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Synoptic climatology of tornadoes in the northeast USA

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ABSTRACT: A tornado climatology is constructed for the northeast USA (hereafter, Northeast) for the period 1950–2014. This region is highly susceptible to tornado damage as it includes dense populations in several major cities. This study provides a general climatology of tornadoes in the Northeast by exploring the spatial and temporal characteristics of the region's tornadoes. Additionally, 86 days defined as active tornado days (5+ reports per day) are used to examine the synoptic patterns associated with Northeast tornado environments. Tornadoes in the Northeast were most frequently reported in the late spring and summer months (May to July), during the late afternoon and early evening hours, between 18:00 and 23:00 h UTC (14:00 and 19:00 h local sidereal time [LST]). Tornadoes were reported most frequently along the densely populated Interstate 95 corridor, which connects several of the largest cities in the USA. Approximately 79% of all Northeast tornadoes were given an Enhanced Fujita Scale intensity rating of ≤1. Composite synoptic maps indicate that Northeast tornado outbreaks are commonly associated with a 500 hPa trough and a surface low pressure system over the Great Lakes. Differential positive vorticity advection and warm advection contribute quasi-geostrophic forcing, modifying thermodynamic profiles making them favorable for convection. These lifting mechanisms and associated instability (represented by high equivalent potential temperature and an unstable lifted index), along with sufficient lower tropospheric wind shear, provide the ingredients necessary for severe convection.

KEY WORDS: Tornado · Climatology · Northeast USA · Severe weather

1. INTRODUCTION

Tornadoes are reported less frequently in the northeast USA (hereafter, Northeast) than in many other areas of the country. As a result, the majority of tornado research does not analyze Northeast tornado risk in great detail. Historically, tornadoes in the United States are most commonly reported in the Great Plains in what is often referred to as 'tornado alley' (Kelly et al. 1978). Recently, studies have argued that the location with the greatest risk of tornado activity has shifted over time, primarily to the southeastern USA (Coleman & Dixon 2014, Agee et al. 2016).

While the Northeast may be less prone to tornado reports than other highly studied areas of the USA, the Northeast contains ~27% of the total United States populace (US Census Bureau 2014). Furthermore, 7 of the 10 most densely populated states are found in the Northeast. Wurman et al. (2007) highlighted the potential devastation that a tornado could inflict on Northeast cities like New York or Washington, DC. The potential loss of life and damage to infrastructure, property, and crops from Northeast tornadoes warrant the need for an updated and expanded regional climatology.

Several studies have emphasized the importance of examining tornado reports in the Northeast. However, the only climatology to focus exclusively on the entire Northeast region was developed by Leathers (1993). Others have developed climatologies for smaller areas within the Northeast, including New England (Johns & Dorr 1996), Pennsylvania (Nese & Forbes 1998), and New York City and Long Island (Colle et al. 2012). In addition, several case studies

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have focused on the atmospheric processes that promote tornadogenesis in the Northeast. Riley & Bosart (1987) analyzed complex sub-synoptic cyclonic structures that spawned a short-lived F4 tornado in Windsor Locks, Connecticut, on 3 October 1979. Giordano & Fritsch (1991) examined synoptic patterns associated with strong tornadoes (≥F3) in the Mid-Atlantic States during the warm season. Complex synoptic forcings (specifically, the enhanced divergence aloft created from the positioning of the left exit and right entrance regions of 2 coupled upper level jets at 250 hPa) led to a severe weather outbreak on 31 May 1998, with tornadoes reported throughout the Northeast (LaPenta et al. 2005). The importance of terrain for Northeast tornadoes has also been discussed in several studies (Wasula et al. 2002, Bosart et al. 2006). Bosart et al. (2006) utilized Doppler radar reflectivities and velocities to try to explain how the variations in the complex terrain of eastern New York contributed to mesoscale intensification and tornadogenesis of an F3 tornado near Great Barrington, Massachusetts on 29 May 1995.

Lombardo & Colle (2010, 2011) produced 2 separate studies identifying the distribution of convective storm structures in the Northeast. The first (Lombardo & Colle 2010) focused mainly on identifying Northeast convective structures from all convective storms. The second study (Lombardo & Colle 2011) investigated convective structures in relation to Northeast severe weather events. Murray & Colle (2011) found that Northeast convective days were associated with positive equivalent potential temperature (Θ_e) advection east of the Appalachians and a mean 500 hPa trough over the Great Lakes.

The purpose of this study is to supplement the work of Leathers (1993, 1994) and develop a reference climatology of tornado reports for the Northeast, as defined by the Northeast Regional Climate Center (see Fig. 1). This climatology will include the spatial and temporal distributions for all Northeast tornadoes reported over a 65 yr period (1950 to 2014). Composite maps will also be used to identify synoptic patterns associated with tornadoes during active tornado days (≥5 reports per day).

2. DATA AND METHODS

2.1. Tornado data

The tornado data used in this study were obtained from the Storm Prediction Center (SPC) GIS website at www.spc.noaa.gov/gis/svrgis/. Tornado track data were available for all United States tornado reports as a GIS shapefile. Tornado track data were collected for all states within the Northeast region, an area that includes West Virginia, Maryland, Delaware, Pennsylvania, New Jersey, New York, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire, and Maine. The availability of this dataset as a shapefile provided valuable spatial information useful for creating maps and other visual tools. While incomplete at times, this dataset has been maintained and quality controlled for the entire USA since 1950 (Grazulis 1993, Verbout et al. 2006). There are other problems in the dataset, such as the retroactive rating of tornadoes after the adoption of the Fujita scale in 1973 (Coleman & Dixon 2014). However, despite its limitations, especially early in the period of record, the entire tornado dataset (1950–2014) was used in this analysis.

Tornadoes that originated outside of the study region, yet whose tracks moved into the study region at some point during the tornado lifespan, were also considered in this analysis. All subsequent mapping from this dataset was created using the Environmental Systems Research Institute (ESRI) Desktop ArcGIS 10.1 GIS program package. The data mapped in this study were visualized using the United States Lambert Conformal Conic Projection with the Geographic Coordinate System North American 1983 datum.

2.2. Active tornado days

Tornado days (or a day in which ≥1 tornado is reported) are often used as a measure of tornado frequency within a region. The SPC records severe weather reports from 12:00 to 11:59 h UTC the following day. This study uses the same time frame when defining Northeast tornado days.

Recent studies have shown that the number of days in the USA with ≥1 tornado rated EF1 or higher on the Enhanced Fujita Scale has decreased, yet the number of days with a large number of tornado reports has increased (Brooks et al. 2014, Elsner et al. 2015). After examining the distribution of tornado days in the Northeast, it was apparent that the majority of tornado days have only 1 associated tornado (719 of 1152 total tornado days). Trying to identify synoptic scale atmospheric patterns on days with only 1 report could prove misleading, given the large number of single event tornado days. Thus, a subjective definition for active tornado days was developed in order to create a manageable number of tornado days in which to examine synoptic environments. Active tornado days are defined as days with ≥5 tornado reports in the Northeast. This definition represents the top 8% of the most active tornado days in the region. These dates were used to determine Northeast synoptic patterns during tornado outbreaks, which will be discussed in Section 2.3.

Tropical cyclone induced tornadoes were considered while investigating synoptic patterns on active tornado days. The only tropical cyclone day with enough tornado reports to be considered an active tornado day was 4 August 2004 and this was removed from the analysis (Hurricane Alex).

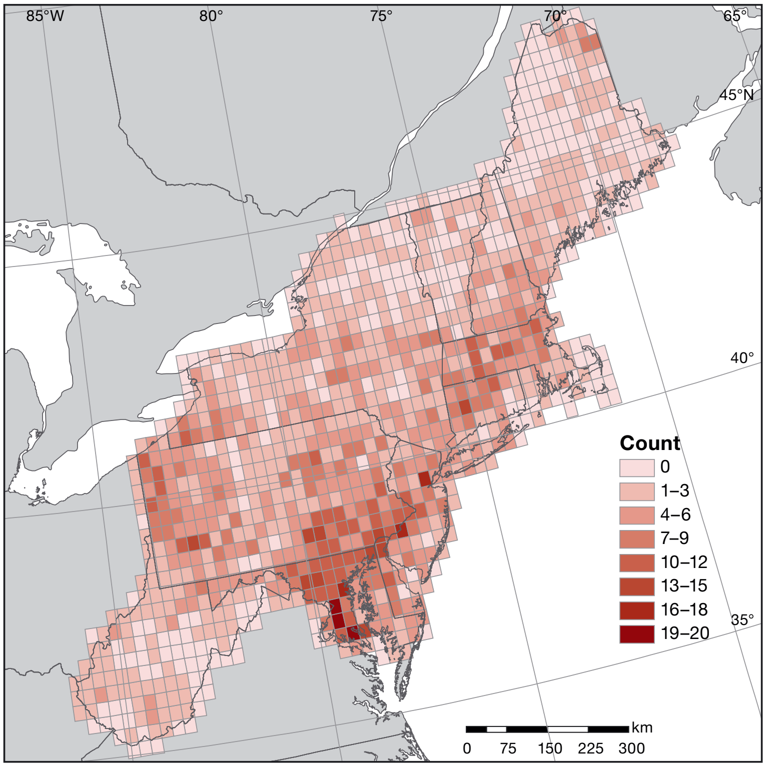

Fig. 1. Northeast tornado reports from 1950 to 2014 binned to a 0.25° × 0.25° grid

2.3. Composite synoptic patterns

Vertical wind shear, upward motion (from atmospheric instability or quasi-geostrophic processes), and sufficient moisture are essential parameters needed for convection (Rasmussen & Blanchard 1998, Li & Colle 2014). Therefore, in order to determine the general atmospheric patterns associated with Northeast tornadoes for active tornado days, synoptic composite maps were created from the Earth System Research Laboratory (ESRL) synoptic 6 h mean composites website at www.esrl.noaa.gov/psd/data/composites/hour/. This website utilizes dates uploaded by the user to create composite mean, anomaly, or climatological synoptic maps at 6 h intervals. The resulting output is available as text or netCDF files derived from the NCEP/NCAR reanalysis dataset (Kalnay et al. 1996). The netCDF files were obtained from the ESRL, and synoptic maps were created using the NCAR Command Language (NCL). Synoptic maps were created for 18:00 h UTC in order to represent the environment as tornado reports reach a maximum. Numerous atmospheric variables at the surface, 850 hPa, and 500 hPa were obtained for the 86 active tornado days in the synoptic analysis. These variables include sea level pressure, geopotential heights, temperature, precipitation, thickness, vorticity, vertical velocities, Θ_e, lifted index, wind speeds, and wind shear.

3. RESULTS

3.1. Northeast tornado climatology

During the 65 yr of analysis a total of 2361 tornadoes were reported across the Northeast. The greatest concentration of tornado reports were observed east of the Appalachian Mountains in Maryland and southeastern Pennsylvania (Figs. 1 & 2). Fewer tornadoes were reported in the mountainous regions of West Virginia, through central Pennsylvania and New York. In general, the northernmost portions of the region reported fewer tornadoes than areas farther to the south, which suggests an inverse relationship between tornado reports and latitude in the Northeast.

The spatial distribution of weaker tornadoes (EF0 to EF2) indicated that tornadoes are capable of forming throughout the Northeast (Fig. 2). Overall, the distribution of Northeast tornadoes was dominated by weaker tornadoes, as the majority of reports were assigned an Enhanced Fujita Scale rating of either EF1 or EF0 (Table 1). Mean path lengths were comparable to reports for the entire USA, while mean path widths were much smaller for reports rated EF2 and higher (Elsner et al. 2014, their Table 1).

Only 98 tornado reports (approximately 4.15%) were rated ≥EF3 during the entire period of record. Tornadoes with intensities of ≥EF3 were far less common north of Massachusetts compared to the rest of the Northeast. EF4 tornadoes were only reported in

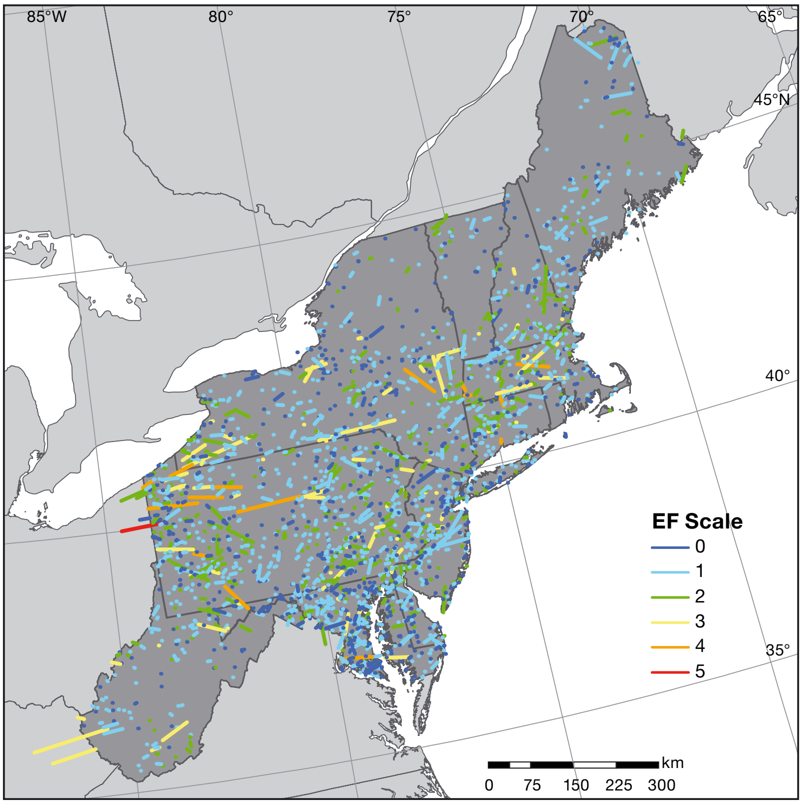

Fig. 2. Tornado reports in the northeast USA from 1950 to 2014. Colored symbols: EF rating and track length

western Pennsylvania, central Connecticut, eastern New York and western Massachusetts. EF4 tornadoes have been reported on 10 separate days since 1950, and only during an outbreak of ≥4 tornadoes. Several of the strongest tornadoes were reported in western Pennsylvania, the majority of these reports occurred during the 31 May 1985 outbreak.

The interannual variability of Northeast tornadoes is shown in Fig. 3a. The apparent upward trend is likely associated with enhanced reporting practices (Coleman & Dixon 2014, Farney & Dixon 2015). This upward trend becomes less evident after 1990. Overall, the number of Northeast tornado reports was highly variable from year to year. Similarly, the interannual variability of tornado days in the Northeast indicates the inconsistency of tornado reports from one year to the next. (Fig. 3b).

Table 1. Tornado reports, percentage, mean path length, and mean path width by Enhanced Fujita (EF) scale

EF scale	Reports	% of total reports	Mean path length (km)	Mean path width (m)
0	731	30.96	2.0	57.3
1	1136	48.12	4.1	92.8
2	396	16.77	7.2	131.8
3	82	3.47	22.1	245.2
4	15	0.64	45.5	762.8
5	1	0.04	75.6	411.5

Tornadoes were reported most frequently between May and August, with a maximum evident in July (Fig. 4). Tornadoes were also reported in April and September, although reports were far less common. An overall tornado report minimum was observed from December through February.

The spatial distribution of the seasonality of Northeast tornado reports was also examined (Fig. 5). With only a few exceptions, tornadoes were reported only in the lower latitudes of the Northeast during meteorological winter. A south to north trend was evident during spring as reports increased and moved north into New York and southern New England. This northward trend continued into the summer months as tornadoes were found in all Northeast states during the summer season (Fig. 5c). The transition from summer to fall was evident as the bulk of tornado reports from September onward retreated farther south in the region.

The diurnal distribution of Northeast tornado reports showed a steady increase in reports after 16:00 h UTC (12:00 h local sidereal time [LST]), with a clear report maximum from 18:00 to 23:00 h UTC (14:00 to 19:00 h LST) at the peak of diurnal heating (Fig. 6). Tornado reports dropped considerably after 00:00 h UTC (20:00 h LST) with the fewest number of tornadoes reported from 05:00 to 13:00 h UTC. Spatially, late afternoon tornado reports were most concentrated along the densely populated Interstate 95 (I-95) corridor that connects Washington, DC, Baltimore, Maryland, Wilmington, Delaware, and Philadelphia, Pennsylvania (Fig. 7a). Western Pennsylvania and central Massachusetts also reported a large number of tornadoes during this time. Tornado reports were much more dispersed after 00:00 h UTC (20:00 h LST), and mostly confined to the lower latitudes in the early morning hours (Fig. 7b,c). As diurnal heating increased in the late morning, tornado reports were once again made throughout the region. A climatology of reports during active tornado days was also

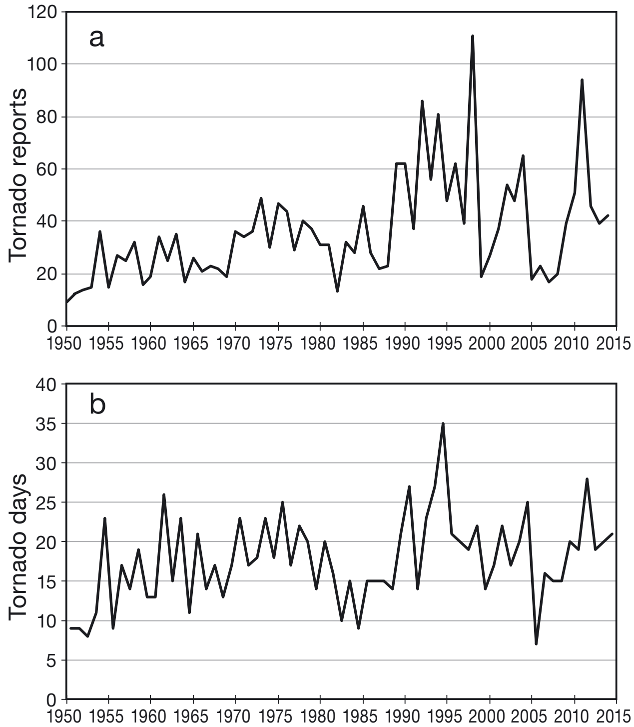

Fig. 3. Interannual variability of Northeast tornado (a) reports and (b) days (1950–2014)

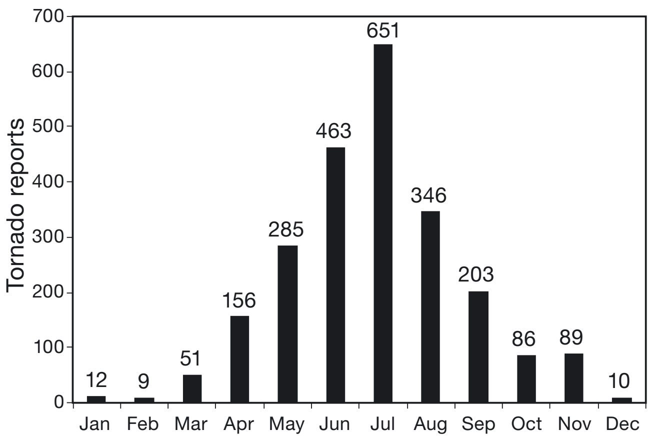

Fig. 4. Monthly distribution of Northeast tornado reports (1950–2014)

examined; however, the distributions and spatial patterns of this climatology were similar to those identified using the entire dataset and will not be discussed further.

3.2. Synoptic processes

This section examines mean synoptic patterns associated with active tornado days. The following composite maps represent the average atmospheric

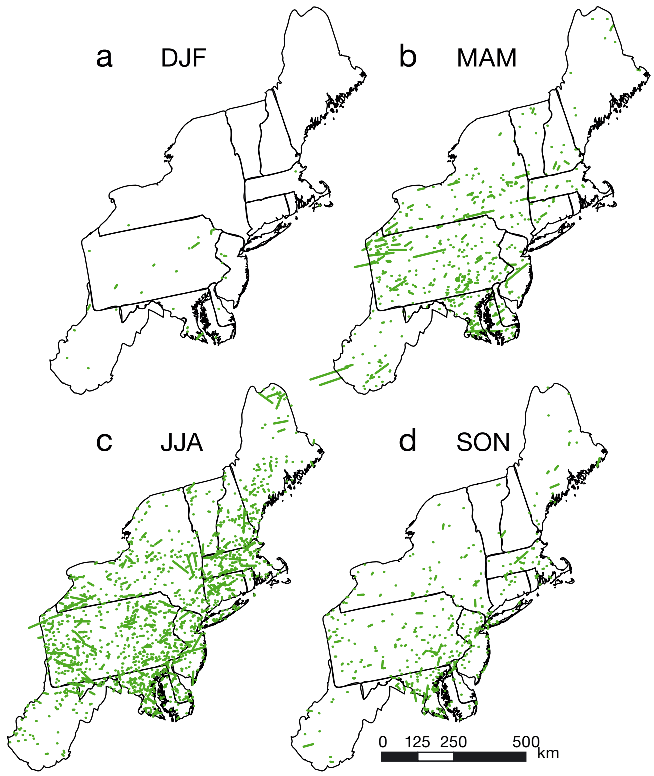

Fig. 5. Seasonal distribution of Northeast tornado reports. (a) December to February (DJF), (b) March to May (MAM), (c) June to August (JJA), (d) September to November (SON)

conditions present at 18:00 h UTC on the 86 days previously identified as active tornado days. Composite surface conditions on active tornado days are shown in Figs. 8 & 9. A closed surface low, with sea level pressure anomalies 7 hPa lower than average, is found over Lake Ontario (Fig. 8). These features indicate that closed surface low-pressure systems over the eastern Great Lakes are characteristic of active tornado days across the Northeast.

Surface temperature anomalies are 2°C warmer in southern portions of the Northeast, while negative anomalies as cool as 3°C are found in the northern plains states. The position of the temperature anomaly gradient suggests the presence of an incoming surface cold front coincident with the low pressure over the Great Lakes during active tornado days.

A ridge of high Θ_e values is found across the Northeast during active tornado days (Fig. 8). As Θ_e takes into account both moisture content and temperature, high Θ_e values are indicative of warm, moist, and unstable air. In addition, negative lifted index values are found coincident with the Θ_e ridge, suggesting the presence of an unstable atmosphere across the region (Fig. 9). Composite 1000–500 hPa thicknesses plotted with sea level pressure reaffirm the presence

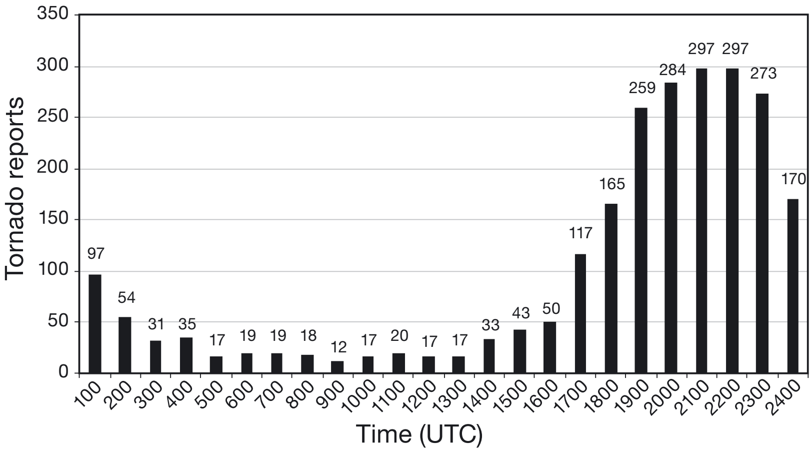

Fig. 6. Diurnal cycle of Northeast tornado reports

of a thermal ridge across much of the Northeast. Warm advection is implied ahead of the cold front while strong cold advection extends throughout the Midwest behind the cold front (Fig. 9).

Temperature anomalies at 850 hPa are more pronounced than at the surface (Fig. 10). Positive anomalies are apparent across the entire Northeast, reaching as high 3°C above normal from the eastern shore of Maryland through southern Maine. Winds at

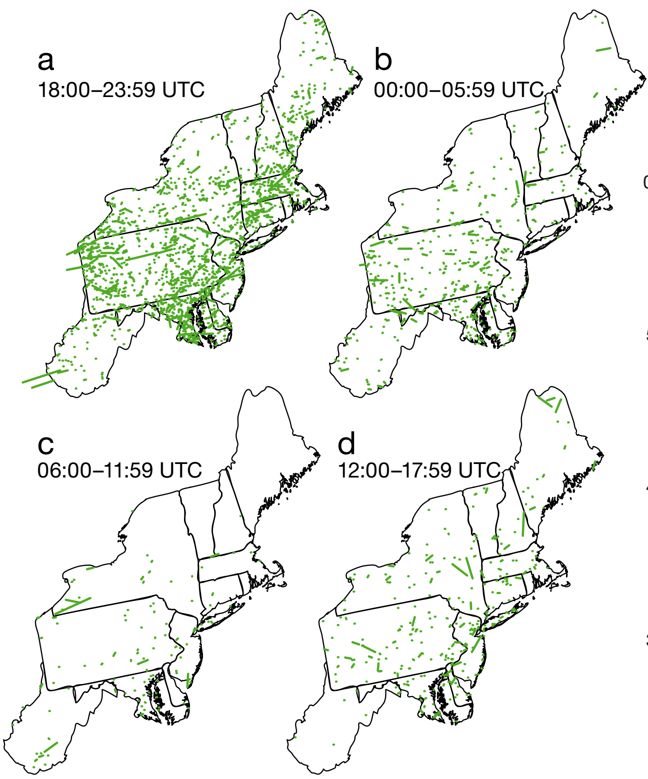

Fig. 7. Distribution of the diurnal cycle of Northeast tornado reports. (a) 18:00–23:59 h UTC, (b) 00:00–05:59 h UTC, (c) 06:00–11:59 h UTC, (d) 12:00–17:59 h UTC

850 hPa are stronger in the Northeast compared to the rest of the eastern USA. Upward vertical velocities are also present throughout most of the Northeast on active tornado days (Fig. 10).

The geopotential heights at 500 hPa highlight the presence of a positively tilted mid-tropospheric trough over the Great Lakes (Fig. 11). Vorticity values are highest in the base of the trough along the Ohio/Indiana border. Differential positive vorticity advection is apparent throughout much of the Northeast, coinciding with the warm temperature advections in Fig. 9. Thus, quasi-geostrophic forcing for upward motion is found throughout the region.

The wind speeds at 500 hPa indicate the presence of a jet streak extending from southwestern Pennsylvania through northeastern Maine (Fig. 12). Composite wind speeds are as fast as 22 m s^{-1} in the jet streak. In addition, wind vectors at the surface and 500 hPa highlight a veering wind profile ahead of the surface cold front. The strongest bulk surface to 500 hPa vertical wind shear corresponds with the area of the strongest differential positive vorticity advection. Wind shear values are as high as 18 m s^{-1} in the front-right quadrant of the observed jet streak. The position of the right entrance region of this jet

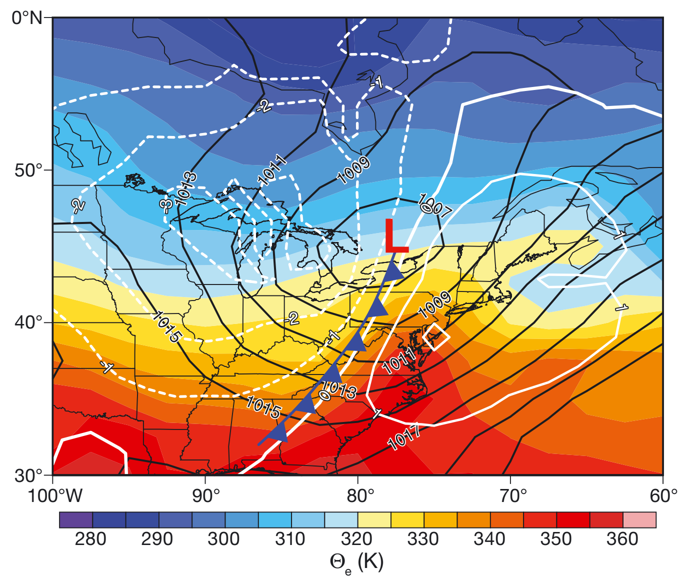

Fig. 8. 18:00 h UTC composite sea level pressure (hPa, black lines), surface temperature anomalies (°C, white lines), and equivalent potential temperature (Θ_e, colored shading). Cold front is positioned based on temperature anomaly distribution

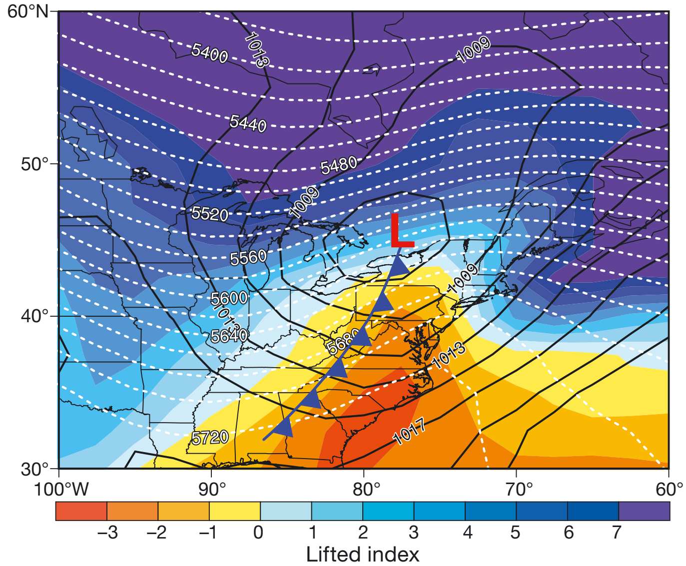

Fig. 9. 18:00 h UTC composite sea level pressure (hPa, black lines), 1000–500 hPa thicknesses (m, white lines), and lifted index (color)

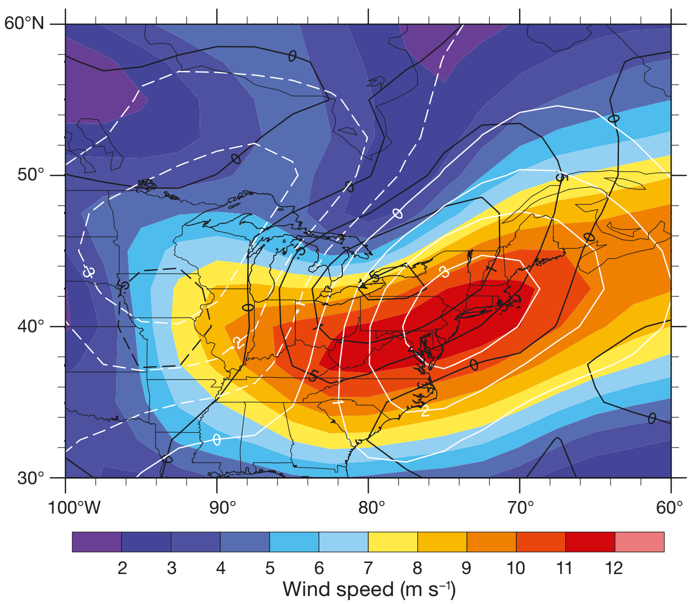

Fig. 10. 18:00 h UTC composite 850 hPa vertical velocity (cm s^{-1}, black lines), temperature anomalies (°C, white lines), and wind speed (color)

streak and its associated secondary circulations coincides with the position of quasi-geostrophic forcing. The upward motion provided by these synoptic processes along with sufficient lower tropospheric shear in an unstable atmosphere provide the ingredients necessary for convection during Northeast tornadogenesis.

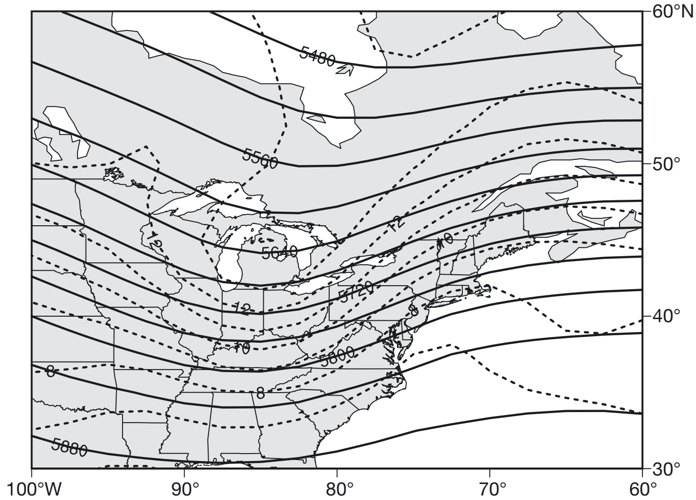

Fig. 11. 18:00 h UTC composite 500 hPa geopotential heights (m, solid lines) and absolute vorticities (s^{-1}, dashed lines)

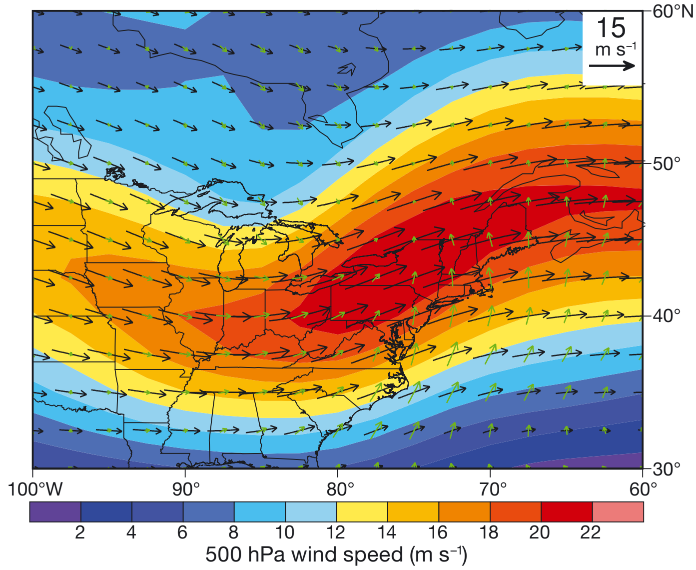

Fig. 12. 18:00 h UTC composite surface wind vectors (green arrows), 500 hPa wind vectors (black arrows), and 500 hPa wind speed (color). Reference vector scalable at both surface and 500 hPa

4. DISCUSSION AND CONCLUSIONS

This study focuses solely on tornado reports and tornado environments for the northeast USA. While reaffirming and building upon the results of Leathers (1993, 1994), it extends the period of study to include all 65 yr of available tornado report data. Many of the findings presented are similar to tornado climatologies for the entire USA, as well as to Northeast studies that include all types of severe weather.

The overwhelming majority (around 79%) of all tornado reports were given intensity ratings of either EF0 or EF1. Spatially, tornado reports were inversely related to latitude, with a greater number of tornado reports in the southern portions of the region. The greatest concentrations of tornado reports were east of the Appalachian Mountains in Maryland and southeastern Pennsylvania. Specifically, the I-95 corridor within this area connects dense populations as well as large amounts of infrastructure, making it particularly vulnerable to potential tornado damage. Fewer tornadoes were reported along the coast, likely due to reduced thermodynamic instability as a result of synoptic flow over colder ocean waters (Murray & Colle 2011).

An overall increase in Northeast tornado reports since 1950 has been shown for the entire USA (Coleman & Dixon 2014), in part due to enhanced reporting practices. Overall, the spatial distribution of tornado reports closely resembles the distribution of warm season convective storms in the Northeast (Murray & Colle 2011). Furthermore, the spatial Northeast tornado report maximum, shown in Fig. 1, was identified by Brooks et al. (2003) and Farney & Dixon (2015). The seasonal and diurnal characteristics of Northeast tornadoes are also consistent with several previous studies (Leathers 1993, Johns & Dorr 1996, Wasula et al. 2002, Colle et al. 2012, Hurlbut & Cohen 2014).

Composite maps were created from 86 days that were classified as active tornado days (days in which ≥5 tornadoes were reported). These maps clearly show synoptic-scale lifting mechanisms that generated upward motion on active tornado days. A surface low pressure system was found over Lake Ontario with an advancing cold front moving across the Northeast. This cold front has also been identified in other studies of Northeast severe weather (LaPenta et al. 2005, Hurlbut & Cohen 2014). Lower tropospheric warm advection provided some quasi-geostrophic forcing for upward motion, although the forcings for upward motion were greater in the mid troposphere.

A mean 500 hPa trough was identified over the region with differential positive vorticity advection providing quasi-geostrophic forcing to generate upward motion. The presence of this trough has proved common among Northeast tornado outbreaks (Leathers 1993, Murray & Colle 2011). Surface to 500 hPa wind shear values were comparable to soundings associated with significant tornadoes (Rasmussen & Blanchard 1998). The position of a 500 hPa jet and its attendant secondary circulations likely enhance and focus upward motion throughout the region. Lombardo & Colle (2010, 2011) associate the right entrance region of an upper level jet with Northeast convective systems, specifically linear convection, a factor also found in the present study. These lifting mechanisms, along with sufficient lower tropospheric wind shear, the thermodynamic instability represented by high Θ_e values, and an unstable lifted index, provide the ingredients necessary for the convection that leads to tornado outbreaks in the Northeast.

There are still several research questions to explore in the future. For example, the orographic effects (Bosart et al. 2006) and the influence of population (Anderson et al. 2007, Elsner et al. 2013) on Northeast tornado reports were not discussed in this study. Furthermore, a more robust investigation of the thermodynamic structure of Northeast tornado outbreaks as a way to complement the synoptic analysis and assess the environment on active tornado days is currently in progress. Finally, it should be noted that the reporting, collection, and quality of tornado data have limitations (Doswell & Burgess 1988, Edwards & Brooks 2010, Agee & Childs 2014). However, continued refinement of radar technology and improvement of reporting practices should improve the overall quality of the SPC tornado dataset and tornado climatologies in the future.

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