height (m) in the region of interest. The locations of the Schenectady (SCH), Albany (ALB), and Glens Falls (GFL) airports are indicated. The red line is the track of the Mechanicville tornado.
Figure 2: The domain structure of the WRF simulation utilized in this study.
Figure 3: A comparison between simulated (blue) and observed (red) temperatures (solid lines),
dewpoint temperatures (dashed lines), and winds (barbs, m s\(^{-1}\)) for (a) KALB, (b) KSCH, (c) KGFL, and (d) KBGM. The shaded area highlights 1830–1930 UTC.
Figure 4: A comparison between the 1800 UTC Albany, New York RAOB (red) and a simulated profile at the same location (blue). (A.) The temperature (solid, °C), dewpoint (dashed, °C), and mandatory-level winds (barbs) for the profiles. Winds are in m s\(^{-1}\) with one flag, full barb, and half barb denoting 25, 5, and 2.5 m s\(^{-1}\), respectively. (B.) The temperature, dewpoint, and winds below 700 hPa. (C.) Hodographs for the simulated (blue) and observed winds (red), neglecting questionable observations between 850 hPa and 799 hPa. The solid lines reflect winds in the 0–1-km layer, and the dashed lines reflect winds in the 1–6-km layer.
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Figure 7: Mesoscale analysis for 1600 UTC 31 May; (A.) theta-e at the lowest model level (K) and 10-m winds (streamlines); (B.) 2-m dewpoint (°C), near-surface frontogenesis > 3 K km⁻¹ hr⁻¹ (blue) and terrain height > 500 m (gray).

Figure 8: Same as Figure 7, but for 1700 UTC.
Figure 9: Same as Figure 7, but for 1800 UTC

Figure 10: Same as Figure 7, but for 1900 UTC. The light blue line indicates the location of the northern cross section in Figure 12. The purple line indicates the location of the southern cross section in Figure 12.
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Figure 14: Hodographs corresponding to a location west of the boundary (blue, see Figure 13 for location) and east of the boundary (red, see Figure 13 for location). The solid portions of the line indicate the 0–1-km above ground level layer, and the dashed portions of the line indicate the 1–6-km above ground level layer. The wind units are m s$^{-1}$. 
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Figure 18: Back trajectories seeded (A.) at 1945 UTC within the 5-km updraft core, (B.) at 2000 UTC within the 5-km updraft core, (C.) at 1945 UTC within the 2-km updraft core, and (D.) at 2000 UTC within the 2-km updraft core. The colored dots indicate the 1900 UTC location and height (m MSL, shaded) of the trajectories. The 1-km AGL reflectivity (dBZ) and terrain height (m) are shaded following Figure 5.
Figure 19: The starting height (m, y-axis) and theta-e (K, x-axis) for parcels located in the mid-level (5-km) updraft core at 1945 UTC (red) and 2000 UTC (blue). The dashed line indicates a 4-nearest-neighbors line fit to the points.
Figure 20: The 2-m temperature (fill, °F), 2-m dewpoint (°F, contours every 4°F), and 10-m winds (vectors) at 1800 UTC 31 May 2017, interpolated from the New York State Mesonet station data. This product is available in real time at https://operations.nysmesonet.org/~nbassill/.