Reanalysis of Southern New England Tornadogenesis Events from 1997 – 2006 to Improve Forecast Verifications

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Abstract

The results of a synoptic and mesoscale study conducted to determine characteristics of Southern New England tornadoes are discussed in this paper. A total of 12 days with tornadoes since 1997 are classified into 5 different categories based on their associated environments. In addition, there are detailed analyses of Storm Relative Motion and Radar Reflectivity data for selected cases. Tornadoes are found in varying types of severe environments, including supercells, squall lines, and pulse convection. Several tornadoes form in non severe environments, such as events with cold-pool vorticies. Most events in the study require deep moisture at low levels and are enhanced by terrain boundaries. Also, a low level coastal jet is found to form when stronger tornadoes occur during certain synoptic conditions.

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I. Introduction

The purpose of this paper is to assist forecasters in improving performance and accuracy during potential tornadic events. The primary purpose is to create a criteria of conditions to identify days with tornadogenesis potential. The secondary purpose is to determine differences in Southern New England tornadogenesis compared to the rest of the country.

II. Background

A. Problem

The Taunton, MA County Warning Area (CWA) has a low frequency of tornadoes. Chronologically-ordered verification data from Taunton is in *Table 1*. As one can see, the probability that a tornado is discovered in an operational setting is low.

Table 1: **National Weather Service, Taunton, MA Tornado Warning Verification Data.**
Boldface rows indicate years when tornadoes formed.

Year	Prob. of Detection	False-Alarm Ratio	Num. of Events	Avg. Lead Time
1998	**100 %**	**86 %**	**1**	**3 min**
1999	0 %	100 %	0	0 min
2000	**33 %**	**89 %**	**1**	**6 min**
2001	**0 %**	**0 %**	**3**	**0 min**
2002	**0 %**	**0 %**	**1**	**0 min**
2003	0 %	0 %	0	0 min
2004	**0 %**	**100 %**	**1**	**0 min**
2005	0 %	0 %	0	0 min
2006	**0 %**	**0 %**	**1**	**0 min**

When compared to areas west of the Rockies, New England has a greater risk of tornado formation (Brooks 2003) despite a low frequency. Nevertheless, tornadoes that do form impact communities (i.e., the Great Barrington, MA tornado in 1995 as discussed by Bosart et al. 2006).

B. Current Knowledge

There are several accepted conclusions regarding why tornadoes form. With supercells, studies suggest a link to the low level mesocyclone. It is believed that conservation of angular momentum is also one of the root causes of supercell tornadoes as well as the requirement of a wall-cloud, which suggests that the downdraft in a supercell is also critical to the formation (Doswell and Burgess 1993).

Many of the tornadoes in this study, however, are non-supercellular. These consist of landspouts (simple shallow vertical vortices stretched upward), and cold pool vortices (which are not well understood). These vorticies form when surface heating couples the shallow boundary layer with very cool (occasionally post-frontal) air in the mid troposphere (Doswell and Burgess 1993). Cold pool vortices typically stretch from very high cloud bases and rarely touch the ground.

A multiple scale analysis is important to determine the environment conducive to tornadogenesis (LaPenta et al. 2005). One of the more important features is the jet stream's positioning and strength. The right-entrance and left-exit quadrants of any given jet have inherent positive vorticity advection; this enhances lift and strengthens both synoptic and mesoscale storms.

Several mid-level features are also important to examine, like temperature advection and wind velocity (David 1967). Temperature advection aloft changes the total amount of buoyancy that a parcel will encounter in an upward ascent. It has also been shown that mid-tropospheric winds impact the formation of supercell thunderstorms as well as tornadoes through large scale flow convergence (Brooks et al. 1994).

Analyzing the amount of atmospheric moisture through surface-based precipitable water shows the amount of latent heat energy release that can occur when a parcel rises. The 2 meter dew point temperature indicates the moisture at the surface, and therefore when a parcel will reach it's lifting condensation level (LCL) (David 1967). According to Rasmussen et al. (1998), LCLs are believed to be much lower for tornadic supercells than non-tornadic ones. For tornadoes to form, dew point temperatures should exceed 18 °C (65 °F) (Williams 1976).

An important pair of mesoscale features to examine are the Convective Available Potential Energy (CAPE), and the low level shear. The 0-3 km storm-relative environmental helicity (SRH) is available in the reanalysis system and used to represent low level shear. It is a common parameter in several severe weather studies (Weisman and Rotunno 2000).

CAPE is an effective measure of buoyancy potential in the atmosphere. A higher value implies that a parcel reaching the level of free convection will encounter less resistance upon ascent. SRH is a measure of the potential for cyclonic updraft rotation in storms and is computed by calculating the area under the hodograph from the 0 km to 3 km measurements (Weismann and Rotunno 2000). There are no clear cutoff values of SRH for tornadogenesis, but with most events, any environment with over 250 m^2 s^{-2} is considered strongly-conducive (Thompson 2007).

CAPE and SRH are typically analyzed in unison, due to the recent increased popularity of SRH as a forecast tool. As a result, climatological studies of sounding derived parameters began to focus on combinations of CAPE and SRH, determining a median value for SRH is roughly 180 m^2 s^{-2} (Rasmussen and Blanchard 1998).

Forecasters use WSR-88D data to diagnose mesocyclones that are associated with tornadoes. This has resulted in an improved view of storm motion, especially mesocyclones (Donaldson and Desrochers 1990). It has also resulted in an overall improvement of tornado warning lead times (Beringer and Ray 1996). The overall average probability of detection had increased to 50% at the time the WSR-88D gained operational use (Anthony and Leftwich 1992).

A mesocyclone signature consists of strong inbound flow adjacent to outbound flow perpendicular to the radar beam, as identified on Storm Relative Motion (SRM) scans (Dunn 1990; Donaldson and Desrochers 1990). There are two types of signatures. A *tornado signature* (TS) forms when the tornado diameter is larger than the radar's effective half-power beamwidth. A *tornado vortex signature* (TVS) forms when the tornado diameter is less than the radar's effective half-power beamwidth (Brown et al. 2002) (*Fig. 1*).

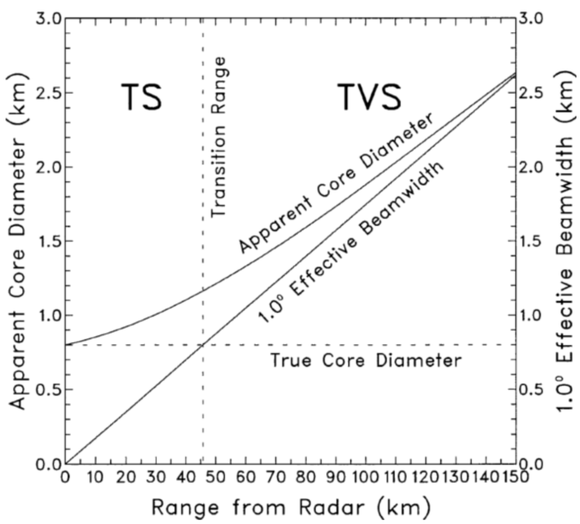

Fig. 1: **Distinction between TS and TVS.**
Tornado Core Size and Beamwidth displaying distinction between TS and TVS (image from Brown et al. 2002).

C. Current Research

Detailed tornado climatologies that investigate either strong, high-impact tornadoes, or large-scale outbreaks (mostly in the Midwest) already exist (David et. al. 1976; Doswell et al. 1980; Dunn et al. 2001; Rasmussen et al. 1998; Roebber et al. 2002; Wilczak et al. 1992). This study involves weaker tornadoes in a less-studied region. The high CAPE values found in the Midwest are much less common in the Northeast, and warm moist air is rarer (Bosart et. al.

2006). Tornado formation, however, is still an issue in Southern New England, as shown in *Fig. 2*. More advanced warning is important in this region as the public is generally less prepared for a tornado.

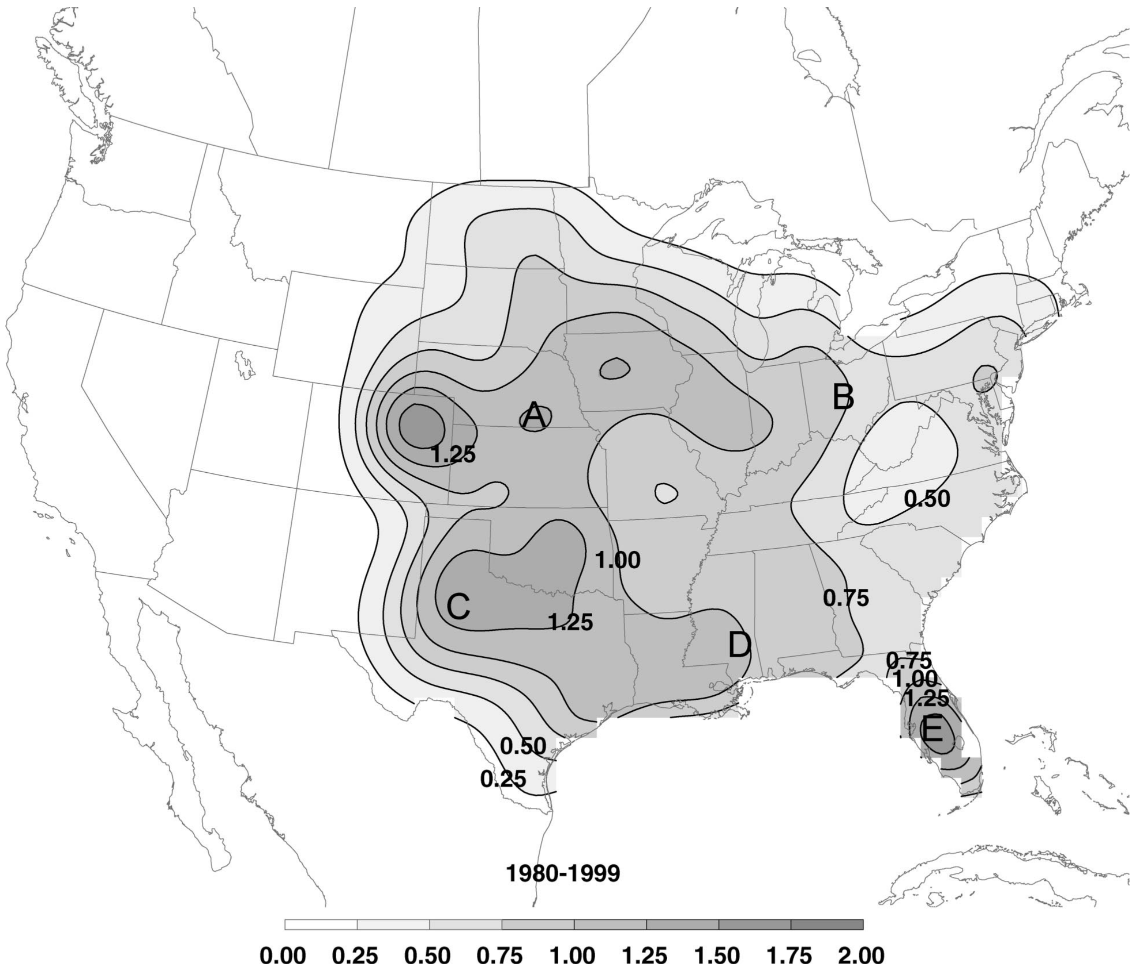

Fig. 2: **United States Tornado Frequency Distribution.**
Mean number of tornado days per year in the United States [1980-1999] (Brooks et al. 2003).

III. Data Used for the Study

A. North American Regional Reanalysis (NARR)

The NARR is a National Centers for Environmental Prediction (NCEP) project for long-term, high resolution atmospheric data based on Eta model initializations covering a 25-year period. Most parameters are available on 29 levels with 32 km resolution (Mesinger et al. 2006).

There are improvements in the NARR over other reanalyses, such as more accurate 2 m moisture over land (useful for this study) which will be discussed later. *Table 3* and *Table 4* show which parameters were used in the analysis of the dates shown in *Table 2*.

Table 2: **Dates Used for the NARR Data.**

Date	**Details**
3 July 1997	4 tornadoes occurred across Northwest Massachusetts and Southern New Hampshire. There were 3 EF1 strength, and 1 EF2.
6 August 1997	A weak storm cell produced an EF0 tornado in Westport, MA in Southeast Massachusetts.
31 May 1998	A squall line produced an EF2 tornado in the town of Antrim, NH in Southwest New Hampshire.
2 June 2000	A cold front moving east across interior Massachusetts spawned a squall line which produced an EF1 tornado in Leeds, MA.
16 August 2000	Two tornadoes occurred on this date. The first was an EF1 in Ellington, CT in North Central Connecticut. The second was an EF0 in Foster, RI, which is in Northeast Rhode Island.
17 June 2001	The remnants of Tropical Storm Allison moved across New England and produced an EF2 tornado in Princeton, MA in North Central Massachusetts.
23 June 2001	A weak EF0 tornado was produced in East Hartland, CT in Northern Connecticut.
30 June 2001	An EF0 tornado was produced over Bellingham, MA southwest of Boston in a south-moving squall line.
23 July 2002	A squall line ahead of an advancing cold front produced an EF1 tornado in West Brookfield, MA, in Central Massachusetts.
21 August 2004	A squall line leading an advancing cold front produced an EF1 tornado in Wrentham, MA, near the Rhode Island state line.
20 May 2006	An EF0 tornado was formed in an unfavorable environment with cool temperatures aloft as the primary support in Portsmouth, RI in Southeast Rhode Island.
11 July 2006	An EF2 tornado was produced in Wendell, MA in interior Massachusetts and occurred in an isolated storm cell.

Table 3: **NARR variables used in the Synoptic Analysis.**

Level	**Parameters**			
200 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)		
500 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)	Absolute Vorticity (s^{-1})	Temperature (°C)
700 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)	Temperature (°C)	
850 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)	Temperature (°C)	
Surface	Mean Sea-Level Pressure (hPa)	Precipitable Water (mm)		

Table 4: **NARR Paremeters used in the Mesoscale Analysis.**

Level	Parameters	
925 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)
950 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)
975 hPa	Wind Speed on a Pressure Surface (m s^{-1})	Geopotential Height (m)
10 meter	Isotachs (m s^{-1})	
Surface	Surface-based CAPE (J kg^{-1})	0–3 km SRH (m^2 s^{-2})
Surface	2 m Dew Point (°C)	Mean Sea-Level Pressure (hPa)

B. NCDC NEXRAD Data Archive

NEXRAD data for all sites is archived at the National Climatic Data Center (NCDC). Radar data 1 hour prior to, and 30 minutes following the time of the tornado were used to observe storm evolution. The lowest scan of the base reflectivity was used to identify signatures such as hook echoes. The *Mesocyclone Recognition Guidelines* at the NWS require the use of SRM, so it is also used. The SRM product is the base velocity with Nyquist velocity folding removed and overall storm motion subtracted such that motion within the storm is shown.

C. Data Limitations

With 32 km horizontal grid spacing, the NARR has limited capabilities with smaller scales of motion since features must span at least 6 to 8 grid points to be resolved properly (COMET Program 2007). The temporal resolution is also limited as data is only present every 3 hours (00 UTC, 03 UTC, 06 UTC, 09 UTC, 12 UTC, 15 UTC, 18 UTC, and 21 UTC). NARR data also takes up to one month to publish to the NCDC server, which prompted the removal of event 13.

Many of the events in this study occur in the western and northwestern region of the CWA, where radar resolution is coarse. The lowest radar scan is over 2 km higher than its source at these horizontal distances, returning echoes above low-level features. SRM data is affected by *range folding* (caused by second-trip echoes from the much shorter pulse repetition frequency to obtain meaningful velocity readings) preventing a clear view of signatures in distant regions. Radar resolution limitations, however, can occasionally be overcome by using neighboring sites.

This project was also underway during the conversion to the Enhanced Fujita Scale on 1 February 2007. In order to keep the study consistent (in the event of any events occurring in 2007), Joe Dellicarpini, Science and Operations Officer at the Taunton Forecast Office, reclassified each event to this new scale. Only event 6 saw a numerical change through this (from F1 to EF2).

IV. Methods

A. Synoptic Scale and Mesoscale Data Acquisition / Analysis

NARR data was collected through the 'nomads' web server and was analyzed to note the evolution of prominent features as the time of tornadogenesis approached. This included the evolution of troughs, upper-level circulations, jet streaks, moisture and temperature advection. Mesoscale analysis included low-level wind patterns, moisture, pressure, CAPE, and SRH. Each event was placed in specific categories (A through E), which are listed below. *Table 5* details the final criterion for classifying each event.

Type A: Closed Low over Southern Ontario

Overall, 5 of the 12 events are classified as Type A. In these events, a strong upper-level closed low at 500 hPa is present in Southern Ontario, Canada (see *Fig. 3*). A strong jet at 200 hPa is located in the vicinity of the Northeastern United States (either with Left Exit or Right Entrance positioning). The example in *Fig. 4* shows the right entrance region jet. The jet's core velocity is upwards of 120 kts. Ample moisture is present in these cases, with precipitable water near 50 mm (*Fig. 5*), and dew points approach the mid 20 °C range (70 °F) (*Fig. 6*).

Temperatures at 700 hPa are around 5 °C, and CAPE values of 1500 J kg^{-1} are common. The environment is also strongly sheared, with SRH values ranging from 160 m^2 s^{-2} up to 300 m^2 s^{-2}. Both CAPE and SRH example analysis can be found in *Fig. 7*.

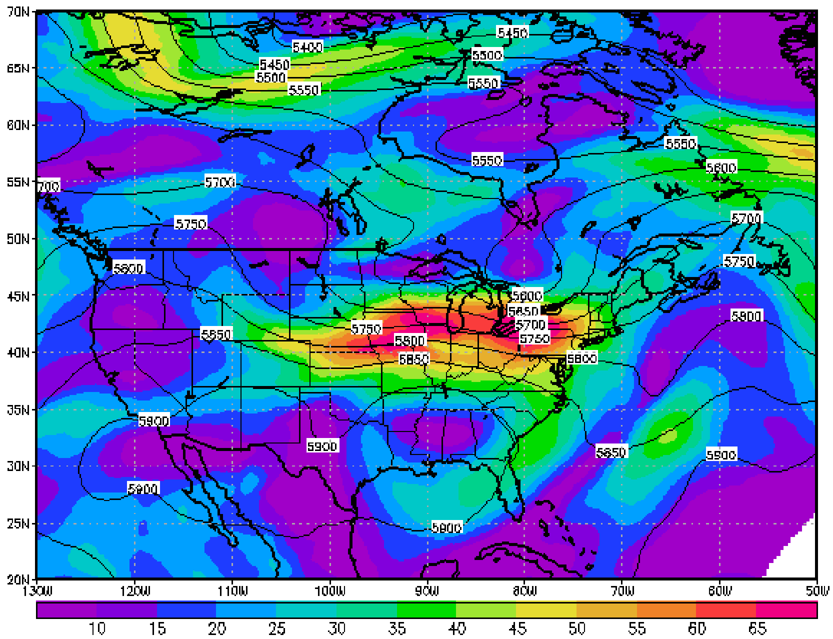

Fig. 3: **Type-A Midtropospheric Flow Pattern.**
Chart showing 500 hPa winds (shaded, kts) and geopotential height contours from 21 UTC on 3 July 1997.

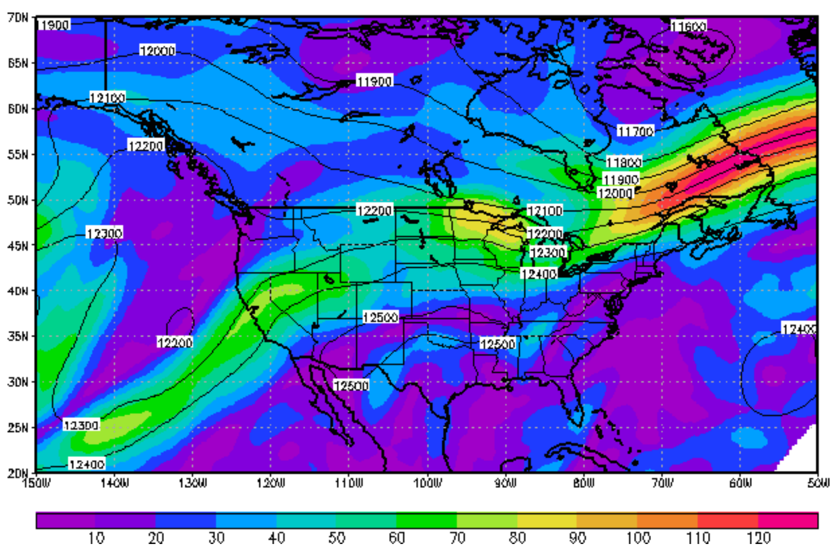

Fig. 4: **Type-A Jet Stream Pattern.**
Map showing 200 hPa winds (shaded, kts) and geopotential height (m) from 18 UTC on 23 July 2002.

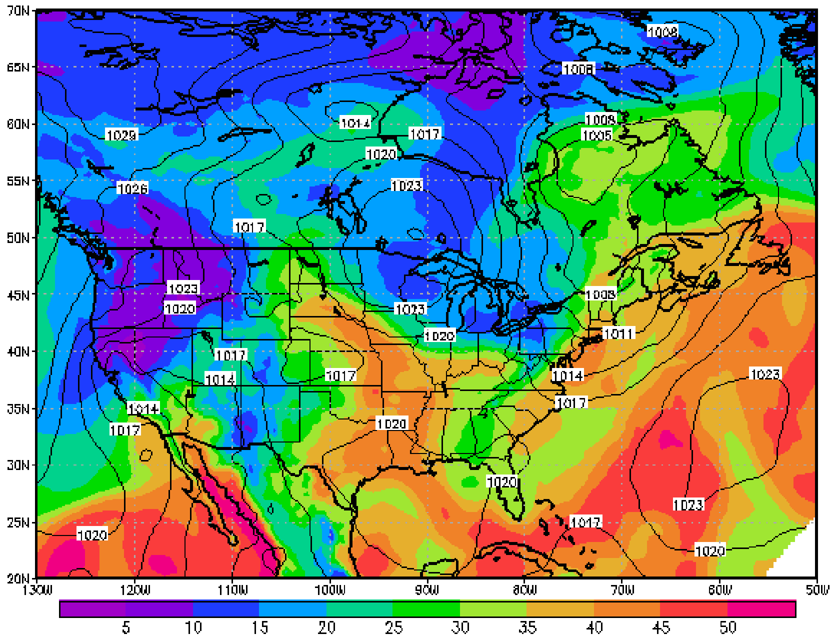

Fig. 5: **Type-A Low Level Moisture Analysis.**
Surface-based precipitable water (shaded, mm) and MSLP from 12 UTC on 16 August 2000.

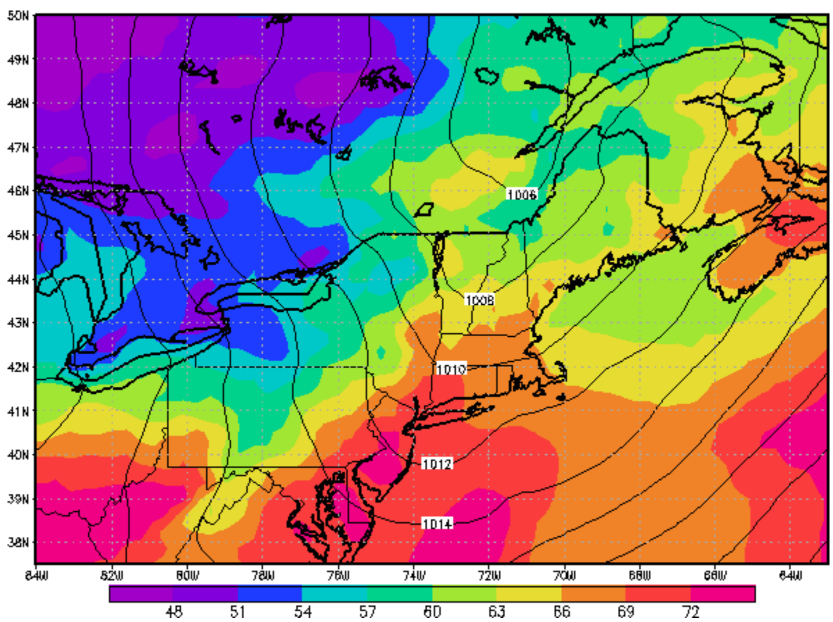

Fig. 6: **Type-A Mesoscale Dew Point Temperatures.**
2 m dew point temperatures (shaded, °F) and MSLP from 15 UTC on 16 August 2000.

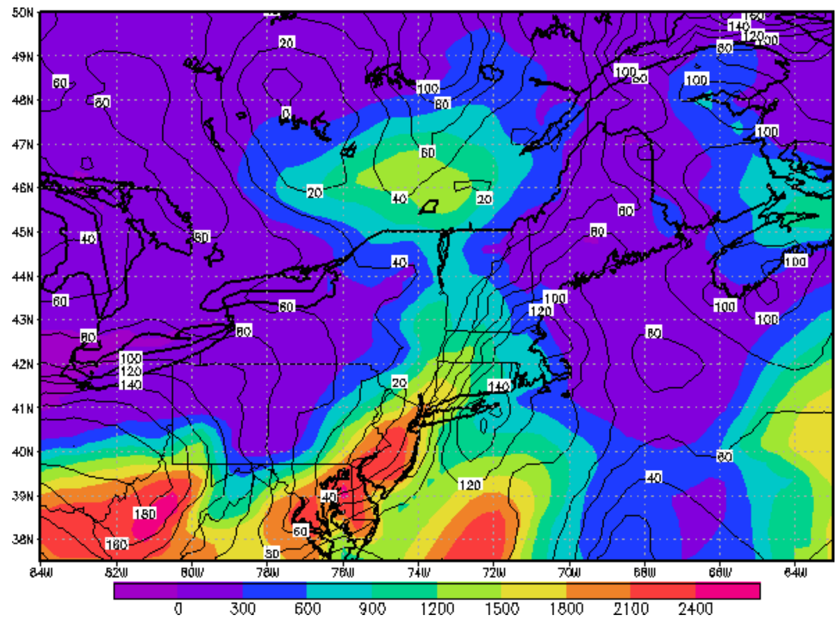

Fig. 7: **Type-A CAPE/SRH Parameters.**
Surface-based CAPE (shaded, J kg^{-1}) and 0-3 km SRH (m^2 s^{-2}) from 15 UTC on 16 August 2000.

Type B: Open Trough over Great Lakes

A total of 3 events in the study are categorized as Type B. Their distinguishing feature is a trough at 500 hPa over the 95 °W longitude line (*Fig. 8*). There is also a shortwave with a vorticity maximum present in the Northeast. Due to the trough placement, flow aloft is predominantly southwest. Most other parameters are similar to Type A events. At 700 hPa, temperatures are between 5 – 10 °C. Surface-based CAPE values range from 1000 to 1500 J kg^{-1} and SRH values are consistently over 150 m^2 s^{-2}. Sufficient moisture is present in the Northeast, with precipitable water values around 40 mm and dew points near 21 °C (70 °F).

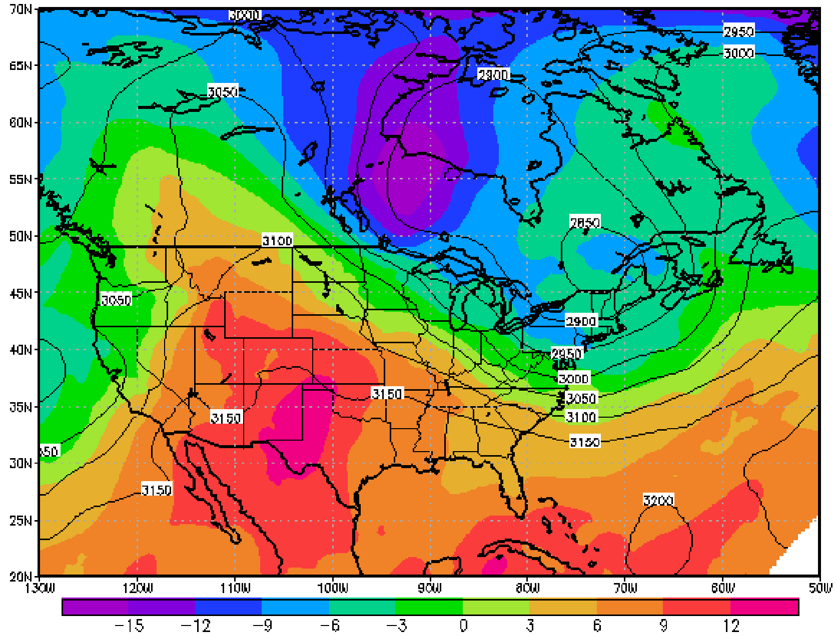

Fig. 8: **Type-B Midtropospheric Flow.**
500 hPa Absolute vorticity (shaded, s^{-1}) and geopotential height from 21 UTC on 30 June 2001.

Type C: Deep Trough over Great Lakes

Only one Type C event exists in this study. It is similar to Type B events in that there is a trough over the East-Central United States, as seen in *Fig. 9*. This trough has a short wavelength but is very deep, as signs of it appear in the upper troposphere. This, combined with CAPE values not exceeding 500 J kg^{-1} and higher shear prevent the event from being categorized as Type B. Nevertheless, there is ample atmospheric moisture, as indicated by precipitable water and 2 meter dew point temperatures.

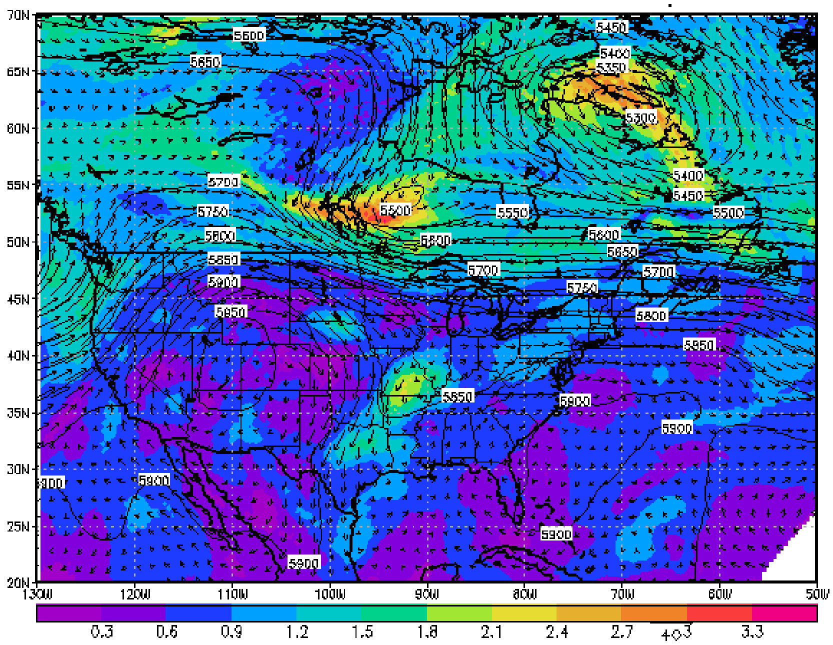

Fig. 9: **Type-C Midtropospheric Flow.**
500 hPa wind (shaded, kts) and geopotential height analysis (m) from 15 UTC on 23 June 2001.

Type D: Tropical Remnants in Northeast

Tropical cyclones that produce tornadoes are rare in New England, a case in point being that this study has only one such event. In this case, the Northeast is under the influence of the right entrance region of a 90 kt jet. As shown in *Fig. 10*, the environment is perturbed due to the storm's presence. There is ample moisture provided by the tropical air which enters a cooler regime. Precipitable water values exceed 50 mm (*Fig. 11*), and dew point temperatures reach around 21 °C (70 °F). Surface temperatures are lower as a result of the inherent cloud deck in advance of the system. Because of this, only modest CAPE (1000 J kg^{-1}) and SRH (120 m^2 s^{-2}) are present.

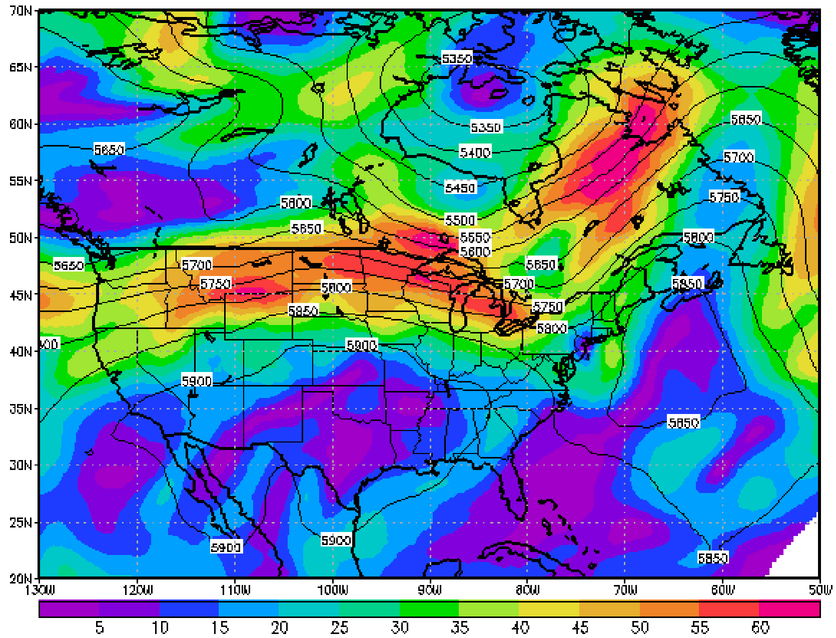

Fig. 10: **Type-D Midtropospheric Flow.**
500 hPa winds (shaded, kts) and geopotential height from 15 UTC on 17 June 2001 showing perturbed flow in Northeast.

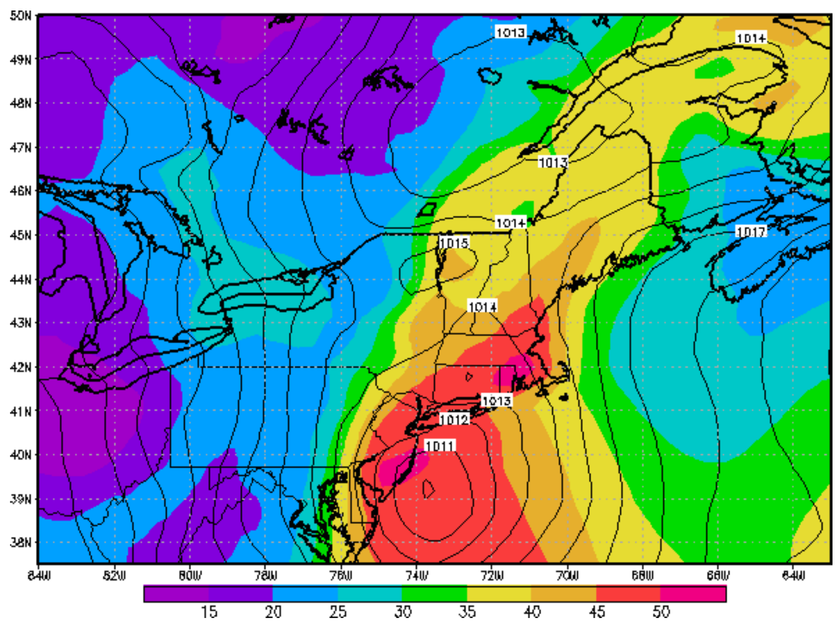

Fig. 11: **Type-D PWAT / MSLP Parameters.**
Precipitable water analysis (shaded, mm) and MSLP (Eta analysis, hPa) from 15 UTC on 17 June 2001.

Type E: Cold Air Pool Aloft

Of the events in this study, 2 are categorized as Type E. The most notable feature of these events is the cold daytime temperature at 700 hPa. Compared to all other events in this study, the

700 hPa temperatures are nearly 15 °C colder. The 700 hPa temperature analysis from Event 11 is in *Fig. 12*, where temperatures are between -3 and -9 °C. Little moisture is present, and with cooler surface temperatures, dew point values below 60 °F and precipitable water is only 20 mm. These events are similar to what Doswell and Burgess (1993) discussed about cold pool vorticies. It is uniformly dry at the surface across the Northeast. Dew point values are low (10 °C (50 °F)), which increases the LCL, making it less likely for tornadogenesis.

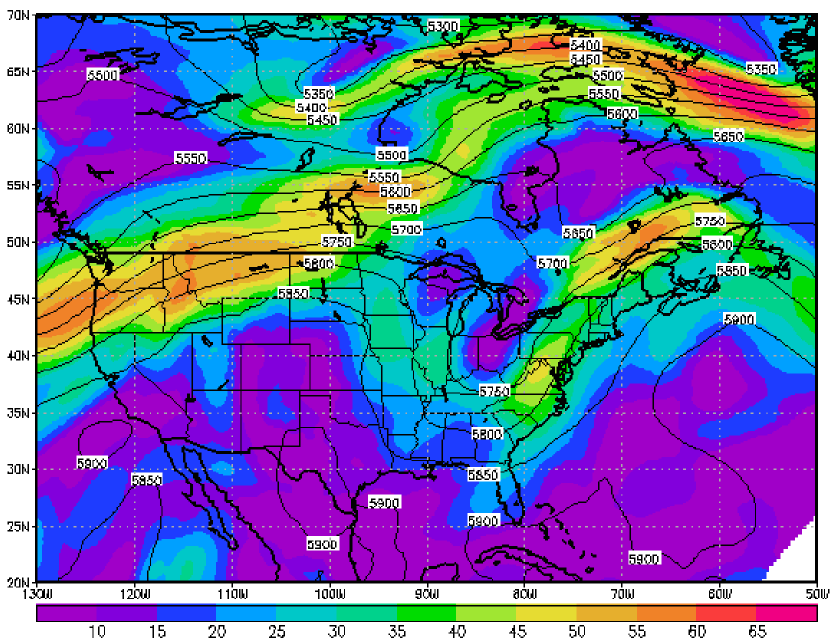

Fig. 12: **Type-E Lower Tropospheric Temperature.**
700 hPa temperature (shaded, °C) and geopotential height (m) from 15 UTC on 20 May 2006.

Table 5: **Summary of Categorization derived from NARR**

Type	Jet Position	Jet Strength	700 hPa Temp.	Approx. SBCAPE	Approx. 0-3 km SRH
A_1	Left Exit	60 m s^{-1}	5 °C	1750 kg^{-1}	250 m^2 s^{-2}
A_2	Right Entrance				
B	Right Entrance	50 m s^{-1}	7 °C	1250 kg^{-1}	160 m^2 s^{-2}
C	Right Entrance	50 m s^{-1}	5 °C	500 kg^{-1}	150 m^2 s^{-2}
D	Right Entrance	45 m s^{-1}	5 °C	1000 kg^{-1}	120 m^2 s^{-2}
E	Variable	Variable	-15 °C	400 kg^{-1}	< 50 m^2 s^{-2}

B. NEXRAD Data Acquisition

NEXRAD data from NOAA's archive can be retrieved through the National Climactic Data Center's (NCDC) Hierarchical Data Storage Access System (HAS). The relevant radar parameters detailed in Section 3b were analyzed for each case. SRM data was compared to the Mesocyclone Recognition Guidelines Chart used operationally by the NWS (*Fig. 13*), where the rotation is found as a function of a couplet's rotational velocity and its radial distance from the radar.

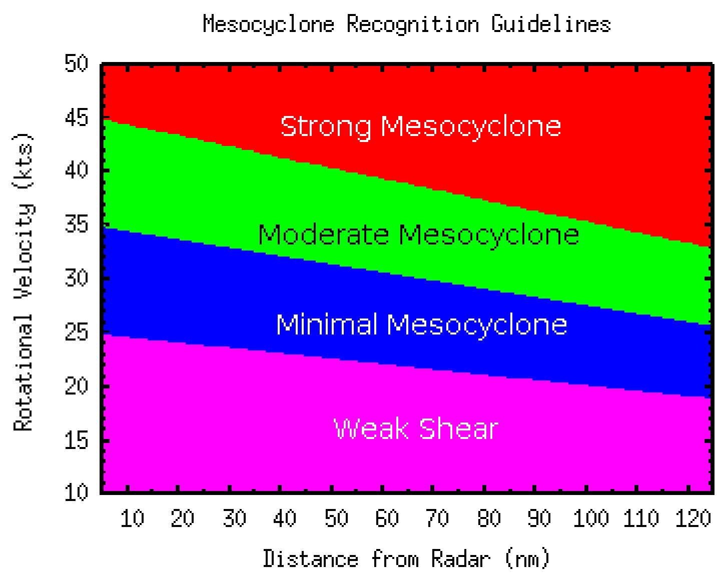

Fig. 13: **NWS Mesocyclone Recognition Chart.**
(created with GNUPLOT and The GNU Image Manipulation Program).

To determine the strength of the mesocyclone, the rotational velocity must be determined through the use of the formula,

$$v_r = \frac{v_{\text{max in}} + v_{\text{max out}}}{2}$$

This computes rotational velocity by averaging the strongest inbound pixels to the strongest outbound pixels in a couplet. The Data Viewer / Exporter application can sample the distance of a feature from the radar source. The mesocyclone is then categorized by plotting on *Fig. 13* using this radius and radial velocity.

V. Analysis

This section contains the analyses of selected events from each category. The events discussed are Event 10 (21 August 2004), Event 4 (2 June 2000), Event 7 (23 June 2001), Event 6 (17 June 2001), and Event 11 (20 May 2006). These events were selected for this section due to their strong adherence to the criterion determined after all cases were compiled.

A. Closed Low over Southern Ontario

Event #10: 21 August 2004 – Wrentham, MA

On this day, a squall line associated with an approaching cold front originating in eastern New York and advanced across central and southern New England (Vallee et al. 2006). This storm produced an EF1 tornado in Wrentham, MA at 19:45 UTC.

This storm is classified as a Type A event due to the jet positioning and other defining mid-tropospheric features, most notably the geopotential height field. Also worth noting is a coastal jet stretching from Long Island to the Gulf of Maine, which forms and strengthens to 40 kts through the afternoon. An analysis of the radar (*Fig. 14*) shows the approaching squall line beginning to hook near 19:45 UTC. The associated velocity couplet can be seen clearly in *Fig. 15*. After the event at 19:53 UTC, a well-defined hook echo emerges, but the entire supercell weakens by 20:00 UTC and transitions back into the bow echo (Vallee et. al. 2006).

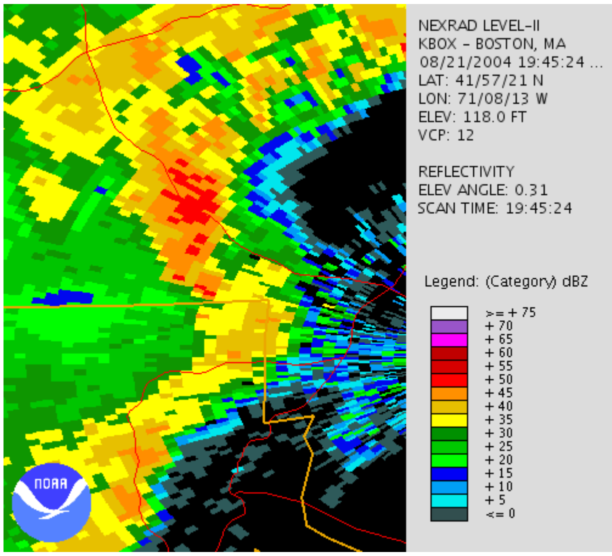

Fig. 14: **Event 10 Base Reflectivity.**
Reflectivity shows hooking section of storm cells.

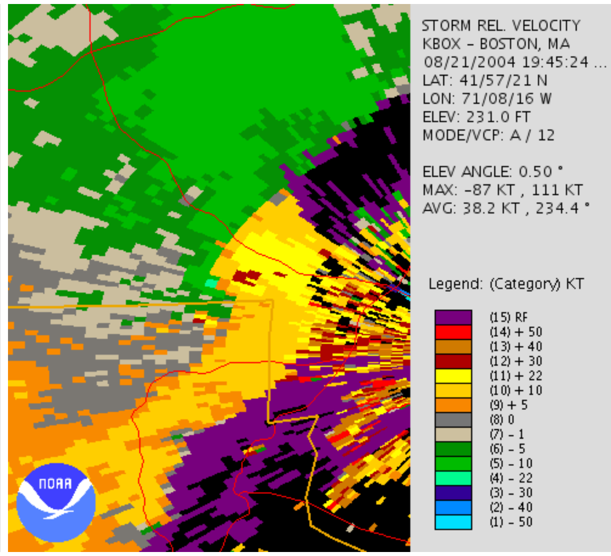

Fig. 15: **Event 10 Storm Rel. Motion.**
SRM showing minimal mesocyclone signature.

B. Open Trough Over Great Lakes

Event #4: 2 June 2000 – Leeds, MA

At 21:00 UTC, a passing cold front from a low pressure system over Quebec produced an EF1 tornado in Leeds, MA. A surface analysis reveals a warm front passage 24 hours prior to the event putting New England in the warm sector. This provides more moisture for the severe environment.

The radar tracks a strengthening cell with a +65 dBZ core ahead of a squall line and stratiform precipitation (*Fig. 16*). After the tornado is produced, the reflectivity values increase, indicating a strengthening core. The SRM product in *Fig. 17* shows a clear rotational couplet, rating as a minimal mesocyclone.

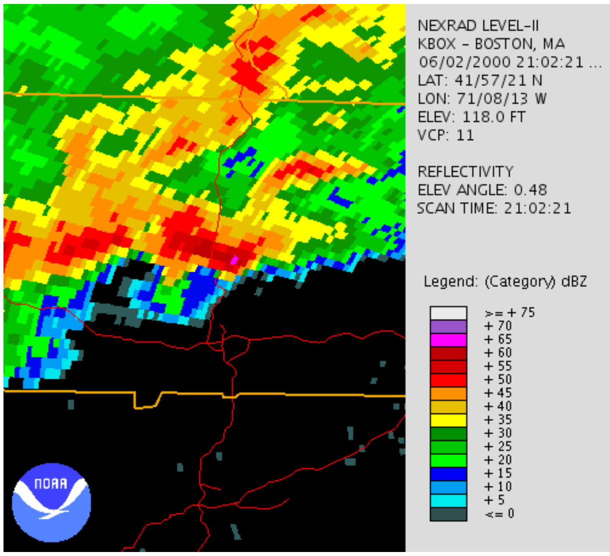

Fig. 16: **Event 4 Base Reflectivity.**
Cell with 65 dBZ core showing slight hooking.

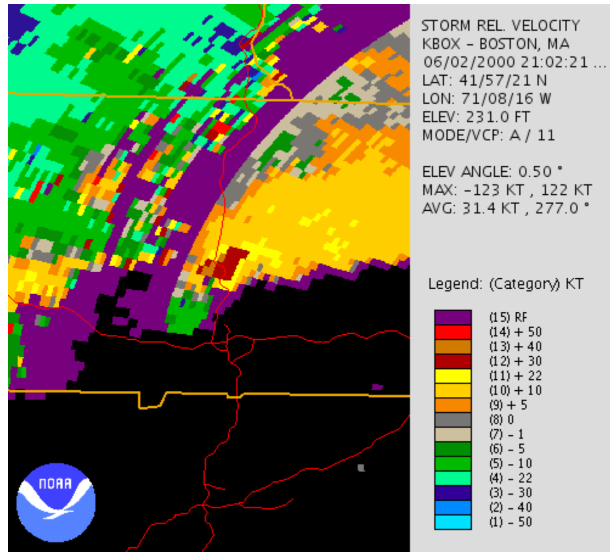

Fig. 17: **Event 4 Storm Rel. Motion.**
SRM shows difficulty with range-fold just to the west of the mesocyclone.

C. Deep Trough Over Great Lakes

Event #7: 23 June 2001 – East Hartland, CT

During the early afternoon hours, several storms were present in southwestern New England, one of which produced an EF0 tornado in East Hartland at 19:18 UTC. New England is located in the warm sector of a surface low during the event. Thus, this convection occurs without the presence of a significant boundary.

This event is an important example for the use of neighboring radar sites (if available). The Taunton (KBOX) radar data shows no signs of rotation or significant reflectivity values. The KENX radar (in Albany, NY) tracks several cells as they develop in western Massachusetts and Connecticut (*Fig. 18*). While the Albany radar provides greater resolution, the storm has only 20 kts of rotational velocity (*Fig. 19*). This cell registers as weak shear according to the mesocyclone recognition guidelines.

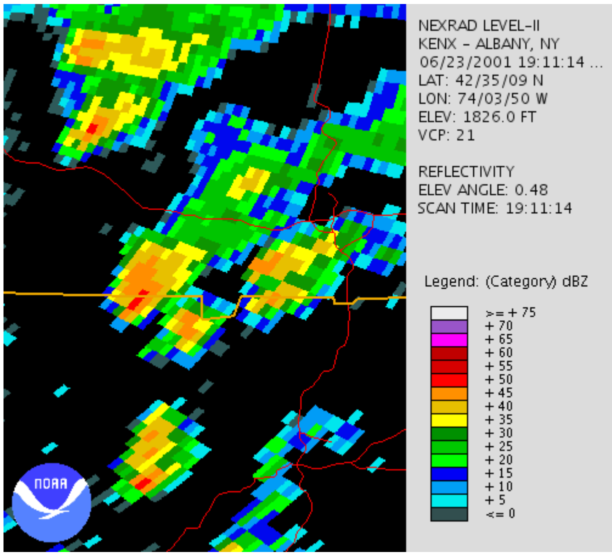

Fig. 18: **Event 7 Base Reflectivity.**
Radar from KENX shows tornado-producing cell near East Hartland, CT.

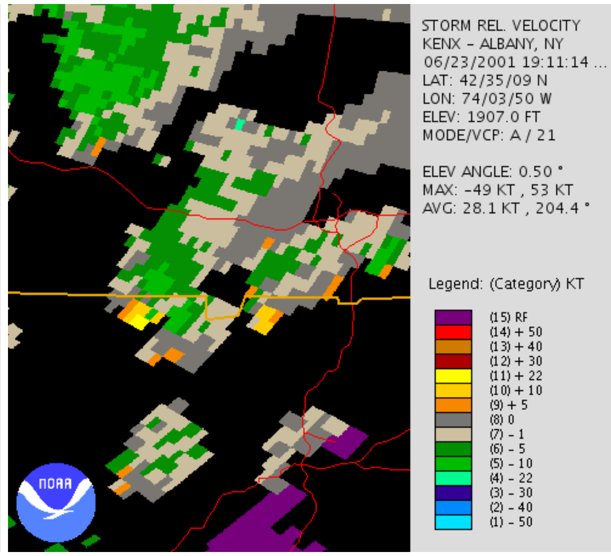

Fig. 19: **Event 7 Storm Rel. Motion.**
SRM shows very weak cyclonic rotation.

D. Tropical Remnants

Event #6: 17 June 2001 – Princeton, MA

During the morning hours, the remnants of Tropical Storm Allison moved up the East Coast of the United States and brought both large scale stratiform rain and thunderstorms. One of the stronger cells in Princeton, MA produces an EF2 tornado at 15:41 UTC. The remnants of Allison moved into the right entrance region of the 200 hPa jet core just west of New England.

The radar data with this event is the clearest of all event in this study, with a rotational signature appearing several scans prior to tornado formation. The reflectivity tracks the northeast-moving line of storms through central Massachusetts (see *Fig. 20*), but the most northern portion appears to detach from the rest of the line, showing signs of rotation in its +60 dBZ core. The SRM data (*Fig. 21*) shows the strong rotational couplet, which classifies as a moderate mesocyclone due to its proximity to the radar and 36 kts of rotational velocity.

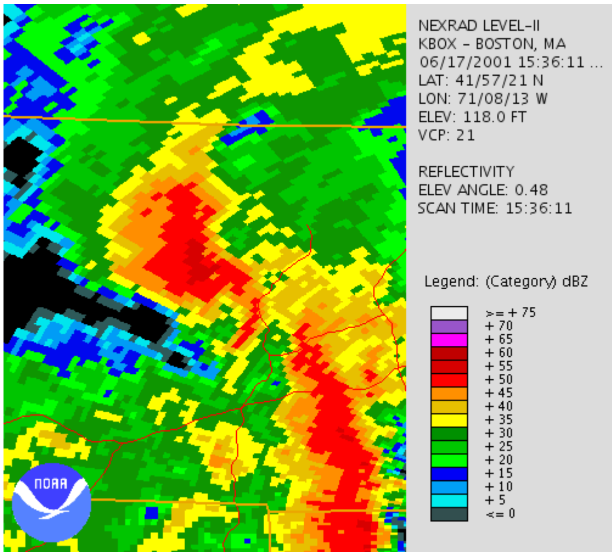

Fig. 20: **Event 6 Base Reflectivity.**
Base reflectivity scan shows +60 dBZ core cell that produced EF2 tornado over Princeton, MA.

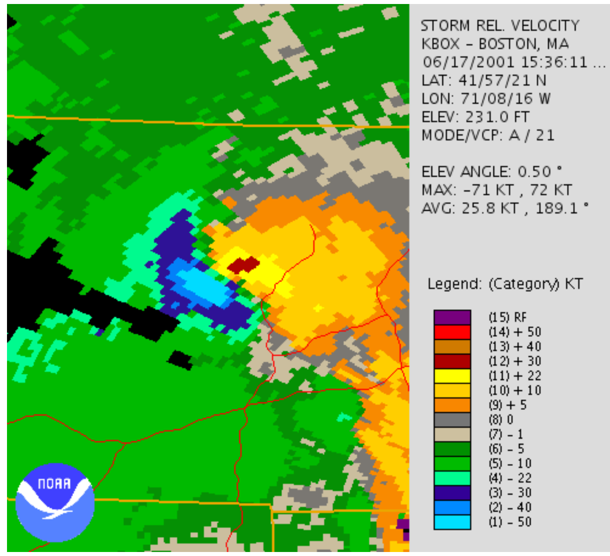

Fig. 21: **Event 6 Storm Rel. Motion.**
SRM data shows clear rotating mesocyclone signature.

E. Cold Air Pool Aloft

Event #11: 20 May 2006 – Portsmouth, RI

The EF0 tornado in Portsmouth, RI formed in an unfavorable environment but with cold temperatures aloft. This event follows most of the Type E classification, but is unique in that New England is between the left entrance region of one jet and the left exit region of another. There are no storms in the immediate vicinity of Portsmouth during the time of tornadogenesis. The radar reflectivity (*Fig. 22*) at the time of tornadogenesis reveals a single +15 dBZ pixel. The base velocity data is inconclusive, but suggests some pixels of weak ground-relative rotation, as shown in *Fig. 23*.

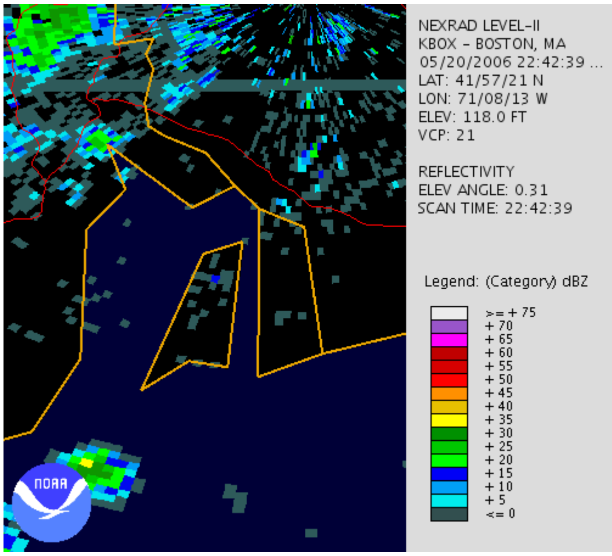

Fig. 22: **Event 11 Base Reflectivity.**
There is a single 15 dBZ pixel over Portsmouth, RI.

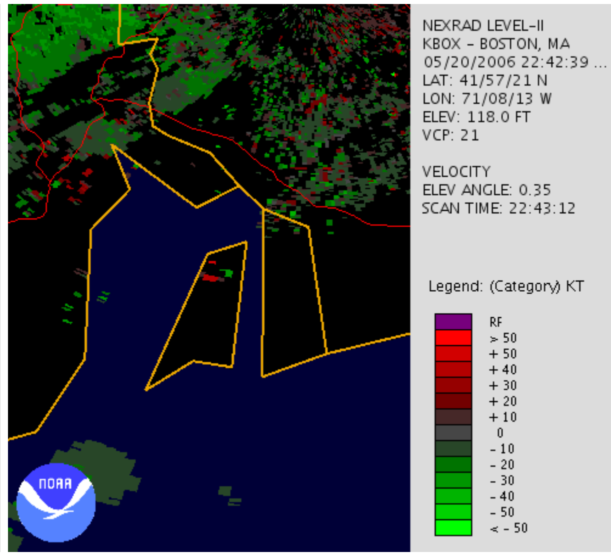

Fig. 23: **Event 11 Base Velocity.**
Base velocity showing possible rotation.

VI. Results

A. The Low-Level Coastal Jet

A low level coastal jet forms along the Southern New England coast in several events. The jet is a localized feature, which parallels the coastline at 975 hPa and can reach up to 45 kts. It tends to appear 6-9 hours prior to when tornadogenesis occurs and exists for several hours. It only occurs in Type A and B events when a strong EF1 or stronger tornadoes occur. This rule is followed for most cases, except for event 12, which is a Type B producing a moderate EF2, with no coastal jet present. *Table 6* details the events which contain the jet.

Table 6: **Local Jet Event Comparison Table.**
Each tornado day is represented. Type A and B days with stronger tornadoes should have a coastal jet, according to the rule, event 12 is the only noted exception, and is shown in boldface. Type A1 events had left exit region jet positioning whereas Type A2 indicates right entrance region jet positioning.

Event #	Date / Time	Intensity	Classification	Local Jet?
1	3 July 1997, 23:55 UTC	EF1, EF1, EF1, EF2	Type A1	Present
2	6 August 1997, 18:15 UTC	EF0	Type E	Absent
3	31 May 1998, 22:03 UTC	EF2	Type A1	Present
4	2 June 2000, 21:00 UTC	EF1	Type B	Present
5	16 August 2000, 19:00 UTC	EF1, EF0	Type A1	Absent
6	17 June 2001, 15:41 UTC	EF2	Type D	Absent
7	23 June 2001, 19:18 UTC	EF0	Type C	Absent
8	30 June 2001, 23:25 UTC	EF0	Type B	Absent
9	23 July 2002, 19:15 UTC	EF1	Type A2	Present
10	21 August 2004, 19:45 UTC	EF1	Type A2	Present
11	20 May 2006, 22:45 UTC	EF0	Type E	Absent
12	**11 July 2006, 18:30 UTC**	**EF2**	**Type B**	**Absent**

B. 0-3 km SRH and SBCAPE Values

Shear, as defined by the 0 – 3 km SRH, is a more consistent parameter than surface-based CAPE. Most events have SRH values in excess of at least 120 m^2 s^{-2}. In general, CAPE values should be above 1500 J kg^{-1} if stronger tornadoes (EF1 to EF2) are to form. A graphical comparison of CAPE and SRH can be found in *Fig. 24*. In the rest of the country, low CAPE is typically offset by increased SRH, and vice versa (*Fig. 25*). In our study, there is little correlation between CAPE and shear, but on average, these tornadoes require less CAPE than their Midwestern counterparts.

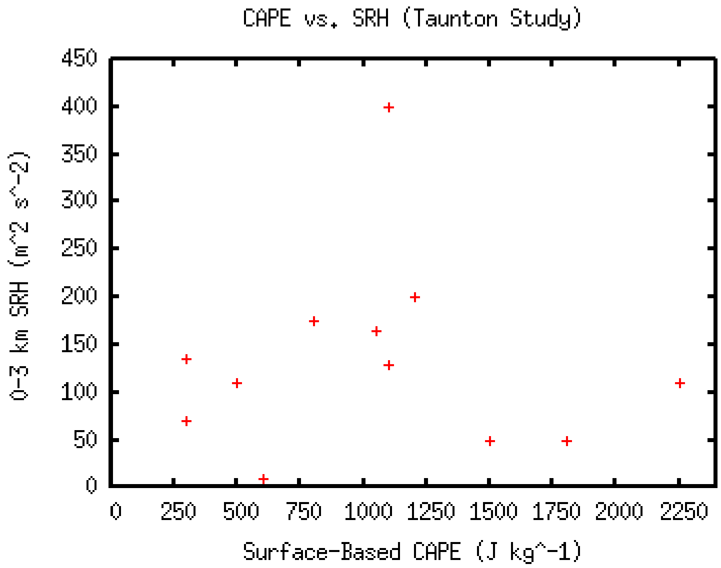

Fig. 24: **CAPE vs. SRH (Taunton Study).**
Comparison of CAPE to SRH values from the events in this study. Image generated with GNUPLOT.

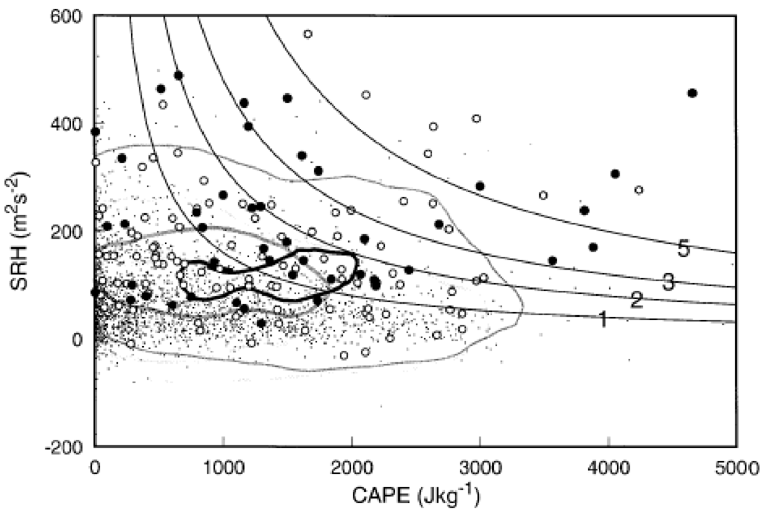

Fig. 25: **CAPE vs. SRH (Rasmussen and Blanchard 1998)**
CAPE / SRH comparison chart shows larger values for each quantity required for tornadogenesis.

C. Deep Low-Level Moisture

Stronger tornadoes in this study require high levels of moisture. The minimum dew point needed for tornadogenesis is 20 °C (68 °F) at 2 meters. This value aligns well with the 18 °C (65 °F) benchmark determined by Williams (1976). Precipitable water amounts in the pre-storm environment should be above 40 – 45 mm (1.5 – 1.75 in). One can infer lower LCL values and greater latent heat energy exchange with these parameters.

D. Terrain Influences in Western New England

Recent research of this region suggests terrain boundaries influence the development of severe weather (Bosart et al. 2006; LaPenta et al. 2005; Wasula et al. 2002). While complex terrain tends to inhibit tornadogenesis, long lived tornadoes have been observed in cells crossing these regions, and some analysis suggests a sharp rise in shear when cells cross over increasing elevation while crossing valleys as shown in *Figure 26* (Bosart et. al. 2006).

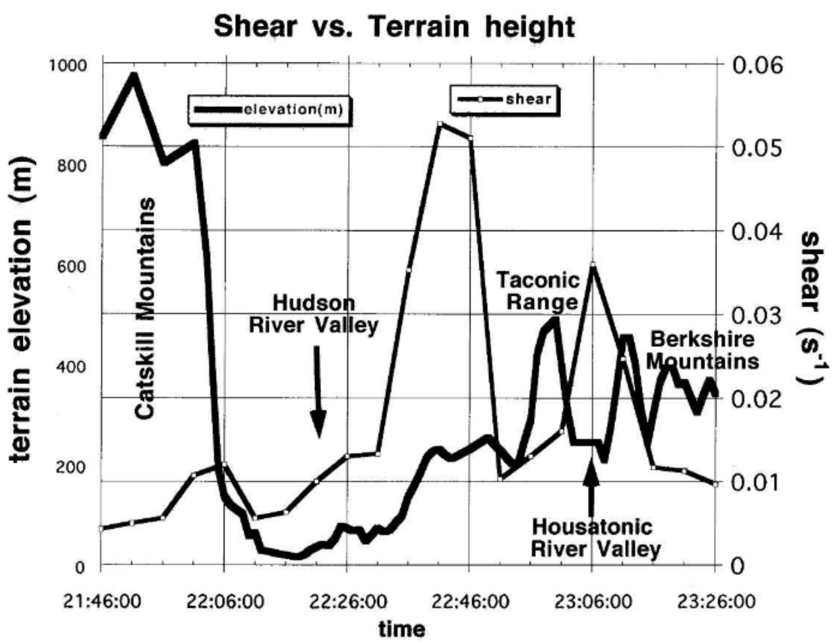

Figure 26: **Shear vs. Terrain Height.**
Comparison of upstream shear and terrain features in Eastern NY and Western MA (Bosart et. al. 2006).

Due to a lack of observations in the Eastern New York and Western Massachusetts regions, mesoscale knowledge is reduced. Research suggests an enhancement of southerly flow along valleys in Western New England, bringing warm, moist air into the region (LaPenta et. al. 2005). Also, SRH is increased in this area of channeling due to the change in flow direction causing passing storms to encounter pockets of greater shear. However, the resolution of the NARR makes these features undetectable in the reanalysis.

E. Variety of Environments with Tornadogenesis

Analysis of the radar data shows that Southern New England tornadoes occur most often at the leading edge of a squall line. Tornadogenesis also occurs within pulse convection, which frequently occurs in Southern New England during the summer months. Supercells also provide a means for tornadogenesis, but occur infrequently. Tropical storms which produce tornadoes are even rarer in the region. While cold pool vorticies are also rare, they provide an example of non-threatening environments and cells that are capable of producing a tornado.

VII. Conclusion

A. Research Conclusion

Several differing environments and influences can be conducive to the formation of weak tornadoes in Southern New England. Strong jet streaks are required aloft, and the midtropospheric flow is also influential. The required low-level shear is lower than that of Midwestern systems. Deep moisture and warm surface temperatures are required. Potential buoyancy in the environment is inconsistent and the inverse relationship of CAPE and SRH present in Midwestern systems does not to apply in these events.

This study demonstrates the limitations of radar data, especially over western portions of Massachusetts where resolution degrades and data is above important features beyond the Worcester Hills. When future tornadoes develop, more complete conclusions about radar data will be possible. Also, future resolution enhancements to the WSR-88D system allowed by Open RDA will allow for improved detection of mesoscale features in these areas. *Fig. 27* shows the much clearer sampling possible through this enhanced resolution. The left side shows enhanced resolution and the right side shows the current WSR-88D 1.39° effective beamwidth used operationally. The *effective beamwidth* is a phenomenon that occurs as the radar constantly rotates as it sends and receives data (Wood et al. 2001).

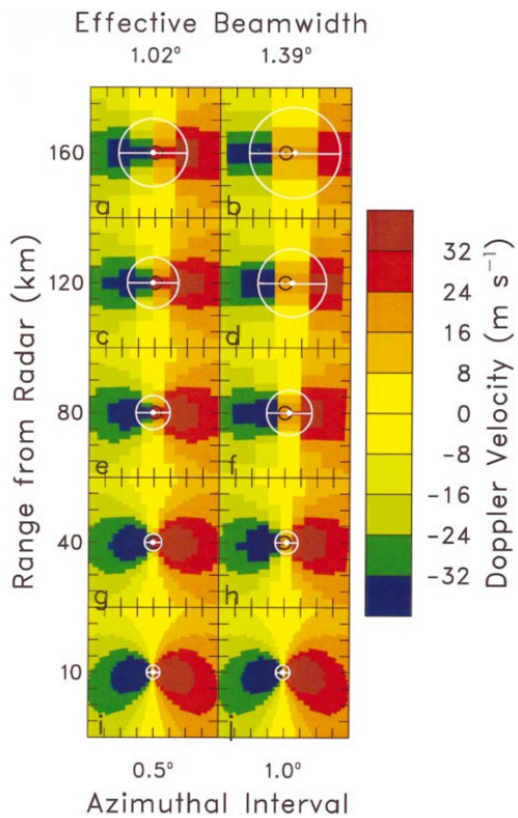

Fig. 27: Idealized Mesocyclone signatures with resolution enhancement on left side (image from Brown et al. 2002).

Future studies will be enhanced by the use of improved data that will further populate the categorization scheme and provide more examples of the echo types within storms. This will supply a basis to do a statistical analysis on which classifications occur more frequently. Further research should also focus on the formation of the low level coastal jet to clarify its role in Southern New England tornadogenesis.

The results of the project suggest a connection with the low level jet and certain synoptic environments when tornadoes are present. This is a previously unstudied feature and could be an interesting area of further study. It could also be useful to compare the success rates of tornado identification with the implementation of this study's results and improved radar resolution.

B. Project Conclusion

The ability to work with the newer NARR data demonstrated a great amount of power for this type of research, especially in a way that non-professional or undergraduate meteorologists can utilize. It was also interesting to work with NEXRAD data present when tornadoes formed as it provided an ability to understand the data at a steady pace without the worry of producing warnings simultaneously.

This study demonstrates that radar data availability and quality remains a weak aspect of meteorology. Although events close to the radar source are present, higher resolution will improve the data quality of distant events. The NARR project is a start for understanding past events, and there is greater potential for mesoscale reanalyses with the Weather Research and Forecasting (WRF) model.

C. Summary

Verification data from the Taunton, MA NWS WFO demonstrated a need for improved detection of tornadoes in Southern New England. Out of 13 events in the study, none were greater than EF2, and few were detected with lead time. Tornado climatologies exist for intense events, but are nearly nonexistent in the Northeast U.S.

Prior research has demonstrated required parameters for more potent tornadogenesis in common systems, but climatologies show that there is a low (yet notable) tornado presence in the Northeast. In recent years, studies of Northeast tornadoes have been conducted and suggest terrain has a strong influence (at least with systems occurring in interior regions).

Synoptic and mesoscale data was obtained through reanalysis data provided by NARR. After the events were compiled and summarized, they were categorized into 5 different synoptic and mesoscale groups, *Types A* through *E*. The majority of stronger events are Type A (Southern Ontario Closed Low) and B (Open Great Lakes Trough). The results of each category's benchmarks are displayed in *Table 5*. Each event's radar data was also analyzed. There are detailed analyses of representative events for each category. A summary of them can be found in *Table 2*.

NARR data is limited since it is powered by a forecast model initialization. Its resolution is also too coarse to resolve many mesoscale features. With 3-hour time steps, it is rare that an analysis is close to the time when a tornado forms. The radar data is also limited in several ways. Since several tornadoes were in distant regions of the CWA's radar, resolution was greatly reduced. The radar beam is over 2 km above the ground in these regions. SRM data was also limited as the range-fold was near the mesocyclone signature in several events.

This project indicates Southern New England tornadoes have inconsistent buoyancy, consistent shear, and large amounts of moisture. Terrain has been showed to impact shear and low level moisture, especially in western Massachusetts. Tornadoes were found to form in a variety of severe environments, mostly with squall lines, supercells, and pulsed convection storms. They also form in non-severe environments, such as those influenced by cold pool vorticies. Finally, the presence of a low level jet off the coast of Southern New England near Long Island was shown to be consistent with *Type A* and *B* events, with the exception of event 12.

D. Final Remarks

Overall, this independent research project was a fulfilling experience. Collecting and interpreting the data was difficult, but finding several key differences in the environments associated with Southern New England tornadoes compared to the remainder of the United States proved that this project had a valid purpose. Many of the details of the study seemed overwhelming to comprehend at times, but the act of placing all of the ideas and results into this final paper certainly simplified the findings and made them easier to understand. This type of research was much more difficult just a few years ago. Currently, however, the data needed for it is easy to get and should be a very powerful tool for similar studies in the future. It was also empowering to know that the results of this research is going to be applied to future NWS training sessions in assisting forecasters for future tornadic scenarios.

Acknowledgments

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