July24th, 2008 New Hampshire tornado

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ABSTRACT

On July 24th, 2008 at approximately 1530Z, an EF-2 tornado struck the town of Epsom, New Hampshire. Special attention will be given to the synoptic and mesoscale features that facilitated the development of the tornadic cell, even in the absence of significant thermal instability. Data focusing on the 12Z timeframe were analyzed and presented to help understand this case. It was found that a strong, cut-off surface cyclone centered over New York State helped amplify the strong southerly low level jet which aided advection of warm, moist air from the Atlantic Ocean. This resulted in convective activity over southern New Hampshire that eventually produced a cell which evolved into a bow echo and spawned a tornado.

Introduction

Tornadoes are common in the central and southern United States, but these events are very rare in the New England area. New Hampshire typically receives only two tornadoes per year, which is insignificant compared to the hundreds observed throughout the Great Plains. The last major tornado to hit the region in the past century occurred in 1953 in Worcester, Massachusetts, when an F4 tornado struck the city of Worcester, killing over 150 people. The local climate and topography are quite different than that of tornado alley, and represent an inferior environment for severe weather. As such, there is very rarely an ideal combination of dynamical and thermodynamic forcing for severe thunderstorm formation to occur, even in the hot summer months. However, even in a generally poor environment for severe weather, occasionally conditions become favorable. Such was the case on July 24th, 2008.

On July 24th, 2008 at approximately 1530Z (11:30 am local time), an EF-2 tornado was reported to have touched down in Deerfield, New Hampshire (part of Rockingham County) where it resulted in one fatality and damaged nearly 100 homes. The 52 mile long damage path was the longest damage path for any tornado in New Hampshire, and extended from Deerfield through several other New Hampshire counties before crossing into Maine. The final sighting was reported in Cumberland County, Maine at 1645Z. The following analysis will attempt to analyze why the tornado formed in such an unusual geographic location, especially in the absence of large amounts of convective potential energy (CAPE).

An exceptionally strong, cut-off upper level low pressure system centered over New York State facilitated advection of warm, moist air from the eastern seaboard. Additionally, a high pressure system situated off the coast of Maine created an intense pressure gradient and helped amplify the low-level southerly jet. These convenient features provided sufficient dynamical forcing for the tornado spawning storm. With the help of substantial surface heating from the strong midsummer sun, and warm air advection, temperatures in southern New England reached the mid 70s, while dewpoints were consistently in the high 60s and lower 70s. These features were crucial to the formation of the convective cells that developed ahead of the cold front. Eventually, they began to merge into a squall line, with the leading cell developing into a bow echo. This leading bow echo cell would later drop the tornado.

However, not all factors were ideal for convective activity. Surface CAPE values remained very low prior to the storm's intensification, reaching only 168 J/kg in Gray, Maine at 12Z, although values as high as 555 J/kg were reported in Albany, New York at 12Z. Additionally, there was very little directional shear in the wind profile in either city, as the winds remain southerly from the surface through the upper levels. Furthermore, northern New England is quite mountainous, as the Appalachian mountain chain extends through the area. This topographical profile is hardly conducive to the development of severe weather, unlike the vast plains and rolling hills of tornado alley which are constantly under the threat of severe weather.

The cell from which the tornado spawned progressed into a bow-echo, where intense circulation developed. A tornado developed from this circulation and progressed to the north-northeast for 52 miles before dissipating. Bow echo tornadoes are not extremely rare, but they usually have a damage path of less than 10 miles, so the 52 mile path of this tornado was exceptional.

This paper will analyze and attempt to explain why such an exceptional tornado occurred. The reasons why it had such an exceptional path length, and why it was able to persist for so long will be explored through an analysis of synoptic and mesoscale conditions, and analysis of dynamic instability and moisture influx.

Data

Data were obtained from NOAA Storm Prediction Center (SPC) website, Unisys, and archived satellite and radar data from the University of Wisconsin. The four-panel plots from July 24th, 2008 at 00Z and 12Z which convey crucial synoptic information at major levels (**Figure 1**, displaying 300mb, 850mb, 850-500mb lifted indices, and the surface) were gathered from the Unisys Weather data archives. Additionally, surface observations (**Figure 4**, from July 24th, 2008 at 12Z) were gathered from the Unisys website to monitor surface features and frontal characteristics. Satellite imagery was obtained through use McIDAS-V software program for **figure 3**.. Radar data from July 24th, 2008 was also obtained from the Weather Channel's study on the storm, and can be seen in **figures 9, 10, and 11**. The conceptual model of a bow echo evolution was borrowed from Fujita, 1978 (**figure 12**). The topographical map used for **figure 6** was obtained from www.geology.com. Soundings used in **figures 7 and 8** were obtained from the Storm Prediction Center website. The Miller Diagram used for **figure 5** was constructed by the author.

Synoptic Overview

July 24th, 00Z

On July 24th, 2008 at 00Z, a deep low pressure system was centered over Lake Huron. The right entrance region of the southesterly 300mb jet streak (maximum wind speeds at the core of about 90 knots) just downstream of the low was positioned

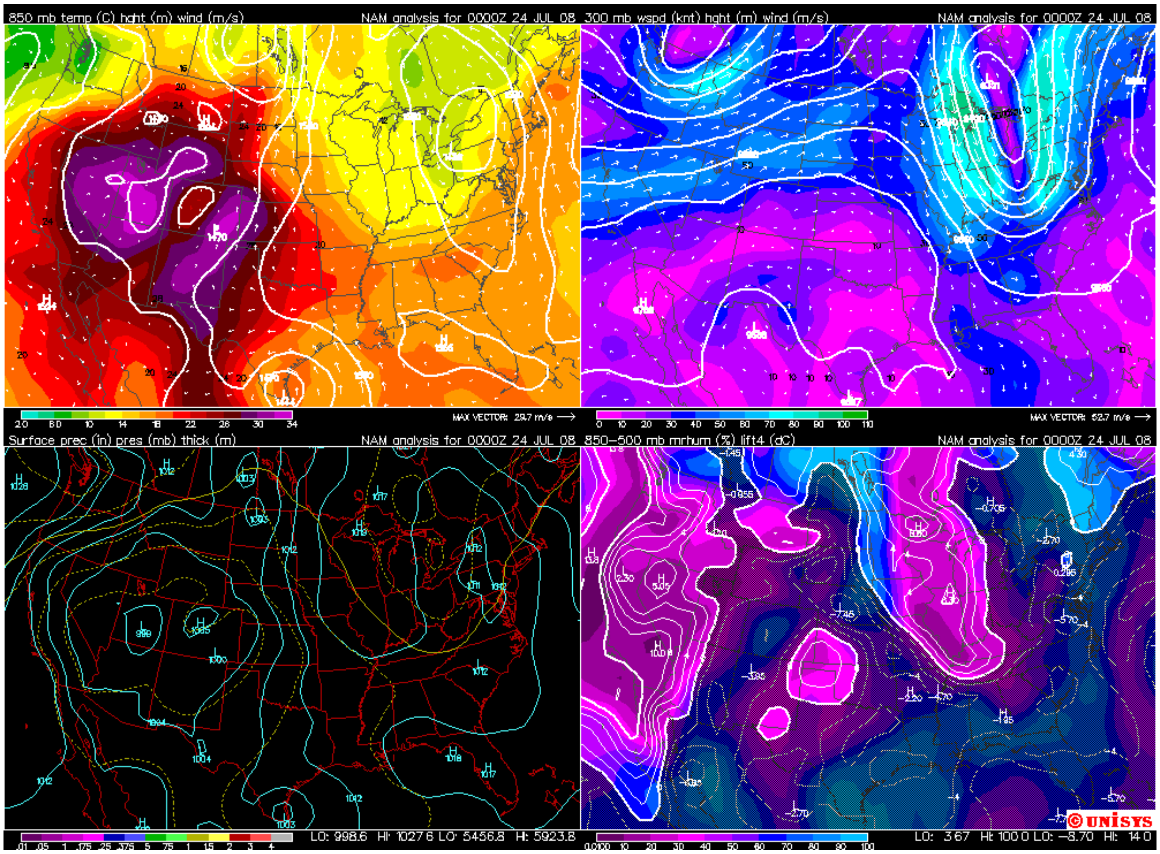


Figure 1: July 24th, 2008 at 00Z **,** 850mb temperature in the top left, 300mb geopotential heights and wind speeds on the top right, surface pressure on the bottom left, and lifted indices on the bottom right

over the Virginia-North Carolina border, thus facilitating upward vertical motion at the surface, and divergence aloft. The right entrance region was positioned over the Maine-Quebec border, and was encouraging downward vertical motion near the surface and convergence aloft. There was some difluence in the exit region of the upper level jet in northern Vermont and into Quebec, but this feature appeared to be too far north to affect dynamic forcing in southern New England. At 850mb, the winds were southerly and advecting warm air and moisture from over the Atlantic Ocean. Meanwhile, in far eastern New England and into Nova Scotia, a region of abnormally high pressure persisted. Because of the steep pressure gradient between the low and high pressure systems, it became apparent that they would cooperate to amplify the southerly low level jet as the low propagated further east. This situation can be observed in **figure 1** which displays the 300mb, 850-500mb, 850mb, and surface conditions.

July 24th, 12Z

By 12Z, the low pressure system had intensified and propagated further to the east and was now centered over central New York. The trough had also taken on a distinctive negative tilt and had the appearance of a well-organized mid latitude cyclone. A satellite image displaying the cyclone's formation can be seen in **figure 3**, which also displays the influx of moisture into the affected region. A trough typically becomes more negative as a low pressure system organizes and develops into a cyclone. The negatively tilted trough is often a reliable indicator of severe weather, as it indicates that the low pressure has reached maturity, and that there is significant differential advection (i.e. cold air advection in the upper levels while the lower levels remain warm) and wind shear,

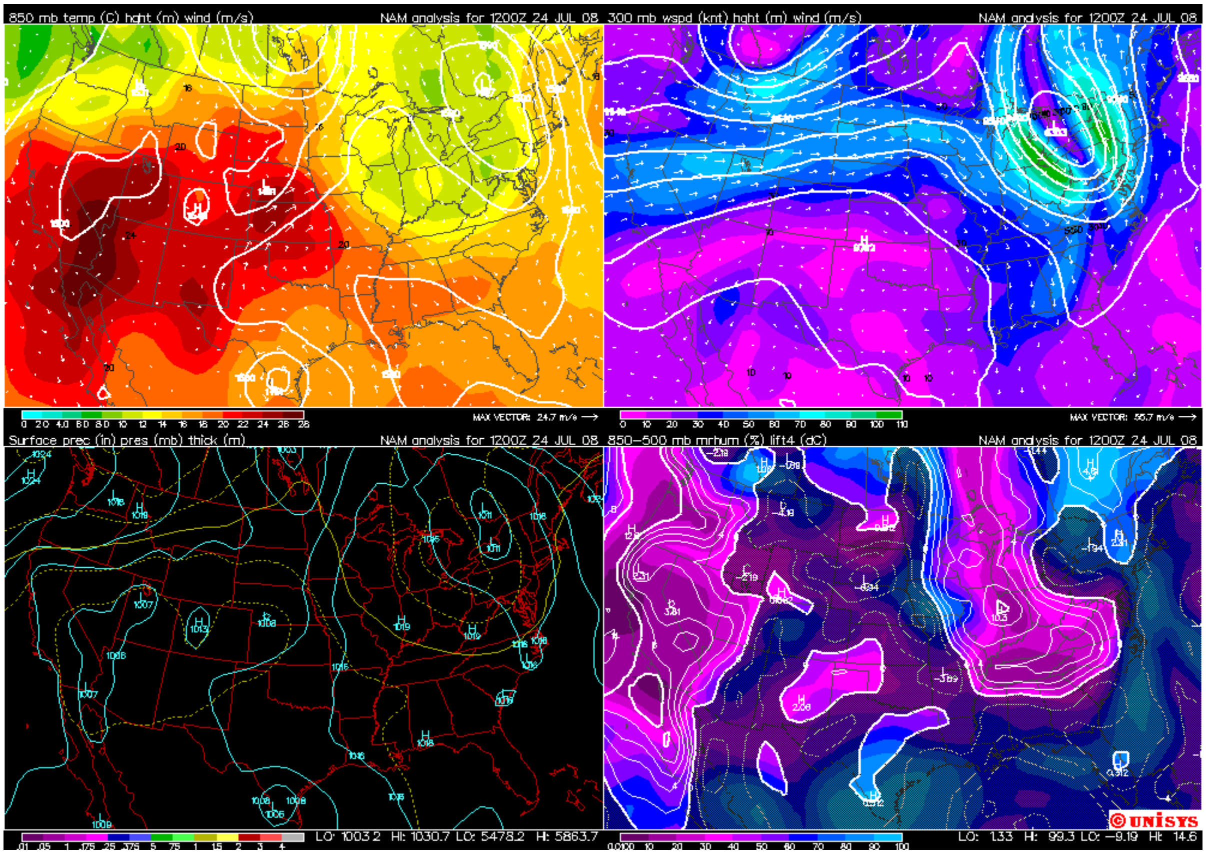


Figure 2: July 24th, 2008 at 12Z, 850mb temperature in the top left, 300mb geopotential heights and wind speeds on the top right, surface pressure on the bottom left, and lifted indices on the bottom right

thus leading to dynamic instability. Dynamic instability is crucial for severe weather to occur, and is especially important when considering that the area was lacking in CAPE. Having a mechanism for enforcing instability therefore made it possible for severe weather to develop. Additionally, the high pressure system over eastern New England remained stationary, and maintained moderately strong anticyclonic flow. The result was that the two pressure systems acted to intensify the low level southerly jet. The 300mb jet had intensified to a maximum core wind strength of 110 knots, thus strengthening upward vertical motion and divergence at the right entrance region, and downward vertical motion and convergence at the right exit region. At 500mb, the center of circulation for the low pressure system was just east of Lake Huron, over Ontario. It featured winds of about 65 knots over the New York-Vermont border and winds of about 50 knots over eastern Massachusetts. This implies some mid-level cyclonic horizontal shear over the target area, which may have helped the tornadic cell continue to develop. Also at 500mb is a region of difluent flow over northern New Hampshire and extending into southern Quebec. Moving down to 700mb, the flow appears to be in the same direction as in the upper levels, although the wind speeds are slightly slower, being about 35 knots over Albany and 45 knots over eastern Massachusetts. Additionally, these features were accompanied by a stronger, southerly low-level jet streak just to the East of the cold front. The jet extended south from the Maryland-Virginia border to southeastern Quebec in the north. The orientation of the jet streak facilitated upward vertical motion through the middle levels over Connecticut (and thus divergence of the winds at the upper levels) and downward vertical motion in southern Quebec (and convergence of the wind at the upper levels). The divergence aloft over Connecticut ensured that surface warm, moist air propagated north towards Massachusetts and New Hampshire. In **figure 1**, a four-panel plot illustrates the synoptic situation on July 24th, 2008 at 12Z. The 300mb geopotential heights and wind speed plot shows the position of the most intense region of the jet to be over central New York, and upper level wind vectors indicating advection from the south. On the bottom right, the stability of the region between the 850-500mb level is shown with lifted indices, and humidity is indicated with color fills. The lifted indices over New England indicate high stability, which is an unusual situation for tornadic storm formation. The 850mb temperature plot in the top left of the figure shows the warm and cold sectors, with the leading edge of the cold sector running along the Vermont-New York Border, and the warm sector extending north through Maine. The wind vectors to the south of Connecticut clearly show that warm air is being advected northward from over the Atlantic towards Maine. These synoptic properties are crucial to understanding why the tornadic cell formed, especially considering the absence of low-

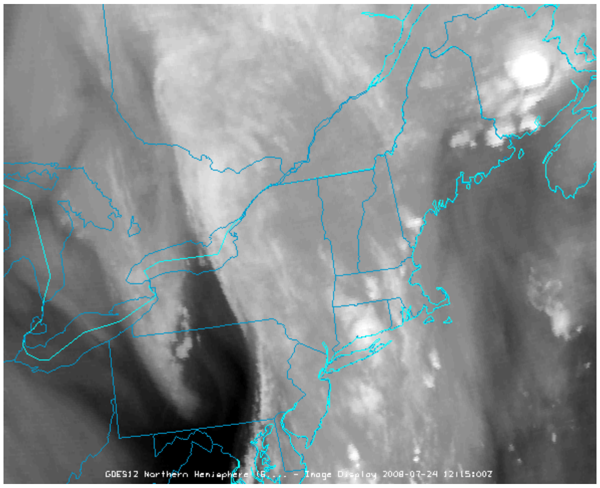


Figure 3: GOES-12 infrared satellite image taken from July 24th, 2008 at 12:15Z (10.7 micron water vapor channel). This image shows the massive influx of moisture into the New England region from the Atlantic. The center of circulation for the cyclone is over central New York. Image was gathered using McIDAS-V software

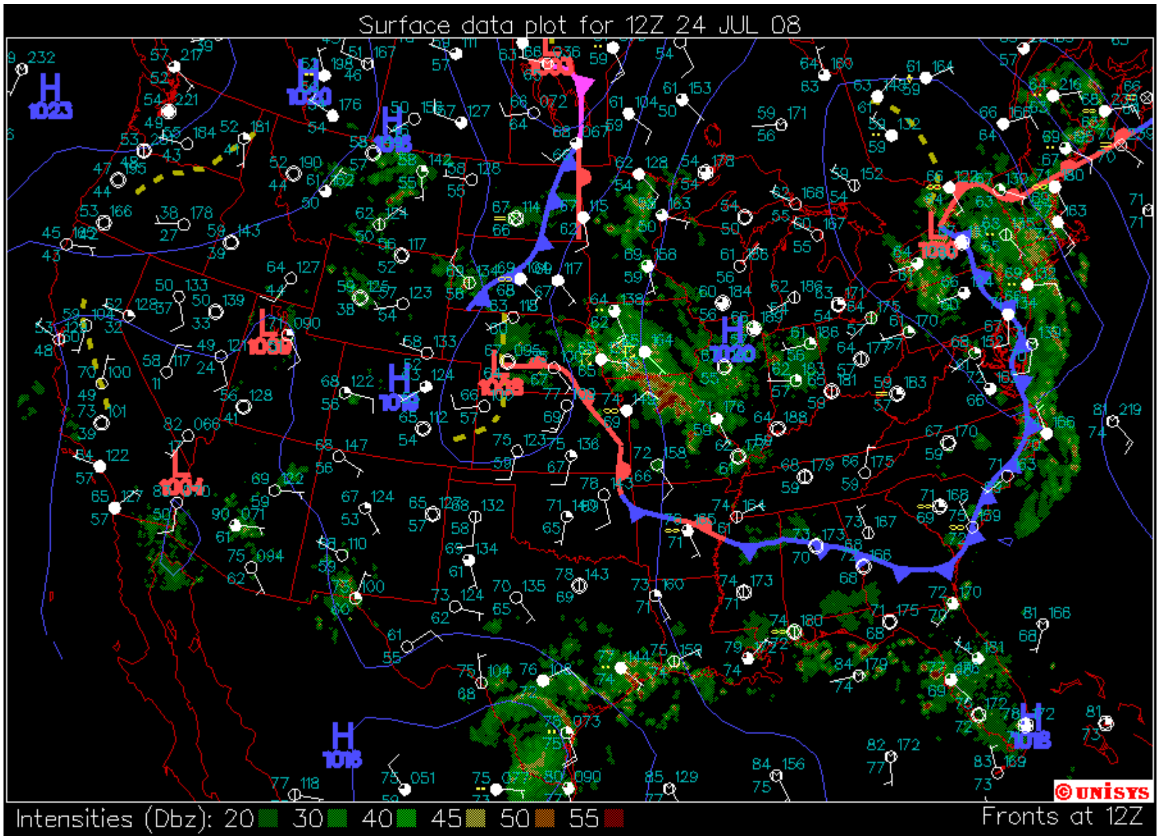


Figure 4: July24th, 2008 at 12Z surface analysis

level instability. However, the other synoptic properties of New England are ideal for thunderstorm formation. In **figure 4**, the cold front can be seen extending along the eastern seaboard. Although there is no discernible dryline, note the wind shift along the front. In the warm sector, warm, moist air is being advected from the Atlantic towards southern New England. Although this situation is not a perfect setup for tornadogenesis, it proved to be quite sufficient to facilitate the development of tornadic cells.

One very interesting factor to consider when analyzing the impact of the southerly low level jet is that sea surface temperatures were about 2 to 3 degrees warmer than average on the east coast of the United States. Although the cause of this anomaly is unknown, it is important to note. This likely enhanced the thermodynamic forcing created by air being advected off the Atlantic.

Figure 5 is a Miller Diagram which displays the synoptic situation leading to the formation of this storm. The set-up can be most closely identified as a Synoptic Type B Pattern, although there are some interesting variations from the traditional pattern. Key elements of the Type B Pattern include a major upper trough, an east-moving surface cold front that is advancing upon the area of concern. Cells typically develop along the front and quickly merge into a squall line which may spawn tornadoes if instability is sufficient (Henz). Most of the conditions outlined in the Type B pattern are satisfied, although development of convective cells began about 50 km to the east of the surface cold front instead if right along it. The diagram shows the continued southerly influx of warm, moist air below the 850mb level. The flow pattern also displayed the strong low pressure system to the west, and cold air advection to the west and northwest up to 500mb. The warm, moist low-level air from the south converged with the cold low-level air, and a squall line developed to the east of the cold front. The initial thunderstorms ahead of the front were

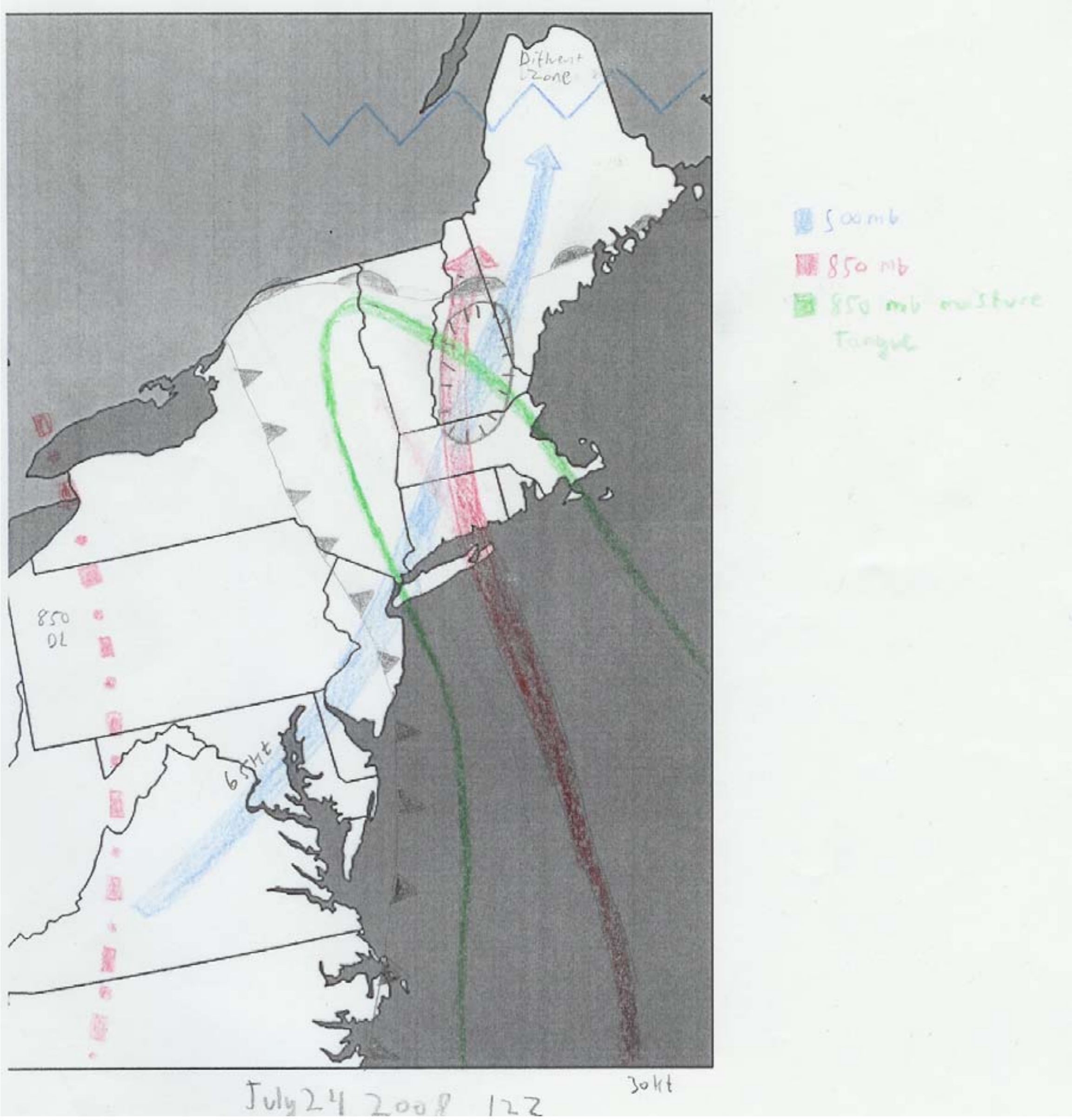


Figure 5: A miller diagram detailing the conditions on July 24th, 2008 at 12Z

enhanced by the surface cold front overtaking the warm, moist air to the east.

Mesoscale Analysis

The role of topography

The topography in eastern New York and northern New England is extremely variable and populated by many mountains. Although the highest peak is only 1917 meters, at the summit of Mount Washington. Even though this does not seem very high, keep in mind that the mountain's proximity to the ocean, which is the main moisture source for storms. In **figure 6**, a topographical map of New Hampshire is presented with the path of the tornado drawn on it. As we can see, the tornado did not encounter any major elevation changes, which helps explain why it had such a long damage path. However, the mountains'

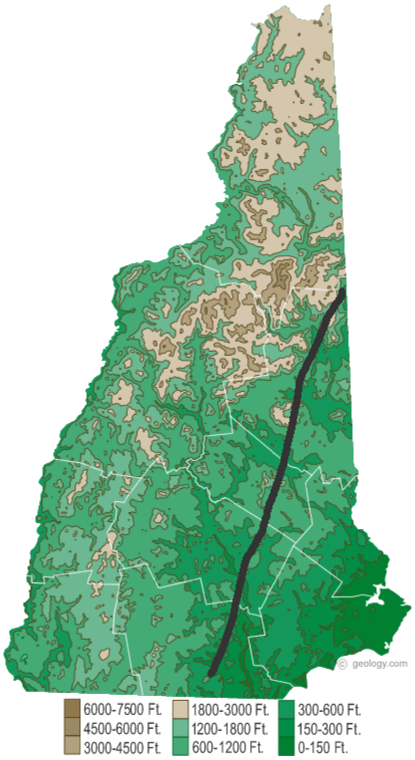


Figure 6: A topographical map of New Hampshire, showing the mountainous regions to the north and west and the damage path in black

presence cannot be ignored, as they may have had a substantial impact on other dynamical processes.

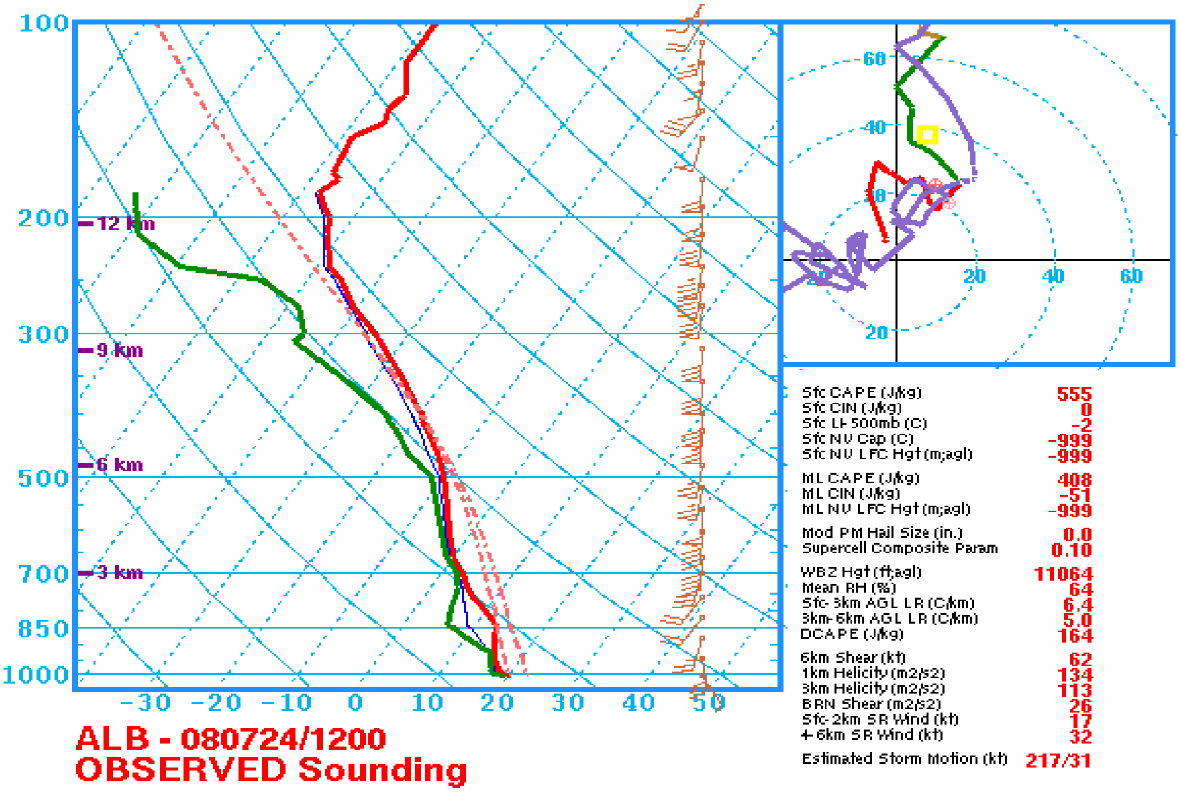
The cold front

On July 24th at 12Z, the surface cold front extended from central New York to South Carolina. The temperature in Buffalo, New York at 12Z was 59 F, just after the cold front passed through. Meanwhile, temperatures in Albany were at 70 degrees, making for a temperature gradient of about 11 degrees between the cold and warm sectors. However, following the advance of the cold front through Vermont and into New Hampshire shows that the mountainous terrain may have had an impact on its propagation, and allowed the relatively flat southeastern portion of New Hampshire that lay to the leeside of the mountains to remain warm. The progression of the cold front from 12Z through 18Z was marked by more rapid advancement of the front in the southern states than in New York. It appears that there is some interaction from the mountains in preventing the surface cold front from advancing toward the area where the tornado occurred. Although one must keep differential advection in mind when considering the effects of topography, it is still important to note this interaction.

The warm sector

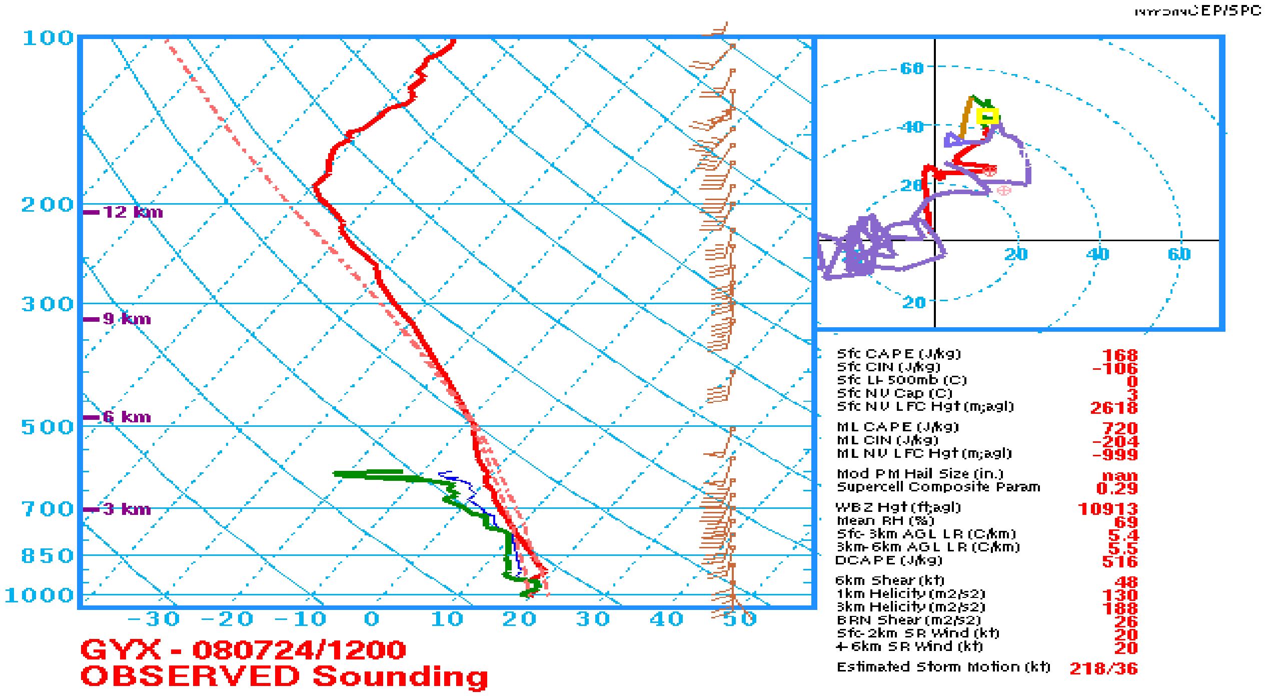
By 12Z, the warm sector (bordered by the cold front in the west and the warm front in the north) extended from the New Hampshire-Quebec border in the north and from central New York to the Gulf of Maine in the East. This warm sector of the low-pressure system (centered over New York) was continuously advecting warm, moist air from the Atlantic. This pattern of flow ensured that the dewpoint depression (T-Td) remained in single digits in New England. Additionally, by 12Z, surface temperatures in the warm sector were already in the lower 70s. At the time of day that the storm matured, the warm front provided the most significant forcing mechanism for lifting. Additionally, the lower level jet streak continued to remain stationary over Massachusetts, thus continuing to enhance low level warm air and moisture advection.

The sounding from Albany, New York on July 24th, 2008 at 12Z (**Figure 7)** displays an environment that is not especially conducive to tornadic storm development, although it does display a slight level of risk. Notice that there is only moderate CAPE at the surface (555 J/kg) and the winds do not veer with height, although there is substantial speed sheer from the surface to 700mb. Note that this sounding also lacks an elevated mixed layer, and there is no convective inhibition (CIN) present at all. The hodograph, pictured in the upper right of **figure 7**, does not show favorable conditions for either a right-



Sfc CAPE (J/kg)	555
Sfc CIN (J/kg)	0
Sfc LI-500mb (C)	-2
Sfc NV Cap (C)	-999
Sfc NV LFC Hgt (m;agl)	-999
ML CAPE (J/kg)	408
ML CIN (J/kg)	-51
ML NV LFC Hgt (m;agl)	-999
Mod PM Hail Size (in.)	0.0
Supercell Composite Param	0.10
WBZ Hgt (ft;agl)	11064
Mean RH (%)	64
Sfc-3km AGL LR (C/km)	6.4
3km-6km AGL LR (C/km)	5.0
DCAPE (J/kg)	164
6km Shear (kt)	62
1km Helicity (m2/s2)	134
3km Helicity (m2/s2)	113
BRN Shear (m2/s2)	26
Sfc-2km SR Wind (kt)	17
+6km SR Wind (kt)	32
Estimated Storm Motion (kt)	217/31

Figure 7: Sounding from Albany, NY on July 24th, 2008 at 12Z



Sfc CAPE (J/kg)	168
Sfc CIN (J/kg)	-106
Sfc LI-500mb (C)	0
Sfc NV Cap (C)	3
Sfc NV LFC Hgt (m;agl)	2618
ML CAPE (J/kg)	720
ML CIN (J/kg)	-204
ML NV LFC Hgt (m;agl)	-999
Mod PM Hail Size (in.)	nan
Supercell Composite Param	0.29
WBZ Hgt (ft;agl)	10913
Mean RH (%)	69
Sfc-3km AGL LR (C/km)	5.4
3km-6km AGL LR (C/km)	5.5
DCAPE (J/kg)	516
6km Shear (kt)	48
1km Helicity (m2/s2)	130
3km Helicity (m2/s2)	188
BRN Shear (m2/s2)	26
Sfc-2km SR Wind (kt)	20
+6km SR Wind (kt)	20
Estimated Storm Motion (kt)	218/36

Figure 8: Sounding from Gray, Maine on July 24th, 2008 at 12Z

moving or left-moving cell. However, the 1km helicity was measured at 134 m^2/s^2, which is not extremely high, but not inhibitive of tornadic formation. The sounding from Gray, Maine (**Figure 8)** also exhibits an environment that is not very accommodating to convective activity. The CAPE is only 168 J/kg, although there is some CIN, but breaking this small cap would not yield violent convection by itself. Helicity was measured to be 130 m^2/s^2. Much like Albany, there is substantial speed shear in the vertical, although the winds do not veer with height. Nevertheless, at 12Z, NOAA's Storm Prediction Center (SPC) upgraded their convective outlook for New England to “slight” and predicted that there was a five percent chance of a tornado touching down within twenty-five miles of any given point throughout most of New England. Clearly, they realized that something was brewing, but not all of the conditions were present to justify issuance of a more dire warning. In their statement regarding the threat to New England, they recognized that there was, “A favorable kinematic environment for a threat of organized storms including supercells and fast northward moving bowing segments.” However, they recognized that the thermodynamic environment would be “marginal” and characterized by weak mid-level lapse rates, but that significant heating could result in convective activity.

The cells that formed ahead of the cold front in the east began to merge, although they did not yet form a well-defined squall line. The cells propagated toward the north-northeast, and eventually merged into a squall line. Ahead of the squall line, a bow echo was spawned. The situation regarding the tornadic cell can be observed in the radar shown in **figures 9 and 10**, which were taken while the tornado was on the ground. Additionally, the vortex signature can be viewed in **figure 11**, which has an arrow to indicate the direction of propagation of the tornado.

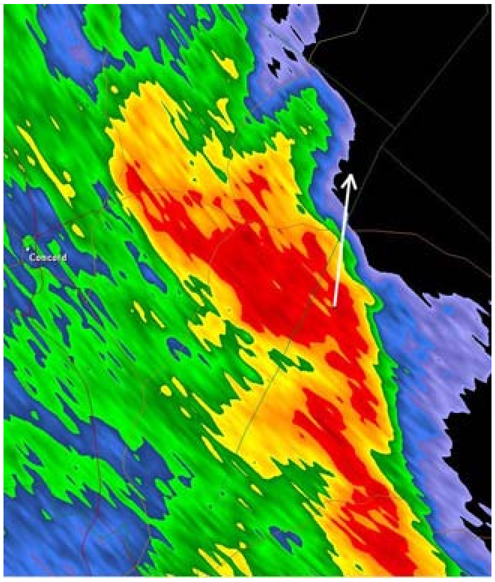


Figure 9: Evolution of the bow echo into the characteristic comma shape from the mature bow echo, taken on July 24th, 2008 at 15:34Z. The tornado is located at the end of the arrow shaft.

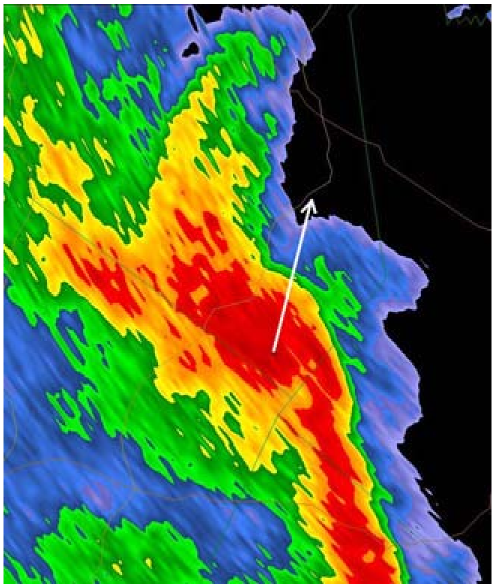


Figure 10: Evolution of the bow echo into the characteristic comma shape from the mature bow echo, taken on July 24th, 2008 at 15:48Z. The tornado is located at the end of the arrow shaft.

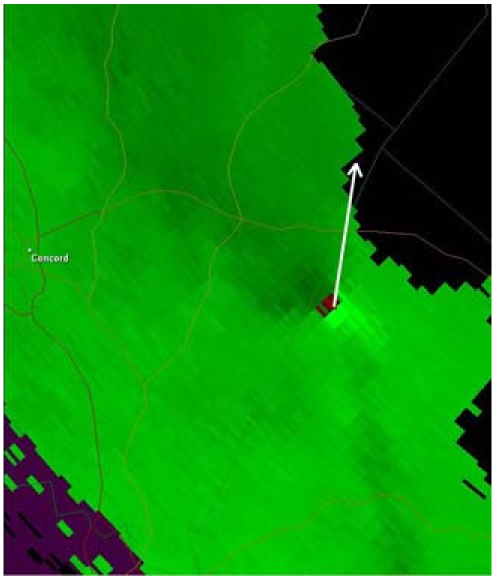


Figure 11: Tornado vortex signature caught on Doppler radar, taken at 15:34Z

Formation of the bow-echo

This tornado developed out of a bow echo instead of a single, isolated supercell thunderstorm. A bow echo is an isolated mesoscale convective system (MCS) (Weisman, 1993) that often evolves from a single strong cell, or in association with a line of convective cells, or a squall line. They are most infamous for damage caused by straight line winds, but they do sometimes lend themselves to tornadic development. These types of storms have also been associated with derechos, although this case could not be classified as a derecho event. Dr. Fujita first described the birth of bow echoes as being created by strong downbursts, with the maximum winds acting to push some cells further out, creating a bowing effect. **Figure 12** shows Fujita's conceptual model for the formation and evolution of a bow echo. Notice the progression as the rear inflow strengthens. The characteristic comma shape strengthens its form during the declining stage. At this point, the northern vortex has survived and circulation is at its maximum. This is the time and place where a tornado is most likely to form.

The typical mesoscale situation that favors bow echo formation includes strong northwesterly upper level flow (Johns and Hirt, 1987), coupled with a 500mb shortwave trough. At lower levels (700 and 850mb) warm air advection is usually extremely strong. Dry air at middle levels (500 to 700mb) is favorable for entrainment and thus intensification of the downdraft and cooling due to evaporation (Pfost and Gerard, 1997). Bow echoes usually form when there is significant shear in the lower levels of the atmosphere. The beginning stage of bow echo evolution begins with thermodynamic instability, where the updraft produces precipitation, which evaporates after falling and leaves a pool of cold air at the surface. The cold air spreads and creates convergence and thus upward vertical motion at the surface. If vertical wind shear near the surface is substantial enough, convective cells can form and evolve. Justification for this argument was made by Rotunno et. al in 1988. They found that convective activity is most likely to occur when vorticity created by the difference in buoyancy between the cold pool and the surrounding warmer areas is countered by vorticity created by near surface vertical wind shear. This led to substantial upward vertical motion at the intersection of the cold pool and surrounding warm air which further amplifies ascent. In the case of the New Hampshire tornado, these dynamic properties were satisfied and the warm air advection from the south helped fuel the storm's creation. Additionally, the substantial speed shear in the vertical was vital for the formation of the bow echo and helped amplify the atmosphere's response. These processes help explain how bow echo systems can survive for many hours, and why they can be so strong.

On radar returns, bow echoes have a

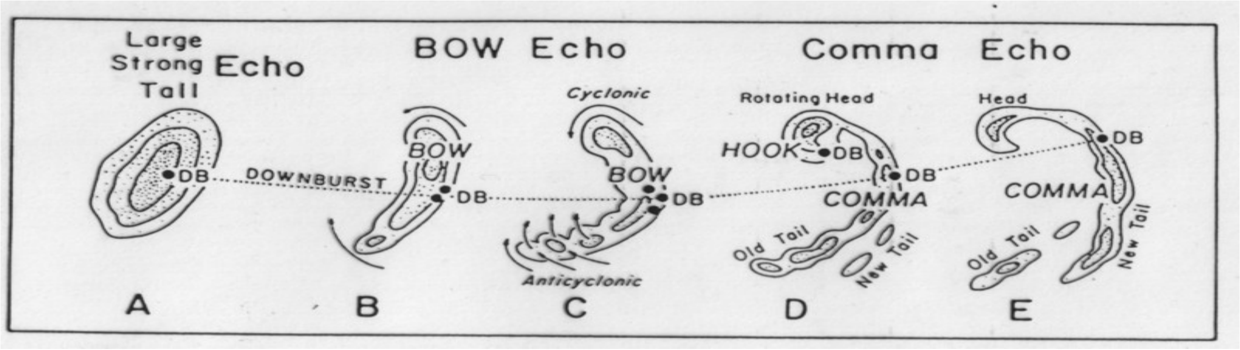


Figure 12: Fujita's conceptual model of the evolution of a bow echo

similar appearance to squall lines, although they are much smaller, as they are rarely more 100km in length. Their radar signature has a characteristic bowing to it, which gives it the appearance of an archer's bow. Formation of a bow echo requires strong midlevel inflow from the rear. The strong flow helps create small vortices at either end of the inflow jet, which usually have the appearance of a comma on radar signatures. Interestingly enough, because there are vortices at both ends of the inflow jet, there are both cyclonic and anticyclonic vortices, so it is possible for anticyclonic tornadoes to form, although this is rare. However, the anticyclonic vortex usually fades as the storm evolves, giving the system a characteristic comma-like shape. Bow echoes often result in very strong straight line winds, and occasionally tornadoes can often develop. However, bow echo tornadoes very rarely have damage paths longer than 10 miles and are usually short-lived.

Influence of evapotranspiration

Evapotranspiration (the transfer of water from soil and plants into the atmosphere) from the production of agricultural crops like corn is thought to have a significant influence on daytime humidity and thus severe weather formation. This is a significant factor to consider in the great plains where corn is a major crop and covers much of the urban landscape. As the Although New Hampshire is generally not thought of as part of the Corn Belt, much of the land area is sparsely populated and includes a wide array of vegetation. During the summer months, broadleaf trees are in full bloom and agricultural development is at its peak. The vegetation "sweats" or transpires and this water evaporates into the atmosphere, raising the mixing ratio and humidity (Chavas, 2007). Increased moisture content in the atmosphere (especially in the boundary layer) would decrease theta-e values and lower the height at which clouds would form. The influence of evapotranspiration may not be extremely severe, but any increase in dewpoints can enhance the potential for convective activity to occur, so its influence on the atmosphere must be taken into account when analyzing the storm.

Conclusion

The EF-2 tornado that surprised central New Hampshire on July 24th, 2008 was one of the most powerful tornadoes ever to occur in New England, and had the longest damage path of any tornado to hit the region. It was a rare and deadly event, and was also the only tornado in the United States to result in the loss of life in the month of July, 2008. It left one person dead, and destroyed over two hundred homes in New Hampshire.

The storm was set up by a low pressure system centered over New York that facilitated advection of warm, moist air into the New England region. As the low pressure system propagated eastward, the trough took on a highly negative tilt, an indicator that there was significant instability and shear in the atmosphere. The low pressure system also advanced upon a region of high pressure off the coast of Maine. The cyclonic circulation of the low and the anticyclonic circulation of the high acted to further intensify the low level jet and facilitate warm air advection. As the cold front from the low pressure system advanced, thunderstorms developed. Sufficient dynamics and surface heating from the strong summer sun broke the weak capping inversion over the area and facilitated the development of convective cells, which eventually began to merge to form a squall line. As the squall line progressed, sufficiently strong inflow developed behind its leading edge. This strong inflow and vertical shear made conditions favorable for a convective cell to evolve into a bow echo. The bow echo further evolved and developed two bookend vortices. Soon after, the northernmost vortex gained strength and made tornadogenesis feasible. This part of the bow echo grew stronger and eventually spawned a tornado. Although tornadoes are often associated with bow echoes, those that spawn from these features rarely have a path length of over 10 miles. Although the mountains between New York and New Hampshire may have stalled the advance of the surface cold front, it appears that even if the area was void of topographical features, the cold front would not have advanced quickly enough to affect the storm's evolution. Evapotranspiration may have played a role in increasing boundary layer humidity, but studies regarding the role of evapotranspiration in affecting severe weather have been inconclusive. This tornado was truly exceptional, as it had a path length of 52 miles, the longest ever recorded in New Hampshire. Additionally, the tornado stayed on the ground for over an hour and a half, a remarkable time period for a tornado in the New England region.

References /Acknowledgements

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