Introduction
Strong and violent tornadoes are rare in southern New England but not unheard of. The latest significant tornado occurred on 1 June 2011 in Hampden and Worcester Counties in Massachusetts. The tornado was on the ground for over 37 miles, did nearly a quarter billion dollars in damage, killed 3, and injured 200 people between Westfield, MA and Sturbridge, MA.

There are several similarities between this tornado and other northeastern U.S. tornadoes including the 1995 Great Barrington, MA tornado and the 1998 Mechanicville, NY tornado. Understanding the synoptic and mesoscale features that are common in northeast severe weather outbreaks and tornadoes is vital to providing accurate forecasts and long lead time for severe weather alerts.

Synoptic Environment
The synoptic setup over the northeastern United States on 1 June 2011 was similar
to that of other significant northeast severe weather episodes. The 1200 UTC 1 June 500 hPa analysis shows a sprawling subtropical ridge from the Mid Atlantic southwest toward the southern plains. At the same time a strong short wave was moving east just north of the Great Lakes.

A relatively intense (sub 992 hPa) surface low pressure was located near the southern tip of Hudson Bay at 1200 UTC ahead of the 500 hPa short wave in an area of strong quasi-geostrophic forcing.

The presence of a surface cyclone north of the U.S./Canadian border is not atypical for large severe weather outbreaks in the northeastern United State. 31 May 1998, 10 July 1989, and 29 May 1995 all featured surface lows tracking northwest of Montreal, Quebec (CYUL) from Ontario into Quebec (per PSU NARR reanalysis).

The mid tropospheric (500 hPa) flow was out of the west and west-northwest during the day on 1 June 2011. Many significant severe weather days in southern New England
are associated with west or northwest 500 hPa flow (Johns and Dorr, 1996). Johns and Dorr found the presence of a west or northwest flow aloft can help advect elevated mixed layer air into the northeast. West or northwest flow also allows backed winds in the boundary layer (out of the south or southwest, for instance) to produce strongly curved hodographs without advecting in more stable marine-influenced air in the boundary layer.

The 1 June 2011 tornado occurred in the presence of steep mid level lapse rates and an elevated mixed layer (EML) which is typical of northeastern U.S. severe weather outbreaks (Banacos and Ekster, 2010). 1200 UTC soundings from Albany, New York (ALB) and Brookhaven, NY (OKX) reveal the presence of steep mid level lapse rates in excess of 7.5°C/km between 500 hPa and 700 hPa. In fact both soundings show nearly dry adiabatic lapse rates centered around 600 hPa which is indicative of a remnant EML plume.
Banacos and Ekster showed that 7.6% of significant severe weather days across the northeast were associated with an EML but those days produced a disproportionate number of fatalities and injuries. Most historic severe weather days in recent decades were associated with an EML including 9 June 1953, 10 July 1989, 20 June 1995, 15 July 1995, and 31 May 1998 to name a few.

**Mesoscale Environment**

**Prestorm Environment**

At 1200 UTC 1 June deep moist convection was ongoing across portions of eastern New England fueled by elevated CAPE in excess of 1000 j kg\(^{-1}\) and a mid level warm front (not shown). By 1445 UTC convection had moved into the Gulf of Maine and Atlantic Ocean while convective initiation was occurring along a cold front across upstate New York west of Binghamton (BGM) and across northern Pennsylvania east of Bradford (BFD).
Meanwhile, strong heating below the aforementioned elevated mixed layer created very unstable conditions across southern New England between the departing convection over the Atlantic Ocean and the new convection firing to the west across New York and Pennsylvania. An inversion at the base of the EML prevented boundary layer dew points from “mixing out” maintaining impressive CAPE across southern New England.

By 1600 UTC SPC mesoanalysis showed surface based CAPE values exceeding 4000 j kg$^{-1}$ across Litchfield County, Connecticut and Berkshire County, Massachusetts.

Steep mid level lapse rates, strong diabatic heating, and 850 hPa dew points approaching 15ºC lead to strong to extreme instability across western southern New England by 1600 UTC. The extreme instability would spread east during the remainder of the afternoon throughout Connecticut and central Massachusetts ahead of the advancing cold front.

*Supercell Environment*

At 1708 UTC Albany, New York (ENX) Doppler radar showed several thunderstorms across eastern New York and adjacent sections of Vermont (0.5° ENX Base Reflectivity shown below). Two storms exhibited rotation with mesocyclones present based on storm-relative velocity data (not shown).
The thunderstorms were moving east toward an area of extreme instability in excess of 4000 \( \text{j kg}^{-1} \) per SPC mesoanalysis data. Vertical wind shear was also increasing ahead of the thunderstorms in New York and Vermont thanks to strengthening mid and lower tropospheric flow as seen in RUC soundings (not shown).

While 0-6km vertical wind shear was increasing on a synoptic scale there were also pockets of locally enhanced 0-1km vertical shear due locally backed surface winds in south-north oriented river valleys such as the Connecticut River Valley in Massachusetts and Connecticut.

At 1800 UTC Pittsfield, MA (PSF) reported a 210° wind at 8 knots. Farther east, in the Connecticut River Valley at Westfield, MA (BAF), the wind was 170° at 13 knots. The channeled flow in the valley was substantially more backed than in the hills on the west side of the valley in the Berkshires. This is not unusual for north-south oriented river valleys. A look at wind roses based on January-December climatology for PSF and BAF reveals substantial differences in the climatological wind direction due to orography. The BAF wind rose reveals a striking tendency for winds to remain channelled by terrain with due north and due south the favored wind direction climatologically.
The first Massachusetts supercell of the day at 1900 UTC moved south of PSF near Lee, Massachusetts east toward Northampton, MA. The rotation on the ENX 0.5º storm relative velocity slice remained weak until the supercell descended the Berkshire foothills in western Hampshire County, MA into the Connecticut River Valley. Below is the ENX 0.5 SRV from 1900 UTC and 1939 UTC.

Though this supercell was non-tornadic, it produced large hail and damaging winds around Northampton, MA, and showed rapid intensification when it encountered stronger low level shear in the Connecticut River Valley. Part of the reason for intensification of the low level mesocyclone may have been the backed 0-1km channeled flow.

The 1900 and 2000 UTC RUC proximity hodographs at BAF show strong clockwise curvature indicating strong vertical wind shear. The backed winds in the valley locally
enhanced the storm relative helicity exceeding 400 m$^2$s$^{-2}$. Had winds not remained at 170° or 180° the hodographs below would be shortened and storm relative helicity would be less, particularly in the 0-1km layer.

The second supercell in Massachusetts developed along the Connecticut border around 1930 UTC. By 1940 UTC ENX storm relative velocity (1.8 degree elevation) showed a relatively weak mid level mesocyclone as the storm passed near Great Barrington, Massachusetts. Below is the 0.5° base reflectivity and 1.8° storm relative velocity.

Much like the supercell near Northampton, MA this supercell did not strengthen until it emerged from the spine of the Berkshires and descended down into the Valley. Unlike the Northampton supercell, this supercell became tornadic.
By 2006 UTC a strong tornado vortex signature developed at approximately 5500 ft AGL about 6 miles west of Westfield. ENX 0.5° SRV is displayed above at 2006 UTC. Within 10 minutes tornadogenesis occurred and the tornado would be on the ground for another 37 miles.

Tornadogenesis in north-south river valleys is nothing new in the northeast. In fact the role of channeled flow and increased storm relative helicity has been well documented (Bosart et. al, 2006; LaPenta et. al, 2005). It appears that the 2011 Hampden and Worcester County tornado may have formed in part due to locally backed boundary layer flow in the Connecticut River Valley.

Analyzing the 1995 Great Barrington, MA tornado Bosart et. al (2006) speculated channeled flow in north-south river valleys may have aided in tornadogenesis for several reasons. The most obvious reason is a lengthened clockwise-turning hodograph due to backed boundary layer flow. Other reasons may have included higher theta-e air found in the Hudson River valley during tornadogenesis and changes is friction due to decreasing roughness length over the Hudson Valley compared to the Catskills. While it’s unclear how much impact the aforementioned factors had on the Great Barrington case Bosart et al. felt the channeled flow and increased storm relative helicity in the Hudson Valley was the most important factor in tornadogenesis. The Great Barrington case by Bosart et. al is interesting as the storm cycled twice with tornadogenesis occurring in the Hudson Valley followed by a weakening mesocyclone and tornado damage ceasing over the Taconic Mountains. While descending the Taconic Ridge into the Housatonic River Valley in Great Barrington, MA tornadogenesis occurred again with F4 damage in Great Barrington followed by a gradual weakening as the supercell ascended into the Berkshire Mountains east of Great Barrington, MA.
Many of the factors present in the Great Barrington case were present 16 years later with the mesocyclone that descended from the Berkshires toward the Connecticut River Valley.

Another factor that may have lead to tornadogenesis near BAF was the presence of an outflow boundary from the previous supercell that tracked north of Springfield, MA. 2000 UTC surface observations show variable winds at 6 knots at Chicopee Falls, MA (CEF) while winds at nearby BAF were 170° at 13 knots gusting to 20 knots. The previous observation at CEF from 1900 UTC was a 210° at 8 knots gusting to 13 knots. Additionally, due to some type of equipment issue, the wind data at CEF was estimated by an observer.

Un fortunately it’s impossible to know the exact evolution of outflow boundaries from the Northampton supercell given the lack of a dense (both spatially and temporally) mesoscale observation network. That said, given the change in wind direction and velocity at CEF from 1900 UTC to 2000 UTC and the presence of a supercell to the north it’s reasonable to infer one or more outflow boundaries were present south of the Northampton cell.

The presence of this apparent outflow boundary may have increased low-level horizontal vorticity enough to aid in tornadogenesis as the supercell descended from the Berkshires toward Springfield. Markowski et. al (1998) found that during VORTEX-95 nearly 70% of significant tornadoes occurred near low-level boundaries not associated with the forward or rear flank downdrafts of supercells.
The outflow boundary and subsequent interaction may have been one of the reasons the southern supercell near Westfield, MA became tornadic while the initial supercell near Northampton, MA did not. The Northampton supercell, however, did do wind damage and produced hail to the size of golf balls in the city.

The presence of outflow boundaries near the location of tornadogenesis for significant northeast tornadoes has been explored by Bosart et. al in the 29 May 1995 Great Barrington, MA case and by LaPenta et. al in the 31 May 1998 Mechanicville, NY case. Incidentally both cases had different but notable interactions with outflow boundaries around the time of tornadogenesis. The Great Barrington case was an outflow boundary travelling south down the Hudson River valley from another storm to the north (similar to 1 June 2011 case) while the Mechanicville, NY case featured an outflow boundary from a squall line catching up with a rogue cell that formed ahead of the line.

**Tornado Environment**
After tornadogenesis occurred around 2015 UTC 1 June the tornado moved through Westfield, West Springfield, Springfield, Wilbraham, Monson, Brimfield, Sturbridge, and Southbridge, Massachusetts.

Fueled by extreme instability with surface based CAPE in excess of 4000 jkg-1 and a strongly sheared environment the tornado remained on the ground for another 37 miles. The 2000 UTC RUC sounding for BAF shows a lifted condensation level (LCL) of 600m and 0-1km helicity of 257 m²s⁻².
Edwards and Thompson (2000) found the mean LCL height for significant tornadoes per RUC proximity soundings was 649m. The mean 0-1km storm relative helicity (SRH) was 153 m$^2$s$^{-2}$ for significant tornado cases. Both LCL height and 0-1km SRH in the Massachusetts case were more extreme than the mean of significant tornado events studied by Edwards and Thompson.

The storm on radar exhibited classic characteristics of a tornado producing supercell including the presence of a debris ball. Below is the 2036 UTC 0.5º Taunton, MA (BOX) doppler radar base reflectivity and storm relative velocity.

As the tornado crossed the Connecticut River the low level rotation on radar increased and the beginning stage of a debris ball is present about 6,000 ft AGL over Springfield. As the tornado moved east toward Monson and Brimfield, MA both rotation and the debris ball signature on the 2100 UTC BOX 0.5º base reflectivity and storm relative velocity scans became more clear as the tornado was doing high end-EF3 damage.
Summary
The presence of an elevated mixed layer coupled with strong vertical wind shear and a potent mid tropospheric shortwave indicated the potential was there for a high-end severe weather outbreak on 1 June 2011. Though the synoptic ingredients were in place it was fine mesoscale details that may have ultimately lead to tornadogenesis in the Connecticut River Valley.

While channeled flow may have helped increase 0-1km storm relative helicity it may have been the interaction with the outflow boundary from the earlier supercell to the north that ultimately lead to tornadogenesis in Westfield, MA. The supercell that tracked over Northampton, MA showed signs of a strengthening mesocyclone when descending down the Berkshire foothills it remained non-tornadic. It is possible the outflow boundary interaction coupled with the locally enhanced 0-1km storm relative helicity was enough to trigger tornadogenesis.

This event is also a reminder that there are several areas in the northeast that may be somewhat more susceptible to significant tornadoes due to topography. The presence of channeled 0-1km flow in north-south river valleys, especially the Connecticut and Hudson, appears to be a significant factor in tornadogenesis for some significant northeast tornadoes. Smaller scale terrain features cannot be ignored either for the role they play in tornadogenesis as was apparently the case in the Great Barrington, MA F4 in 1995.

While the synoptic setup was a classic one for a high-end severe weather outbreak in the northeast it was the juxtaposition of favorable synoptics and finer mesoscale features, including locally enhanced storm relative helicity and preexisting outflow boundaries, that helped produce the most damaging Massachusetts tornado since the 1953 Worcester F4.
References


