A SYNOPTIC CLIMATOLOGY OF SEVERE CONVECTIVE WINDS IN THE NORTHEASTERN UNITED STATES

by

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ABSTRACT

Although much research has been conducted investigating the spatial distribution of severe convective winds in many areas of the United States, few studies have focused specifically on the Northeast. Because of the large population and general lack of hazard awareness, high wind disasters are most common in this section of the country. This study provides a baseline climatology of severe convective wind reports from 1955-2010 using data from the Storm Prediction Center. Population biases inherent in the dataset as well as synoptic and thermodynamic environments associated with "significant" event days are examined in order to better understand the meteorological characteristics specific to the region that are responsible for severe convective surface winds. After a population-bias model is applied to the data, "hot spots" for wind reports are identified along the windward and leeward sides of the Appalachian Range, with significant clusters positioned in upstate New York and west of Washington D.C. The highest number of wind reports occurs diurnally around 2100 GMT and in the months of June and July on an annual basis. Synoptically, high numbers of events occur when there is anomalous low pressure north of New York state in association with a low-amplitude trough at the 500 hPa pressure level. Thermodynamic information obtained from 00z soundings at 11 upper air stations in the Northeast show that although severe weather indices are not necessarily good indicators of hazardous weather in every region, the K-Index and Total Totals index may be helpful in forecasting the potential for severe convective winds in the Northeast.

Chapter 1

INTRODUCTION

There have been several studies investigating the distribution of convective storms throughout the United States. Many studies focus on the Great Plains and Midwest simply because of the frequency and intensity of the convective storms that occur in these regions. Of the most common thunderstorm hazards (hail, wind, lighting, and flooding), convective winds are the most dangerous to both life and property (Schoen and Ashley 2010). Relatively few studies have focused on severe convective winds in the Northeast U.S. despite the fact that several states in this region are located in the main fatality axis associated with nontornadic convective winds (Black and Ashley 2009; Ashley and Mote 2005). The extremely large population that resides in this area and the overall lack of public hazard perception is cause for concern.

The purpose of this study is to develop a baseline climatology that examines the spatial and temporal distributions of severe convective winds in the Northeast United States. Convective wind damage reports from 1955-2010 were acquired from the Storm Prediction Center (SPC) for analysis. Although completely correcting population issues is not possible, this study attempts to partially minimize the population bias that is inherent in wind report data in order to locate areas that receive more or less reports than population alone would suggest. Interannual, annual, diurnal and spatial distributions are developed for the Northeast U.S. Significant event days are separated from the full dataset and used to produce composite synoptic maps that may help meteorologists better understand the large-scale conditions that initiate convective winds. In addition, the thermodynamic environments of the significant days are examined to identify the severe weather indices that may be helpful in predicting this hazard.

Even though there are many discontinuities and errors fundamental to a report-based dataset, the convective wind damage report dataset is the most comprehensive information available on the locations of damage caused by nontornadic convective winds. Despite the obvious issues, discussed in chapter 3, it is important to study the existing data to not only attempt to understand the physical processes causing this hazard but to also create public awareness concerning the true destructive ability of convective weather in the Northeast. This research is performed with the intent to provide a climatological foundation for forecasters and researchers interested in hazards affecting this region.

Chapter 2

LITERATURE REVIEW

2.1 Formation of Convective Winds

It is necessary to understand how convective winds form and the structures that produce them in order to appreciate general climatologies and the complicated nature of forecasting this environmental hazard. The source of any convective system is buoyancy. Basic to convective updrafts and downdrafts, buoyancy is the vertical movement of an air parcel due to density differences. Environmental buoyancy and wind shear profiles strongly influence the development of convective systems. Severe surface winds are produced by both (1) thunderstorms associated with synoptic-scale frontal systems and (2) organized mesoscale convective systems (MCSs).

A downdraft is a generic term for descending air within a convective cloud. Thunderstorm downdrafts occur mainly when evaporative/sublimative cooling, entrainment of dry air and/or precipitation loading leads to the formation of negative buoyancy within a convective cloud. As the downdraft accelerates and reaches the ground, the rapidly moving air spreads horizontally, sometimes causing serious damage to surrounding structures (Kuchera and Parker, 2006). The cold pool is the combined outflow from discrete convective cells and all negative buoyancy below the strongest convection (Corfidi, 2003; Figure 2.1). A large temperature difference between the cold pool and the surrounding air can contribute to higher wind velocities.

A mesoscale convective system (MCS) is a group of thunderstorms that synergistically organize along a leading edge and share a common cold pool. They can evolve from an isolated cell, a group of cells, or start out as a linear system. There are three major storm types that are considered MCSs; squall lines, bow echoes, and mesoscale convective complexes (MCCs; UCAR 2012). Squall lines are lines of convective cells with a large length to width ratio that are likely to be initiated by a linear forcing mechanism, such as a front or dry line. Bow echoes are a particularly strong type of MCS that start as strong isolated cells and evolve into non-transient crescent shapes that are known for long swaths of damaging surface winds. Bow echoes, and sometimes squall lines, can have an internal dynamical feature called a rear-inflow jet that is created when the rearward spreading convective cell transports warm air aloft and the deepest part of the cold pool is transported backward in response to the most active region of precipitation (Figure 2.1). The horizontal buoyancy gradient associated with the thermal difference is directly related to the strength of this elevated jet (UCAR 2012).

The final and largest form of MCS is the mesoscale convective complex (MCC). These storms are classified based on spatial extent and duration as observed in infrared satellite imagery. MCCs must have a diameter of at least 600 kilometers for 6-12 hours with a cloud top temperature of -32 °C over 100,000 km^2 and an internal cloud region of -52 °C over 50,000 km^2. They often develop overnight and are most common in the U.S. Great Plains. MCCs depend on interactions with synoptic forcing features, as an elevated buoyancy source is required for their development (UCAR 2012).

According to Kuchera and Parker (2006), MCSs can intensify surface winds in several ways. As rear-inflow jets accelerate from the rear of the convective line to the front, they descend towards the surface. If the descending jet reaches the surface, local increases in severe winds can be devastating. Also, the periphery of the cold pool, called the gust front, is an area of convergence and ascent that can often maintain the system by initiating new cell development in an environment that is already experiencing intense downdrafts (Corfidi 2003; Kuchera and Parker 2006) (Figure 2.1).

When describing damaging surface winds from severe convective systems, microbursts and derechos are events that cannot be overlooked. A microburst is a particularly severe downdraft that is smaller than 4 km in extent. Because these events are small in scale, short-lived and generally difficult to predict, they are extremely dangerous to aircraft (Dance and Potts 2001). A derecho, considered to be the most powerful type of non-tropical windstorm, is an extensive and nearly continuous straight-line wind storm that is convective in nature (Ashley and Mote 2005; Cohen et al. 2007). Although many climate scientists have developed their own criteria for labeling such a storm a "derecho," the major features include: (1) wind damage and gusts that exceed 26 m/s within a concentrated path longer than 400 km, (2) a chronological progression, (3) at least three reports of F1 damage/gusts larger than 33 m/s divided by more than 64 km, and (4) less than 3 hours between reported wind damage (UCAR 2012). Derechos have received much attention for their ability to create devastating loses (Cohen et al. 2007).

2.2 Hazards

Hurricanes, hail, and flooding immediately evoke images of destroyed landscapes, ruined infrastructure and human casualties. Surprisingly, however, of all thunderstorm hazards, convective winds (both tornadic and nontornadic) remain the most dangerous to life and property (Schoen and Ashley 2010; Changnon 2011).

Changnon (2011) reports that windstorms were responsible for 21 deaths and 100 injuries per year on average in the years between 1955 and 1997. According to Black and Ashley (2010), there were 1,195 fatalities directly related to nontornadic convective winds recorded from 1977-2007. Together, nonconvective and nontornadic convective winds pose a threat comparable to tornadoes; but since they receive much less attention in both media and research, there is very little public appreciation for this hazard. These two types of wind events caused 49.2% of all recorded wind fatalities, whereas tornadoes were accountable for 45.9%. For nontornadic convective winds, the majority of fatalities take place in aircrafts, followed by outdoor activities, in a vehicle and while boating. Most fatalities are caused by fallen trees, flying debris or building collapse (Black and Ashley 2010).

Black and Ashley (2010) found two major fatality axes in the United States. One stretches from the Great Lakes region into the Northeast/Mid-Atlantic and the other across the South and Southeast. The Great Plains are subject to a large number of convective wind events, but do not show a high fatality rate as a result. This is most likely due to the severe weather awareness of the region, lower populations, and the lack of forested areas and water bodies. In a study examining the morphologies of fatal convective storms, Schoen and Ashley (2010) found the same high-fatality sectors and believe that derechos are responsible for many of the deaths in the Great Lakes corridor. They also found that 45% of the nontornadic convective winds were produced by weakly organized systems. While the public is well-warned of severe storms, such as linear systems and supercells, it is important that they are made aware of the destructive power of more “ordinary”, or unorganized, storms (Schoen and Ashley 2010).

Ashley and Mote (2005) discovered that derecho fatalities exceeded those caused by F0 and F1 tornadoes during the 18-year period from 1986-2003. Although hurricanes were shown to cause more deaths than derechos, many hurricane-related deaths are caused by associated tornadoes and flooding as opposed to wind alone. The minimal wind speed for a derecho is enough to knock down trees, overturn boats and cause damage to houses. A detailed study from Fujita and Wakimoto (1981) illustrates how a derecho can be more damaging than most hurricanes and tornadoes that affect the United States. A derecho that impacted Minnesota, Wisconsin, Illinois and Michigan in July of 1980 caused $650 million dollars in damages to the four states. After accounting for inflation, the cost of this single event surpasses damage estimates from many U.S. hurricanes and all major U.S. tornadoes (Ashley and Mote 2005).

In addition to human fatalities, damages to property and agriculture are another serious hazard associated with severe convective winds. Losses with an annual average of $311 million to property and $68 million to crops are attributed to this hazard type (Changnon 2011). The primary growing months (May, June and July) are the months in which many convective storms occur throughout the United States. According to Bentley et al. (2002), $1 to $3 billion in damages to agriculture and property occur annually. Wind in conjunction with hail (wind-driven hail) can be especially devastating to crops. As one would expect, the agricultural destruction caused by wind-driven hail is anywhere from 3 to 12 times greater than crops shielded from the wind (Towery et al. 1976).

2.3 United States Convective Wind Climatologies

Like tornadoes and hail, severe thunderstorm winds are a warm season occurrence. June and July are the months of most severe thunderstorm activity, followed by May and August, respectively. A secondary maximum is shown in November, which has also been observed with tornadoes (Kelly et al. 1985). Diurnally, thunderstorm wind events hit a maximum in the late afternoon/evening, with 55% of wind reports happening between noon and sunset. Kelly et al. (1985) separated the United States into 10 homogeneous regions in terms of climate. They found that the Central Plains region experiences the highest frequency of severe thunderstorms, followed by the Southern Plains and Northern Plains. There is a relative minimum on the West Coast.

In a 2005 study, Doswell et al. calculate the probability of nontornadic severe weather events near any location in the contiguous United States for any day of the year. The Storm Prediction Center (SPC) damage reports that they utilized had to meet the following criteria; (1) wind speeds greater than or equal to 25.7 m/s (50 knots), or (2) hail diameter of 2 inches or more. Similar to findings previously mentioned, the Great Plains is the preferred region for significant severe events with a secondary axis running through the Ohio Valley. Their results indicate that wind-producing storms are most prevalent around the Gulf of Mexico early in the year and spread latitudinally across the southeast and the southern plains as the year progresses. The peak frequencies occur in early to mid-summer around the Central Plains and into the Ohio Valley. As the year proceeds and frequencies lessen, the higher probabilities extend to the east and north. By mid-fall, the frequencies start to migrate southward again towards the Gulf of Mexico. Generally, convective wind events are more evenly and widely distributed on the eastern side of the continental divide than hail events.

However, severe events (here defined as those greater than or equal to 65 knots) are largely confined to the Central Plains. The convective wind events that take place in the plains are overwhelmingly due to supercell thunderstorms, while those storms in the Ohio Valley are mostly caused by derechos (Doswell et al. 2005).

In an effort to define environments conducive to severe convective surface winds, Kuchera and Parker (2006) examine and compare over 50 thermodynamic and wind shear parameters using Rapid Update Cycle (RUC) model analysis soundings that may be important in developing organized systems and downdrafts. The most skill found for a wind parameter is the wind speed at the highest positively buoyant level in the surface inflow layer (WINDINF). The best thermodynamic parameter in determining the likelihood of convective winds is downdraft convective available potential energy (DCAPE). After normalizing the two indices by their approximate optimal Peirce (1884) skill score (OPSS) threshold values, they were combined to create a composite parameter named DMGWIND to indicate when a severe convective environment has the ability to produce damaging surface winds. The new parameter is calculated as:

$$DMGWIND = \frac{WINDINF}{8.0} \times \frac{DCAPE}{800.0}$$

Kuchera and Parker investigate 11 case studies where the DMGWIND parameter scored above the threshold value of 1.0. They were able to discriminate a few ambient conditions where damaging winds are more likely to occur. When WINDINF vectors are mostly perpendicular to a cold front and the main line of convection, the event is likely to produce damaging surface winds in the warm sector of the mid-latitude cyclone. Severe surface winds tend to occur on the cold side of a stationary (or warm front) when the WINDINF vectors are perpendicular to the convective outflow boundary, but parallel to the frontal position. However, when the WINDINF vectors are oriented parallel to the convective line, the gust fronts move too slowly to create serious damage. In addition, when WINDINF flows perpendicular to the convective line but crosses from the warm sector into the cold sector, only elevated convection is created.

It is apparent that climatologies of severe convective winds are extremely useful for meteorological technicians and operational meteorologists as guidance for forecasts and warnings. Climatologies aid in daily forecast probabilities and pose relevant questions for storm dynamicists (Kelly et al. 1985). And since they illustrate potential risks to life and property, the importance of climatologies extends much further than the earth sciences. Those concerned with government policy and possible climatic changes rely on the accuracy of climatologies, an issue that will be discussed later. Effective management of emergencies at the local, state and national levels depends on this type of research in order to develop and coordinate plans to mitigate hazards. Architects and engineers involved in structural standards and codes along with insurance agencies concerned with risk assessment use climatologies to make decisions. Finally, sociologists who study public response to natural disasters can also use climatologies as a tool in their research (Weiss et al. 2002).

Most research on convective winds, and all convective phenomena, have taken place in the Midwest and Great Plains simply because of the frequency and severity of such events in those locations. But according to Changnon (2011), high wind “catastrophes” in the United States, catalogued by the insurance industry as any natural hazard that causes greater than or equal to $1 million in property loss, were most common in the Northeast region, followed by the Central U.S. In fact, of the 16 states with the highest frequencies of wind catastrophes, New York, Pennsylvania and Maine are 5th, 6th and 7th, respectively, with Ohio, New Hampshire, Vermont, and West Virginia ranking 10th, 13th, 14th and 16th (Changnon 2011). Thus, the Northeast U.S. is an important area for the study of convective winds. Because there is a large difference in terrain between the Midwest and the Northeast, the development and organization of convective structures will be unique to the region. The Northeast U.S. is a topographically interesting landscape; convective storm development and evolution can be affected by coastal boundaries, the Appalachians, and large urban locations (Lombardo and Colle 2010). These diverse regions make forecasting, especially convective storms, difficult. The Northeast is even more vulnerable to disaster because of its large population. In order to better predict destructive convective winds, we must understand their frequency, spatial and temporal evolution, and the synoptic conditions that promote their formation (Lombardo and Colle 2010).

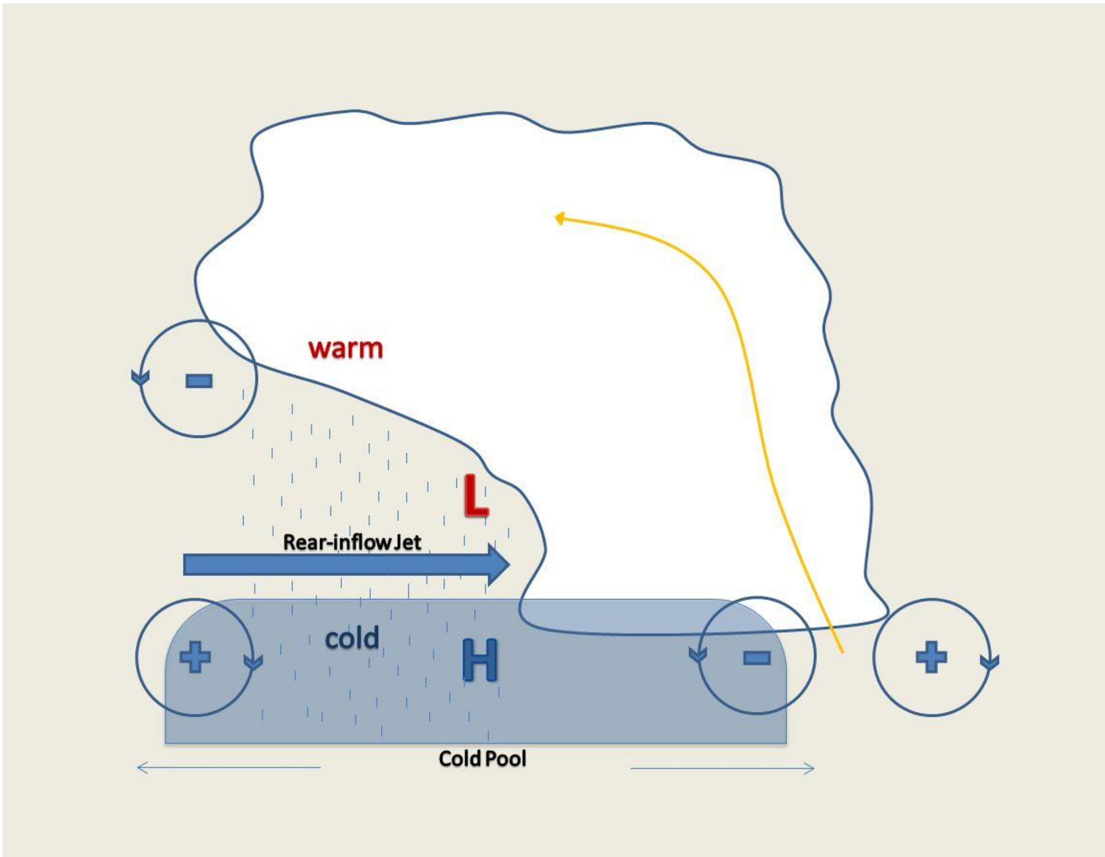

Figure 2.1: Schematic showing the simple internal dynamics of a convective thunderstorm. The yellow arrow represents the updraft transporting warm air into the system and thus sustaining it. Warm air positioned on top of the cold pool creates low pressure aloft and high pressure at the surface. The buoyancy gradient associated with the thermal difference induces a stacked vorticity couplet that forms the rear-inflow jet. This internal jet contributes significantly to surface winds if it descends and reaches the ground. Based on a COMET MetEd figure by Weisman 1992.

Chapter 3

METHODS

3.1 Study Area

The Northeastern United States was chosen for this study due to the relative lack of research on severe convective winds in this region. In addition, the high population density in the Northeast highlights the importance of climatologies and risk assessments of serious meteorological hazards. As noted earlier, this area of the country has the highest frequency of high wind catastrophes and overall, there is little public perception regarding the dangers associated with severe convective winds. The states included in this region are Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland, Virginia, West Virginia, and Ohio (Figure 3.1).

3.2 Convective Wind Data

Data were obtained from the Storm Prediction Center's (SPC) database containing convective wind damage reports collected by both the National Weather Service (NWS) and the SPC dating back to 1955. The database includes information such as latitude, longitude, state, date, and time along with magnitude and fatalities where available. Report times were converted from Central Standard Time (CST) to Greenwich Mean Time (GMT) for consistency with meteorological standards. The SPC Severe Weather GIS (SVRGIS) webpage supplied point shapefiles for use in a geographic information system (GIS) representing the location of individual reports that were used for analysis. Reports for the period 1955-2010 that fell within the specified study region totaled 55,771 reports in all (Figure 3.2).

3.2.1 Issues with Reporting

There are several fundamental issues involved with datasets containing meteorological hazard reports. In order for a report within a climatology to be considered accurate, “a severe event must be observed, properly perceived as a severe event, and must stimulate the observer (or observing system) to report it for the record” (Kelly et al. 1985). Although this seems like an obvious statement, in reality, a perfect climatological record is impossible. The total area affected by a severe thunderstorm event has diverse geographical impacts, but is represented by a single point. It would be truly accidental if that point happened to represent the absolute peak wind speed in an event. In addition, it is often natural for the most intense, destructive event to be reported, such as a tornado, while the accompanying hail or wind gust would not be reported (Kelly et al. 1985).

Severe thunderstorm events can go unobserved due to the nature of the landscape (topography/intervening structures), the time of day, and the lack of population or appropriate/accurate measuring devices (Kelly et al. 1985). Defining the incident properly is crucial. Most people reporting events are untrained and can often classify a nonsevere event as severe, and vice versa. Virga can be misperceived as a tornado and a tornado as a downburst. Another issue is that someone who experiences a downburst or severe convective wind storm may feel no duty to report it (Kelly et al. 1985). Trapp et al. (2005) used ground surveys and aerial photography in an effort to verify reports of wind damage in the National Climatic Data Center’s (NCDC) Storm Data. They found instances of both exaggerated and underestimated damage reports. The time of day is better able to predict the number of hazard reports than actual property damage. The overall concern is that misrepresentations in climatologies can distort perception of the true ability of quasi-linear mesoscale convective storms to create serious damage (Trapp et al. 2005). Weiss at al. (2002) even point out regional biases and incongruities along several geographic borders in the United States and also between different NWS jurisdictions. The lack of consistency in the procedures and requirements involved with reporting events between different forecast offices and throughout time adds to the discrepancies (Doswell et al. 2005).

Population density is obviously one of the largest problems in a dataset like that used in this study. While weighting the data by population can perhaps provide a clearer picture, there are other factors to consider such as the education level of those reporting, distribution of highways, distance from reporting stations and degree of urbanization (Kelly et al. 1985). Population change is one reason why there has been an almost exponential increase in the number of severe convective wind reports since 1955. Not only has population increased over time, but many rural and suburban areas have turned into urban centers. With more people reporting the same event, denser populations in certain regions can lead to a distorted climatology. More population issues will be discussed in greater detail later.

There are several other reasons why the number of severe convective wind reports has increased by an order of magnitude in the last 30 years (Weiss et al. 2002). Remote discovery and identification of severe systems has greatly advanced since the deployment of the NEXRAD (Next-Generation Radar) network in the early 1990s. In 1986, the NWS also created a national warning verification program that has increased accountability for their weather products. The growth of trained storm spotter networks throughout the country has led to increased probability that a severe event will be witnessed and reported. Lastly, there has been an overall increase in public weather awareness in many regions of the United States due to better media coverage and government involvement (Weiss et al. 2002).

3.2.2 Incorrect Report Locations

As previously stated, the point shapefiles acquired from the SPC include information such as the latitude, longitude, and state of occurrence of each wind report made from 1955-2010. When analyzed in a GIS, there were several examples in which the coordinate location of the report did not match the assigned state in the attribute table. Most mislabeled reports are those events that occurred on or near a state border. However, there are several reports attributed to a given state that are in actuality hundreds of miles from the report coordinates. Throughout the northeast, there were a total of 467 mislabeled severe wind damage reports out of the 55,771 (0.8%) (Figure 3.3). For this study, the latitude and longitude position of the report was used instead of the assigned state name.

3.3 Population Correction

Since it is well known that severe convective wind damage will only be reported if there are structures to be damaged and there is someone in the vicinity to observe the event, this study attempts to correct for the obvious population bias in the data. Climatologies have long shown a tendency for most hazard reports to cluster around major cities, leaving more rural areas relatively devoid of reports (Wasula et al. 2002, Cohen et al. 2007). Although it is possible that the reason for a spatial distribution showing high concentrations of wind reports around cities for a particular event is meteorological in nature, it can reasonably be assumed that a 56-year climatology of severe convective wind data has a significant population bias.

Population count data for the study region were acquired from the Socioeconomic Data and Applications Center (SEDAC) at Columbia University (http://sedac.ciesin.columbia.edu/). Population count data (as opposed to density) can be used in this analysis because the difference in grid box size with latitude is negligible in this latitude range. Because the 2010 census data had not yet been released for public use when this analysis began, Gridded Population of the World: Future Estimates (GPWFE) for the year 2010 (adjusted to match United Nations national level population estimates) were used in 1, 0.5, and 0.25 degree resolutions in ArcInfo GRID format. The data had a spatial reference of GCS_WGS_1984, Geographic latitude/longitude Coordinate System with the WGS1984 datum in units of decimal degrees. These three spatial resolutions were used in order to determine if there is a better relationship between population and wind reports at smaller or larger resolutions. Similar 1, 0.5, and 0.25 degree grid boxes were created to represent the total number of convective wind reports that occurred within each grid box throughout the 56-year period. The attributes from both layers were joined, so that each grid box's population and wind report count would be combined. This allowed for a simple linear regression to be performed between the population (independent variable) and the wind report count (dependent variable) of each grid box.

The objective of the linear regression is to "predict" the values of the dependent variable based on the values of the independent variable using the least squares method. Four locations in the 1 degree analysis (New York City, North Central New Jersey, Buffalo, and Boston) and two in the 0.5 and 0.25 degree analyses (Both around New York City) were removed from the regression analysis, as they were clearly outliers in terms of population.

The regression equation from the 1 degree population bias model is $y=0.0004x+256.7$, where y is the number of wind reports predicted and x is the population count. The R^2, or the ratio of the variance of the predicted values of the dependent variable to the variance of the observed values of the dependent variable, is 0.4926. In other words, about 50% of the spatial variation in wind reports can be attributed to population. Even without considering the fact that weighting the data by population count does not consider the many other important factors mentioned earlier, this result is statistically significant at the 99% level. In a study conducted by King (1997), there was no apparent relationship found between tornado reports and population density in Southwestern Ontario. However, a scatterplot of population density vs. *possible* F0-F2 tornadoes (events that produced damage similar to an F0-F2 tornado, but may have been a derecho or microburst) showed a correlation coefficient of 0.48, significant at the 95% level. King suggests that population biases are more likely for nontornadic events because of the more inconsistent definitions and the fact that loss could be overestimated in populated areas where there are more damageable structures. Although the explained variance decreased with higher spatial resolutions, the alternate grid box sizes produced significant results as well. The 0.5 degree regression equation is $y=0.0002x+110.68$ ($R^2 = 0.3783$) and the 0.25 degree regression equation is $y=0.0002x+35.44$ ($R^2 = 0.3178$).

Because the 0.25 degree resolution shows the population bias in greater detail, this resolution will be used for subsequent analyses (Figure 3.4). The Spatial Analyst Raster Calculator tool in ESRI's (Environmental Systems Research Institute) Desktop ArcGIS: ArcMap 10 application was used to apply the simple linear regression equation on the population raster in order to create a layer that gives the population-predicted wind reports for each grid box. After a raster was created to represent the actual number of wind reports for each grid box, the predicted wind report raster was then subtracted from the actual wind report raster using Raster Calculator. This produced a layer that shows which areas observed more or less wind reports than could be explained by population (Figure 3.5). The red-shades depict areas with greater wind reports than predicted and the blue-shades represent areas with less wind reports than predicted throughout the 56-year period.

There are some grid boxes across the region that stand out immediately as areas that receive more wind reports than predicted by population. Northeastern Ohio and extreme western Pennsylvania are areas where there are more wind reports than expected from population. Ohio is known to have more severe weather than other parts of the Northeast for several reasons including its spatial location on the windward side of the Appalachian Mountains, allowing for intrusions of deep moisture from the Gulf of Mexico. It is also clear that areas west of the I-95 corridor experience more wind reports than predicted from population, perhaps because of their location just to the lee of the Appalachian Mountain range. Parker and Ahijevych (2007) discovered that the probability of developing convection is largest on either side of the Appalachians with a relative minimum at the highest regions. Murray and Colle (2011) came to the same conclusions and found that convection is also favored along some of the major river valleys. The Hudson and Mohawk River Valleys near Albany, New York are clearly locations that support a lot of convection along with the Connecticut River Valley in Massachusetts, although less so (Figure 3.5).

Similar to the findings of Parker and Ahijevych (2007) and Murray and Colle (2011), the crests of the Appalachians show a relative minimum of reports in the present study. The yellow color (near zero difference) represents the fact that the regression equation did a good job at predicting the actual amount of wind reports in this area. Several areas of the Northeast experience less wind reports than predicted by population. The light blue/gray shades in Figure 3.5 show that the population bias model over-predicted the number of wind reports based upon population in Northern New England and Northern New York. The model severely over-predicted wind reports for locations with very large population centers such as New York City, Boston, Philadelphia and Buffalo. Across the northern portions of the region, the over-prediction is most likely associated with a true meteorological lack of severe convective winds even with the small populations. Over-prediction in large population centers is likely a result of the large population (resulting in higher predicted values) and a relative lack of convection in more stable, coastal areas such as Boston, New York City, and Buffalo. Over all, the results gathered from the difference raster coincide with those of Murray and Colle (2011) who found:

> Maxima located along the coastal plain from eastern Virginia through New Jersey, the lee of the Appalachians in eastern Pennsylvania, the windward side of the Appalachians, and the Mohawk and Hudson River Valleys in New York. Minimum areas were located mainly from western Virginia northward through the central Appalachians as well as in the marine-influenced locations of coastal New England and Long Island (Murray and Colle 2011).

In addition to the difference map created using the simple linear regression equation, two hot spot analyses were applied to the 0.25 degree grid box resolution. The Hot Spot Analysis tool in the Spatial Statistics ArcToolbox determines where in the study region high and low values of a variable cluster together. Each weighted value is analyzed in relation to neighboring values. In order for a specific area to be considered a "hot spot," not only does that region need to have a high value, but it needs to be surrounded by high values as well. The Getis-Ord Gi* statistic is calculated for each weighted feature and produces a z-score. A local sum is calculated for a particular point and the surrounding points and is then compared to the sum of all points. When the local sum is greatly different than the expected sum and the difference is larger than what can be explained by random chance, the z-score for that area is statistically significant (ESRI 2010). The calculations are as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}$$

where x_j is the wind count value for each grid box, $w_{i,j}$ is the spatial weight between any two grid boxes, n is equal to the total number of grid boxes and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$$

A preliminary hot spot analysis was performed on a point shapefile that consisted of one point per grid box representing the actual number of wind reports within that area (Figure 3.6). A second hot spot analysis was carried out using points corresponding to the number of actual wind reports minus the population-predicted wind reports (the same numbers used in the difference raster) (Figure 3.7). The goal of creating two hot spot analyses is to better compare the statistically significant areas before and after the population correction is applied.

In the 0.25 degree hot spot analysis of the actual wind reports (before the population correction), many of the largest cities in the Northeast fall within the areas deemed statistically significant at the 99% level. Cleveland, Pittsburgh, Washington D. C., Philadelphia, New York City, and Albany all come out of the analysis as the regions that receive the most convective winds. The entire I-95 corridor from Virginia to New York (a highly populated region) is considered a hot spot. The analysis of the population-corrected data demonstrates a more believable climatology and agrees well with the difference raster. There are still significant hot spots on both the windward and leeward sides of the Appalachian Mountains, with a relative minimum at the crest. Little change can be detected between the analyses in the hot spots in the Ohio/Western Pennsylvania and Albany areas, proving that these places experience large amounts of convective wind reports despite population. Just as in the difference raster, the populations of New York City and Boston severely over predicted the number of wind reports for those grid boxes and therefore are very significant "cold" spots on the map. Most of the hot spots at both the 95% and 99% level of significance have moved away from major cities along I-95, leaving clusters near Harrisburg, Pennsylvania and where West Virginia, Virginia and Maryland merge. Further research is needed to understand the exact reasons why these locations receive an unusually large number of wind reports.

3.4 Definition of Significant Event Days

In order to investigate the synoptic and thermodynamic environments associated with severe convective wind reports, only those days associated with a significant, enhanced number of events is considered. For this study, days with reports at least three standard deviations above the mean were considered significant.

The number of reports, on days with reports, range from one report per day to 279. The mean number of reports per day is 13 with a standard deviation of 25. Thus, a single day had to have at least 87 wind reports to be used in further analyses. Out of the 4,258 days with severe convective wind reports throughout the 56-year period, 104 days (13,405 reports) are regarded as significant (Table 3.1).

3.5 Composite Synoptic Maps

To better understand what large-scale atmospheric patterns and conditions help to create damaging surface winds in the Northeast United States, composite mean and anomaly synoptic maps were constructed using all 104 significant event days. The National Atmospheric and Oceanic Administration's (NOAA) Earth System Research Laboratory (ESRL) webpage creates composite maps of both means and anomalies of variables from the NCEP/NCAR Reanalysis and other datasets for user-specified dates (Kalnay et al. 1996). The variables used for this analysis include sea-level pressure, 500 and 850 hPa geopotential heights, surface temperature and Lifted Index.

3.6 Atmospheric Soundings

Examining the thermodynamic environments and associated stability parameters of the 104 significant event days can provide insight on what convective indices may best forecast severe convective surface winds in the Northeast United States. Atmospheric soundings and severe weather indices were acquired from the University of Wyoming's Department of Atmospheric Science website, which allows users to retrieve upper air information from 00z and 12z soundings from around the world on any day dating back to 1973. Data were gathered from the 11 upper air stations around the Northeast that covered the largest area and captured the most reports; Wilmington, OH (KILN), Pittsburgh, PA (KPIT), Roanoke, VA (KRNK), Sterling/Washington, VA (KIAD), Wallops Island, VA (KWAL), Albany, NY (KALB), Buffalo, NY (KBUF), Upton, NY (KOKX), Gray, ME (KGYX), Chatham, MA (KCHH), and Detroit, MI (KDTX) (Figure 3.8).

Similar to the method used by Craven and Brooks (2004), reports had to fall within 180km of the upper air station and occur between 2100 GMT and 0300 GMT (within 3 hours on either side of 00z). Only 00z soundings were acquired, as this observation will show the atmospheric conditions closest to the time of most wind reports in the diurnal distribution. Soundings were obtained for the days corresponding to reports that fall within a particular station's buffer zone. Figure 3.8 shows that many reports fall within 2 or 3 of the 180 km buffers around the upper air stations. In this case, soundings for those days were acquired from each station whose buffer surrounds them. After querying the convective wind reports representing the 104 significant event days, 103 significant days and 5,241 reports fit the above criteria. 520 out of 581 soundings were obtained since there were several days that did not have sounding data available.

14 mandatory pressure levels were used to make the mean station Skew-T Log-P diagram to allow for uniformity across stations and days. The 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50 and 10hPa pressure levels were obtained from the full soundings for analysis. If a station's elevation was higher than the 1000hPa level, that value was simply omitted from the average. The parameters for each pressure level in the soundings for each station were averaged and only the height (m), temperature (°C), dew point (°C), wind direction (degrees) and wind speed (m/s) were put into CMA (Chinese Meteorological Administration) file format for

analysis in Unidata's Integrated Data Viewer (IDV). The IDV is a Java-based software specifically designed to analyze and visualize geoscience data (Murray et al. 2003). Mean skew-T diagrams were produced for each of the stations along with a composite skew-T representing the mean of all the acquired soundings from all 11 stations.

The University of Wyoming's upper air website also calculated several severe weather indices with each sounding. Convective Available Potential Energy (CAPE) (J/kg), Lifted Index (LI), K Index (KI), Cross Totals (CT), Vertical Totals (VT), Total Totals (TT), and Severe Weather Threat Index (SWEAT) were used to create (1) box plots comparing the value distribution of indices at each station and (2) index contour maps that show the spatial distribution of index values over the Northeast U.S. The DMGWIND parameter developed by Kuchera and Parker (2006) was not calculated for this analysis in the interest of comparing only the most common indices that have been used by forecasters for many years. Subsequent analyses will investigate the skill of the DMGWIND parameter in predicting severe convective winds in the Northeast U.S. CAPE is calculated as follows:

$$CAPE = \int_{LFC}^{EL} (F/\rho')dz$$

where F is the upward buoyancy force per unit volume on the rising parcel of air due to the temperature difference between the environment and the air parcel, ρ' is the air parcel density, LFC is the level of free convection (the level at which the rising air parcel becomes warmer that it's environment), and EL is the equilibrium level (where the temperature of the air parcel and the temperature of the environment become equal again) (Wallace 2006). Convective available potential energy is an estimate of the buoyant energy within a rising parcel and a measure of the integrated effects of potential temperature differences between the rising parcel and its environment (UCAR 2012). The higher the CAPE value, the stronger the updraft if the rising parcel can overcome convective inhibition and/or reach the LFC. The Lifted Index is calculated as:

$$LI = T_{500} - T_{parcel}$$

where T_{500} is the temperature in degrees Celsius of the environment at the 500 hPa pressure level and T_{parcel} is the temperature of the parcel once it has been lifted adiabatically from the near surface to 500 hPa. "Near surface" often means taking the average temperature and dewpoint from the lowest 100 hPa and moving up the stew-T diagram from that point. The more negative the LI, the more buoyant the parcel and the more unstable the atmosphere (UCAR 2012). The K-Index is defined as:

$$KI = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700})$$

where T_{500}, T_{700}, and T_{850} are the temperatures at the 500, 700, and 850 hPa pressure levels respectively, and T_{d700}, and T_{d850} are the dew point temperatures at 700 and 850 hPa. The KI is most useful for determining convective potential for air mass thunderstorms, as opposed to thunderstorms triggered by dynamic forcing (DLESE 2012). The Cross Totals index is computed by:

$$CT = T_{d850} - T_{500}$$

where T_{d850} is the dew point temperature at 850 hPa and T_{500} is the temperature at 500 hPa. The Cross Totals index estimates buoyancy by exclusively considering low-level moisture (DLESE 2012). The Vertical Totals index is calculated as:

$$VT = T_{850} - T_{500}$$

where T_{500} is the same as defined above and T_{850} is the temperature at 850 hPa. Similar to the Cross Totals equation, Vertical Totals estimates buoyancy by considering the temperature at low-levels (DLESE 2012). Total Totals is computed by:

$$TT = (T_{850} + T_{d850}) - \left(2(T_{500})\right)$$

This index is the arithmetic sum of Cross Totals and Vertical Totals. Total Totals accounts for both low-level moisture and temperature. Generally, the higher the 850 hPa temperature and dew point and the lower the 500 hPa temperature, the greater the instability (UCAR 2012). Finally, the SWEAT index is calculated as:

$$\begin{aligned} SWEAT = 12(T_{d850}) + 20(TT - 49) + 2(V_{850}) + V_{500} \\ + 125(\sin(d_{500} - d_{850}) + 0.2) \end{aligned}$$

where T_{d850} is the dew point temperature at 850 hPa, TT is the Total Totals value, V_{850} and V_{500} are the wind speeds in knots at 850 and 500 hPa respectively, and d_{500} and d_{850} are the wind directions at the 500 and 850 hPa pressure levels. This index is unique because not only does it take low-level moisture and instability into account, but it also incorporates wind direction at different atmospheric pressure levels. Often the factor that determines whether a thunderstorm intensifies or dissipates is the change in wind speed and direction with height. Veering (clockwise turning of wind direction with height) and associated warm air advection can redirect the updraft and downdraft so they do not intersect, increasing instability and intensifying the storm (DLESE 2012).

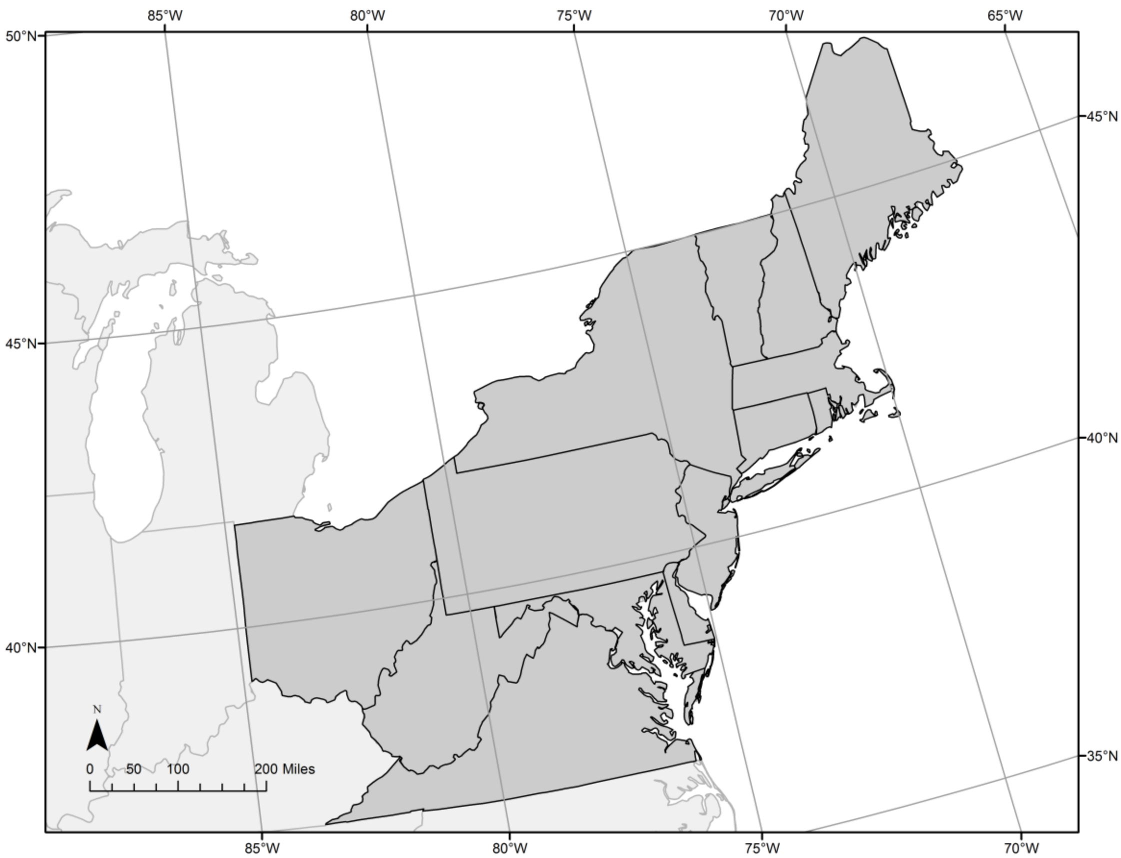

Figure 3.1: Study area (coordinate system: GCS_North_American_1983; projection: Lambert_Conformal_Conic).

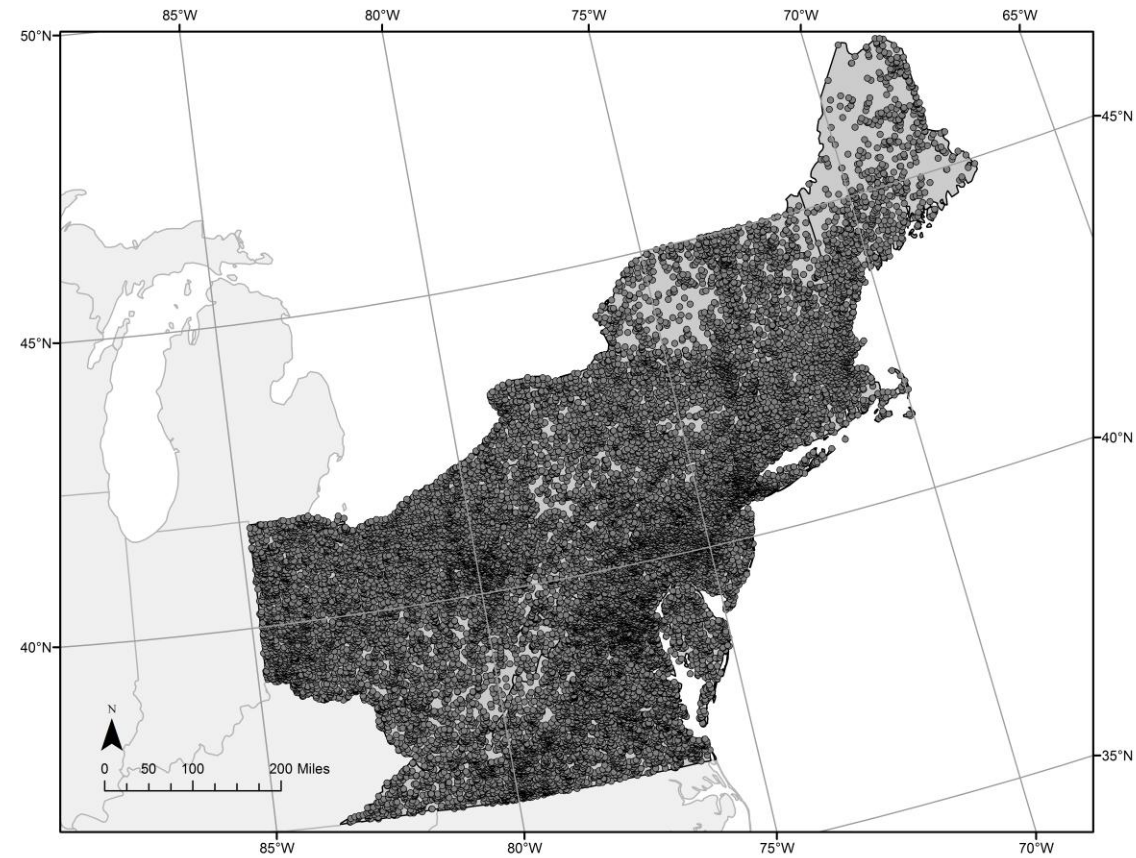

Figure 3.2: Spatial distribution of all 55,771 severe convective wind reports from 1955-2010.

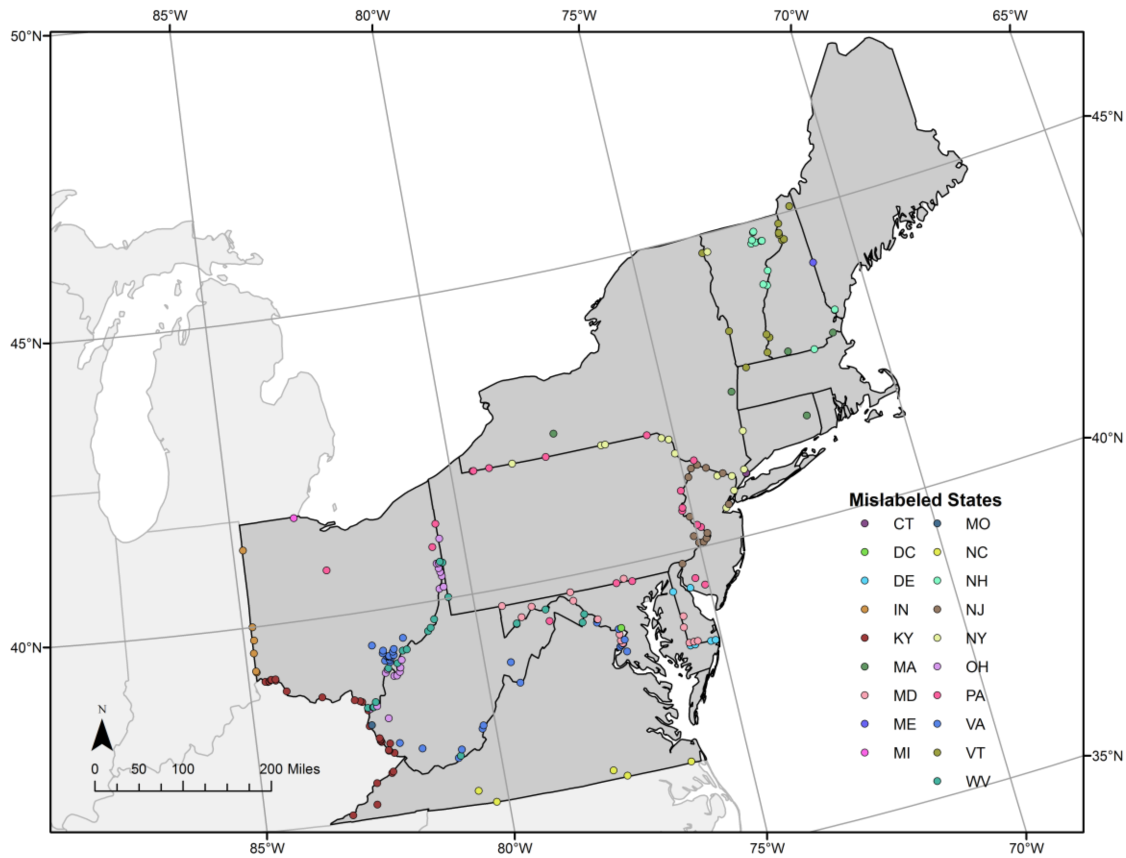

Figure 3.3: Spatial distribution of severe convective wind reports that include an incorrect state identifier.

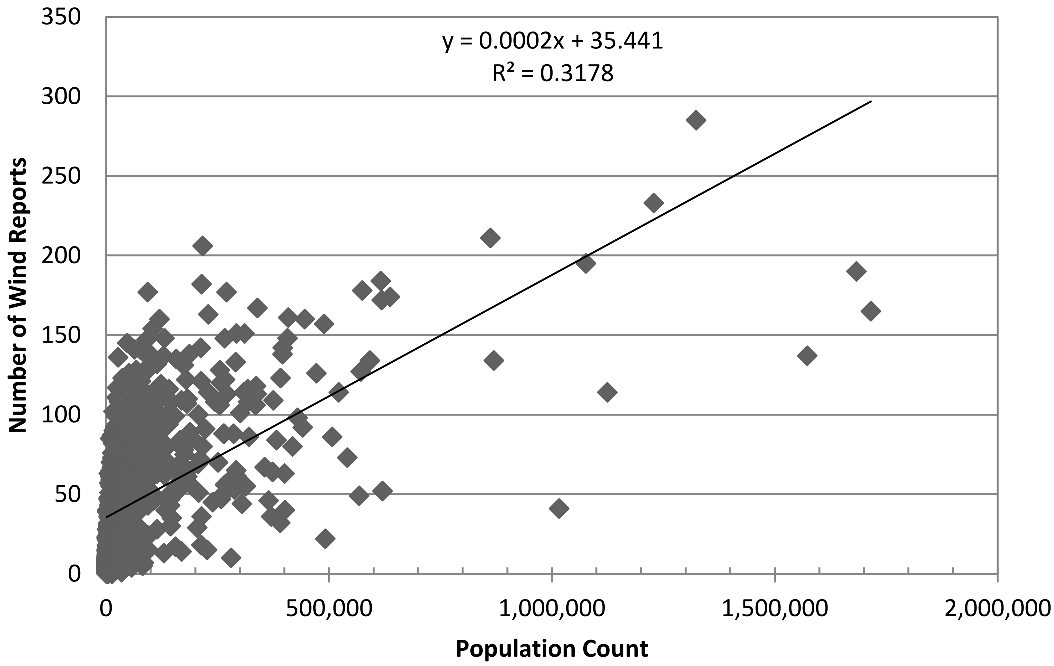

Figure 3.4: Simple linear regression showing the relationship between population count and the number of wind reports in 0.25 degree grid boxes covering the Northeast United States.

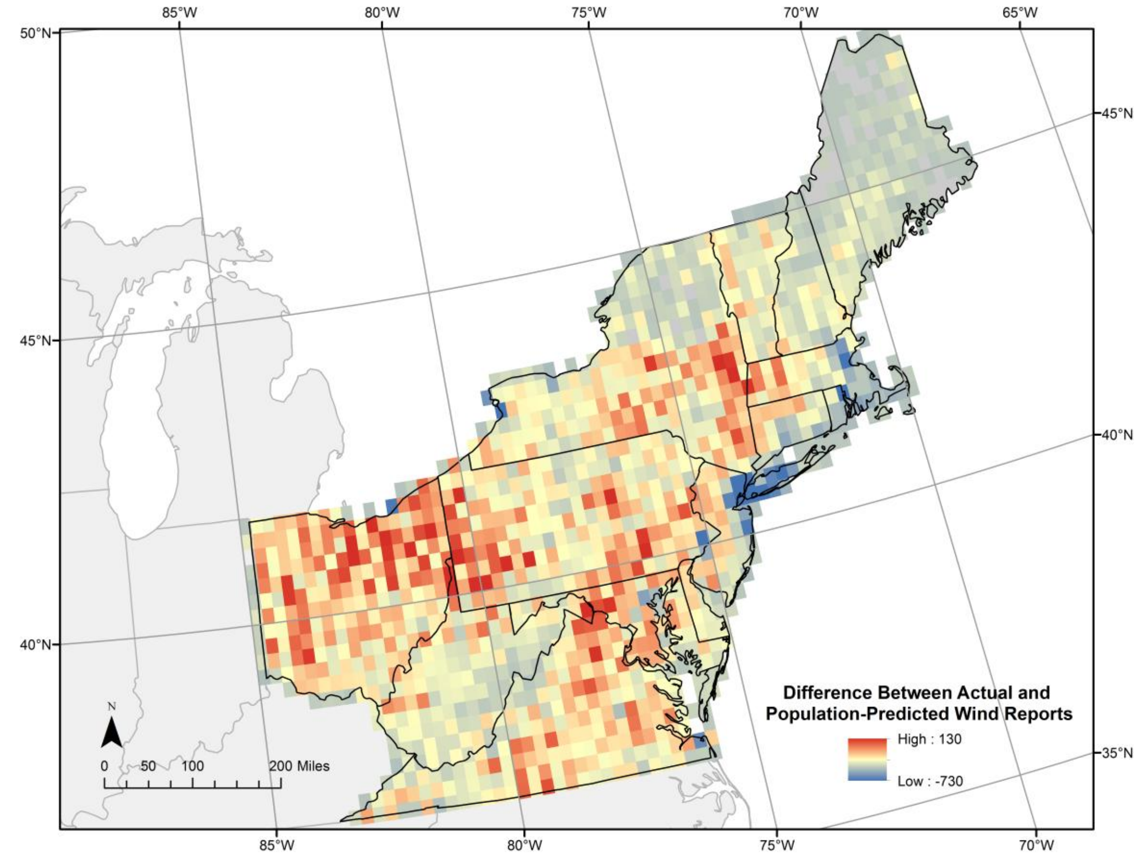

Figure 3.5: The 0.25 degree resolution difference raster showing the difference between actual wind reports and population-predicted wind reports. The red-shaded grid boxes symbolize areas that received more wind reports than predicted by the population bias model. Blue-shaded grid boxes represent regions with less wind reports than expected from population alone.

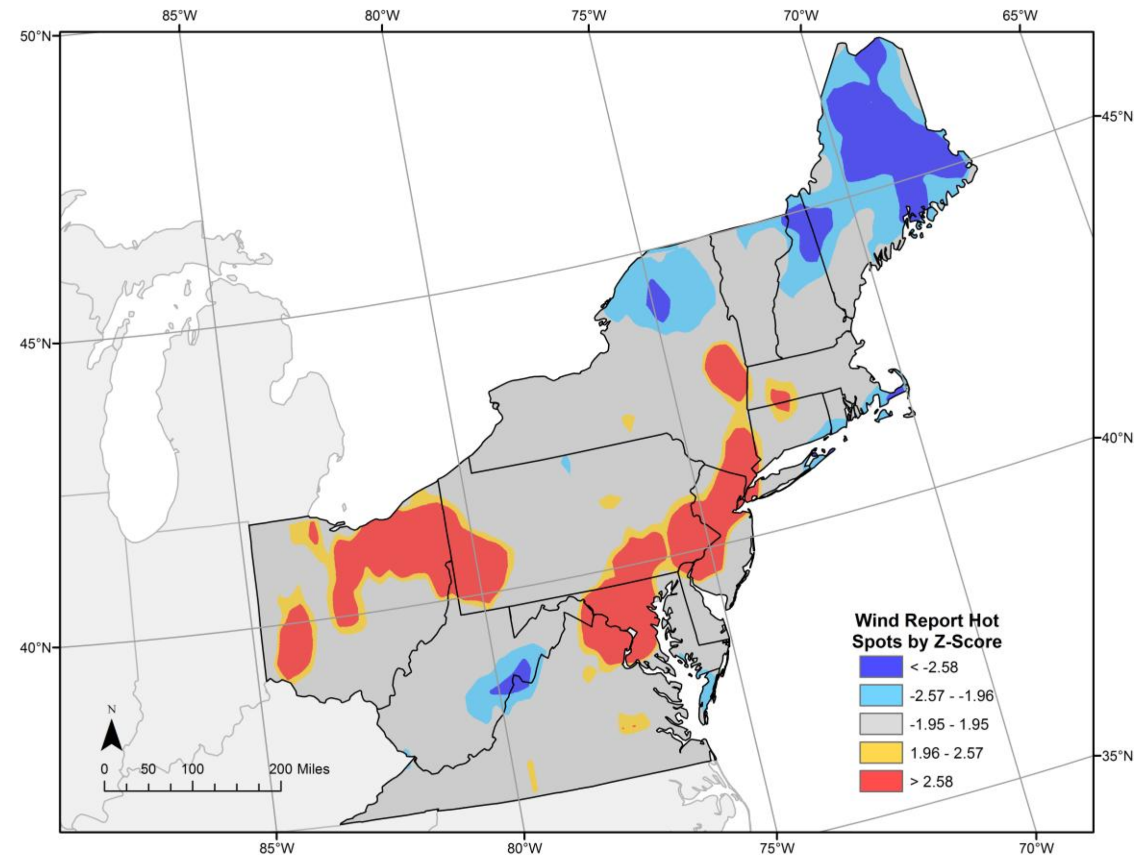

Figure 3.6: The 0.25 degree resolution preliminary hot spot analysis of all severe convective wind reports using the Getis-Ord Gi* statistic.

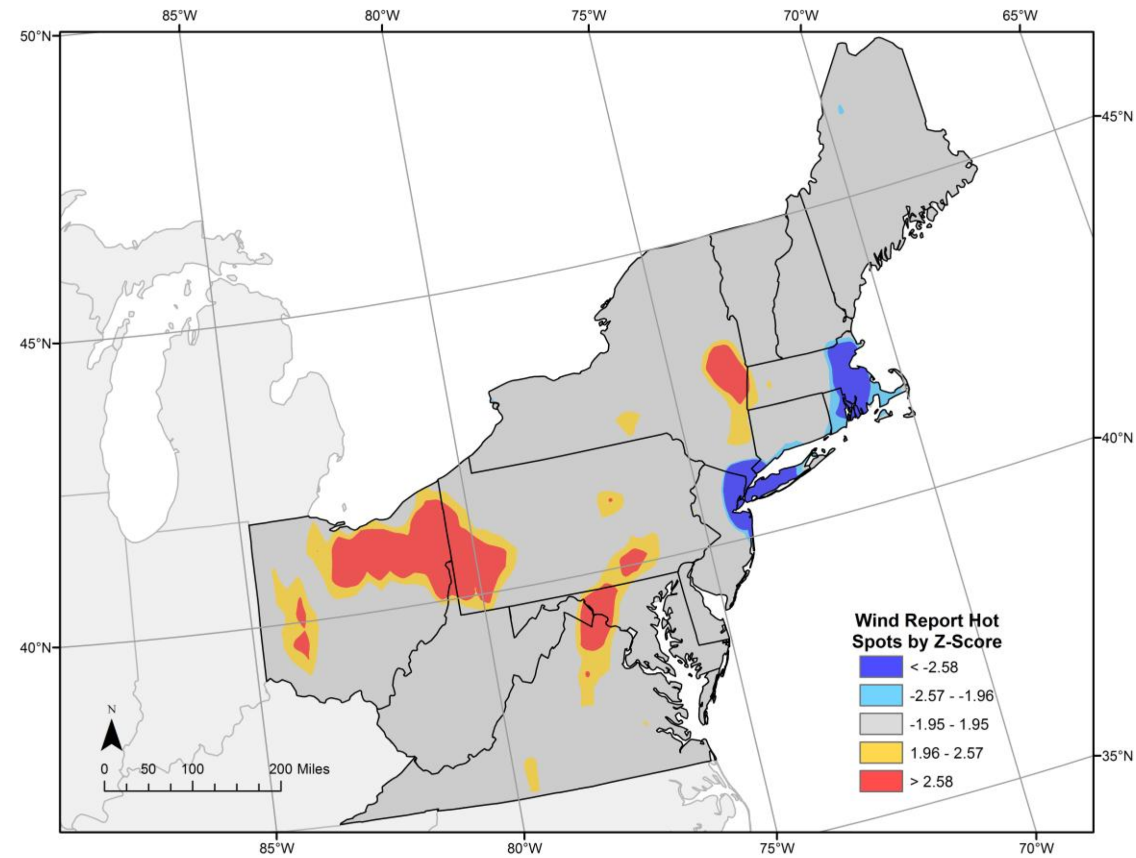

Figure 3.7: The 0.25 degree resolution population-corrected hot spot analysis using the Getis-Ord Gi* statistic and values from the difference raster in Figure 3.5. Red and orange tones denote regions that experienced more wind reports than can be explained by population alone and the blue tones represent areas that received less wind reports than the population-bias model predicted.

Table 3.1: List of dates and associated wind report counts from 1955-2010 considered to be significant convective wind event days.

Date	Reports	Date	Reports	Date	Reports	Date	Reports
19740414	137	19980601	131	20030826	106	20080604	230
19830721	113	19980613	114	20030827	138	20080610	246
19891116	126	19980616	155	20040521	131	20080611	141
19891121	143	19980630	143	20050606	190	20080614	87
19900705	90	19980824	118	20050725	97	20080616	116
19900829	132	19980907	161	20050726	107	20080708	113
19910409	89	19990706	190	20050727	184	20080720	89
19910506	94	19990710	95	20051106	166	20080723	124
19910708	87	19990814	113	20060619	114	20080727	114
19910723	127	19991013	98	20060622	128	20090211	97
19920715	89	20000513	97	20060704	114	20090212	89
19930609	115	20000518	120	20060718	117	20090626	94
19930831	92	20000602	222	20060728	101	20090726	95
19940629	90	20000615	90	20060803	101	20090821	127
19950404	97	20000809	137	20061201	111	20100504	110
19950706	132	20010701	183	20070516	98	20100527	105
19950715	144	20020514	135	20070608	150	20100606	117
19950716	92	20020531	172	20070619	146	20100623	94
19960423	91	20020606	94	20070627	181	20100624	204
19960511	115	20020627	105	20070719	98	20100721	173
19960624	142	20020723	100	20070803	97	20100725	247
19970718	107	20030707	125	20070809	119	20100804	159
19970816	140	20030708	166	20070816	117	20100805	279
19970817	113	20030709	125	20070825	169	20100922	121
19980529	186	20030721	142	20080305	138	20101026	114
19980531	177	20030722	92	20080531	112	20101117	107

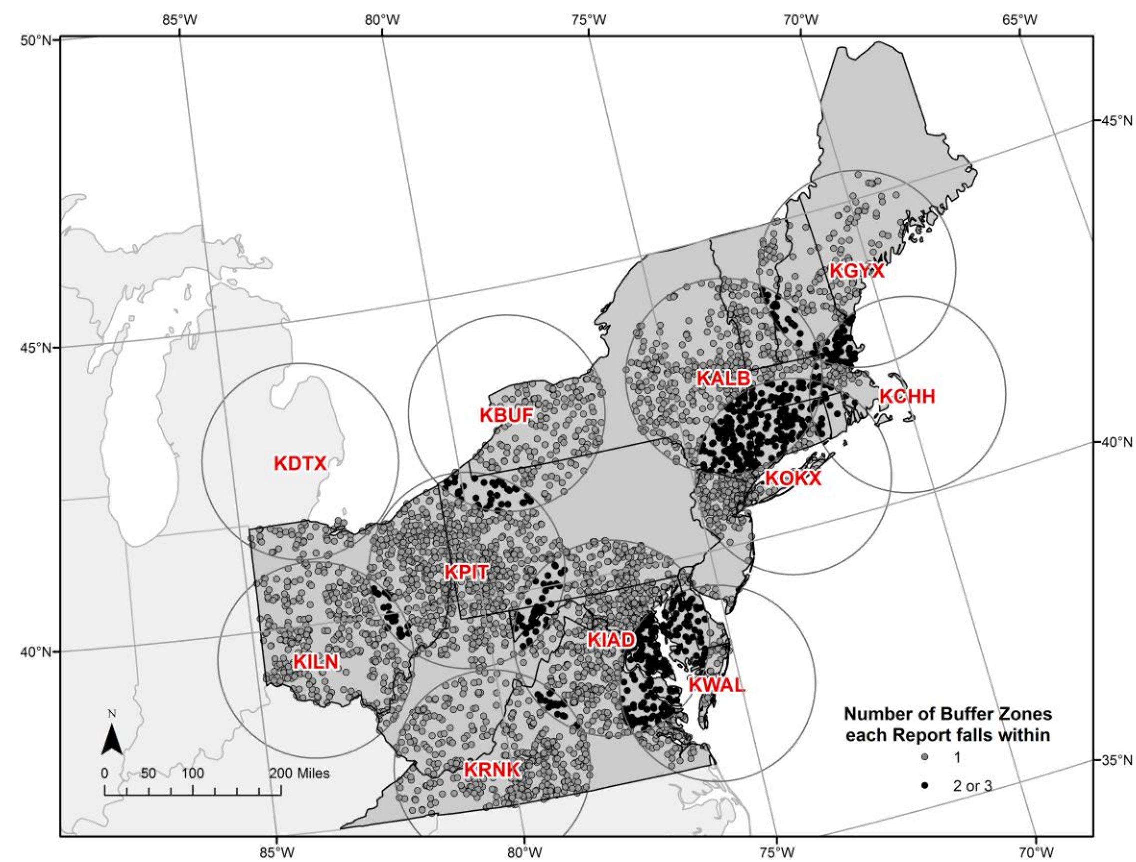

Figure 3.8: The 11 upper air stations used for analysis of thermodynamic environments shown with 180km buffers. Reports are color-coded by the number of buffer zones they fall within.

Chapter 4

RESULTS AND DISCUSSION

4.1 Convective Wind Climatology

Although there have been several studies examining convective winds across diverse areas of the United States, this study focuses specifically on the Northeast in order to create a high resolution analysis of how this hazard affects such a vulnerable region (Kelly et al. 1985, Kuchera and Parker 2006). A climatology has been constructed showing the spatial and temporal variability of severe convective surface winds. This section concentrates on the spatial, interannual, annual, and diurnal distribution of all wind reports from 1955-2010 along with the reports associated with the 104 significant event days.

4.1.1 Spatial Distribution

From the spatial distribution shown in figure 3.2 along with the preliminary hot spot analysis in figure 3.6, it is apparent that wind reports are primarily located near urban centers and major highways. Reports were aggregated into 1 degree grid boxes in order to show the total number of wind reports that occurred in that area over the 56-year period (Figure 4.1). The grid boxes with the largest number of wind reports follow the I-95 corridor from Washington D.C. into upstate New York and Western Massachusetts. The lowest amount of wind reports occur in Maine and around the periphery of the states due to the fact that those grid boxes encompass the edge of the study region.

Figure 4.2 shows the monthly spatial distribution of wind reports throughout the study period. January, February and March are similar in terms of an even scattering of reports on both sides of the Appalachian Mountains. Many of the reports are positioned south of New England. March displays some light clustering around the Washington D.C. area and as April approaches, an even dispersal of reports covers the entire region south of New England and upstate New York. May begins to show a higher number of wind reports along the I-95 corridor from Washington D.C. to Albany, NY, and around Cleveland, OH and Pittsburgh, PA. The Mohawk and Hudson River Valleys in upstate New York are discernible in May and June. According to Wasula et al. (2002), meteorologists have long observed that the local topography has large impacts on this region. Valleys formed by the Adirondack, Catskill, Green and Berkshire Mountains are an important factor in determining the weather. The terrain can direct warm, moist air into upstate New York acting to destabilize the atmosphere and focus convergence (Wasula et al. 2002). By June, the convective wind reports reach their northern extent, covering all of Maine.

The month with the most convective wind reports and most complete spatial distribution is July. Again, clustering is apparent in large urban centers and along major highways, with minimums in the Appalachian Mountains and Northern Maine. With a similar distribution to June and July, the number of wind reports in August starts to decline. Reports quickly become less frequent and migrate south again in September and October, with a slight increase in November especially in the lee of the Appalachians in the mid-Atlantic. Kelly et al. (1985) also found November to have a small secondary maximum in thunderstorms related to wind damage. The minimum amount of convective wind reports occurs in December with the only visible cluster positioned over New York City, which is most likely attributed to population bias.

A histogram displaying the number of wind damage reports per state from 1955-2010 shows the largest counts in Ohio, Pennsylvania, New York and Virginia with significantly fewer occurring in every other state (Figure 4.3). It is understandable that these four states would have the most wind reports simply because they are the largest in the study region. Similar to King (1997), in order to weight the report distribution by land area, each state is normalized to reports per 10,000 square miles using U.S. Census Bureau data. Table 4.1 lists each state's number of wind reports, area, and number of wind reports per 10,000 mi^2. A histogram of the normalized wind reports is shown for comparison (Figure 4.4). The area-weighted reports are now most numerous in New Jersey, Maryland and Ohio, closely followed by other mid-Atlantic states. The normalized distribution results agree well with the population-corrected hot spot analysis from section 3.3 for both Maryland and Ohio. As expected, Maine has the smallest wind report count followed by New Hampshire and Rhode Island.

4.1.2 Interannual Variability

In order to demonstrate the variability of severe convective wind reports from year-to-year throughout the study period, a histogram of all 55,771 wind reports is constructed to show the number of wind reports that occurred each year along with a histogram displaying the number of event days per year (defined as any day where one or more instance of wind damage was reported) (Figure 4.5 and 4.6, respectively). Until 1980, under 500 occurrences of wind damage were reported each year, with many years well below 250. Section 3.2.1 highlights several reasons why the number of reports per year increases significantly throughout the 56-year period, especially from 1980-2010. There were only 43 wind reports in 1972, the minimum throughout the study period, and the maximum occurred in 2010 with 3,885. Figure 4.6 shows much less variability and a less dramatic increase. According to Doswell et al. (2005), using a distribution of event days as opposed to counting individual reports helps to smooth biases caused by secular changes in reporting throughout time. As mentioned before, these increases are recognized as non-meteorological in character. The number of event days per year range from 25 in 1955 to 123 in 2007.

4.1.3 Annual Cycle

It is necessary to consider the annual cycle of severe convective surface winds in order to determine when the Northeast U.S. is the most vulnerable to this hazard (Figure 4.7). Similar to previous studies conducted on convective winds, June and July are the months that experience the highest frequency of wind reports, followed by August and May (Kelly et al. 1985). Together, reports within June and July make up about 52% of those that occurred throughout the study period. April and September have a similar number of reports (around 2,500), with the remaining months falling below the 2,000 report total. Unlike hail and tornadoes, which are springtime phenomena, convective surface winds occur most often in summer (Doswell et al. 2005). The maximum number of all severe weather reports combined (hail, wind and tornadoes) occurs in summer, but more than two-thirds of those reports are from high-wind damage (Wasula et al. 2002). As mentioned briefly in section 4.1.1, November shows a slight secondary maximum, agreeing with Kelly et al. (1985) and McNulty et al. (1979).

4.1.4 Diurnal Cycle

Figure 4.8 is a histogram of the diurnal distribution of all convective wind reports from 1955-2010. Wind damage is reported most frequently during the hours of 2100-2159 GMT (1600-1659 EST) with 7450 reports and 2200-2259 GMT (1700-1759 EST) with 7134 reports. Almost 50% of all reports happen in the four hours between 3pm and 7pm eastern standard time. This result agrees with several studies showing that severe weather events are highly correlated with the diurnal heating cycle and normally occur in the late afternoon/early evening hours (Bentley and Mote 1998; Kelly et al. 1985; Lombardo and Colle 2010; Murray and Colle 2011). Wind reports are at a minimum in the early morning hours which is attributed to the relatively stable atmosphere at this time of day. The fact that people are indoors and often asleep during these hours also contributes to the minimum in reports.

4.1.5 Significant Event Day Distributions

In order to further investigate the synoptic and thermodynamic environments of the 104 significant event days, it is important that the sample represent the entire dataset. The same spatial and frequency distributions for the reports associated with the significant event days are produced to confirm that the sample is suitable for further analysis. The spatial distribution of the 13,405 significant day reports is very similar to the distribution of all 55,771 reports (Figure 4.9), with maxima along the I-95 corridor and on the Ohio/Pennsylvania border. The 1 degree grid showing the significant event day report counts per grid box looks almost identical to figure 4.1 in terms of the maximum and minimum report locations (Figure 4.10).

The normalized distribution of significant day reports across the 14 states also resembles that of the entire population (Figure 4.11). Maryland and New Jersey are the two states that receive the most reports per unit area, but Connecticut has more reports associated with significant event days than Ohio. Surprisingly, Ohio has the fourth highest count, with Pennsylvania and Massachusetts closely following. Maine is once again the state that receives the least reports. Keeping with Doswell et al. (2005), Figure 4.12 shows the distribution of significant event days per year. There are several years in the beginning of the period of record that don't experience significant event days, but there is a steady increase in the number of significant event days from 1989 to 2010. Advances in radar technology, initiation of warning verification programs along with changes in population and reporting procedures are most likely the causes of these increases throughout time.

The annual distribution of significant event reports matches that of the entire population (Figure 4.13). July and June are the months with the highest number of reports, again making up over half the amount of all significant event day reports, followed by August and May. The secondary maximum in November is slightly more apparent in this histogram with about twice the number of reports as September and October. No wind reports associated with significant event days fall within January in this distribution making this month the minimum.

There is also general uniformity between the diurnal distribution of significant event day reports and the entire wind report dataset (Figure 4.14). The peak hour of wind reports is between 2100-2159 GMT (1600-1659 EST), but a steady amount of reports occur between 1900-2259 GMT in accordance with diurnal heating. Both histograms show a minimum in the early to midmorning hours. The number of wind reports range from 91 at 800 GMT and 1759 between 2100-2159. Because the distributions between the sample of reports associated with significant event days and the entire population of severe convective surface winds are very similar, analysis of the synoptic and thermodynamic environments for the 104 significant event days are assumed to be representative of the general population.

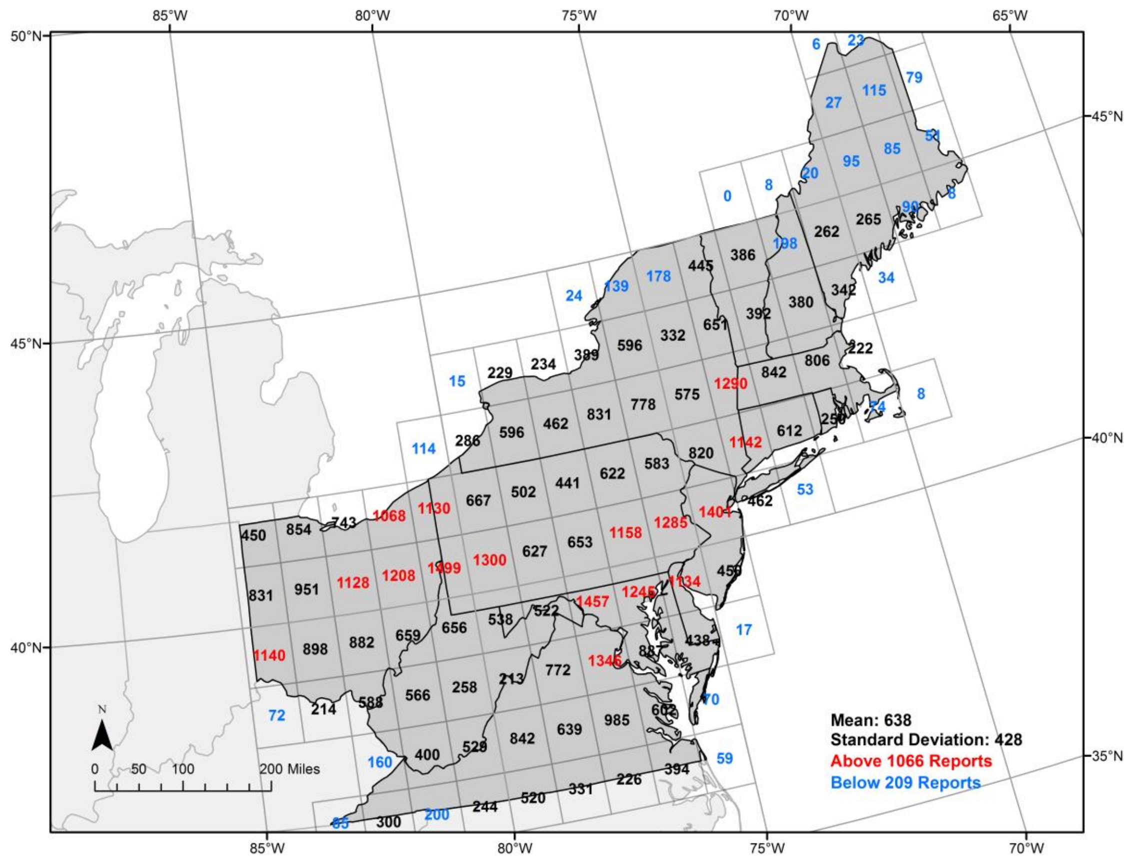

Figure 4.1: Map showing the number of wind reports that occurred within each 1° grid box throughout the 56-year period. Red numbers denote boxes that received a number of wind reports that is more than one standard deviation above the mean. Blue numbers represent areas with fewer reports than one standard deviation below the mean.

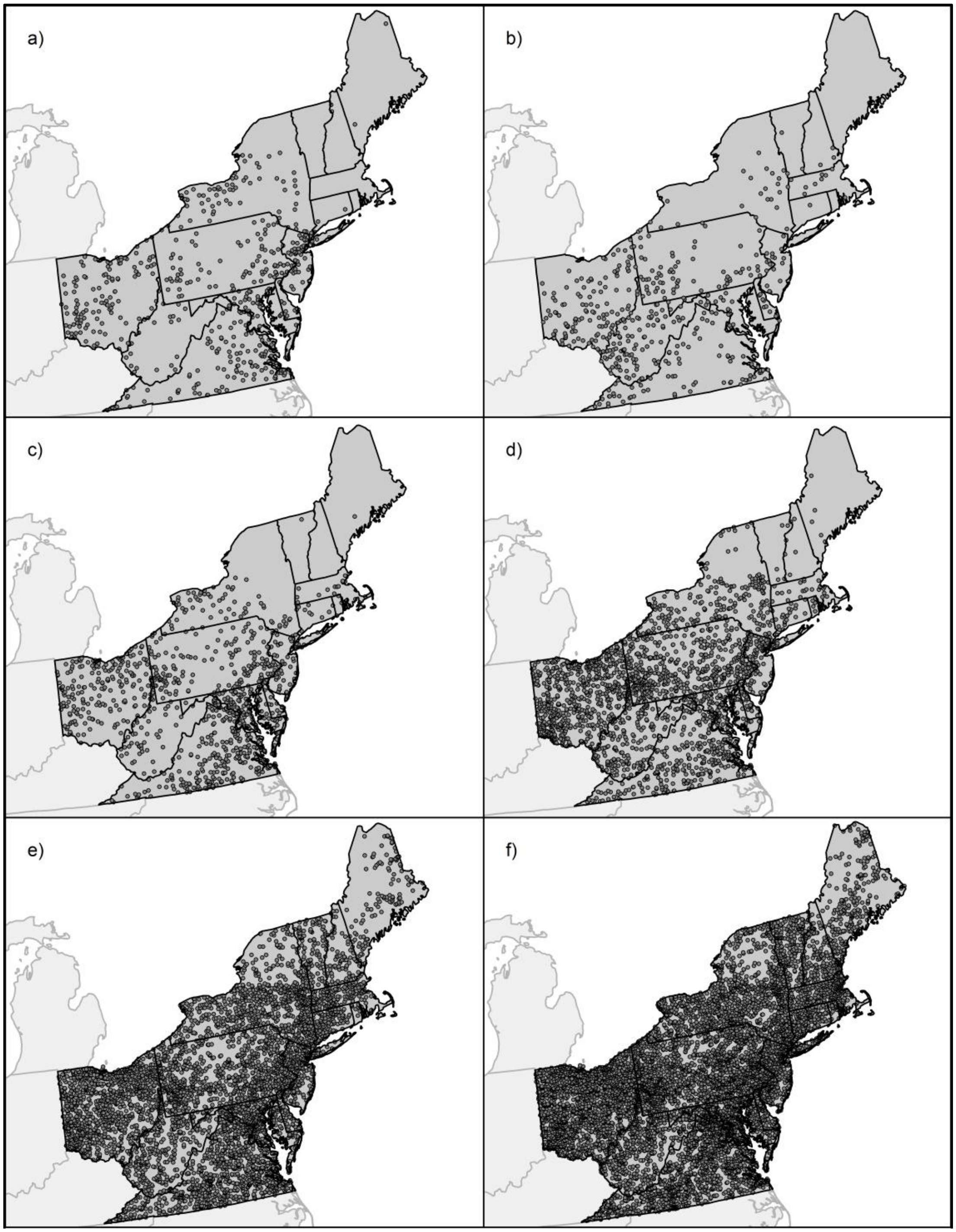

Figure 4.2: Monthly spatial distribution of all convective wind reports from 1955-2010 for a) January, b) February, c) March, d) April, e) May, f) June, g) July, h) August, i) September, j) October, k) November, l) December.

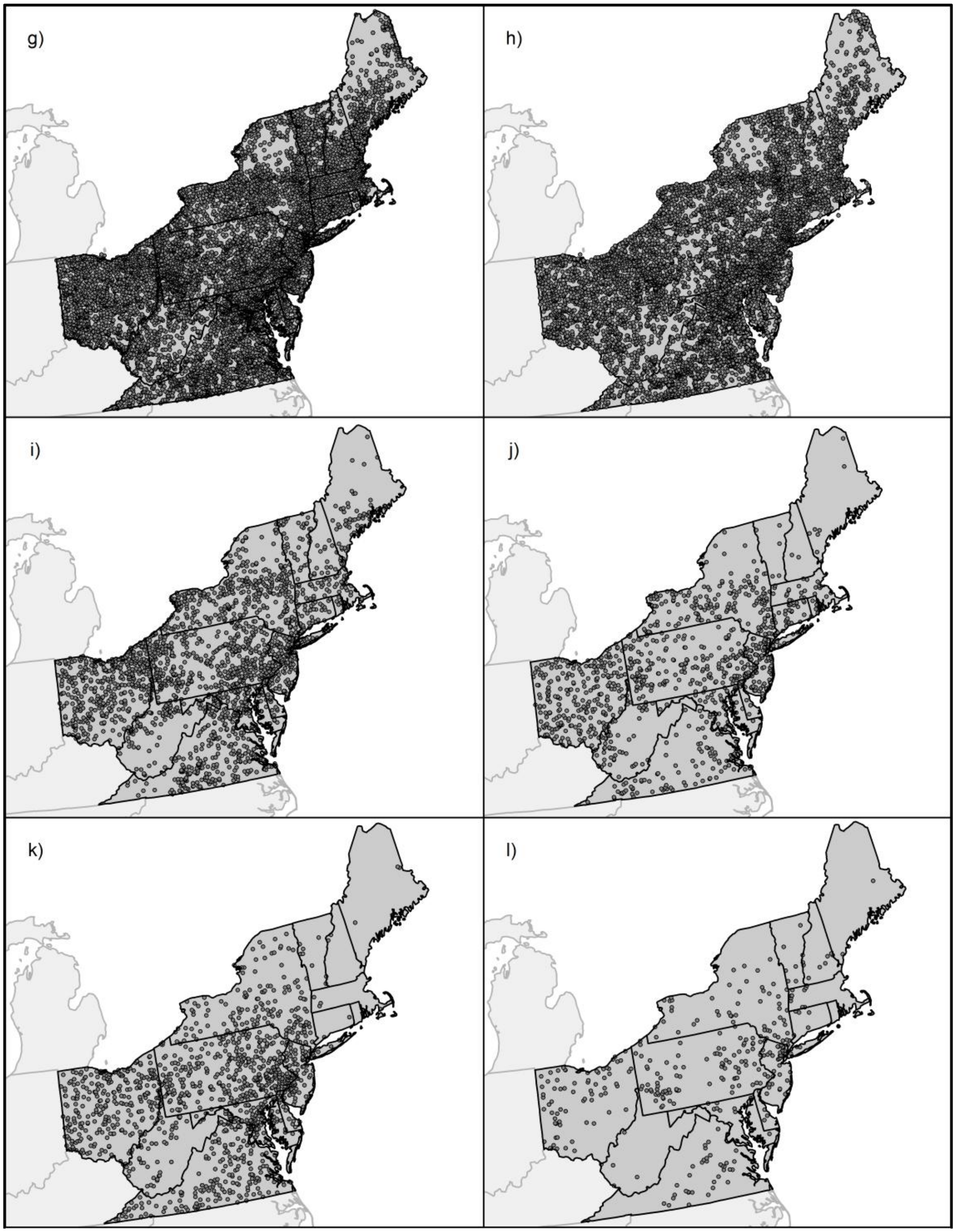

Figure 4.2: Continued.

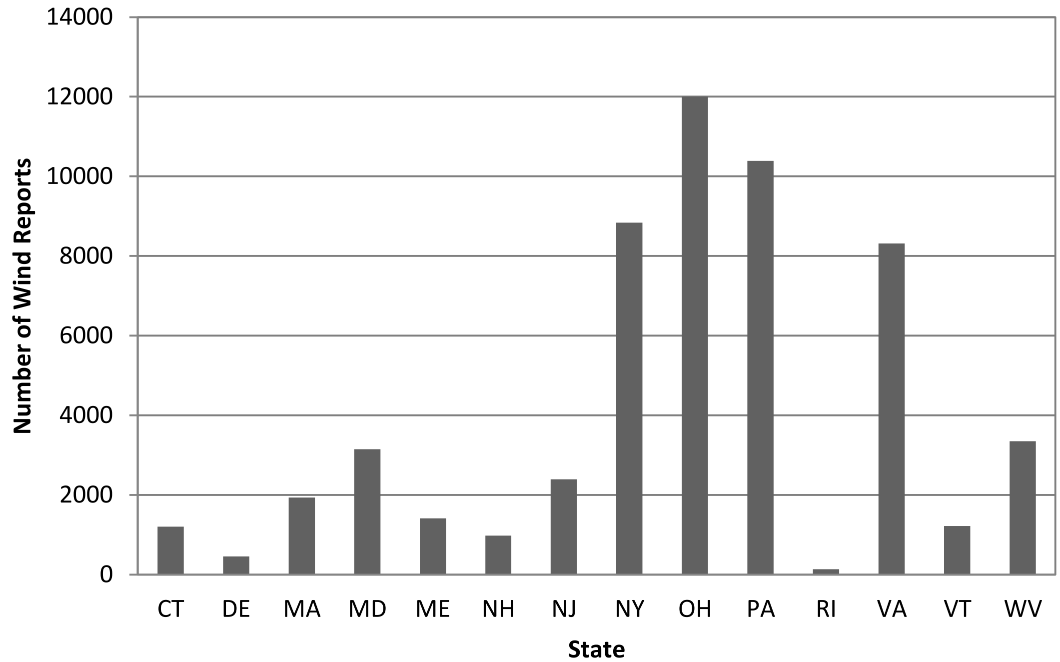

Figure 4.3: Distribution of wind reports by state from 1955-2010.

Table 4.1: Table showing each state's total number of convective wind reports, U.S. Census Bureau land area, and normalized wind report count per 10,000 mi^2.

State	Number of Reports	Area (sq. mi)	Reports per 10,000 sq. mi
CT	1201	4842	2480
DE	457	1949	2345
MA	1935	7800	2481
MD	3148	9707	3243
ME	1413	30843	458
NH	977	8953	1091
NJ	2392	7354	3253
NY	8836	47126	1875
OH	12003	40861	2938
PA	10390	44743	2322
RI	135	1034	1306
VA	8317	39490	2106
VT	1216	9217	1319
WV	3351	24038	1394

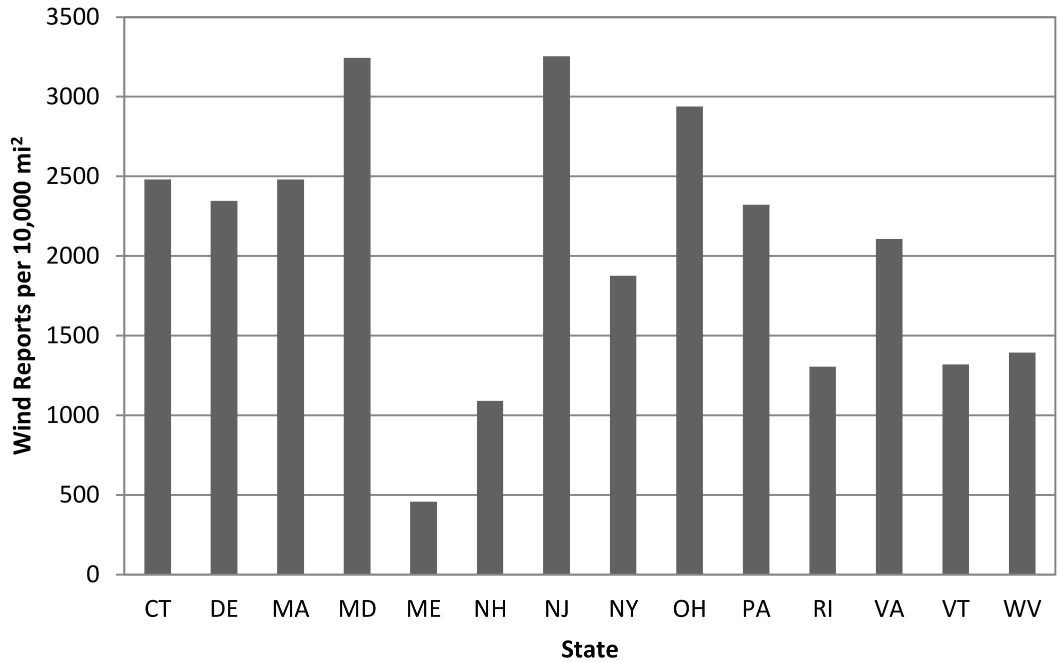

Figure 4.4: Distribution of wind reports by state from 1955-2010; normalized by $10{,}000mi^2$.

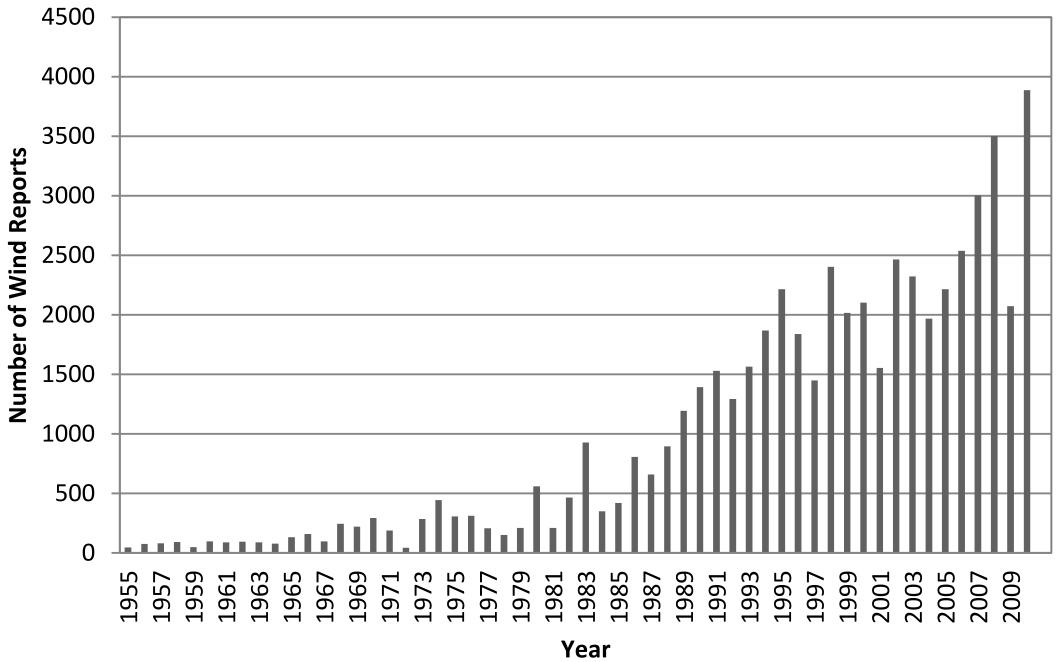

Figure 4.5: Interannual variability of all convective wind reports from 1955-2010.

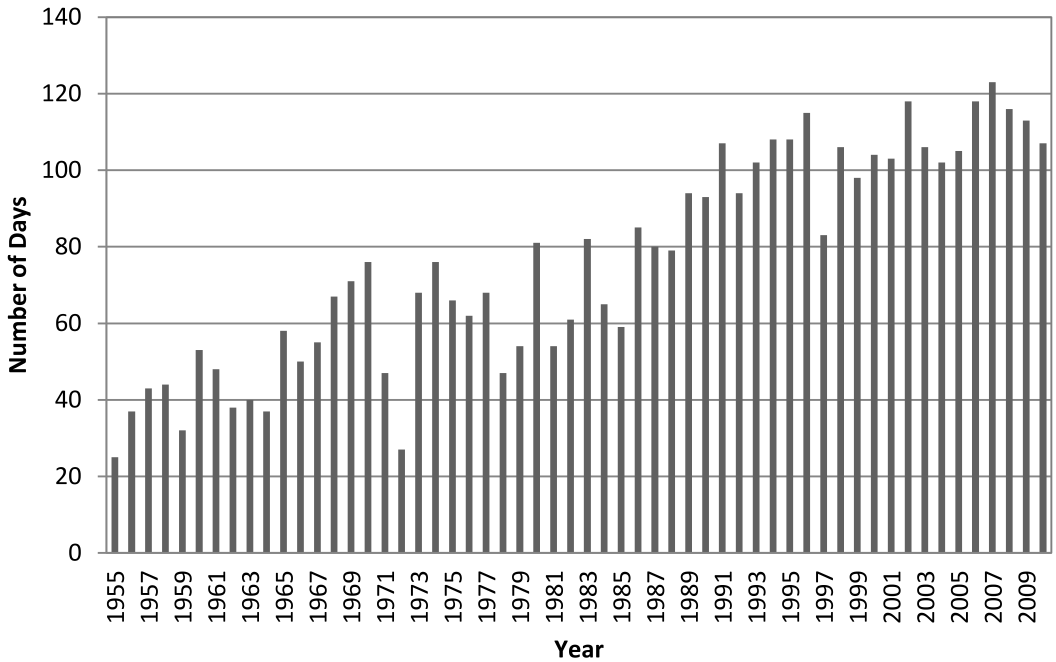

Figure 4.6: Number of event days per year. An "event day" is defined as a day when at least one convective wind report was made.

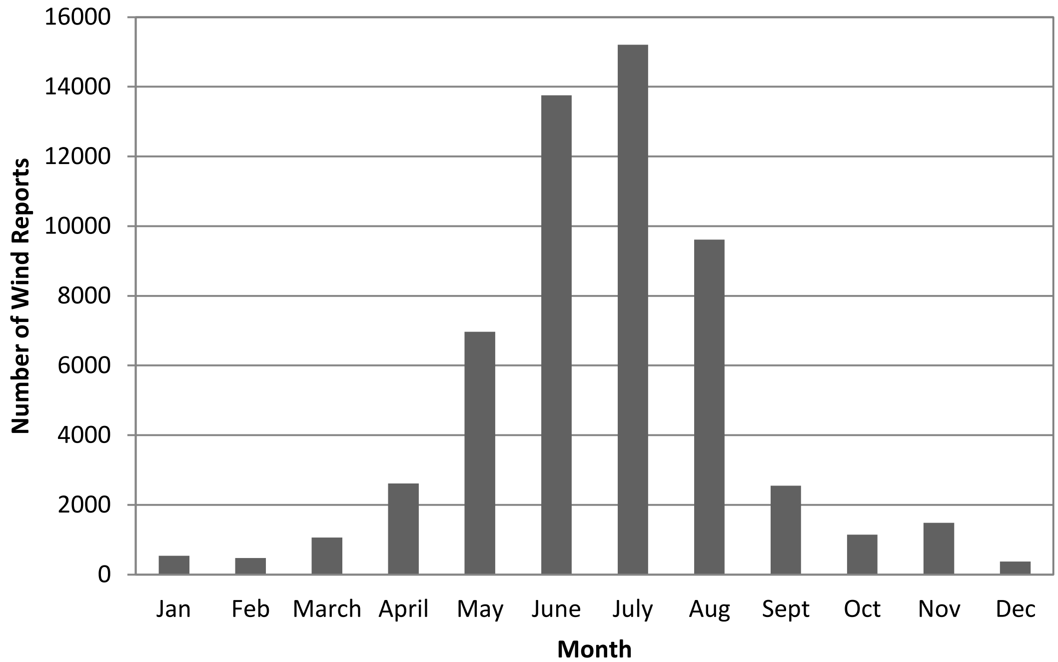

Figure 4.7: Annual distribution of all convective wind reports from 1955-2010.

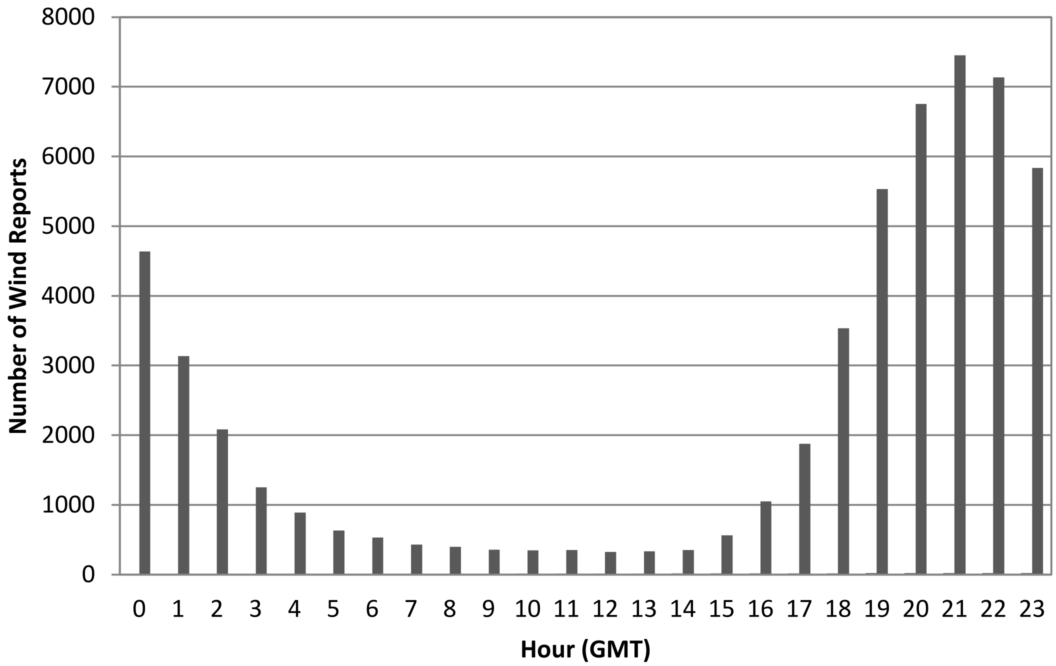

Figure 4.8: Diurnal distribution of all convective wind reports from 1955-2010.

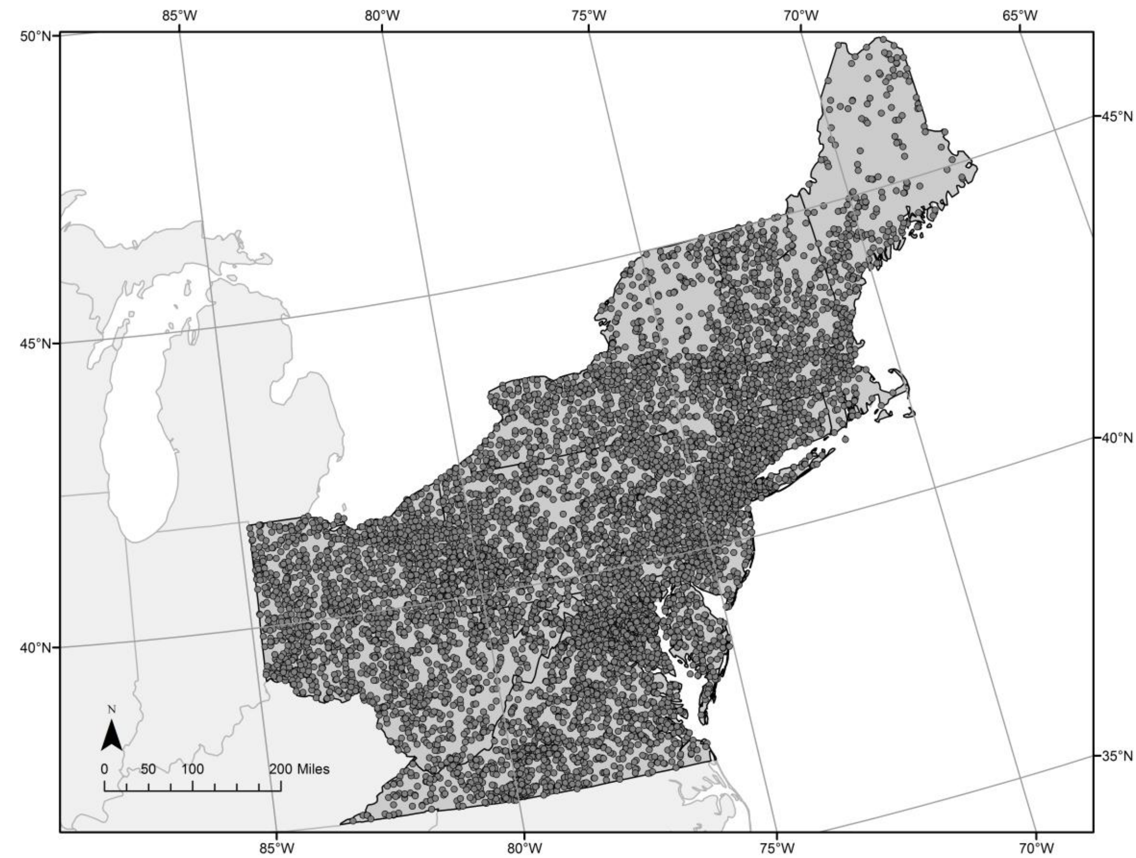

Figure 4.9: Spatial distribution of all 13,405 reports associated with the 104 significant event days from 1955-2010.

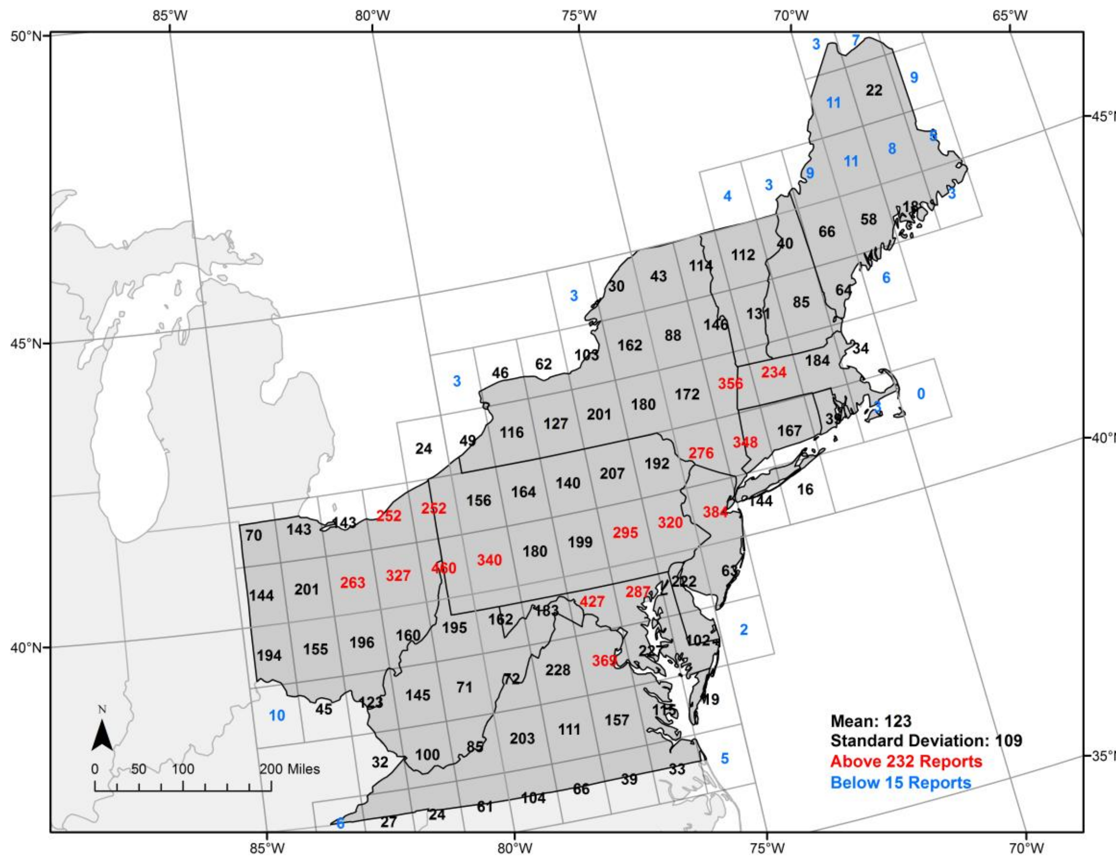

Figure 4.10: Map showing the number of significant event day wind reports that occurred within each 1° grid box throughout the 56-year period. Red numbers denote boxes that received a number of wind reports that is more than one standard deviation above the mean. Blue numbers represent areas with fewer reports than one standard deviation below the mean.

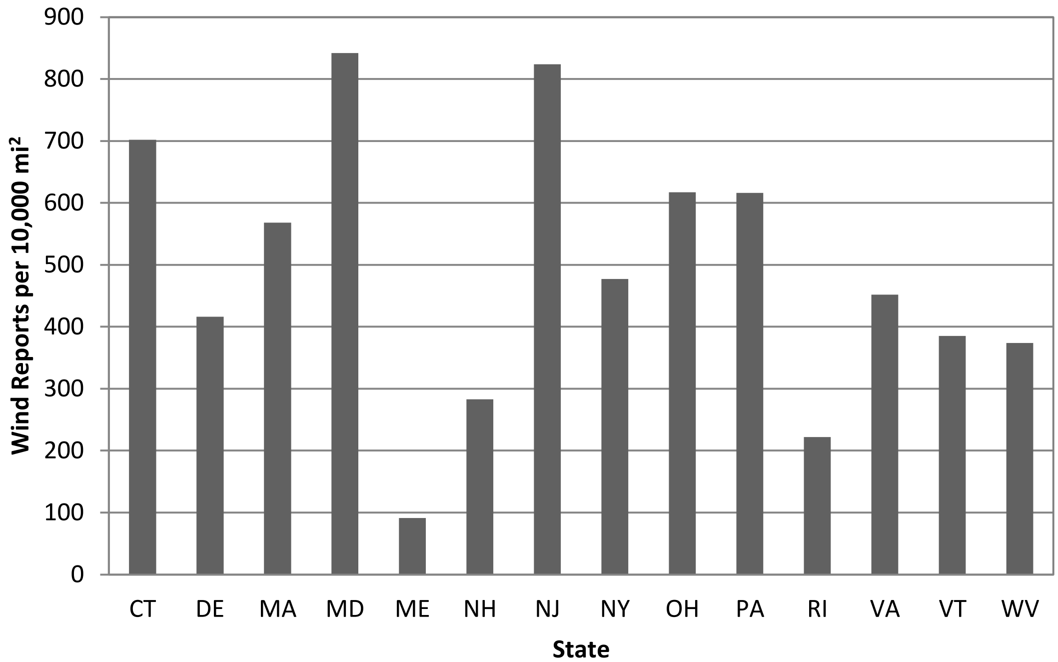

Figure 4.11: Distribution of wind reports within the 104 significant event days by state from 1955-2010; normalized by 10,000mi^2.

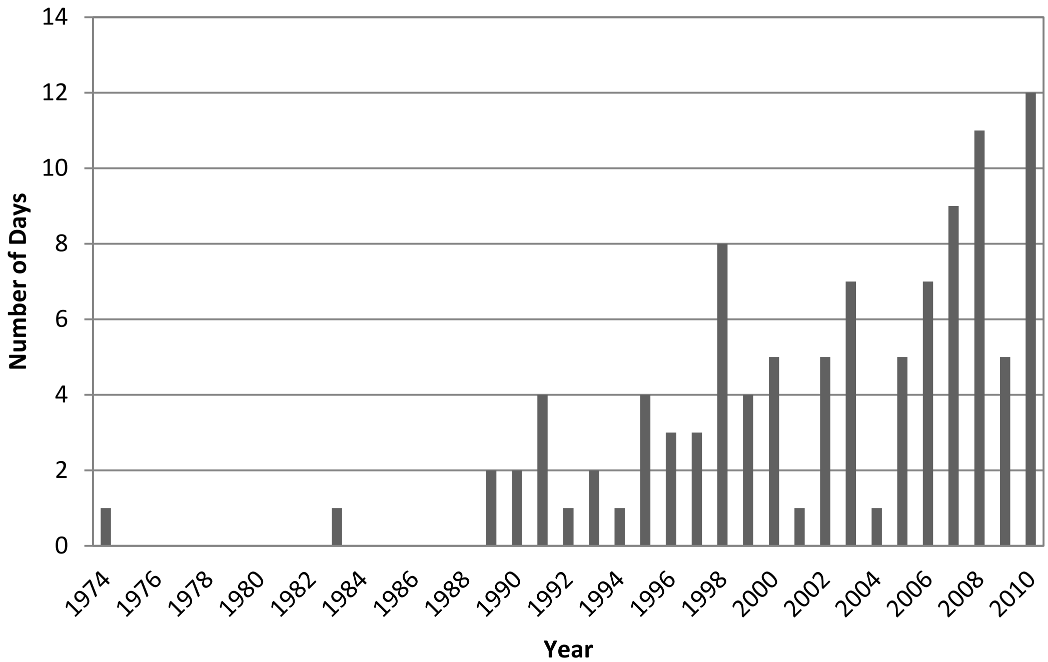

Figure 4.12: Interannual distribution of the 104 significant event days.

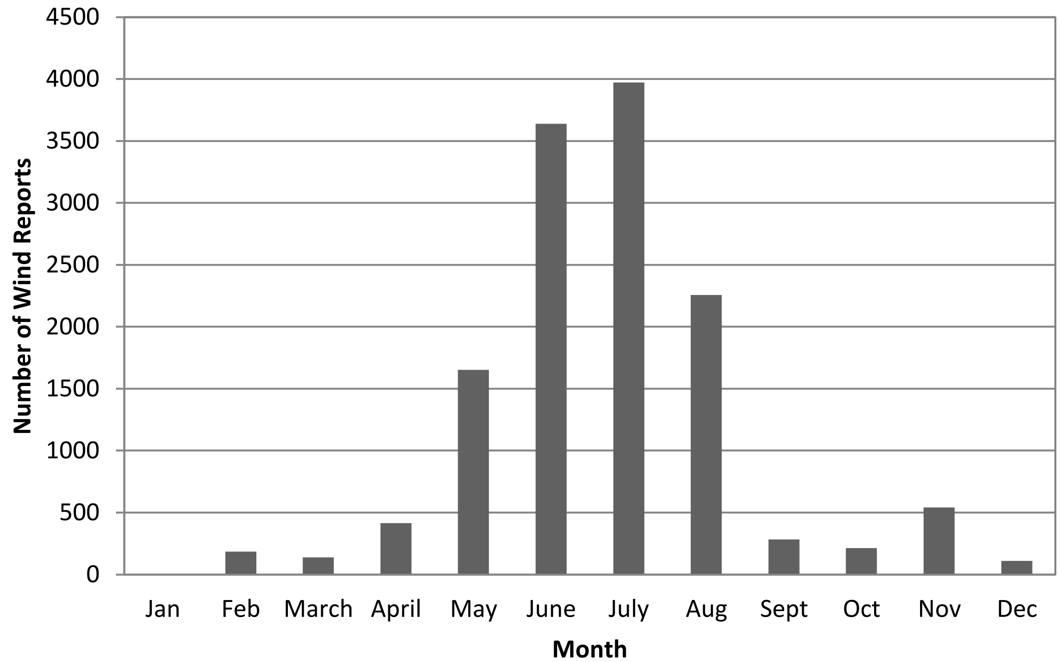

Figure 4.13: Annual distribution of convective wind reports within the 104 significant event days.

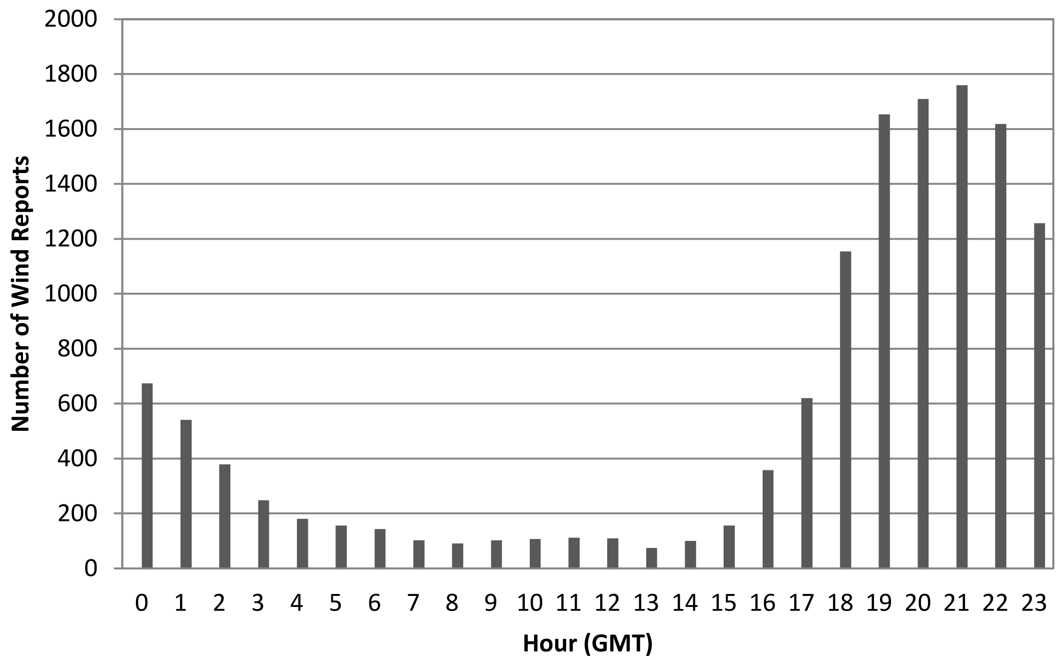

Figure 4.14: Diurnal cycle of convective wind reports within the 104 significant event days.

4.2 Synoptic Patterns

Approaching surface pressure troughs oriented southwest to northeast and quasi-stationary fronts oriented west-northwest to east-southeast have been associated with severe convective weather in the Northeast United States (Murray and Colle 2011). Because severe convective surface winds in this region are most often associated with synoptic forcing as opposed to mesoscale thermodynamics, understanding the synoptic environments associated with this hazard is imperative for forecasting and model validation. This study uses composite synoptic mean and anomaly maps of all 104 significant days acquired from NOAA's ESRL (http://www.esrl.noaa.gov/psd/data/composites/day/) in order to investigate common synoptic patterns related to severe convective winds. Anomalies are calculated from the 1981-2010 mean conditions.

The daily composite mean sea level pressure (MSLP) map shows a weak 1008 hPa closed low north of New York state extending far into Canada (Figure 4.15). Lombardo and Colle (2010) found that similar MSLP conditions occur 12 hours before linear convective events begin developing in the Northeast U.S., with a 1011 hPa low northwest of New York in Canada. The composite anomaly map portrays a -6 hPa surface pressure anomaly northwest of New York, north of Lake Ontario (Figure 4.16), showing that the lows associated with damaging convective winds are relatively strong for the time of year at which these events take place.

The composite mean 500 hPa geopotential heights are indicative of convective storm development as well (Figure 4.17). The study region is located directly under the leading edge of a low-amplitude trough which is associated with upper-level divergence, positive vorticity advection and upward vertical movement of air. Again, this mean 500 hPa pattern closely resembles that found by Lombardo and Colle (2010) 12 hours prior to the initiation of linear convective events. The figure shows a strong zonal component partly because of the map projection, but mostly as a result of the dissolution of the precise locations of short wave troughs and the different flow directions (southwesterly, westerly, northwesterly) during the 104 significant event days (Lombardo and Colle 2010). The mean composite 500 hPa geotepotential height anomaly shows the true strength of the trough over the north-central U.S. (Figure 4.18). The longwave trough centered above Lake Superior is 50 geopotential meters (gpm) below the 1980-2010 mean and the ridge directly off the east coast is 30 gpm above normal. This height configuration is capable of producing upward motion as the trough moves east into the study region with its associated area of upper-level divergence.

From Figure 4.17, severe convective wind reports generally occur when there is southwest flow into the region at 500 hPa. Murray and Colle (2011) found that convection develops much more frequently in association with a southwest flow regime at 500 hPa as opposed to a northwest flow. In their composite 500 hPa geopotential height pattern, they found a mean trough centered over the Great Lakes region, southwest flow over the entire Northeast, and positive absolute vorticity advection ahead of the trough. The results of the current study follow those of Murray and Colle (2011).

Just as the upper-level flow regimes are important in determining how convection relates to the large-scale trough and ridge pattern, investigating the low-level flow can help determine if coastal boundaries and topography modify convective potential (Murray and Colle 2011). The 850 hPa geopotential height pattern shows the Northeast under the leading edge of a low-amplitude trough (Figure 4.19). Much like Lombardo and Colle's (2010) composite 850 hPa heights associated with linear convection at the time of initiation, this pattern is slightly more zonal than the 500 hPa composite mean. Again, the strength of the trough is apparent in the composite anomaly 850 hPa map with -45 gpm anomalies north of Lake Ontario (Figure 4.20).

Focusing on surface air temperature, a small ridge of warm air can be seen extending up the entire east coast, hinting at warmer than usual temperatures over the entire region (Figure 4.21). The surface air temperature anomaly confirms that the Northeast U.S. is on average a few degrees Kelvin warmer than usual when convective wind events occur (Figure 4.22). This is especially true west of the Delmarva Peninsula, directly over the population-corrected hot spot that extends from Maryland, Virginia and West Virginia into Pennsylvania (Figure 3.7). This anomaly map also points to the fact that many of these storms are generated by cold frontal passages associated with the Canadian surface low traveling eastward.

Although thermodynamic indices are known to best predict severe weather in the Great Plains, they can still offer information on stability in other regions of the country. The Lifted Index (LI) is a simple measure of atmospheric stability measured by subtracting the parcel temperature at 500 hPa from the environmental temperature at 500 hPa. The more negative the value, the greater the instability. Similar to the composite mean surface temperature map, the composite mean LI map shows a "ridge" of lower LI values entering the study region (Figure 4.23). The composite LI anomaly is evidence that although the LI values aren't necessarily low enough to be considered severe by Midwestern standards, the LI values are much lower than normal when severe convective wind events occur in the Northeast (Figure 4.24). A tight, negative LI gradient encompasses the entire study region. The most extreme anomaly is -4.5 degrees Kelvin centered over western Pennsylvania and includes the locations of two population-corrected hot spots (Figure 3.7). Both the hot spot located on the border of Ohio and Western Pennsylvania and the hot spot over Maryland that extends into Pennsylvania are incorporated in this region of greater instability than normal for the given time of year.

Lombardo and Colle (2010) classified and highlighted the ambient conditions associated with cellular, linear and non-linear organized convective storms over two warms seasons in the Northeast United States. They found limited synoptic forcing associated with cellular events and hypothesize that these storms are mostly initiated by the upslope flow component affiliated with the orography in this region. It is possible that a fair amount of the convective wind reports that occur on the windward side of the Appalachian Mountains (around the hot spot located on the Ohio/Pennsylvania border) are from cellular events. As previously mentioned, several composite mean and anomaly maps including the composite MSLP, mean 500 hPa geopotential heights, and mean 850 hPa geopotential heights closely resemble the linear convective event findings of Lombardo and Colle (2010). They found that linear convective events are almost always located on the lee of the Appalachians and associated with a prefrontal surface trough ahead of a cold front. These often develop from adiabatic warming or large-scale ascent created by the prefrontal surface trough (Lombardo and Colle 2010). Additionally, Schoen and Ashley (2011) found organized linear convection to be the primary cause of nontornadic convective wind fatalities along the East Coast. Considering these examples, many of the severe convective wind reports east of the Appalachian Mountains are most likely a result of organized linear systems. Because the mean synoptic environments match those of Lombardo and Colle (2010) and Murray and Colle (2011), and the population-corrected hot spots agree with these analyses, it is concluded that synoptic forces are a major initiator of severe convective winds in the Northeast United States.

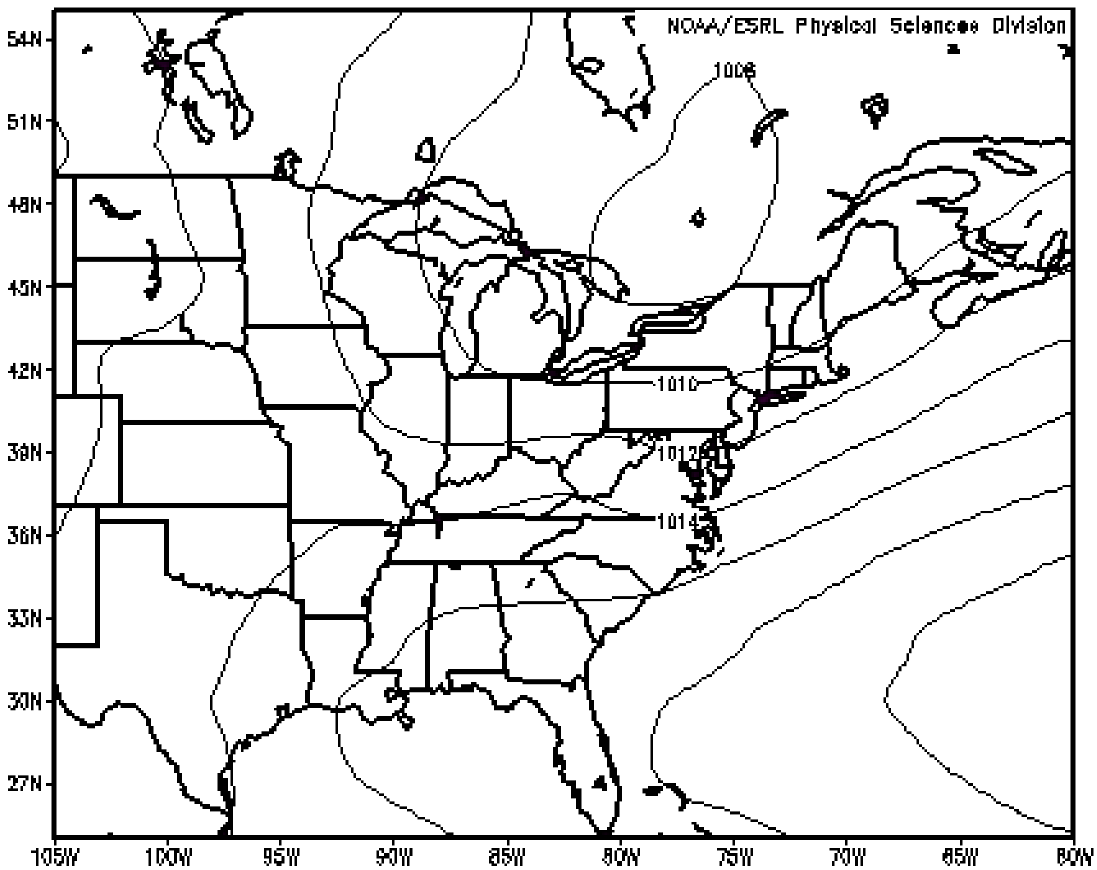

Figure 4.15: Composite mean map of sea level pressure (SLP) (hPa) representing the 104 significant event days.

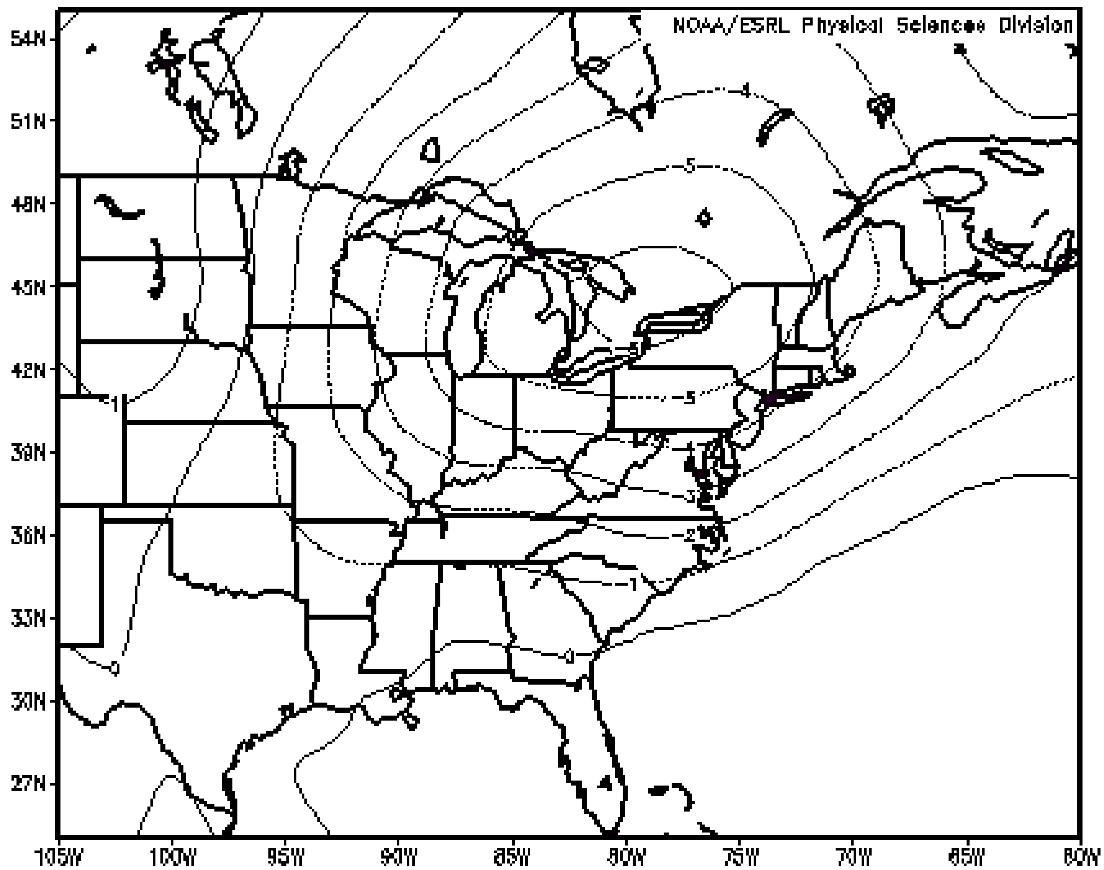

Figure 4.16: Composite map of sea level pressure (SLP) anomalies (hPa) representing the 104 significant event days.

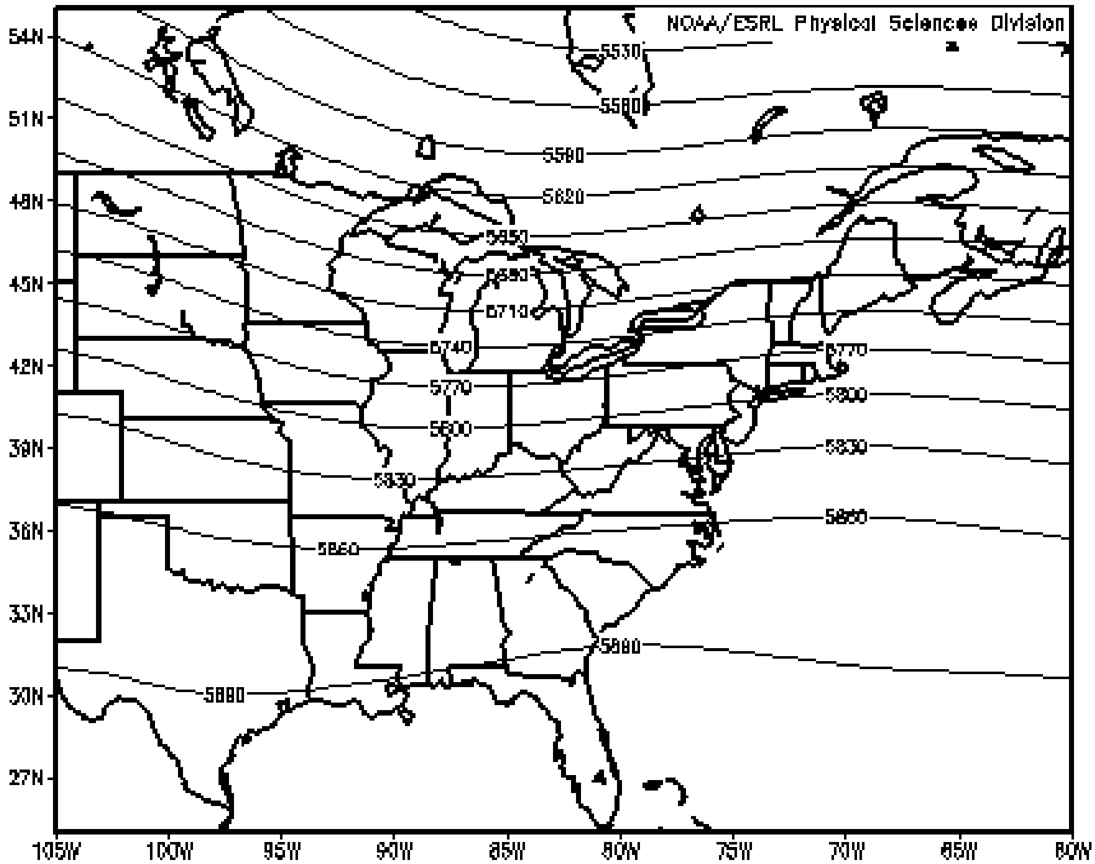

Figure 4.17: Composite mean map of 500 hPa geopotential heights (m) representing the 104 significant event days.

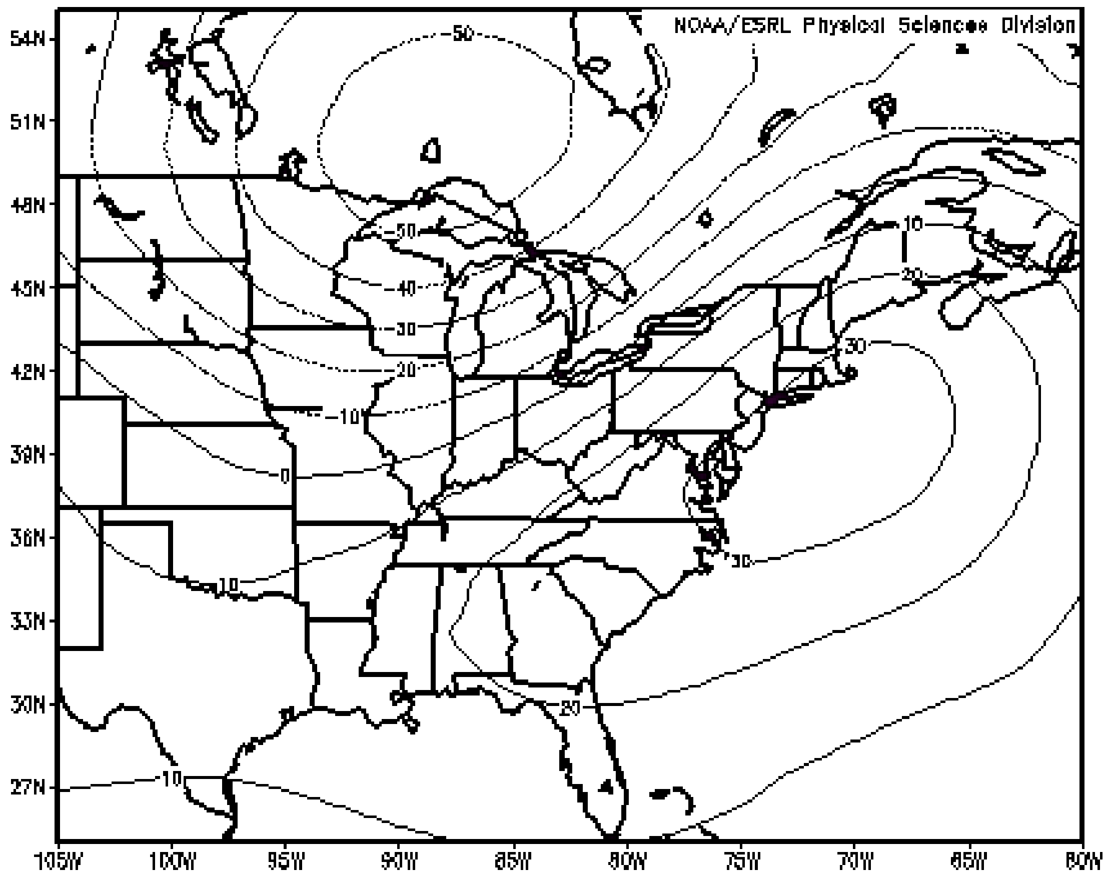

Figure 4.18: Composite map of 500 hPa geopotential height anomalies (m) representing the 104 significant event days.

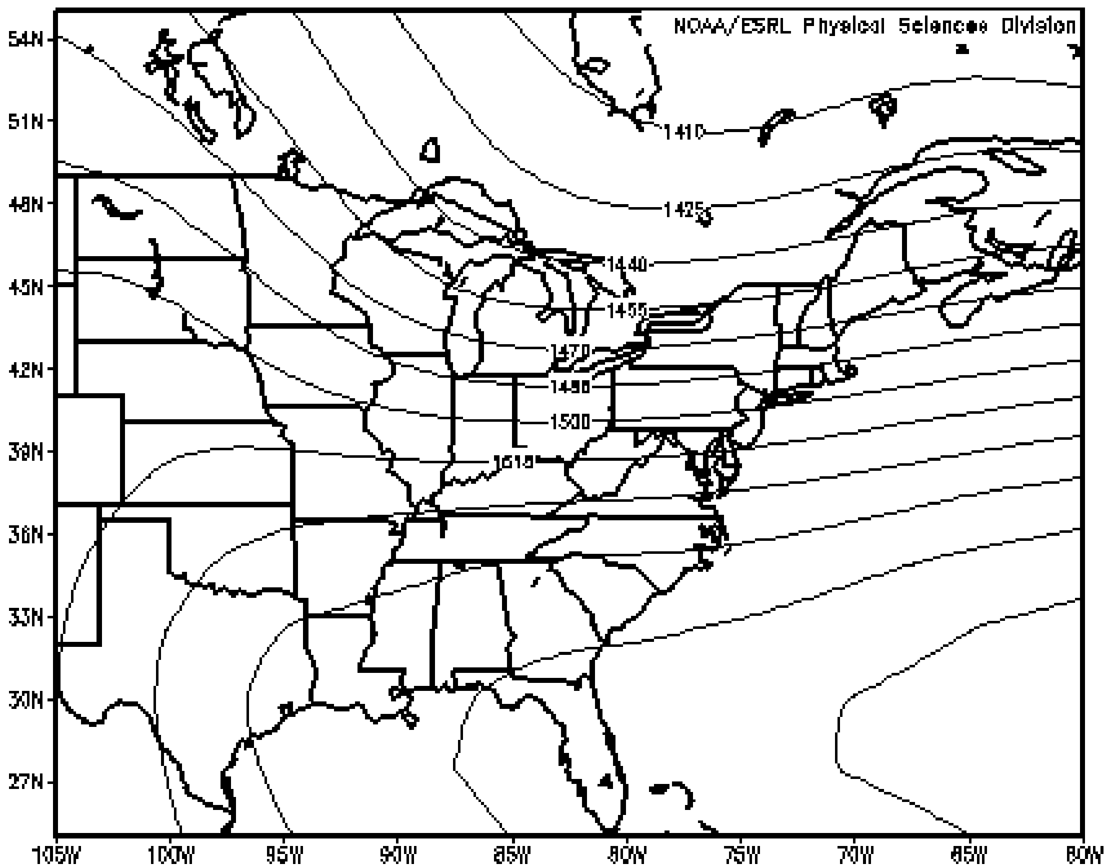

Figure 4.19: Composite mean map of 850 hPa geopotential heights (m) representing the 104 significant event days.

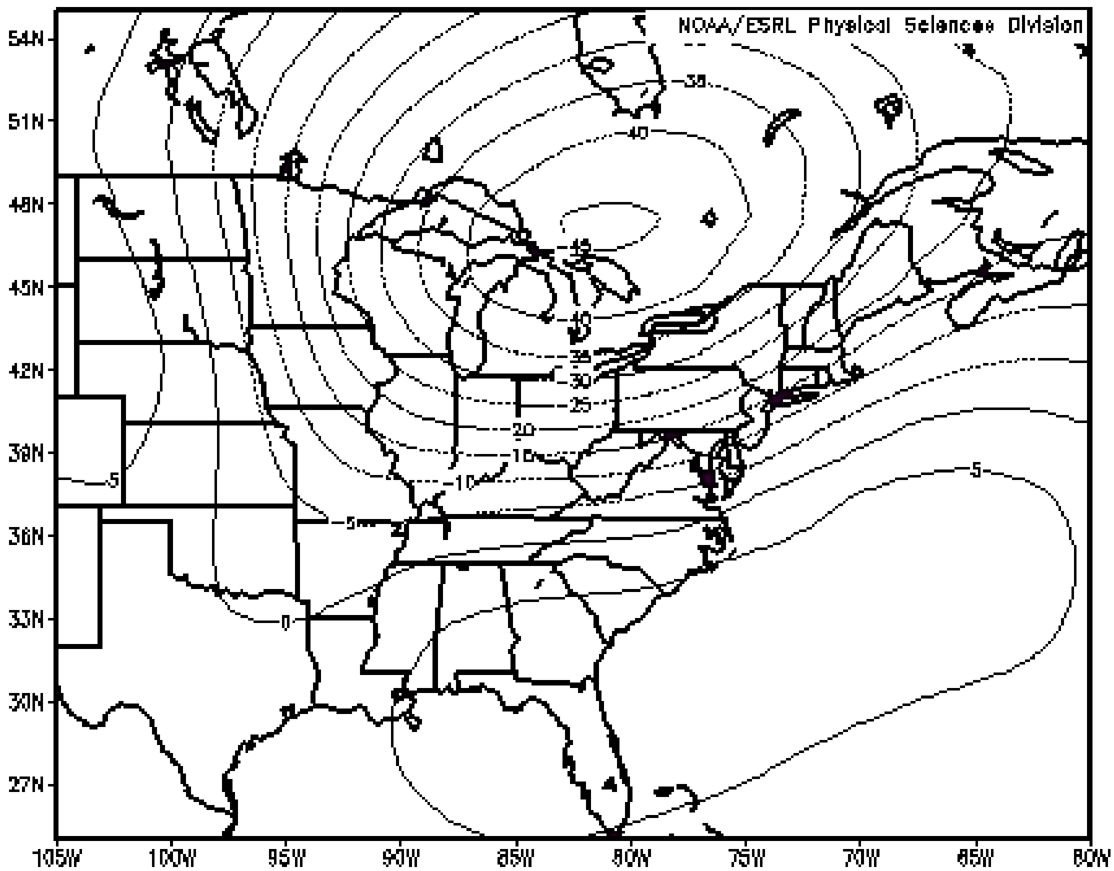

Figure 4.20: Composite map of 850 hPa geopotential height anomalies (m) representing the 104 significant event days.

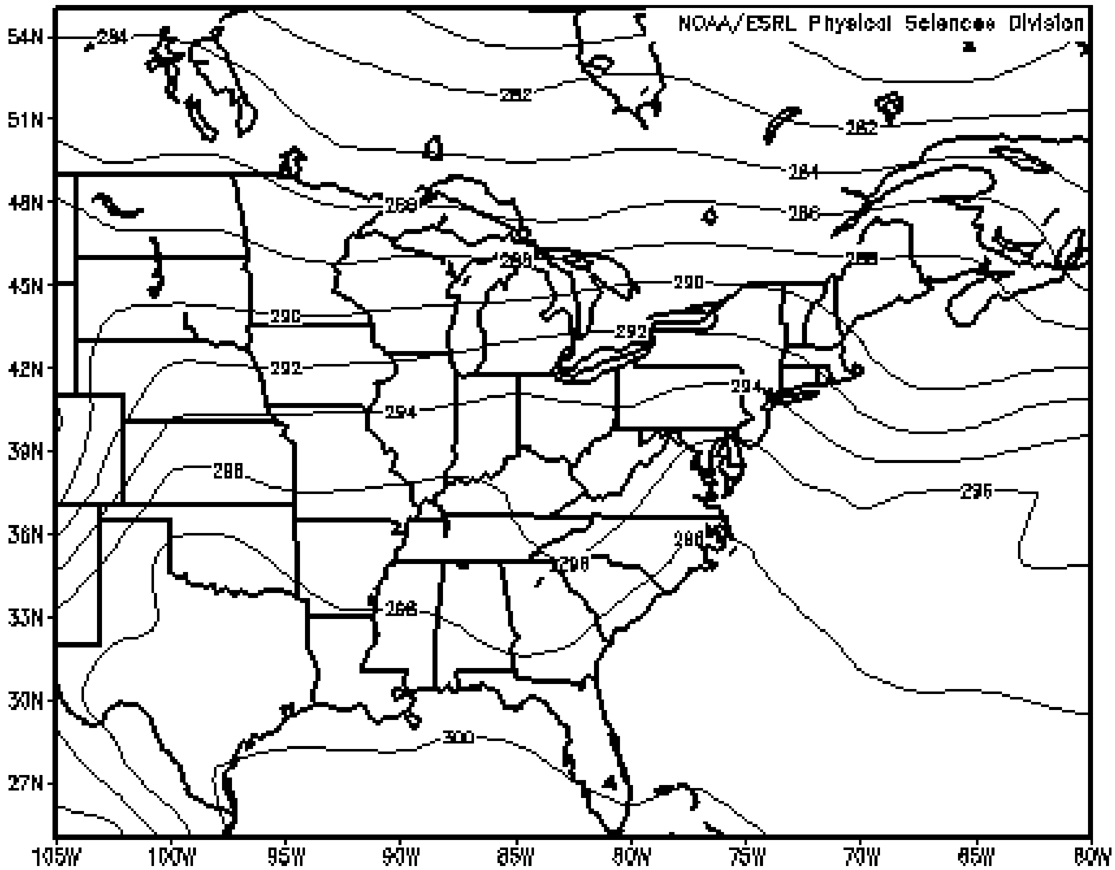

Figure 4.21: Composite mean map of surface air temperature (K) representing the 104 significant event days.

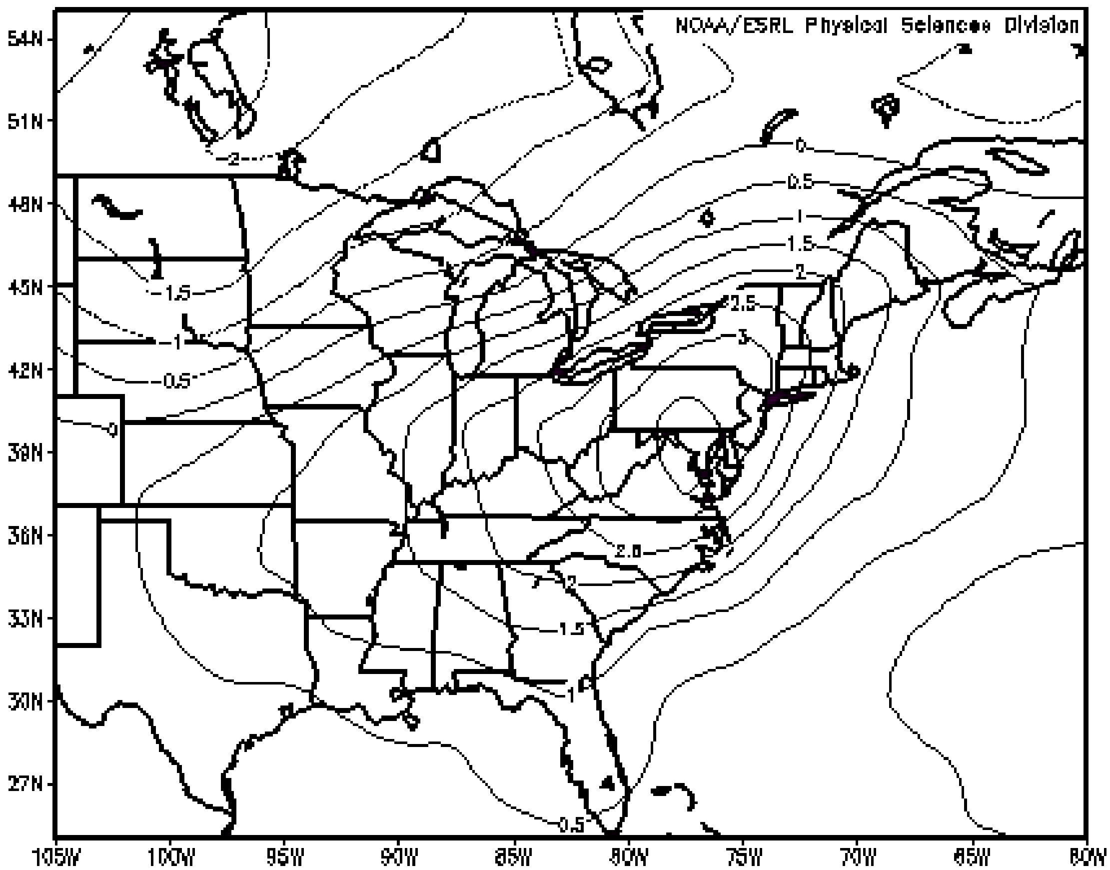

Figure 4.22: Composite map of surface air temperature anomalies (K) representing the 104 significant event days.

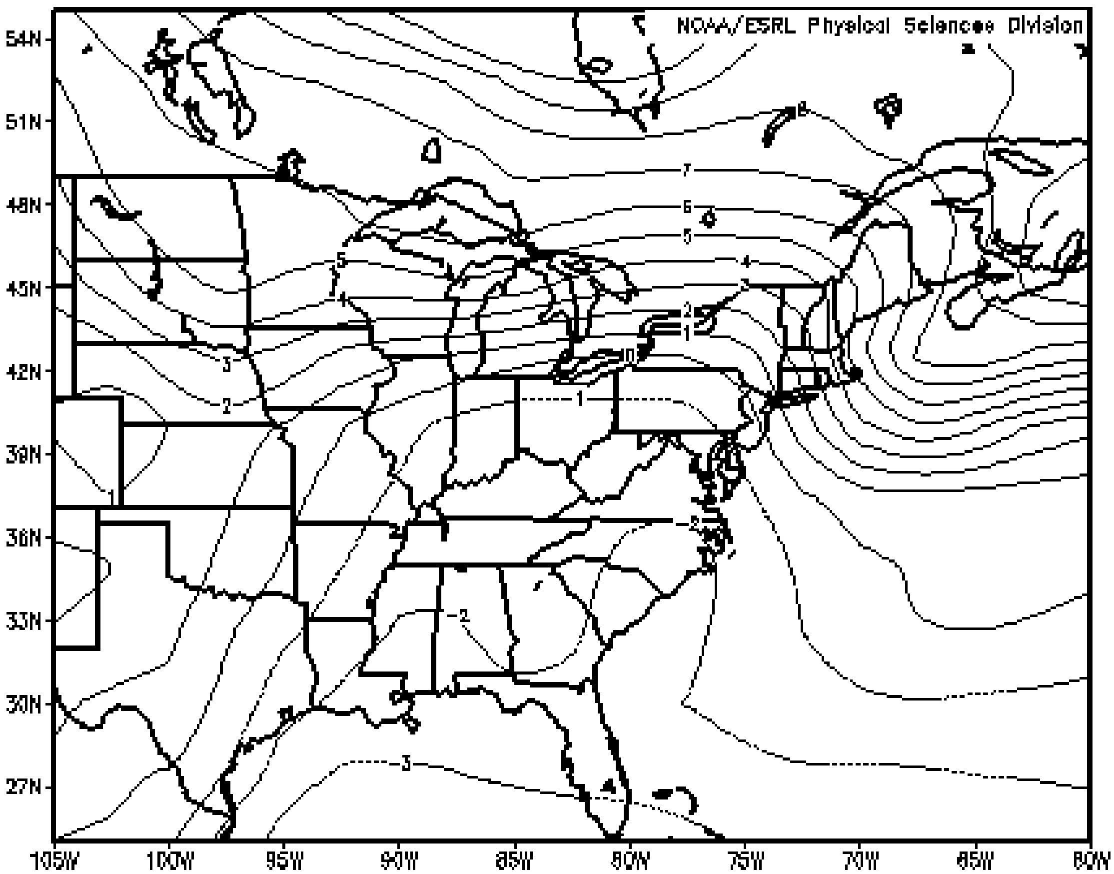

Figure 4.23: Composite mean map of Lifted Index values (K) representing the 104 significant event days.

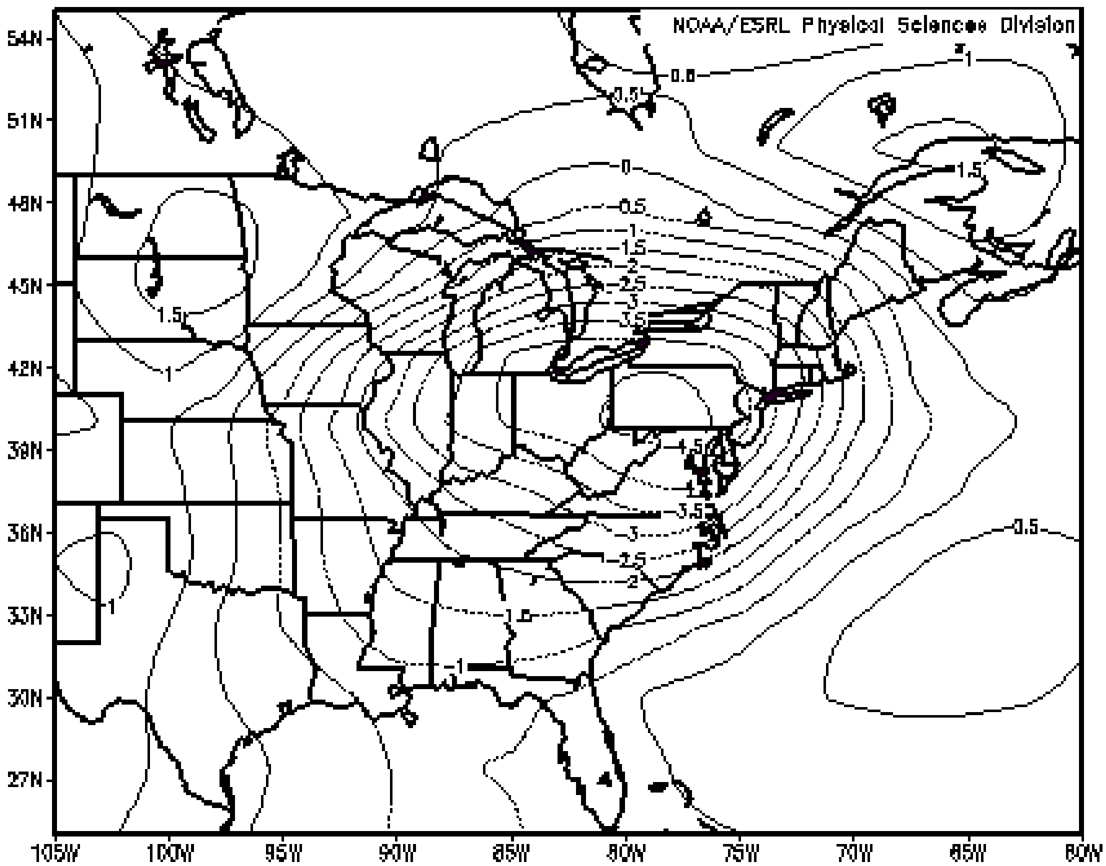

Figure 4.24: Composite map of Lifted Index anomalies (K) representing the 104 significant event days.

4.3 Thermodynamic Environments

Stability indices have been recognized to aid not only in forecasting severe weather in the Great Plains but also discriminating between different types of mesoscale convective systems. There is an added degree of complexity for the Northeast simply because of the Atlantic coastal boundary and topographical features (Lombardo and Colle 2010). Tudorí and Ramis (1997) found that many stability indices were unsuitable for forecasting significant convective events in the western Mediterranean because these indices were developed in a different geographic and climatological region. Despite the obvious dissimilarities between the Midwest and the Northeast United States, the thermodynamic environments associated with convective wind reports in the study region are investigated in order to identify which of the common stability parameters may aid in convective wind forecasting in the Northeast U.S.

Sounding data were acquired from each of the eleven upper air stations for all significant days that had at least one report within the 180km buffer (Figure 3.8) (Table 4.2; Table 4.3). 103 significant event days fit the criteria and were used in the thermodynamic analyses. 00z soundings from the day after the reports were made were obtained since this is the upper air observation closest to the time of maximum convective wind report occurrence and maximum diurnal instability. Because most wind reports occur slightly before the observation time in the diurnal distribution (Figure 4.8), the soundings may not show the exact thermodynamic properties present when the greatest number of reports were recorded. Severe weather indices from each sounding were calculated for each station and the distributions are displayed as side-by-side box plots (JMP 2012) accompanied by maps showing the spatial distributions of index values throughout the study region. The index contours were created using the IDW tool in the Spatial Analyst toolbox. Inverse distance weighting (IDW) is an interpolation method widely used with meteorological datasets (Hartkamp et al. 1999). The surface created by IDW is a weighted average of the surrounding points with weights decreasing with distance from each point (ESRI 2010). A table explaining the values of each index is included for reference (Table 4.4). To compare indices on a station-by-station basis, station-averaged parameters are calculated (Table 4.5).

4.3.1 CAPE Distribution

An overwhelming number of severe convective wind reports occur on days with CAPE values (J/kg) less than 500 J/kg, as shown by the box plots in Figure 4.25a. 67% of the soundings associated with significant event days have a CAPE value that is indicative of only weak convection. All of the station means are below 800 J/kg except for KWAL, which has a mean CAPE of 1404 J/kg. KWAL is the only station that has 25% of the acquired soundings measuring above 2291 J/kg, which is very close to the general cut-off between moderate and strong convection. The bottom 50% of all the station box plots, with the exception of KWAL, are concentrated well below the population mean line, suggesting that a majority of the soundings associated with severe convective wind events in this region have "weak" CAPE values.

Some studies have found CAPE to be a better diagnostic parameter than a forecasting index. CAPE is a number calculated to show the current potential energy of the atmosphere in a particular location, whereas a forecasting index should correlate with predicted severe weather at a future time (Doswell and Schultz 2006). Kuchera and Parker (2006) found that increases in CAPE (instability) may not be as influential in creating severe convective surface winds as increases in ground-relative wind fields. Their data suggests that only a minimal amount of CAPE is required to initiate severe weather of all kinds and that "once CAPE is sufficient for deep convection, damaging winds can occur via downdrafts that transport high-momentum air downward from aloft, or through mesoscale pressure perturbations in the surface outflow" (Kuchera and Parker 2006).

Figure 4.25b shows the spatial distribution of mean CAPE values throughout the study area. The entire region is covered with values suggesting only weak convective potential, again with the exception of the Delmarva Peninsula. Generally, values increase from the northwest to the southeastern portions of the study area.

4.3.2 Lifted Index

Almost every upper air station's median Lifted Index (LI) value resides near zero (Figure 4.26a). 62% of significant event days have an LI below 0, ranging from marginal to extreme instability. Even though a majority of the values signify some level of instability, there are several large positive LI values (indicating high stability). Because of this dichotomy, the mean station LI value is -0.3, signifying a neutral mean atmosphere. The station with the most unstable LI value is KALB with -11.74 (associated CAPE value of 9201 J/kg). This occurred on August 16, 1997 when a forward-propagating MCS traveled from northern Ohio through northern Pennsylvania, southeastern New York, and northern New Jersey (Corfidi 2003). Upper air stations along this path had LI values (and CAPE values) much greater than normal; KDTX: -3.52 (1054 J/kg), KPIT: -9.62 (4113 J/kg), and KBUF: -5.16 (2099 J/kg). The wind reports for this day clearly show the propagation of the MCS (Figure 4.27).

The spatial distribution of Lifted Index values across the Northeast U.S. is very similar to that of CAPE (Figure 4.26b). Most of the study area has mean values slightly above or below 0. Values become more negative moving from the northwest to the southeastern sections of the region. The most unstable mean LI is again at KWAL with a value of -3.06.

4.3.3 K-Index

The overall station mean for the K-Index (KI) is 27.4, which is indicative of moderate convective potential. In fact, over 72% of the soundings had a KI value characteristic of moderate convective potential or higher. This is apparent in the proportion of the boxplots that lie above the station mean line (Figure 4.28a). 35 is generally considered to be high (60-80% probability of thunderstorms) and 9 out of the 11 upper air stations show a 75% percentile at or above this number. Almost all of the stations experienced maximums suggesting strong convection and near a 100% probability for the development of thunderstorms. Only about 12% of the sounding K-Indexes showed no convective potential at all (the outliers in Figure 4.28a). This index did relatively well indicating severe wind potential, especially considering that the KI was developed for air mass thunderstorms and many of the convective storms in the Northeast U.S. are more likely dynamically forced.

Much like the previous two mean index distributions, the mean KI spatial distribution shows that convective potential increases from the northwest to the southeastern portions of the region (Figure 4.28b). A large percentage of the Northeast U.S. indicates moderate convective potential on significant convective wind days. KOKX has the highest mean of all 11 upper air stations with 30.5.

4.3.4 Cross Totals and Vertical Totals

The Cross Totals (CT) box plots show little variation among stations (Figure 4.29a). Almost 80% of the CT values are indicative of the potential for some level of thunderstorm development. A CT value higher than 20 is characteristic of a strong potential for thunderstorms. The overall station mean falls just above this cut-off at 20.2. In addition, many of the stations observed Cross Total maximums higher than 25 which is demonstrative of a high probability of severe weather. Spatially, the mean CT values suggest some potential for thunderstorm development encompassing the entire Northeast region (Figure 4.29b). There is little variation in the mean CT values from station to station. Values of the CT increase towards the northeastern and coastal portions of the study area. The spatial distribution displays KGYX, KALB, KOKX, and KWAL as the stations with the largest mean CT values.

The Vertical Totals (VT) distribution shows all of the station mean and median values to be near 25 (Figure 4.30a). Numbers less than 25 signify an unlikely probability of thunderstorm development. 70% of the Vertical Totals observations are below 27, signifying that VT values are generally not a good indication of when severe convective wind reports occur. The spatial distribution shows the index increasing from west to east (Figure 4.30b). The western portion of the region shows no potential for thunderstorm development, according to the VT index. The eastern portion shows only a slight probability, with Chatham, MA as the maximum. This is unexpected, given the fact that this area does not receive a large amount of convective wind reports. In addition, Cape Cod is far north and completely surrounded by the Atlantic Ocean.

In comparing Cross Totals and Vertical Totals, it seems as though the Cross Totals index is better able to predicted/diagnose weather capable of producing severe convective surface winds. Perhaps the study region's proximity to such a large source of water, the Atlantic Ocean, allows the CT index to better differentiate between nonsevere and severe weather since it takes low-level moisture into account. Vertical Totals only uses temperature and may be better able to predict weather hazards in the Great Plains or other regions devoid of a large moisture source. These two indices are best utilized together in the Total Totals index.

4.3.5 Total Totals

The Total Totals (TT) index is the arithmetic sum of the Cross Totals and Vertical Totals indices. This index measures the buoyancy of the atmosphere due to both low-level moisture and heat content. 72.5% of the sounding observations had an associated TT value of 44 or larger (Figure 4.31a). Numbers between 44 and 50 signify likely thunderstorm development. Values over 50, affiliated with about 20% of the significant event day soundings, often accompany severe storms. Over 50% of the observations at each station have a TT value higher than the overall station mean (45.7) with the exceptions of KDTX and KBUF. This composite mean value suggests the likelihood of thunderstorms, however there are many outliers indicating that the TT index is not the definitive authority in predicting severe convective winds across the region. The spatial distribution looks similar to those described earlier (Figure 4.31b). Most of the region has average values indicative of thunderstorm production. The Delmarva Peninsula and Long Island are the locations with the highest TT values between 47 and 47.5, indicating the likelihood of convective activity.

4.3.6 SWEAT

The overall station mean and individual station median values of the SWEAT index are not impressive (Figure 4.32a). Generally, Severe Weather Threat (SWEAT) values above 250 are considered to be indicative of strong convection and values less than that, associated with about 60% of the soundings in this study, are considered meaningless in predicting convection. The overall station mean falls just below 250 at 241.5 and the median values range from 203-261. Although some maximum values are impressive (reaching over 500), there are very few SWEAT index values that reach these strengths. Figure 4.32b shows that higher interpolated values lie along the coast, the largest of which is Wallops Island.

The SWEAT index is meant to distinguish between severe and non-severe thunderstorms by incorporating wind speed and direction at 500 and 850 hPa. Because this parameter takes winds into consideration, it varies significantly. Wasula et al. (2002) compared SWEAT values associated with wind, hail and tornado reports in Eastern New York and Western New England. They calculated values of 240 for all events, 242 for wind reports, 226 for hail reports, and only 250 for tornado reports, which are extremely low compared to similar events that take place in the Great Plains and southeastern U.S. Because atmospheric profiles in the region tend to show less directional shear between 500-850 hPa and more stability, SWEAT index values are expected to be lower compared to those suggestive of severe weather in the Great Plains (Wasula et al. 2002).

4.3.7 Index Comparison

In order to compare indices at each station, upper air station-averaged parameters are listed in Table 4.5. The highest mean value of each index is highlighted in red and the lowest values are shown in blue. Both KWAL and KOKX have three of the highest average parameters; mean CAPE, Lifted Index, and SWEAT are highest at KWAL and average K-Index, Cross Totals and Total Totals are largest at KOKX. Research has shown that convective frequency (specifically cloud-to-ground lightning) is pronounced along the Atlantic coastal plain from Florida to the Delmarva Peninsula, where Wallops Island is located (Lombardo and Colle 2010). Murray and Colle (2011) also found the Delmarva to be a preferred area for convective development. However, it comes as a surprise that KOKX (located on Long Island) had several maximum mean indices. Murray and Colle (2011) listed Long Island as one of the locations in their study that experienced a convective minimum, most likely due to the relatively cool coastal waters surrounding the island.

KBUF and KDTX were the only stations that experienced any index minimum. The 180km buffer surrounding these stations extends beyond the study region, giving KBUF and KDTX a smaller number of reports compared to the other upper air stations. The stations are likely impacted by their proximity to the Great Lakes region and their northerly geographic location.

Since convective winds can be produced in several ways, different convective indices are important in different situations and not every severe environment can be diagnosed by the same indices. Severe weather indices should always be used in conjunction with a full sounding and other available data. Although stability parameters have been shown to be less effective in the Northeast U.S. compared to areas such as the Great Plains, this study attempts to identify variables that may help predict severe convective surface winds in this region. From this analysis, it is concluded that the K-Index (KI) and Total Totals (TT) index are the most important of the severe weather indices in predicting severe convective winds for the study area. Well over 50% of the KI values were above 27.4 (the overall station mean) at 9 out of the 11 upper air stations, signifying moderate to high convective potential. 72.5% of the sounding observations had TT values larger than 44, indicative of likely thunderstorm development. CAPE, LI, VT, and SWEAT proved to be less effective predictors. This study agrees with research that has shown CAPE (LI) values to be relatively low (high) in the Northeast compared to other regions of the country (Kuchera and Parker 2006). 70% of the significant event day observations had VT values indicative of unlikely thunderstorms or scattered thunderstorms and 60% of SWEAT values don't indicate any convective potential.

4.3.8 Composite Sounding

A composite mean skew-t diagram was created representing all of the soundings from the 103 significant wind event days (Figure 4.33). Because this is an overall average of the observations gathered at each station, and since only the mandatory levels were used in the analysis, loss of extremes and minute details is expected. The small positive area present between the temperature profile (red) and parcel path (pink) indicates a CAPE value of only 78 J/kg. This is indicative of the relatively low CAPE values found in the Northeast U.S. while still representing some level of positive buoyancy. The wind barbs on the right side of the diagram suggest weak veering with height. Veering, associated with warm air advection and increased instability, often occurs in advance of a cold front, which is most likely one of the main catalysts for severe convective winds in the Northeast.

Table 4.2: Table displaying each station identifier with associated city, state and coordinate location.

Station	City	State	Lat	Lon
KALB	Albany	NY	42.75	-73.80
KBUF	Buffalo	NY	42.93	-78.73
KCHH	Chatham	MA	41.67	-69.97
KDTX	Detroit	MI	42.70	-83.47
KGYX	Gray	ME	43.89	-70.26
KIAD	Sterling/Washington	VA	38.95	-77.45
KILN	Wilmington	OH	39.42	-83.72
KOKX	Upton	NY	40.87	-72.86
KPIT	Pittsburgh	PA	40.50	-80.22
KRNK	Roanoke	VA	37.21	-80.41
KWAL	Wallops Island	VA	37.85	-75.48

Table 4.3: Table displaying the number of wind reports and significant event days that took place within 180km of each station from 1955-2010.

Station	Significant Event Days	Wind Reports
KALB	67	918
KBUF	42	284
KCHH	22	126
KDTX	29	78
KGYX	34	257
KIAD	78	1144
KILN	69	498
KOKX	50	692
KPIT	78	1282
KRNK	58	504
KWAL	54	445

Table 4.4: Table explaining common index values.

CAPE	
< 1,000	Weak convection
1,000-2,500	Moderate convection
> 2500	Strong convection
Lifted Index	
-1 to -4	Marginal instability
-4 to -7	Large instability
< -8	Extreme instability
K-Index	
15-25	Small convective potential
26-39	Moderate convective potential
> 40	High convective potential
Cross Totals	
< 18	Weak potential for thunderstorms
18-19	Moderate potential for thunderstorms
20-21	Strong potential for thunderstorms
22-23	Weak potential for severe thunderstorms
24-25	Moderate potential for severe thunderstorms
> 25	Strong potential for severe thunderstorms
Vertical Totals	
< 25	Thunderstorms unlikely
25-27	Scattered thunderstorms
> 28	Strong potential for thunderstorms
Total Totals	
< 44	Convection not likely
44-50	Likely thunderstorms
51-52	Isolated severe storms
53-56	Widely scattered severe
> 56	Scattered severe storms
SWEAT	
300-400	Severe possible
> 400	Tornadoes possible

Table 4.5: Table displaying station-averaged parameters for the 103 significant event days. Numbers in red denote the overall highest value in the category and values in blue represent the lowest.

Station:	CAPE	Lifted Index	K-Index	Cross Totals	Vertical Totals	Totals Totals	SWEAT
KALB	656	-0.05	29.6	20.8	24.9	45.6	253
KBUF	**281**	**1.51**	23.8	19.0	**24.3**	43.3	214
KCHH	440	0.30	29.2	19.0	**26.9**	45.9	235
KDTX	288	1.29	**18.2**	**18.3**	24.4	**42.7**	**189**
KGYX	496	0.45	29.5	20.9	25.9	46.7	253
KIAD	659	-0.67	27.9	20.1	25.9	46.0	244
KILN	773	-1.02	25.8	20.3	25.4	45.8	238
KOKX	469	-0.56	**30.5**	**21.0**	26.3	**47.2**	262
KPIT	348	0.56	27.3	20.1	24.9	45.0	232
KRNK	524	-0.35	29.8	20.1	26.1	46.2	244
KWAL	**1404**	**-3.06**	30.0	20.8	26.4	47.2	**268**

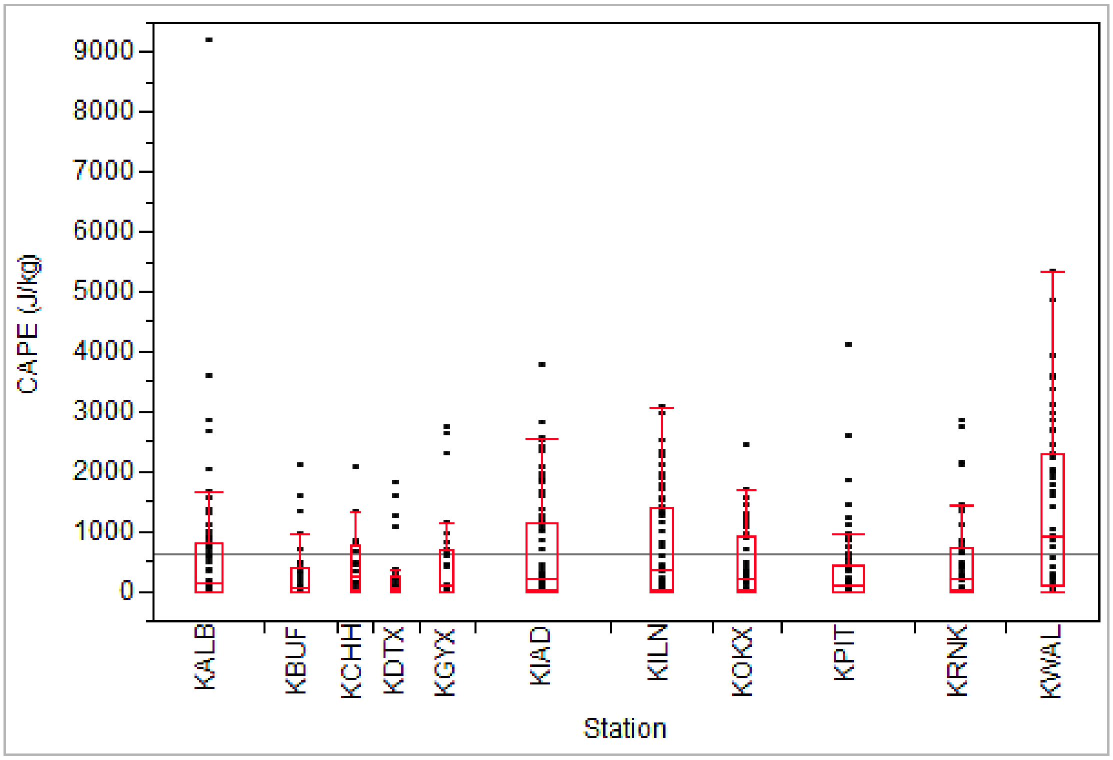

Figure 4.25a:Box plots displaying the distribution of CAPE values associated with the 103 significant event days.

Table 4.6: CAPE (J/kg) box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	0	0	2	126	794	1644	9201
KBUF	0	0	0	59	407	930	2099
KCHH	0	0	5	227	780	1270	2080
KDTX	0	0	5	42	251	1375	1811
KGYX	0	0	2	82	692	2056	2724
KIAD	0	0	20	202	1137	2001	3791
KILN	0	0	13	373	1390	2154	3086
KOKX	0	0	2	199	904	1454	2440
KPIT	0	0	1	104	428	928	4113
KRNK	0	0	9	220	735	1434	2855
KWAL	0	0	107	927	2291	3509	5351

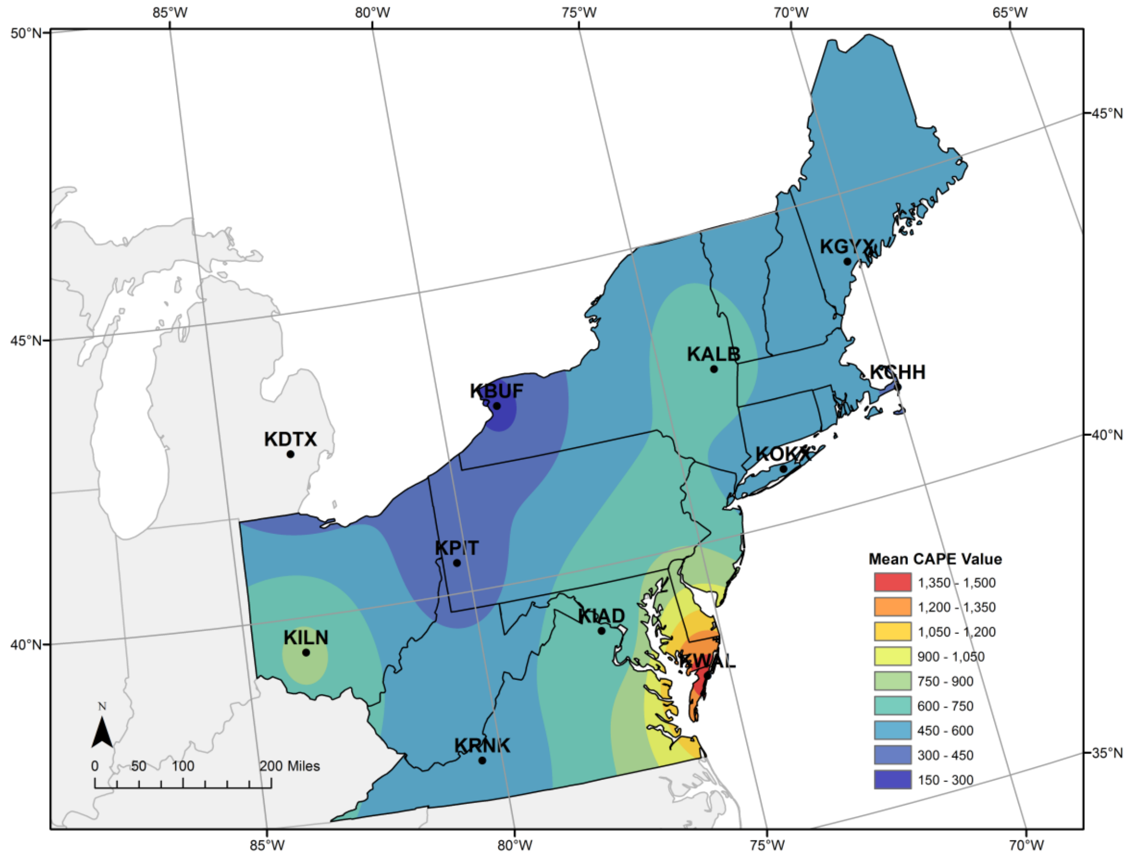

Figure 4.25b:Spatial interpolation of mean CAPE values (J/kg).

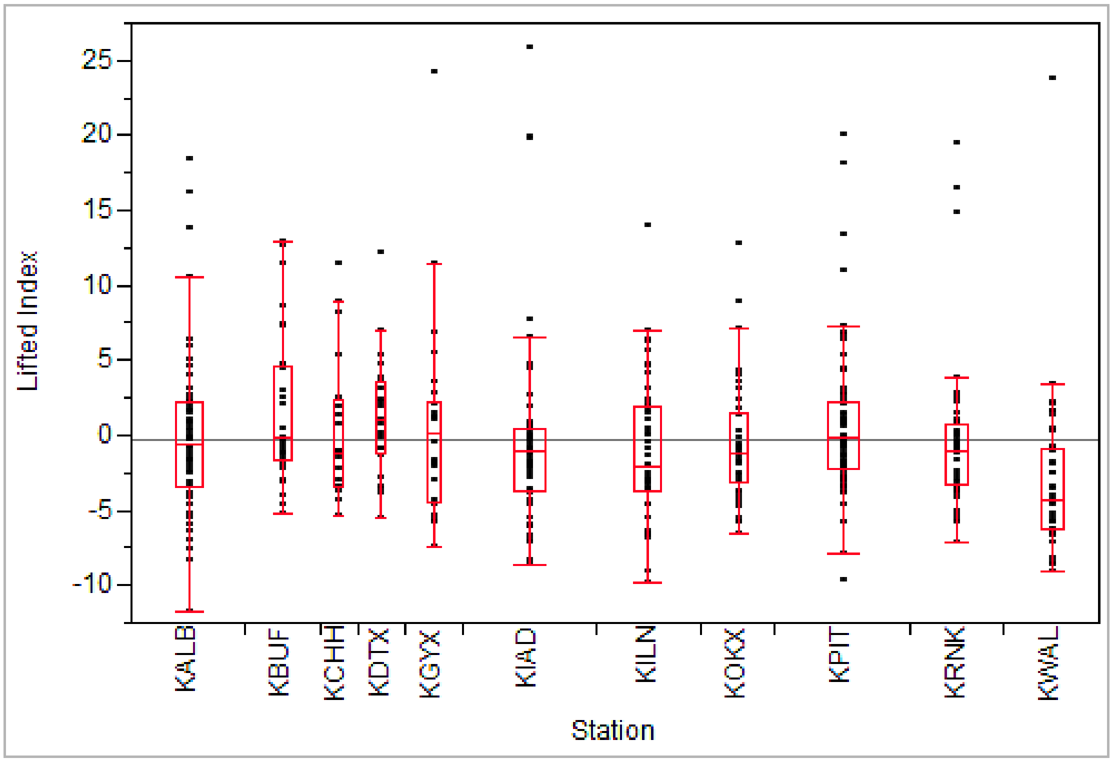

Figure 4.26a:Box plots displaying the distribution of LI values associated with the 103 significant event days.

Table 4.7: LI box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	-11.74	-6.42	-3.48	-0.56	2.22	5.89	18.38
KBUF	-5.22	-3.96	-1.67	-0.18	4.53	8.60	12.99
KCHH	-5.42	-4.25	-3.49	-1.13	2.33	8.86	11.41
KDTX	-5.52	-3.68	-1.14	0.99	3.56	5.96	12.24
KGYX	-7.37	-5.63	-4.42	0.20	2.25	6.70	24.19
KIAD	-8.56	-6.04	-3.77	-1.02	0.47	4.21	25.82
KILN	-9.86	-6.41	-3.65	-2.07	1.90	4.97	13.90
KOKX	-6.58	-5.58	-3.15	-1.21	1.45	4.56	12.71
KPIT	-9.62	-3.67	-2.28	-0.20	2.22	6.55	20.01
KRNK	-7.11	-5.03	-3.26	-1.08	0.76	2.85	19.44
KWAL	-9.01	-7.06	-6.24	-4.36	-0.87	1.68	23.73

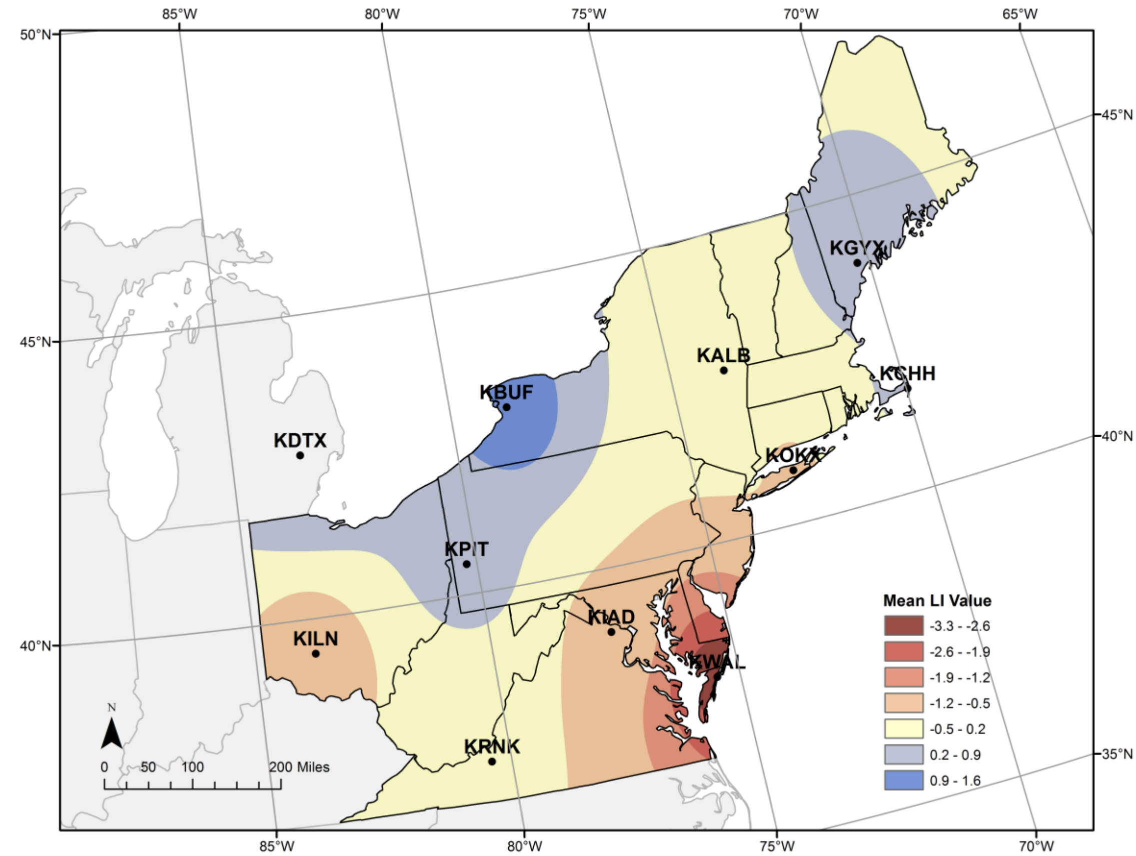

Figure 4.26b:Spatial interpolation of mean LI values.

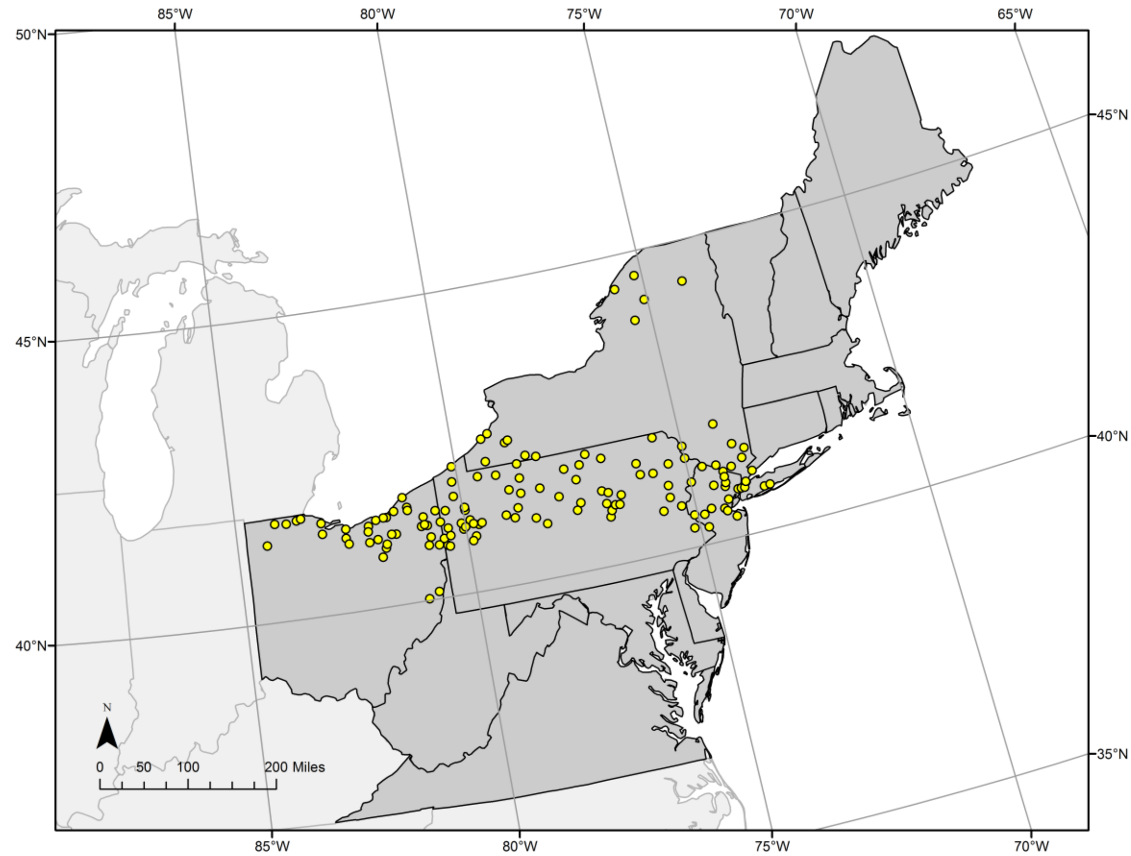

Figure 4.27: Map showing wind reports from August 16, 1997 when a MCS traveled through Northern Ohio, Pennsylvania, New Jersey and parts of New York. The propagation of the MCS is apparent from the wind report locations. This storm was affiliated with extreme CAPE and LI values at KDTX, KPIT, KBUF, and especially KALB.

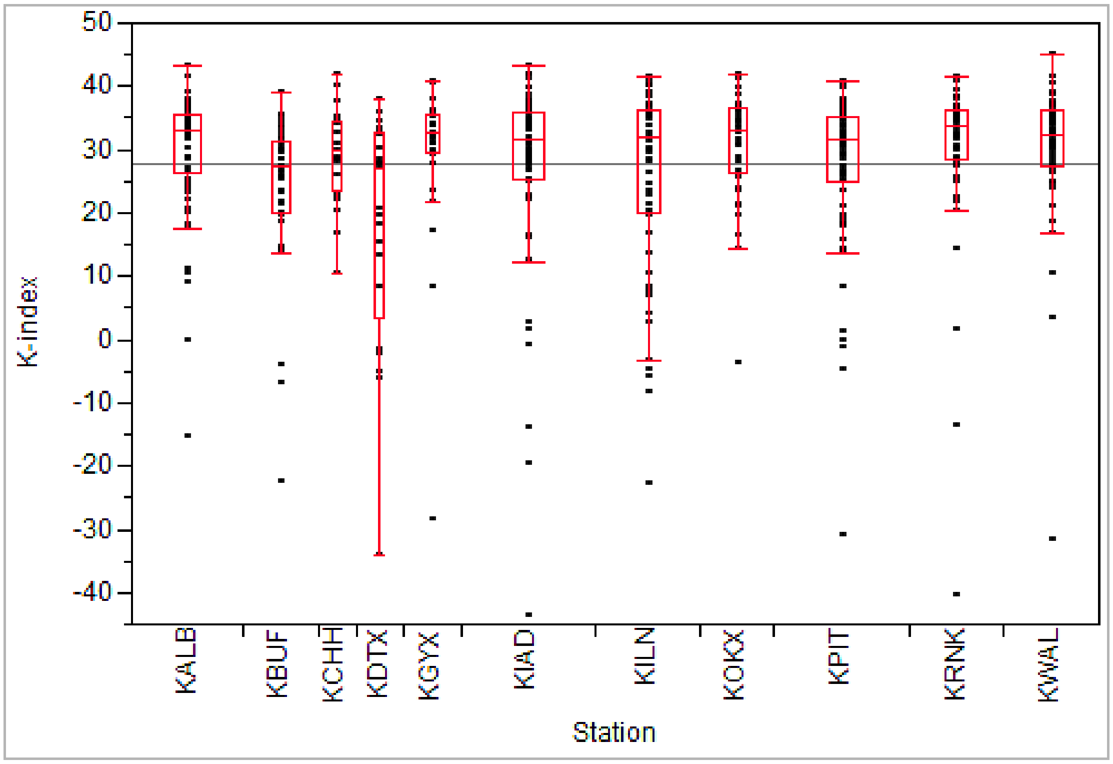

Figure 4.28a:Box plots displaying the distribution of KI values associated with the 103 significant event days.

Table 4.8: KI box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	-15.3	17.5	26.5	32.9	35.6	37.6	43.3
KBUF	-22.3	13.5	20.1	27.4	31.4	34.4	39.1
KCHH	10.5	17.1	23.7	30.0	34.4	39.8	41.9
KDTX	-33.9	-5.4	3.3	27.1	32.6	35.0	37.9
KGYX	-28.3	17.6	29.5	32.7	35.4	37.7	40.9
KIAD	-43.7	12.1	25.3	31.6	36.0	39.8	43.4
KILN	-22.7	0.9	19.9	32.0	36.2	39.3	41.6
KOKX	-3.8	19.4	26.5	33.1	36.4	38.8	42.0
KPIT	-30.9	13.7	24.8	31.8	35.1	36.7	40.7
KRNK	-40.3	20.5	28.6	33.7	36.2	38.4	41.5
KWAL	-31.6	18.8	27.4	32.5	36.2	39.2	44.9

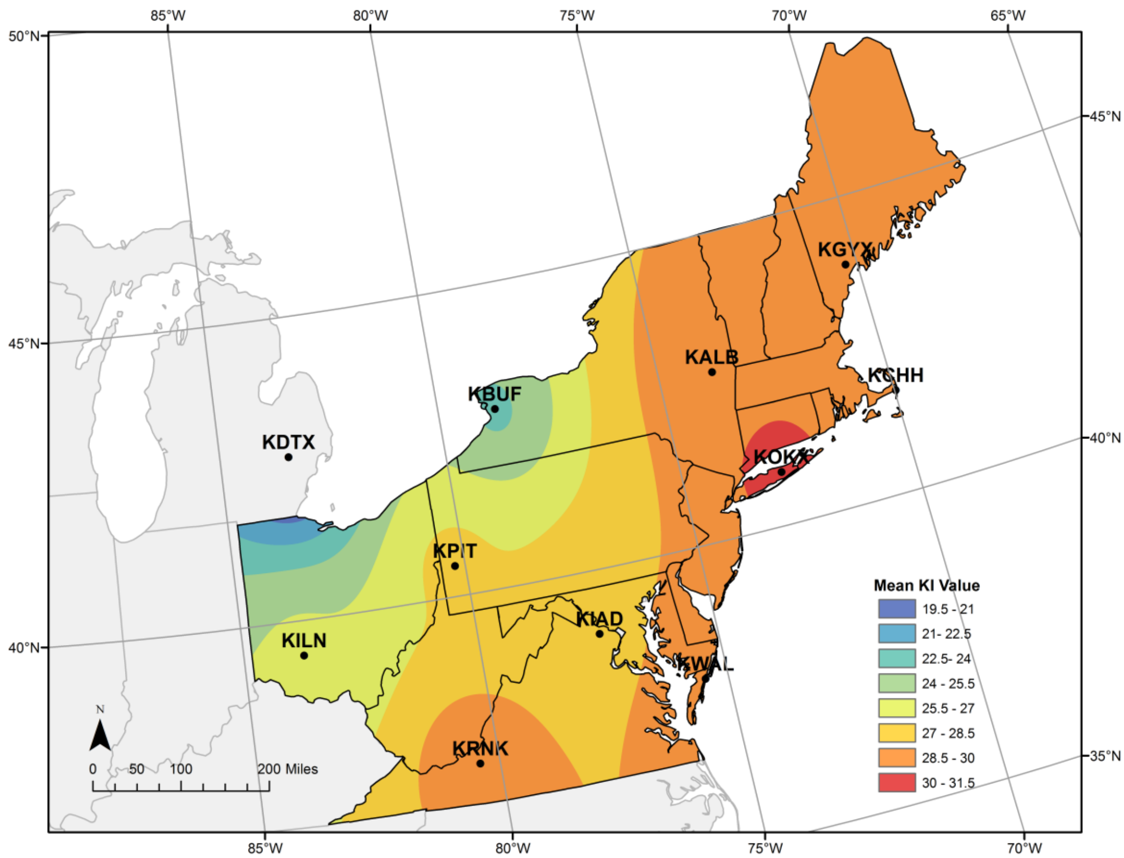

Figure 4.28b:Spatial interpolation of mean KI values.

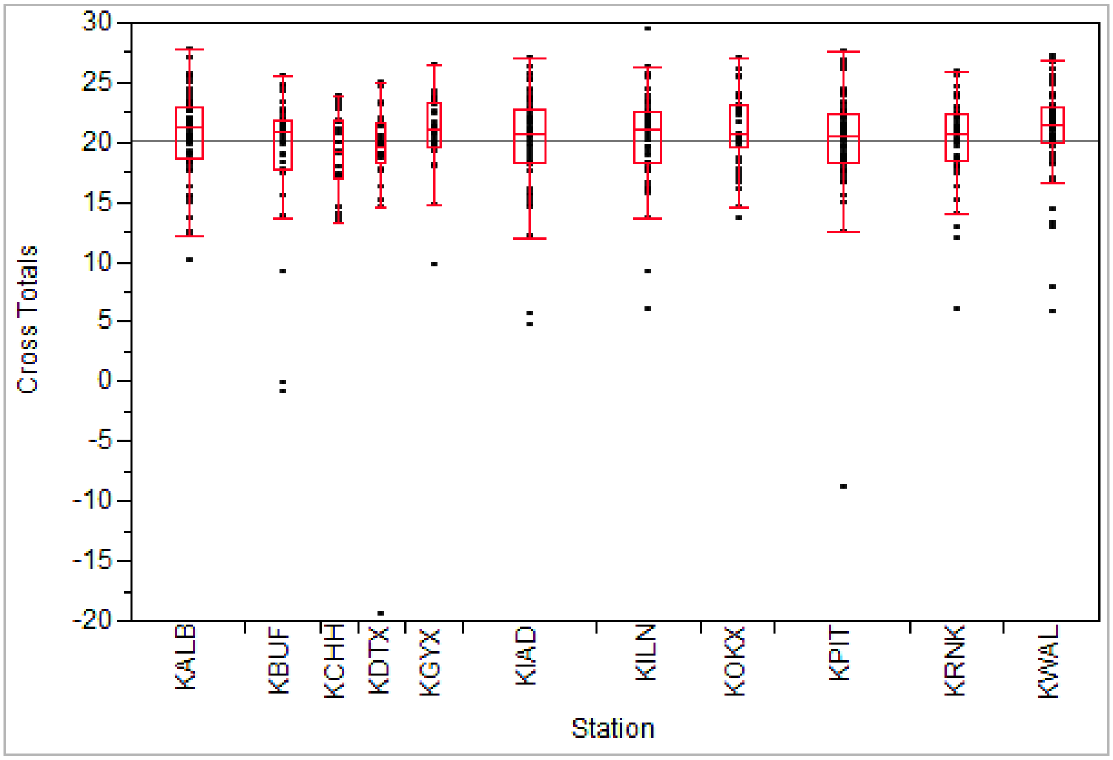

Figure 4.29a:Box plots displaying the distribution of CT values associated with the 103 significant event days.

Table 4.9: CT box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	10.1	15.4	18.6	21.3	23.0	24.9	27.8
KBUF	-0.9	13.7	17.7	20.9	21.9	24.3	25.6
KCHH	13.3	13.7	17.0	19.2	21.9	23.5	23.9
KDTX	-19.5	14.9	18.2	19.5	21.6	23.8	24.9
KGYX	9.7	17.9	19.7	21.1	23.2	23.8	26.5
KIAD	4.7	15.1	18.3	20.7	22.7	25.0	27.0
KILN	6.1	15.8	18.2	21.1	22.6	24.7	29.5
KOKX	13.7	16.6	19.5	20.7	23.1	25.4	27.0
KPIT	-8.8	16.8	18.3	20.6	22.4	24.2	27.5
KRNK	6.1	15.2	18.6	20.7	22.3	23.8	26.0
KWAL	5.9	14.5	20.0	21.4	22.9	25.6	27.3

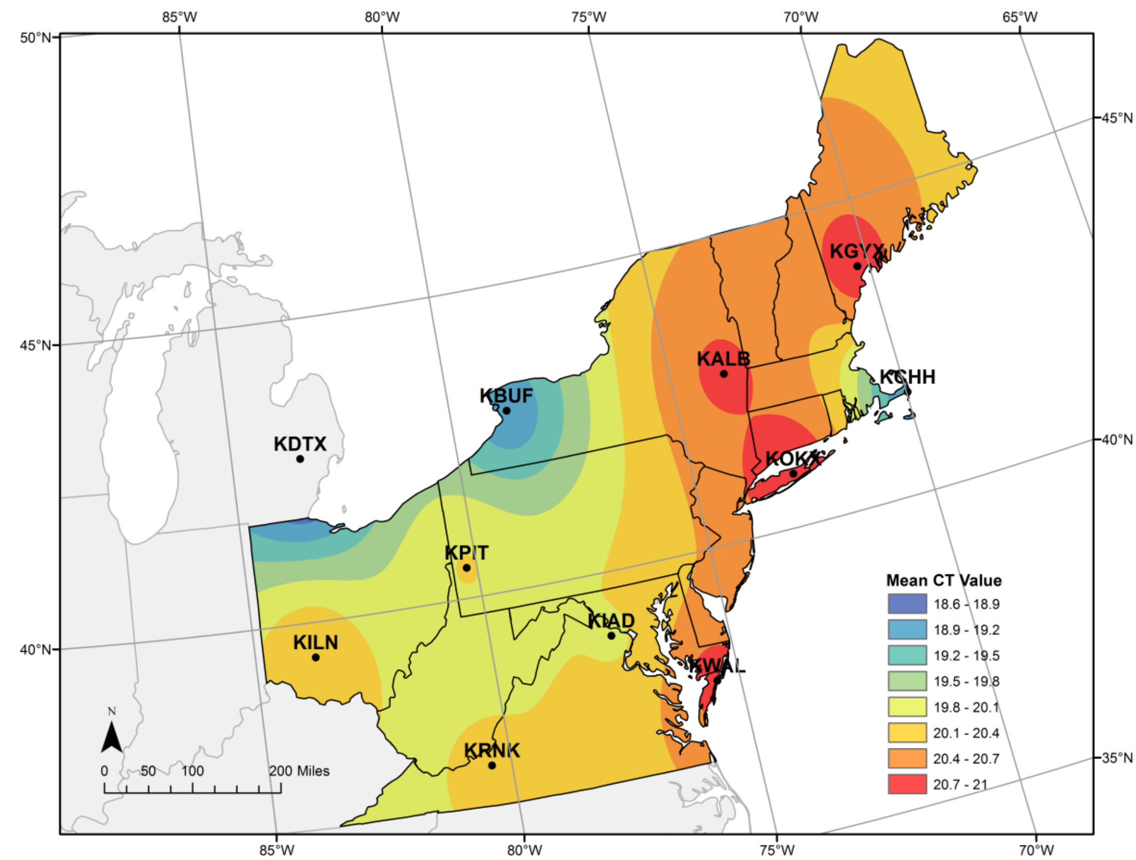

Figure 4.29b:Spatial interpolation of mean CT values.

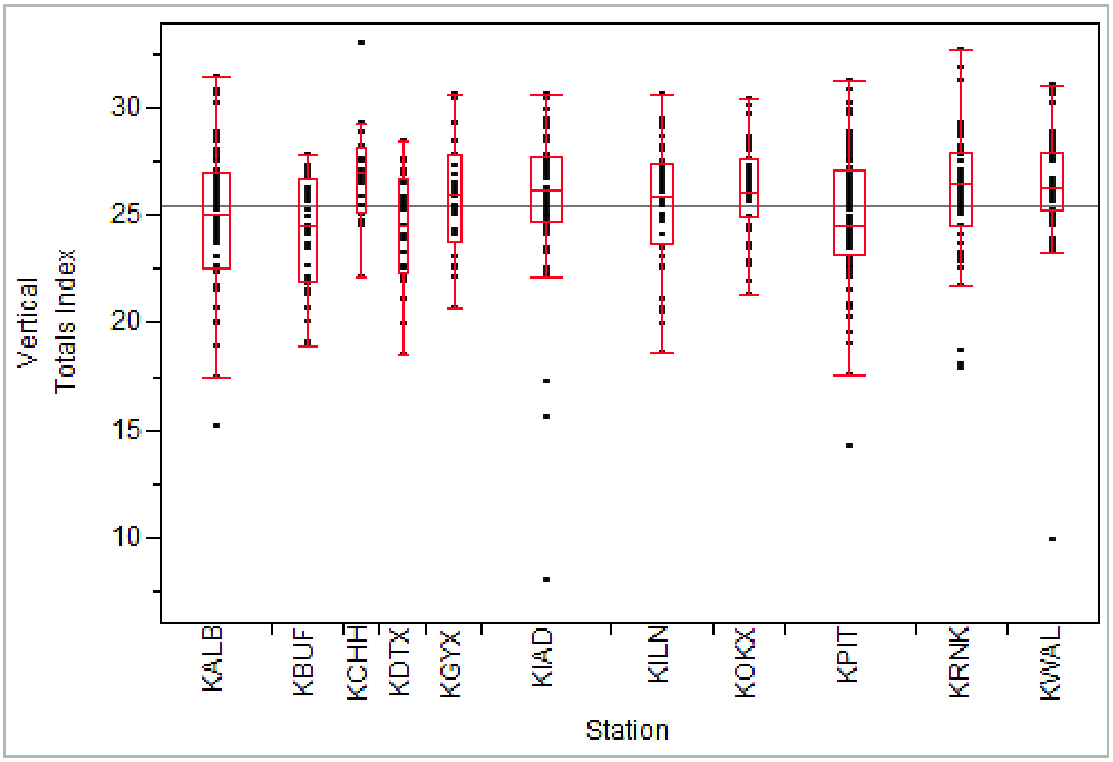

Figure 4.30a:Box plots displaying the distribution of VT values associated with the 103 significant event days.

Table 4.10: VT box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	15.2	20.2	22.6	25.1	27.1	28.7	31.5
KBUF	18.9	20.1	21.9	24.5	26.7	27.1	27.9
KCHH	22.1	24.5	25.2	27.0	28.2	29.3	33.1
KDTX	18.5	20.6	22.3	24.5	26.7	27.6	28.5
KGYX	20.7	22.1	23.9	26.0	27.9	29.2	30.7
KIAD	8.0	23.3	24.7	26.2	27.8	29.5	30.7
KILN	18.6	21.0	23.7	25.9	27.5	29.1	30.7
KOKX	21.3	22.9	24.9	26.1	27.7	29.7	30.5
KPIT	14.2	20.7	23.2	24.5	27.1	28.7	31.3
KRNK	17.9	21.7	24.5	26.5	28.0	29.3	32.7
KWAL	9.8	23.7	25.3	26.3	28.0	30.2	31.1

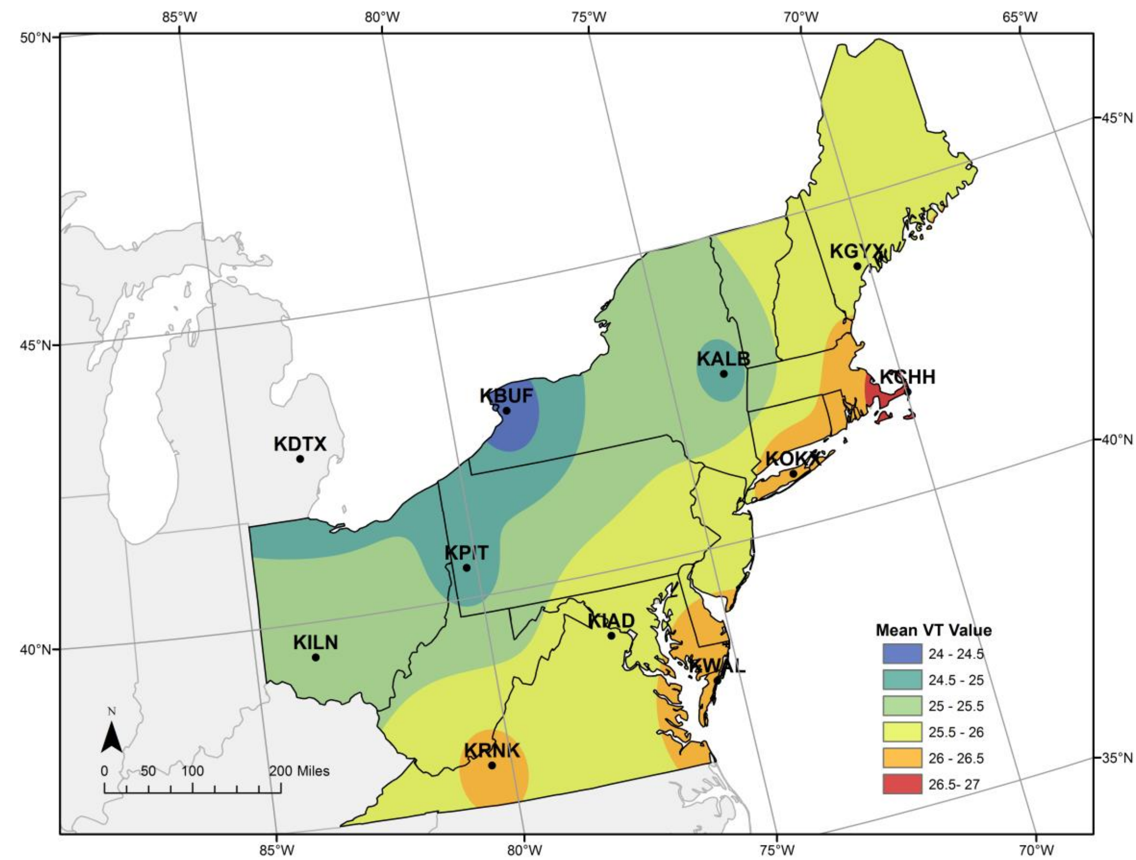

Figure 4.30b:Spatial interpolation of mean VT values.

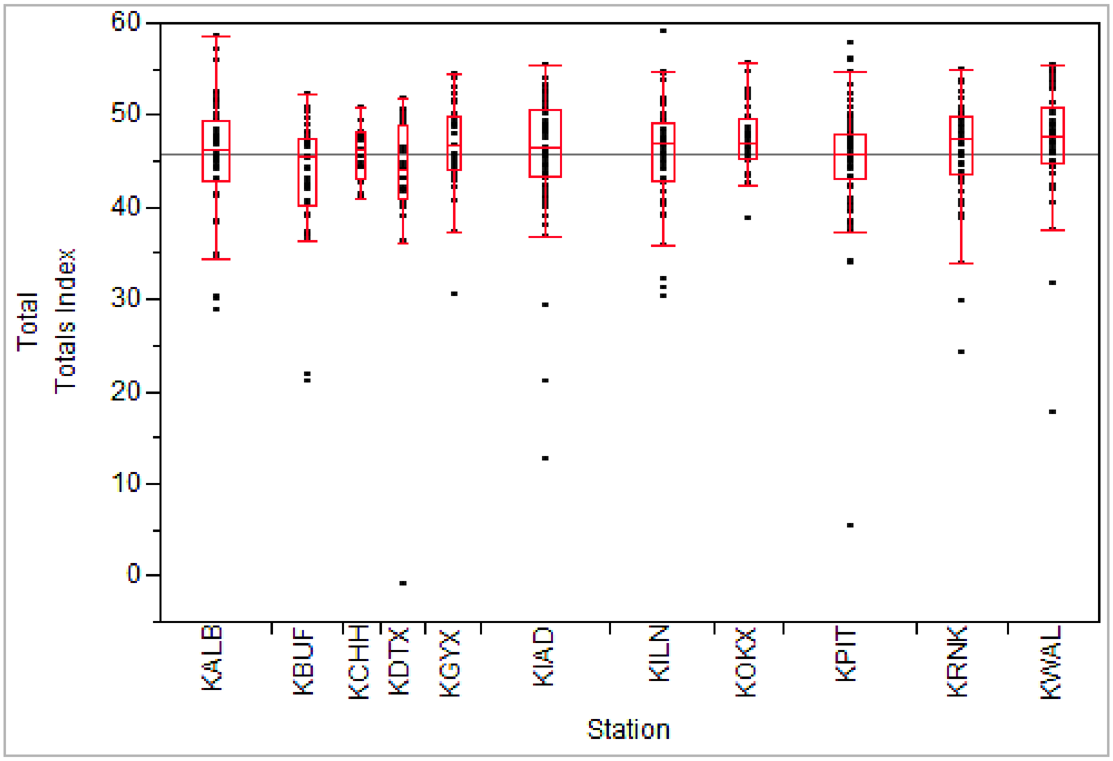

Figure 4.31a:Box plots displaying the distribution of TT values associated with the 103 significant event days.

Table 4.11: TT box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	28.8	38.2	42.9	46.3	49.4	52.4	58.5
KBUF	21.2	36.3	40.3	45.4	47.4	49.6	52.3
KCHH	41.0	41.2	43.2	46.2	48.1	50.6	50.8
KDTX	-1.0	36.2	41.0	44.0	49.0	50.5	51.7
KGYX	30.4	40.8	44.1	46.8	49.8	52.9	54.4
KIAD	12.7	40.0	43.4	46.4	50.6	52.6	55.5
KILN	30.2	39.2	42.7	46.9	49.2	51.7	59.0
KOKX	38.7	42.6	45.3	46.9	49.6	52.3	55.6
KPIT	5.4	38.1	43.1	45.8	47.9	52.0	57.8
KRNK	24.2	39.2	43.5	47.4	49.9	52.4	54.9
KWAL	17.7	41.9	44.9	47.6	50.7	54.3	55.4

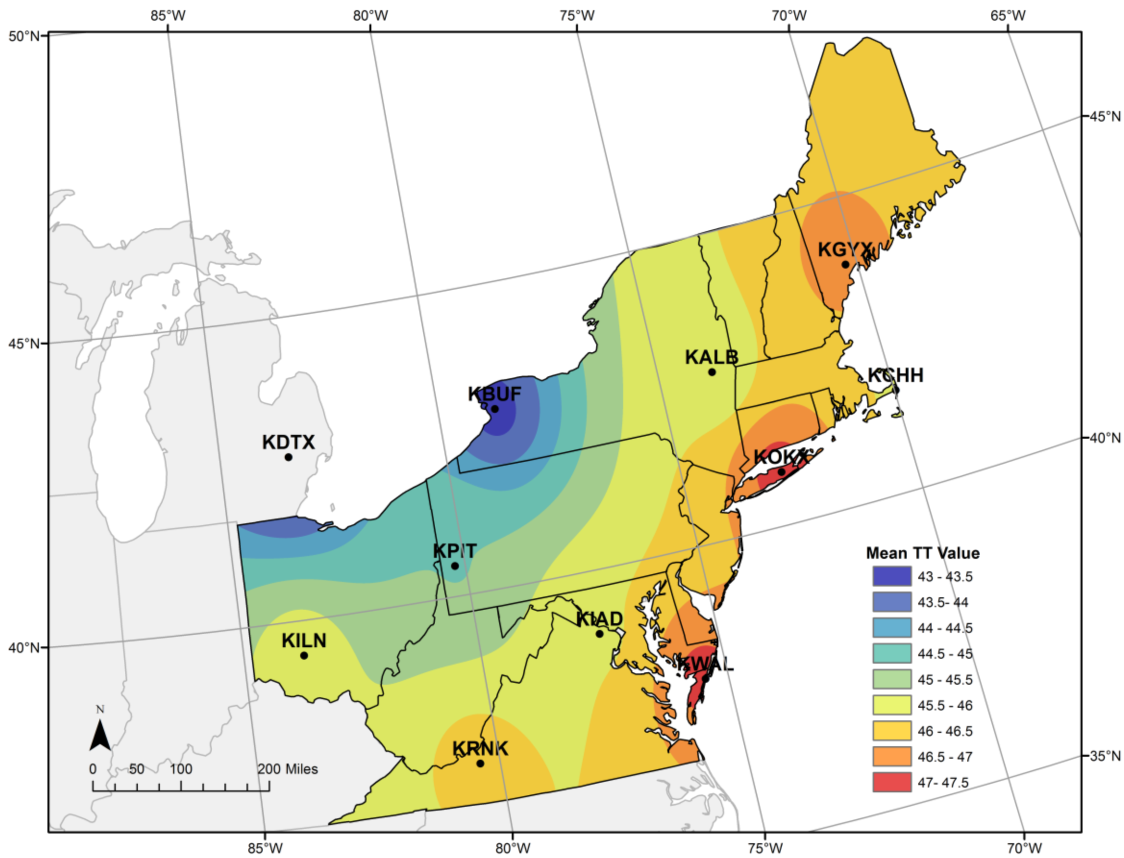

Figure 4.31b:Spatial interpolation of mean TT values.

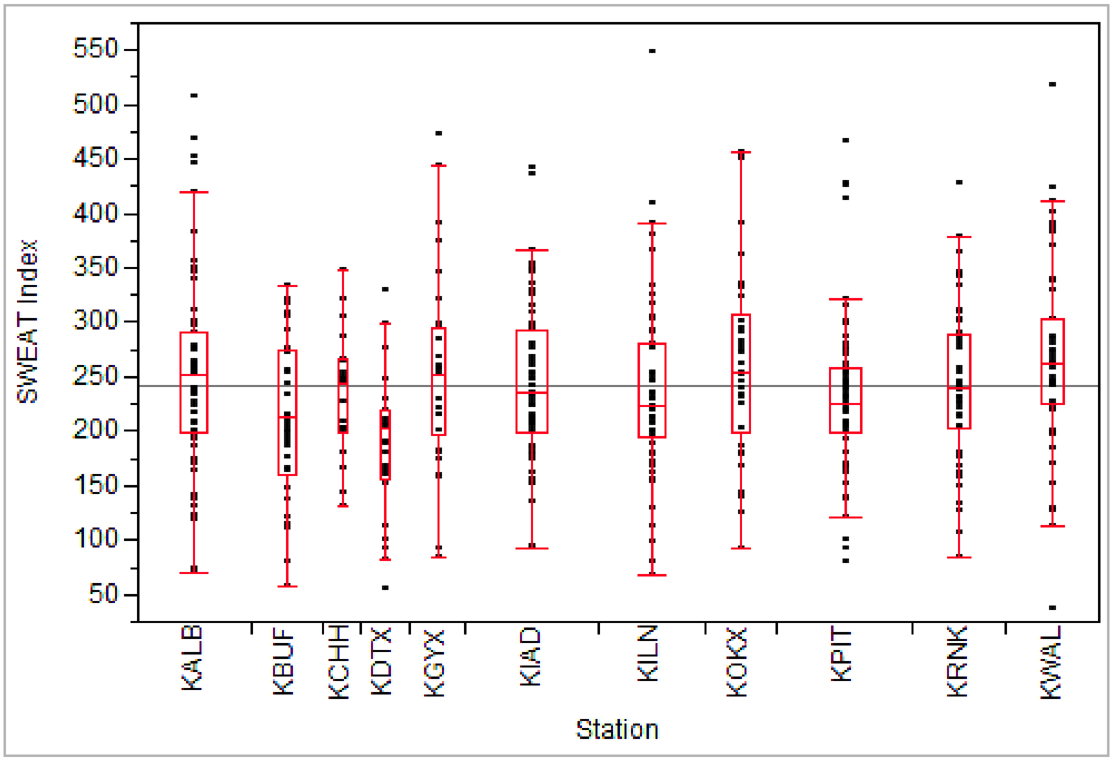

Figure 4.32a:Box plots displaying the distribution of SWEAT values associated with the 103 significant event days.

Table 4.12: SWEAT box plot quantiles.

Station	Minimum	10%	25%	Median	75%	90%	Maximum
KALB	70	131	198	251	291	382	507
KBUF	57	115	160	212	275	317	334
KCHH	131	145	200	245	267	320	347
KDTX	55	88	156	203	220	285	331
KGYX	85	158	196	252	296	389	473
KIAD	93	156	200	236	292	346	442
KILN	68	144	194	224	280	346	549
KOKX	92	144	198	254	307	397	457
KPIT	80	153	198	226	259	301	467
KRNK	85	149	203	240	290	345	427
KWAL	38	152	225	261	304	390	517

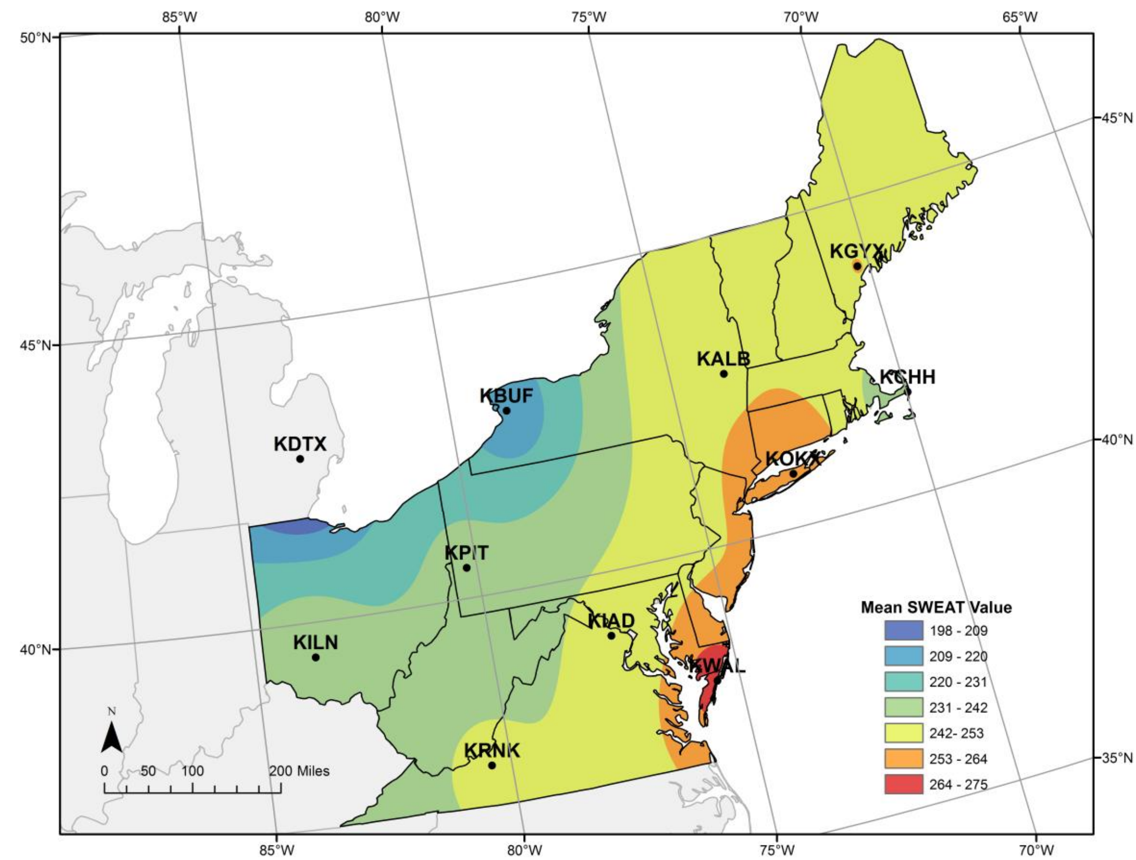

Figure 4.32b:Spatial interpolation of mean SWEAT values.

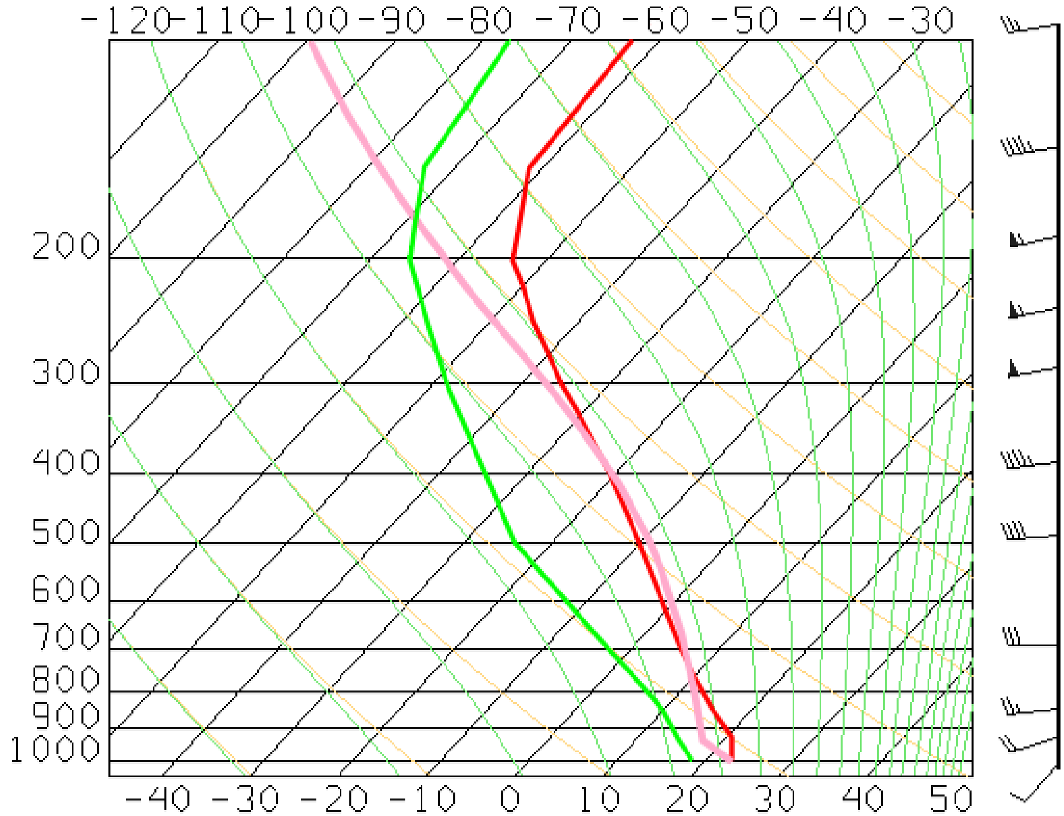

Figure 4.33: Composite mean skew-t diagram representing the 103 significant event days.

Chapter 5

CONCLUSION

Using convective wind report data from the Storm Prediction Center (SPC), a foundational climatology of severe convective winds in the Northeast United States was developed from 1955-2010. The large urban centers located in this region were an initial concern with the wind report dataset. In order to understand the degree of population bias present, a simple linear regression model was created and applied to population data in ESRI's Desktop ArcGIS in order to formulate a spatial representation of predicted wind reports based solely on population. At a 1° resolution, population explains 50% of the variance and explains 38% and 32% of the variance at the 0.5° and 0.25° resolutions, respectively. The relationships at all three resolutions are statistically significant. The population-predicted wind reports were then subtracted from the actual wind reports within each grid box to locate the areas of the Northeast that received more or less reports than population can predict. A hot spot analysis was performed on these numbers in the GIS using the 0.25° resolution grid. Northwestern Ohio/Western Pennsylvania, Albany, NY, and the area west of Washington D.C. stand out as the three hot spots, significant at the 99% level. Because of their large populations and relative lack of convective wind reports, the simple regression equation severely over-predicted wind reports for New York City and the area surrounding Boston, making them "cold" spots on the map.

The interannual distribution of wind reports displays an almost exponential increase in reports from 1980-2010, which is understood to be non-meteorological in nature. The month with the most reports throughout the 56-year period is July. Confirmed by several studies, convective surface winds are a summertime occurrence, with about 52% of the reports taking place in June and July. Regarding the diurnal cycle, convective wind damage is most often reported between 2100-2259 GMT (1600-1759 EST) with a minimum in the early morning. With similar interannual, annual, diurnal and spatial distributions, the 104 significant event days were established as days that experienced a number of wind reports three standard deviations above the mean.

The 104 significant event days were used to acquire composite synoptic maps from NOAA's ESRL. These composite atmospheric patterns represent what normally initiates severe convective surface winds in the Northeast U.S. The study region is located directly under the leading edge of a low-amplitude 500 hPa trough with an anomalous surface low pressure system north of New York. The region is on average a few degree Kelvin warmer than usual for the given time of year when convective surface winds are produced and the Lifted Index values are lower than the mean.

It is concluded by comparing the results of this study with those of Lombardo and Colle (2010), Murray and Colle (2011), and Schoen and Ashley (2011) that a majority of the convective surface winds are likely produced by organized linear convective events. Similar to this investigation, Lombardo and Colle (2010) identified a low-amplitude trough over the Northeast at 500 hPa along with a weak surface low located north of the Great Lakes region and attributed this synoptic pattern to the creation of linear convective systems. They found that linear convection is almost always located on the lee of the Appalachians, a region considered significant in the convective wind hot spot analysis. In addition, Schoen and Ashley (2011) determined that organized linear convection was the primary cause of nontornadic convective wind fatalities on the eastern coast of the United States.

00z sounding observations were acquired from 11 upper air stations around the Northeast for each significant report day that fell within each station's 180km buffer. These data were used to compare mean severe weather indices around the region and to compute a composite mean sounding representing the 103 significant days that fit the above criteria. In general, index values become more unstable moving from the northwestern parts of the region to the coastline. The K-Index and Total Totals did the best at signifying severe convective potential. The overall station mean for the K-Index is 27.4, a value characteristic of moderate convective potential, and over 72% of the soundings have a KI value suggesting this probability or higher. 72.5% of the sounding observations have an associated TT value suggesting likely thunderstorm development. The CAPE, Lifted Index, Vertical Totals, and SWEAT means are not indicative of intense convective surface winds, with many signifying an unlikely probability of any convective development. Although the CAPE value is only 78 J/kg, the composite skew-t diagram appears to be characteristic of storms in this region, as there does not need to be a large amount of CAPE for destructive winds to occur. Weak veering with height suggests warm air advection and instability, which often occurs ahead of a cold front.

The Northeastern United States contains some of the largest population centers in the country, but the majority of the populace is unaware that convective surface winds pose such a great threat to life and property. Because the Northeast U.S. is inadequately represented in convective wind research, there are several suggestions for future work. It would be worthwhile to investigate the significant hot spots in further detail to determine the exact causes for the large amount of wind reports in those locations. Although a few studies have focused on the influence of terrain on convective storms, more research is needed, especially concerning the effect of coastal boundaries on convection.

More atmospheric variables should be analyzed to identify additional parameters helpful in forecasting destructive convective winds in this region of the country. While the DMGWIND parameter developed by Kuchera and Parker (2006) would not necessarily work well in an investigation dealing with mean values and conditions, the direction and speed of the wind at the highest positively buoyant level in the surface inflow layer during the most extreme events should be studied in detail to determine what combinations of flow regimes and convective orientations lead to destructive surface winds in the Northeast.

Although this analysis is not exhaustive, it provides a much-needed climatological basis of severe convective winds in the Northeastern United States. The hot spot analyses, composite synoptic patterns and spatial/temporal distributions produced a better overall understanding of the causes and locations of damaging convective winds. The average sounding is evidence that CAPE may not be a large factor in determining the potential for severe convective winds in the Northeast. Finally, the stability index comparison indicated which of the most common parameters are useful in forecasting convective wind occurrence in the region.

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