Winter 2008

Extreme precipitation trends in New England

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EXTREME PRECIPITATION TRENDS IN NEW ENGLAND

BY

SUSAN GRACE SPIERRE
BS, University at Albany, 2006

THESIS

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

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in
Earth Sciences- Geochemical Systems

December, 2008
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DEDICATION

This thesis is dedicated to my parents, my twin sister, and also to Bill for all of their love, guidance and support.
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ABSTRACT
EXTREME PRECIPITATION TRENDS IN NEW ENGLAND

By
Susan Grace Spierre
University of New Hampshire, December, 2008

Decision-makers require current data and analysis on extreme precipitation events and trends to facilitate effective adaptation. Here, multiple definitions of extreme precipitation (accumulations of one-inch, two-inch and four-inches, ten-, five- and one-yr. recurrence intervals, and the 99th percentile of events) are used to examine changes in the frequency and intensity of extreme precipitation events in New England over the past 60-100 years. Correlations of trends in extreme precipitation events with temperature and with indices of atmospheric circulation patterns are also investigated.

Predominately positive trends were found for all extreme precipitation definitions. For example, increases of 1 events/decade in one-inch events were found across the region. Spatially, positive trends were strongest in southern and central New England. These findings should contribute to flood management efforts and increase awareness of the impacts of climate change in New England.
CHAPTER I

INTRODUCTION

Extreme Precipitation

In May 2006, portions of northern New England experienced a severe flood event, the result of a stalled low pressure system pulling moisture into the region from the Atlantic Ocean. Up to 14 inches of rain fell over three days in some areas causing record flooding on several rivers, damage to infrastructure, and flooding in dozens of communities. The peak discharges were the largest ever recorded at 14 long-term (more than 10 years of record) streamgages in New Hampshire. Peak discharges equaled or exceeded a 100-year recurrence interval at 14 streamgages and equaled or exceeded a 50-year recurrence interval at 22 streamgages. At least 600 roads were closed, and many dams were close to failing. As a result, numerous residents were evacuated (Olson, 2007). The 2006 event, as well as other recent floods in New Hampshire, have exposed the potential danger and costly devastation that can be associated with extreme precipitation events (CMFSC 2008).

Climatologists have provided evidence that storms like the one in May 2006 are increasing in frequency across the globe. Changes in precipitation have been documented on a range of spatial and temporal scales. Groisman et al. (2005) have shown an increase in the total annual precipitation and in the number of heavy precipitation events occurring
in the mid-latitudes from 1970 - 1999 when compared to 1910 – 1970 using daily climate data from the National Climatic Data Center (NCDC). They also found statistically significant increases in heavy (upper 5%) and very heavy (upper 1%) precipitation of 14 and 20%, respectively. This agrees with results presented in Kunkel et al. (2003) for the United States. Globally, the rate of increase in the contribution of very wet days (above the 95th percentile) to the annual precipitation total has doubled from 0.21 ± 0.10 % per decade from 1951 – 2003 to 0.41 ± 0.38 % per decade from 1979 – 2003 (Alexander 2006). Global circulation models agree with observations, and predict that the proportion of total precipitation derived from extreme and heavy events will continue to increase relative to moderate and light precipitation events (Karl and Knight 1998; Wilby 2002).

Studies have found that precipitation trends are also changing across North America. Global Historical Climatology Network (GHCN) data from the National Climatic Data Center (NCDC) shows that for most of North America, annual precipitation has increased from 1901 – 2005 (IPCC 2007). Easterling et al. (2007) found increases in precipitation of 4.5 mm/decade from 1901 - 2006, and 12.1 mm/decade from 1950 - 2006 for the continental United States.

Similar to many other regions, the northeastern United States has seen increases in extreme precipitation. Hayhoe et al. (2007) found a consistent trend in annual precipitation of + 9.5 ± 2 mm/decade over the last century in the northeastern United States that is consistent with the results presented in Keim et al. (2005). Wake et al. (2006) reported that the number of heavy precipitation events (defined as > 2 inches of rainfall, or water equivalent if the storm results in snowfall, in 48 hours) has increased for
a majority of the USHCN weather stations examined from 1949-2002 in the northeastern U.S. and the Canadian Maritime region. Also, a report by Environment America Research and Policy Center reported a 24% increase in the frequency of storms with extreme precipitation (storms with an average recurrence interval of one year or more) across the continental United States since 1948 and an increase of over 50% for the New England states of Rhode Island, New Hampshire, and Vermont (Environment New Hampshire 2007).

In addition to precipitation increases, scientists have also observed changes in precipitation character. Recent warming winter temperatures may be linked to less total snowfall in New England, and possibly more rainfall. Burakowski et al. (2008) report decreases in total winter snowfall by about 3 inches/decade from 1965-2005 associated with increases in maximum, minimum and mean temperatures in the northeastern US. Huntington et al. (2004) found a decreasing trend in the snow to total precipitation (S/P) ratio, a result of decreasing snowfall, and to a lesser extent increasing rainfall, from 1949-2000 in New England. Hayhoe et al. (2007) found significant decreasing trends in snow water equivalent (SWE) and snow days from 1970 – 1999, likely due to increasing temperatures coupled with decreasing S/P ratios. This means earlier spring lake and river ice-out, and snow-melt driven spring runoff which could have detrimental effects on places that depend on the snow pack for water supply (Huntington et al. 2004). There is also evidence that warming is related to an earlier snow retreat in the spring (Burakowski et al. 2008; Groisman et al. 2001; Hayhoe et al. 2007) which allows an earlier onset of spring-like weather conditions because the soil is exposed directly to sunlight.
Precipitation in New England

The amount of precipitation an area receives is often related to how close a location is to a moisture source. Areas located near the coastline tend to receive greater amounts of precipitation compared to inland areas. The time of year, latitude, elevation, and atmospheric circulation patterns also play key roles. Regional and local features such as topography and land use have an influence on local atmospheric dynamics, and in turn modulate precipitation intensity and patterns (e.g., Diem and Brown, 2003). Due to the varying terrain and topography, as well as the land use changes occurring in New England (i.e. more asphalt associated with development), trends in heavy precipitation events will vary at a sub-regional scale, and thus produce different levels of risk of heavy precipitation events across New England.

Precipitation delivery mechanisms in New England vary substantially in character, and thus affect the timing and frequency of heavy precipitation events. There are three basic types of systems that bring extreme rainfall to New England: localized storms that are generated by free convection (such as thunderstorms), synoptic-scale mid-latitude cyclones (for example, nor'easters or Alberta Clippers and their associated frontal systems), and tropical storms or hurricanes and their remnants (Zielinski and Keim 2005).

Thunderstorms primarily occur in the summer, when the dew point temperature is high causing the air to be unstable. The surface is heated by the sun to the point where the air above the surface rises under free convection and cools. This allows condensation to
occur forming a cloud and releasing latent heat, which provides energy to the atmosphere. The updraft sometimes develops into a thunderhead and may produce heavy rainfall that typically lasts minutes to hours and is usually an isolated occurrence (Zielinski and Keim 2005).

Mid-latitude cyclones, also called low pressure systems or sometimes nor’easters, may produce precipitation ahead of a warm front, or the leading edge of a warm, moist air mass. In this case, the warm air gently rises over cooler air creating a wide band of precipitation. Precipitation may also occur at the cold front, or leading edge of cold, dry air. At a cold front the cold air forces the warmer, less dense air ahead of it to rise quickly. This creates a rapid lifting mechanism that may allow clouds and thunderstorms to form causing a risk of precipitation (Aguado and Burt, 2007). If an upper-level low gets cut-off from the major Westerlies, a slow moving or even stationary surface low pressure system can develop, dumping large amounts of precipitation in an area over several days (Davis et al., 1993). Nor’easters are a type of cyclone that typically occur during the winter and named for their strong northeasterly winds blowing in from the ocean ahead of the storm (Aguado and Burt, 2007). Depending on the storm track, nor’easters can bring snow, rain or a mix of both to New England. Large snow accumulations in New England have been associated with nor’easters including the Blizzard of 1978 that completely shut down the Boston metropolitan area (Zielinski and Keim, 2003).

Tropical storms, or hurricanes, are usually formed over the tropical North Atlantic ocean during the summer and early fall and may move inland, re-curving in a north-
easterly direction due to the presence of the Westerlies in the mid-latitudes, eventually affecting New England. These storms usually contain large amounts of moisture and often result in costly wind and flood damage (Zielinski and Keim 2005).

**Precipitation and Climate Change**

Change in the amount and intensity of precipitation have long been key indicators of a changing climate. One reigning hypothesis is that the observed changes in precipitation patterns are due to an increase in global temperatures driven by enhanced levels of greenhouse gases in the atmosphere that originate from the burning of fossil fuel and land use changes (e.g. IPCC 2007, Zhang et al. 2007, Trenberth et al. 2003, Groisman et al. 2005, Karl and Trenberth 2003, Hayhoe et al. 2007). Warmer temperatures lead to greater evaporation rates and allow air to have a higher capacity for water vapor, leading to a more active hydrological cycle (Easterling et al. 2000; Groisman et al. 2004; Huntington 2006). Because more water vapor is in the air, when the air rises and cools due to expansion under lower pressure, more water vapor gas is available to condense into liquid to form clouds and ultimately rainfall (Trenberth 2003).

More moisture in the atmosphere is also linked to temperature increases because water vapor is a very effective greenhouse gas. In a positive feedback loop, greenhouse gases, like water vapor, absorb outgoing longwave radiation from the earth’s surface, trapping energy in the atmosphere. More energy causes the temperature to rise, more evaporation, and more water vapor in the atmosphere to absorb even more energy.
Satellite data show that a 1°C increase in air temperature increases the amount of water in the atmosphere by 7 percent (Wentz 2007).

A recent analysis by Environment Canada found increased annual precipitation in the mid-latitudes of the Northern Hemisphere from 1925 to 1999, and conclude that these changes cannot be explained by internal climate variability or natural forcing, and are therefore likely to be due to anthropogenic emissions of greenhouse gases (Zhang 2007). Global climate model projections forced by higher concentrations of greenhouse gases (IPCC 2007) in the atmosphere indicate an increasing probability of heavy precipitation events for many extratropical regions (Groisman et al., 2005). Using coupled atmospheric ocean general circulation models forced by the A1fi scenario (Nakicenovic et al., 2000), Hayhoe et al. (2007) show that the annual temperature and annual percent change in precipitation will increase in the future under a scenario of increasing greenhouse gas emissions (Figure 1-1).

Still, another cause of recent precipitation changes could also be, in part, due to natural variability in the climate system; Kunkel et al. (2003) found that there was a period of increased heavy precipitation events in the western U.S. during the 1890’s in addition to the increases found in the twentieth century.

The character of precipitation is also changing in that there are more extreme precipitation events but also more dry spells. Under several different greenhouse gas emission scenarios (IPCC 2007) more intense precipitation events are projected, resulting in longer periods of little to no precipitation in between large events. For example, the number of dry days across the United States is expected to increase as a result of
increasing temperatures (IPCC 2007; Hayhoe et al. 2006). Also, the increased
temperatures brought by global warming will increase evaporation rates of moisture from
the land and ocean, which will at least partially offset the effects of more rainfall and
amplify the effects of less rainfall (Environment New Hampshire 2007).

![Figure 1-1. Modeled change in temperature (top) and precipitation (bottom) for
greenhouse gas emission scenarios (low (B1), mid-high (A2), and high (A1)) for the
2035-2064 and 2070-2099 time periods relative to the 1961-1990 average. There is an
increase in temperature (annually and seasonally) in the northeastern U.S. and an
increase in precipitation (annually and during the winter) as emission scenarios
increase. Source: Hayhoe et al., 2007.]

**Impacts of Extreme Precipitation**

One of the most costly effects of extreme precipitation events is flooding. During
the 20th century, floods caused more loss of life and property damage than any other
natural disaster in the United States (Perry 2000). Annual losses have increased from $1 billion in the 1940s to $6 billion during the 1980s and 1990s (Easterling 2000) (based on the 1997 dollar). The growth in flood damage is partially due to society becoming increasingly vulnerable to heavy precipitation. New England has experienced considerable development in many of its watersheds, resulting in more rapid runoff due to an increase in the amount of impermeable surfaces such as asphalt (CFMSC 2008). Therefore, flooding is more predominate even with the same amount of rainfall. Damages from flooding events include, but are not limited to, loss of life, damage to infrastructure (such as bridges, roads, residential communities, etc.), erosion, and pollution from storm runoff (caused by the flooding of areas that contain sewage treatment facilities, farms, farm waste lagoons, chemical and/or petroleum storage facilities) with uncertain long-term consequences to fluvial and coastal ecosystems (Easterling et al., 2000).

Parts of New England have recently experienced several heavy precipitation events and subsequent devastating floods. In particular, a major flooding event occurred in central and southern New Hampshire between May 13 and May 17, 2006. Rainfall totals ranged from 6 inches in inland areas to over 14 inches along the coast over a 48-hr period. This region normally receives only about 3.5 inches of rainfall in an average spring month. Less than one year later, from April 16 to April 18, 2007, major flooding occurred again in the same area. Heavy rainfall ranged from 4 to 8 inches in 2 days. Rapidly melting snow also contributed to the problem. Record peak flood discharges were recorded during both these events, many of them exceeding the 50 year flood level and some surpassing the 100 year flood thresholds (a 100 year flood is a storm that
results in flood levels that have a one-percent chance of being exceeded in a given year). Both of these severe flood events resulted in significant property damage, along with numerous road closures and evacuation of residential areas (FEMA 2007; CFMSC 2008).

Flooding events are relatively rare but naturally occurring in New England, for example, New Hampshire has averaged about one major and destructive flood per decade since the early 20th century. The concern is that New Hampshire has had three recent major flood events, one during each year of 2005, 2006 and 2007 (CFMSC 2008). Decision-makers currently use outdated flood risk information and floodplain maps, based on historic rainfall and peak discharge data that do not represent recent historical, current, or future predicted rainfall patterns (Wake et al. 2006, Hayhoe et al. 2007, Madsen and Fignor 2007). To facilitate effective planning, decision-makers require information on the future implications of changing land use and climate at a local scale, where climate change impacts are felt and understood most clearly (Snover et al. 2007). This study aims to provide a quantitative understanding of the current trends in extreme precipitation for New England so that policy-makers have more of the necessary tools to prepare for and adapt to climate change.

**Objectives**

Because of the risks associated with heavy precipitation events, an improved understanding of their occurrence and trends is desirable. Examining how the frequency, spatial variability, and intensity of heavy precipitation events are changing is a key step
for eventually predicting and preparing for future flooding events. The main objectives of this study are to quantify trends in the frequency and variability of heavy precipitation events over the last 60-100 years in New England using several different mathematical definitions. The purpose of this analysis is to provide an improved understanding of heavy precipitation event frequency which can be used by stakeholders, emergency managers, scientists, and society to prepare for a potentially different precipitation regimes as a result of our changing climate.
CHAPTER II

DATA AND METHODOLOGY

Daily Precipitation Data (DSI-3200)

Daily precipitation measurements were obtained from the National Climatic Data Center’s (NCDC) Summary-of-the-Day Climate Data Set (DSI 3200/3210), available at http://cdo.ncdc.noaa.gov/pls/plclimprod/somdmain.somdwrapper. The dataset provides a suite of surface weather observations, including 24-hour precipitation totals, from stations primarily in the National Weather Service (NWS) cooperative station network. Many observers in the network are volunteers, but the network does include NWS principal climatological stations, also called “first order” stations, which are operated by highly trained observers.

The area of study consists of the New England region (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) of the United States. There are two time periods that were analyzed; 1948 - 2007 (most stations started collecting data in 1948) and 1900 - 2007 from a select few stations that have longer daily precipitation records. Examining extreme precipitation over both time periods allows for comparison of more recent changes with century-long trends.

Precipitation measurements are known to contain errors (Groisman and Easterling 1994); the most significant error comes from losses of water due to wind turbulence
above the gauge orifice and can account for 3%-10% bias for liquid precipitation. The error can be reduced with the installation of a wind shield to the rain gauge, however only a small number of weather stations in the U.S. actually have wind shields installed. The vast majority of stations have remained unshielded throughout the period of record; therefore the magnitude of biases should not affect the overall temporal trend analysis (Groisman and Easterling 1994).

There are also known inconsistencies in how NWS stations measure snow, and these can lead to discrepancies among neighboring stations. For example, weather observers that measure snowfall at 6-hour intervals have been known to result in an inflation of snowfall totals when compared to observers that measure snowfall only once daily. In addition, the use of snowboards is not universal, and early instructions do not mention them, indicating that long-term records are probably not consistent. Other factors that may complicate trend analysis include compaction, gauge undercatch, and assumptions about snow density (Kunkel et al. 2007). It is common practice to assume that discrepancies in observing practices are random and canceled out when studying a large number of stations. In this study, errors in measuring snowfall would likely affect northern New England stations more, where there is typically more snow, than stations in southern regions. The identification of biases introduced by such inconsistencies (both rain and snow) is critical when analyzing precipitation trends. To address this, we analyze the data using a spatial coherence method developed by Kunkel et al. (2007), discussed in the next section.
Data Processing

Quality Control

NCDC performs their own quality control on their data and provides the following statement in regards to the DSI-3200 dataset:

These data have received a high measure of quality control through computer and manual edits. These data are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated against surrounding stations. Quality control "flags" are appended to each element value to show how they fared during the edit procedures and to indicate what, if any, action was taken. The historical data prior to 1982 were converted from existing files then placed in the element file structure format after being processed only through a gross value check. In November 1993 the entire historical period of record was processed through a stringent quality control. Another round of quality control in November 2000 increased the data set's quality still more.

It is important to note that on days where a precipitation measurement was missing but a snowfall measurement was recorded; the missing record was filled in by NCDC using the 10:1 (snow to rain respectively) conversion ratio. This practice may introduce additional errors in the record since the density of falling snow increases with increasing air temperature (Dube 2003).

Missing data can pose difficulties in studying extreme events because if events are not recorded, results may not represent the spatial extent of the event. There was a need to balance the retention of high quality records with maintaining sufficient spatial coverage. The goal was to maximize the number of stations used in order to retain a well distributed, dense network of stations in New England for a detailed precipitation
analysis, and to eliminate stations that did not have high quality data records. Each record was inspected individually to assess its completeness and reliability for use in trend analysis. For the 1948 – 2007 analysis, if a station contained less than 80% of the daily precipitation measurements for the time period (following Karl and Knight, 1998) or had less than 50 years (out of 60 years studied) where there was 90% of daily data for each year, it was removed from further study. Stations with elevations greater than 1000m asl (above sea level) were excluded from analysis because of the significant differences in weather and climate at these locations compared to surrounding stations. The trends resulting from stations at such high elevations are not necessarily representative of typical precipitation trends in New England (Grant et al. 2008; Grant et al. 2005). For the 1900 – 2007 analysis, stations with long enough data histories were selected in New England, each of which have at least 90% of the data for each year for at least ninety of the 108 years between 1900 and 2007.

To normalize the data, Z-score time series were used to compare each station's annual precipitation totals to the five closest neighboring stations. Z-scores were computed using the equation: \( z = \frac{(x - \bar{x})}{SD} \), where \( z \) is the new z-score value for precipitation, \( x \) is the original raw precipitation value for station \( x \), \( \bar{x} \) is the overall mean precipitation for station \( x \), and SD is the overall standard deviation for the precipitation at station \( x \).
Kunkel et al. (2007) call attention to non-climate biases (i.e. change in an observer, observer practices, station location, exposure, instrumentation, etc.) contained in weather data that can significantly influence trends. They describe how to perform spatial coherence analysis on snowfall and snow depth data, a technique used to identify stations containing non-climate biases so they may be removed from analysis. Burakowski et al. (2008) used the same method to remove bias from trends in wintertime climate for the northeastern United States. Here, the spatial coherence technique is used on precipitation data from stations in the 1948 - 2007 analysis.

The spatial coherence analysis consists of computing annual precipitation anomalies for each station (annual precipitation total minus the long-term annual precipitation mean). The annual anomaly $A(y)$ is defined as

$$A(y) = s(y) - \left[ \frac{\sum_{y=a}^{b} F(y) \cdot s(y)} {\sum_{y=a}^{b} F(y)} \right],$$

where $F(y)$ is a flag equal to 1 if data exist for year $y$ or 0 if data do not exist, $s(y)$ is the annual precipitation total, $a$ is the beginning year of the analysis, and $b$ is the ending year of the analysis. Spatial coherence was evaluated by plotting the difference between each annual station anomaly and the annual anomalies of the five closest neighboring stations in a time series. If a station’s record agrees with the records of its five closest neighbors, the differences in anomalies will fluctuate near zero throughout the time series. A station
that is not spatially coherent displays a large negative or positive shift in anomaly differences resulting from a manifestation of non-climatic influences. Shifts in the anomaly time series were identified visually by looking for prolonged time periods (on the order of 10 to 15 years) where the differences in anomalies remained above or below the zero line, followed by a relatively quick shift (over one to two year period) toward differences in anomalies of a different sign. The cause for the shift was investigated by looking at metadata and station histories; however in most cases the reason for the shift was not documented. For example, figure 2-1 shows the anomaly graphs for two stations; New Bedford, MA and Augusta, ME. New Bedford shows a large shift from negative to positive anomalies in the early 1960’s and was therefore rejected, but because the anomalies for Augusta remained spatially coherent with its neighbors throughout the time period, it was retained for analysis. This technique resulted in the rejection of eleven New England stations (out of the 94 stations that had already passed the previous criteria) in the 1948-2007 analysis. Spatial coherence analysis is not performed on the stations used in the 1900 - 2007 analysis because there are too few stations with a long enough data history for this time period and the stations are spread out across New England and therefore do not have “close neighbors” as defined in our study.
Figure 2-1. Time series of annual precipitation anomalies minus neighboring station anomalies for New Bedford, MA (top), and Augusta, ME (bottom). New Bedford displays a large shift from negative to positive anomalies in the early 1960’s and was removed from analysis whereas Augusta behaves much like its neighbors throughout the time period and was retained for analysis.
Station Selection for the 1948 – 2007 Analysis

This study concentrates on the 1948-2007 precipitation analysis because of the large number of stations for which reliable daily precipitation is available across New England. Out of the 144 stations in New England that had 80% of the daily precipitation measurements from 1948-2007, ninety-seven of them had 90% of the daily measurements for each year for at least fifty years of the time period. Two stations (Mt. Washington and Mt. Mansfield) were excluded because they had elevations greater than 1000m asl and would present misleading trends in extreme precipitation. Eleven stations failed the spatial coherence analysis and were therefore also removed from further study. Eighty-four stations (see Table A-1 in Appendix A for a complete list) were found to pass the quality control criteria and will be utilized in analysis(Figure 2-2).

Station Selection for the 1900 – 2007 Analysis

Eleven New England stations were used for the 1900 – 2007 analysis (Figure 2-2). These stations were selected because their period of record began before 1900 and contained more than 90% of the daily precipitation measurements for each year for more than ninety of the years during the period (~85% of the years between 1900 and 2007). These eleven stations are also used in the 1948 – 2007 analysis with the exception of Johnbury, and Storrs, CT. Spatial coherence analysis was not performed on these stations due to the small number of stations that were available for this time period and because of
the larger distance between closest stations. Trends in extreme precipitation events were examined at the eleven stations from 1900-2007 and also from 1948-2007.

Figure 2-2. Distribution of stations used in this study. Stations examined from 1948 – 2007 are shown with red dots. Stations used in the 1900 – 2007 are indicated with black triangles.

Defining Extreme Precipitation

Extreme precipitation has been examined in previous studies using various criteria. For example, Hayhoe et al. (2007) defined extreme precipitation as the accumulation of rain greater than two inches in a 48 hour time period; Brooks and Stensrud (1999) looked at hourly rainfall totals over one inch; Groisman et al. (2005)
used event frequency thresholds, where for a given location or season, extreme events are those that fall in the top 0.1% of all precipitation events; and Shumacher and Johnson (2004) studied events where the 24 hour precipitation total at one or more stations surpassed the 50-year recurrence level. To provide a broad examination of trends in extreme precipitation across New England, three different types of extreme precipitation definitions are used in this study.

(1) Changes in Frequency of Accumulation

We examine the change in frequency over time of the accumulation of one or more inches of precipitation in a 24 hour period (referred to as a one-inch event), two or more inches of rain in a 48 hour period (referred to as a two-inch event) and four or more inches of rain in a 48 hour period (referred to as a four-inch event). The one and two-inch events are common definitions of extreme precipitation events (Hayhoe et al. 2007; Wake et al. 2006), whereas the four-inch event is a more severe, less frequent type of event.

If a station was retained in the analysis because it met the defined criteria, but still contained years that did not have 90% of the daily precipitation measurements, then those specific years of missing data were not included in the trend analysis for one and two-inch events. When analyzing the trend for the much less frequent four-inch events, all the years with missing data were examined closely to assess whether or not the missing days coincided with extreme precipitation events in the area. For each station, every day that did not have a daily precipitation measurement recorded was listed and compared with a
list of days where four-inch events had been measured at any of the five closest neighboring stations. If any day during a four-inch event, which occurred at one or more of the five closest stations, was missing a precipitation measurement at the reference station, an average of the accumulations for that day at the five closest stations was computed and filled into the reference station data to be included in the four-inch event analysis.

(2) 99th Percentile of Precipitation Events

Another way of defining extreme precipitation is to examine event frequency thresholds (e.g., Groisman et al, 2005). Here, the top 1% of 24-hr precipitation measurements for each year are defined as extreme. Changes in the threshold of the 99th percentile of daily accumulations, which exemplify changes in precipitation intensity at stations in New England, are examined over the 1948-2007 period. To calculate the annual 99th percentile accumulation for one day precipitation totals at each station, the 24-hr precipitation measurements greater than zero were ranked from smallest accumulation to largest accumulation for each year in the reference period. Percentiles are computed for each accumulation based on a sum polygon where the kth ranking measurement is the (k-1)/(n-1) percentile, where n in the number of measurements ranked, and intermediate percentiles are obtained by linear interpolation (Dalgaard 2002). Because the annual 99th percentile of daily accumulations are calculated and examined over time, this definition is not broken down seasonally or monthly in further analysis.
(3) Recurrence Intervals

A third method to define extreme precipitation events is by using recurrence intervals (Schumacher and Johnson 2005; Kunkel et al. 1999). A recurrence interval is the average amount of time between events of a given magnitude. We examine the ten, five, and one-year recurrence intervals for each station for one day event durations across New England (The ten-, five-, and one-year intervals were analyzed because they were intervals that could be sufficiently examined over time during the 1948-2007 time period). For example, to find the 24-hr one-year recurrence interval for station x, the 60 largest (1948-2007) one day accumulations at station x are identified. The smallest of the 60 one-day accumulation values will be the threshold for station x, and the number of times the threshold is exceeded each year will be examined over time.

Trend Analysis

To account for the trend’s sensitivity to the start and end year of the time-series, we calculate the mean of the decadal rate of change determined from a least-squares linear regression of ten 51-year time windows with start years ranging from 1948 to 1957, and end years ranging from 1998 to 2007 (e.g. for a time window size of 51 years, trends were calculated for the time series 1948-1998, 1949-1999 ... 1957-2007). The significance of trends was evaluated by computing p-values, for which the assumption of normality was satisfied by inspecting residuals and associated Q-Q plots (quantile vs.
quantile). Station trends with \( p < 0.10 \) for all ten 51-year trends were considered statistically significant.

For the four-inch events and the ten-, five-, and one-year recurrence intervals, trends were determined by computing the linear regression of the sum of the number of events that occurred in discrete ten year time intervals (1948-1957, 1958-1967, 1968-1977, 1978-1987, 1988-1997, 1998-2007). This method of trend analysis was utilized due to the rare nature of these events. No statistical significance tests were completed for the four-inch events or the ten-, five- and one-year recurrence intervals due to the non-normal distribution of the residuals for these definitions. These definitions without significance testing should be used as a supplement to the definitions with more rigorous testing. Due to the longer period of record in the 1900-2007 analysis, trends were calculated with a single time window starting in 1900 and ending in 2007. To access the spatial variability of the trends for all the definitions used in this study, the decadal rate of change for each station was plotted by latitude. Stations located along the coast of New England were flagged to examine the variability between coastal and inland station trends.

**Correlations with Temperature and Atmospheric Circulation Indices**

The following correlations are a relatively simplistic approach to investigate why changes in precipitation patterns have been occurring in New England. One-inch events are correlated with temperature and large-scale atmospheric circulation patterns to determine if they are consistent with changes in extreme precipitation.
Temperature

To study the relationship between temperature and extreme precipitation in New England, scatter plots were created comparing the number of events per month and the mean monthly temperature data from the National Climate Data Center (Monthly Surface Data DS3220). The temperature data was obtained for the same stations used in the 1948-2007 precipitation analysis, however only 55 out of the 84 stations had adequate temperature data for the regression, so the temperature – extreme precipitation analysis is limited to these 55 stations. For each definition of extreme precipitation described above, each station and during each season, the Pearson correlation coefficient was computed for the temperature vs. precipitation plots to evaluate the relationship. Seasonal trends in the northern hemisphere temperature anomalies (with the base period from 1951 to 1980, available at http://data.giss.nasa.gov/gistemp/) were calculated from ten 51-year time series windows and compared to the seasonal trends in one-inch extreme precipitation events. Using seasonal northern hemisphere temperature anomalies will allow us to examine overall regional trends in temperature, rather than month to month variability at individual locations.

Atmospheric Circulation Patterns

Regional changes in climate are often thought to be related to shifts in large scale atmospheric circulation patterns. Here, one-inch extreme precipitation events are
correlated with the North Atlantic Oscillation (NAO) (Hurrell 1995), the Trough Axis
Index (TAI) and the Jet Latitude Index (JLI) (Bradbury, personal communication), which
have been observationally linked to winter precipitation anomalies in the northeastern
United States (Bradbury et al. 2002, Bradbury et al. 2003)

Bradbury et al. (2002) suggests that the NAO is linked to storm-tracking patterns,
primarily during the winter season. The NAO is defined as the sea level pressure
difference between the Azores high and the Icelandic low. The NAO describes the
steepness of the north-south atmospheric pressure gradient across the North Atlantic
Ocean. It has two phases: a positive phase and a negative phase. When the NAO changes
between opposite phases, the North Atlantic Ocean experiences changes in wind speed
and direction, which affects heat and moisture transport to surrounding continents and
seas (Hurrell et al. 2001). A winter (DJFM) NAO index was provided by the Climate
Analysis Section, NCAR, Boulder, USA, as defined by Hurrell (1995), using
Stykkisholmur/Akureyri, Iceland, and Lisbon, Portugal as the sea level pressure (SLP)
nodes. The NAO seasonal index was correlated with Fall (SON), Winter (DJF) and
Spring (MAM) one-inch events from 1948 - 2007, using Pearson R correlation
coefficients. Trends in the winter-time NAO index (calculated from ten 51-year time
series windows) was also compared to mean decadal trends in one-inch events from 1948

The Trough Axis Index (TAI) is a measure of the monthly mean longitudinal
location of the East Coast pressure trough between 40°W to 100°W. Using gridded
geopotential height fields, the TAI is calculated by identifying the longitudinal location
(in degrees) of the grid point between 40°W to 100°W where the minimum 500mb geopotential height occurs at 40°N, 42.5°N, 45°N and 47.5°N latitude. Then, a monthly index value is calculated by averaging these four longitude values (Bradbury et al. 2002).

The Jets Latitude Index (JLI) is a measure of the monthly mean latitudinal position of the subtropical/polar front jet between 20°N and 60°N. The JLI is derived using gridded 200mb zonal wind fields by identifying the latitudinal location of the grid point (between 20°N and 60°N) at which the maximum 200mb zonal winds occur along each longitude between 65°W and 80°W, at 2.5° degree intervals. By averaging these seven latitude values, a monthly index value is calculated (Hayhoe et al. 2006). Both the TAI and the JLI values were provided to us by James Bradbury (pers. comm.).

In this study, the monthly TAI and JLI was correlated with December, January, February, and March one-inch events from 1948-2004. Again, Pearson correlation coefficients were used to access the relationships. The JLI is also correlated with monthly northern hemisphere temperature anomalies during the winter (DJFM).

**Influence of Hurricanes on Extreme Precipitation**

Studies of extreme precipitation in New England warrants the examination of the effect that hurricanes and their remnants have on the frequency of extreme precipitation in the region. To do this, seven stations in New England (Augusta ME, Burlington VT, East Milton Blue Hill Observatory, MA, Hartford CT, Plymouth NH, Plymouth Kingston RI, and Portland ME) were chosen to represent the New England region. The dates of all
hurricanes (i.e., storm must have been classified as a hurricane during their lifetime) that affected New England since 1948 (Boose 2001, Donnelly 2001, and Roth 2008) were compared to the dates of all definitions of extreme precipitation events recorded at each representative station (tropical storms and depressions were also examined but there were only a few that had records of affecting New England). Time series for each station were then created to show the number extreme events caused by hurricanes compared with the annual number of extreme precipitation events.
CHAPTER III

EXTREME PRECIPITATION TRENDS IN NEW ENGLAND

PAPER TO BE SUBMITTED TO A SCIENTIFIC JOURNAL

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Abstract

Decision-makers require current data and analysis on extreme precipitation events and trends to facilitate effective adaptation. Here, multiple definitions of extreme precipitation (accumulations of one-inch, two-inch and four-inches, ten-, five- and one-yr. recurrence intervals, and the 99th percentile of events) are used to examine changes in the frequency and intensity of extreme precipitation events in New England over the past 60-100 years. Correlations of trends in extreme precipitation events with temperature and with indices of atmospheric circulation patterns are also investigated.

Predominately positive trends were found for all extreme precipitation definitions. For example, increases of 1 events/decade in one-inch events were found across the region. Spatially, positive trends were strongest in southern and central New England.
These findings should contribute to flood management efforts and increase awareness of the impacts of climate change in New England.

**Introduction**

**Extreme Precipitation**

In May 2006, portions of northern New England experienced a severe flood event, the result of a stalled low pressure system pulling moisture into the region from the Atlantic Ocean. Up to 14 inches of rain fell over three days in some areas causing record flooding on several rivers, damage to infrastructure, and flooding in dozens of communities. The peak discharges were the largest ever recorded at 14 long-term (more than 10 years of record) streamgages in New Hampshire. Peak discharges equaled or exceeded a 100-year recurrence interval at 14 streamgages and equaled or exceeded a 50-year recurrence interval at 22 streamgages. At least 600 roads were closed, and many dams were close to failing. As a result, numerous residents were evacuated (Olson, 2007). The 2006 event, as well as other recent floods in New Hampshire, have exposed the potential danger and costly devastation that can be associated with extreme precipitation events (CMFSC 2008).

Climatologists have provided evidence that storms like the one in May 2006 are increasing in frequency across the globe. Changes in precipitation have been documented on a range of spatial and temporal scales. Groisman et al. (2005) have shown an increase in the total annual precipitation and in the number of heavy precipitation events occurring
in the mid-latitudes from 1970-1999 when compared to 1910-1970 using daily climate data from the National Climatic Data Center (NCDC). They also found statistically significant increases in heavy (upper 5%) and very heavy (upper 1%) precipitation of 14 and 20%, respectively. This agrees with results presented in Kunkel et al. (2003) for the United States. Globally, the rate of increase in the contribution of very wet days (above the 95th percentile) to the annual precipitation total has doubled from 0.21 ± 0.10 % per decade from 1951-2003 to 0.41 ± 0.38% per decade from 1979-2003 (Alexander 2006). Global circulation models agree with observations, and predict that the proportion of total precipitation derived from extreme and heavy events will continue to increase relative to moderate and light precipitation events (Karl and Knight 1998; Wilby 2002).

Studies have found that precipitation trends are also changing specifically across North America. Global Historical Climatology Network (GHCN) data from the National Climatic Data Center (NCDC) shows that for most of North America, annual precipitation has increased from 1901-2005 (IPCC 2007). Easterling et al. (2007) found increases in precipitation of 4.5 mm/decade from 1901-2006, and 12.1 mm/decade from 1950-2006 for the continental United States.

Similar to many other regions, the northeastern United States has seen increases in extreme precipitation. Hayhoe et al. (2007) found a consistent trend in annual precipitation of + 9.5 ± 2 mm/decade over the last century in the northeastern United States that is consistent with the results presented in Keim et al. (2005). Wake et al. (2006) reported that the number of heavy precipitation events (defined as > 2 inches of rainfall, or water equivalent if the storm results in snowfall, in 48 hours) has increased for
a majority of the USHCN weather stations examined from 1949-2002 in the northeastern
U.S. and the Canadian Maritime region. Also, a report by Environment America
Research and Policy Center reported a 24 percent increase in the frequency of storms
with extreme precipitation (storms with an average recurrence interval of one year or
more) across the continental United States since 1948 and an increase of over 50 percent
for the New England states of Rhode Island, New Hampshire, and Vermont
(Environment New Hampshire 2007).

In addition to precipitation increases, scientists have also observed changes in
precipitation character. Recent warming winter temperatures may be linked to less total
decreases in total winter snowfall by about 3 inches/decade from 1965-2005 associated
with increases in maximum, minimum and mean temperatures in the northeastern US.
Huntington et al. (2004) found a decreasing trend in the snow to total precipitation (S/P)
ratio, a result of decreasing snowfall, and to a lesser extent increasing rainfall, from 1949-
water equivalent (SWE) and snow days from 1970 – 1999, likely due to increasing
temperatures coupled with decreasing S/P ratios. This means earlier spring lake and river
ice-out, and snow-melt driven spring runoff which could have detrimental effects on
places that depend on the snow pack for water supply (Huntington et al. 2004). There is
also evidence that warming is related to an earlier snow retreat in the spring (Burakowski
et al. 2008; Groisman et al. 2001; Hayhoe et al. 2007) which allows an earlier onset of
spring-like weather conditions because the soil is exposed directly to sunlight.
Precipitation and Climate Change

Change in the amount and intensity of precipitation have long been key indicators of a changing climate. One reigning hypothesis is that the observed changes in precipitation patterns are due to an increase in global temperatures driven by enhanced levels of greenhouse gases in the atmosphere that originate from the burning of fossil fuel and land use changes (e.g. IPCC 2007, Zhang et al. 2007, Trenberth et al. 2003, Groisman et al. 2005, Karl and Trenberth 2003, Hayhoe et al. 2007). Warmer temperatures lead to greater evaporation rates and allow air to have a higher capacity for water vapor, leading to a more active hydrological cycle (Easterling et al. 2000; Groisman et al. 2004; Huntington 2006). Because more water vapor is in the air, when the air rises and cools due to expansion under lower pressure, more water vapor gas is available to condense into liquid to form clouds and ultimately rainfall (Trenberth 2003).

More moisture in the atmosphere is also linked to temperature increases because water vapor is a very effective greenhouse gas. In a positive feedback loop, greenhouse gases, like water vapor, absorb outgoing longwave radiation from the earth’s surface, trapping energy in the atmosphere. More energy causes the temperature to rise, more evaporation, and more water vapor in the atmosphere to absorb even more energy. Satellite data show that a 1°C increase in air temperature increases the amount of water in the atmosphere by 7 percent (Wentz 2007).

A recent analysis by Environment Canada found increased annual precipitation in the mid-latitudes of the Northern Hemisphere from 1925 to 1999, and conclude that these
changes cannot be explained by internal climate variability or natural forcing, and are therefore likely to be due to anthropogenic emissions of greenhouse gases (Zhang 2007). Global climate model projections forced by higher concentrations of greenhouse gases (IPCC 2007) in the atmosphere indicate an increasing probability of heavy precipitation events for many extratropical regions (Groisman et al., 2005). Using coupled atmospheric ocean general circulation models forced by the A1fi scenario (Nakicenovic et al., 2000), Hayhoe et al. (2007) show that the annual temperature and annual percent change in precipitation will increase in the future under a scenario of increasing greenhouse gas emissions.

Still, another cause of recent precipitation changes could also be, in part, due to natural variability in the climate system; Kunkel et al. (2003) found that there was a period of increased heavy precipitation events in the western U.S. during the 1890’s in addition to the increases found in the twentieth century.

The character of precipitation is also changing in that there are more extreme precipitation events but also more dry spells. Under several different greenhouse gas emission scenarios (IPCC 2007) more intense precipitation events are projected, resulting in longer periods of little to no precipitation in between large events. For example, the number of dry days across the United States is expected to increase as a result of increasing temperatures (IPCC 2007; Hayhoe et al. 2006). Also, the increased temperatures brought by global warming will increase evaporation rates of moisture from the land and ocean, which will at least partially offset the effects of more rainfall and amplify the effects of less rainfall (Environment New Hampshire 2007).
Impacts of Extreme Precipitation

One of the most costly effects of extreme precipitation events is flooding. During the 20th century, floods caused more loss of life and property damage than any other natural disaster in the United States (Perry 2000). Annual losses have increased from $1 billion in the 1940s to $6 billion during the 1980s and 1990s (Easterling 2000) (based on the 1997 dollar). The growth in flood damage is partially due to society becoming increasingly vulnerable to heavy precipitation. New England has experienced considerable development in many of its watersheds, resulting in more rapid runoff due to an increase in the amount of impermeable surfaces such as asphalt (CFMSC 2008). Therefore, flooding is more predominant even with the same amount of rainfall. Damages from flooding events include, but are not limited to, loss of life, damage to infrastructure (such as bridges, roads, residential communities, etc.), erosion, and pollution from storm runoff (caused by the flooding of areas that contain sewage treatment facilities, farms, farm waste lagoons, chemical and/or petroleum storage facilities) with uncertain long-term consequences to fluvial and coastal ecosystems (Easterling et al., 2000).

Flooding events are relatively rare but naturally occurring in New England, for example, New Hampshire has averaged about one major and destructive flood per decade since the early 20th century. The concern is that New Hampshire has had three recent major flood events, one during each year of 2005, 2006 and 2007 (CFMSC 2008). Decision-makers currently use outdated flood risk information and floodplain maps, based on historic rainfall and peak discharge data that do not represent recent historical,
current, or future predicted rainfall patterns (Wake et al. 2006, Hayhoe et al. 2007, Madsen and Figdor 2007). To facilitate effective planning, decision-makers require information on the future implications of changing land use and climate at a local scale, where climate change impacts are felt and understood most clearly (Snover et al. 2007). This study aims to provide a quantitative understanding of the current trends in extreme precipitation for New England so that policy-makers have more of the necessary tools to prepare for and adapt to climate change.

**Data and Methodology**

**Daily Precipitation Data (DSI-3200)**

Daily precipitation measurements were obtained from the National Climatic Data Center’s (NCDC) Summary-of-the-Day Climate Data Set (DSI 3200/3210), available at http://cdo.ncdc.noaa.gov/pls/plclimprod/somdmain.somdwrapper. The dataset provides a suite of surface weather observations, including 24-hour precipitation totals, from stations primarily in the National Weather Service (NWS) cooperative station network. Many observers in the network are volunteers, but the network does include NWS principal climatological stations, also called “first order” stations, which are operated by highly trained observers.

The area of study consists of the New England region (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) of the United States. There
are two time periods that were analyzed; 1948 - 2007 (most stations started collecting data in 1948) and 1900 -2007 from a select few stations that have longer daily precipitation records. Examining extreme precipitation over both time periods allows for comparison of more recent changes with century-long trends.

Precipitation measurements are known to contain errors (Groisman and Easterling 1994); the most significant error comes from losses of water due to wind turbulence above the gauge orifice and can account for 3%-10% bias for liquid precipitation. The error can be reduced with the installation of a wind shield to the rain gauge, however only a small number of weather stations in the U.S. actually have wind shields installed. The vast majority of stations have remained unshielded throughout the period of record; therefore the magnitude of biases should not affect the overall temporal trend analysis (Groisman and Easterling 1994).

There are also known inconsistencies in how NWS stations measure snow, and these can lead to discrepancies among neighboring stations. For example, weather observers that measure snowfall at 6-hour intervals have been known to result in an inflation of snowfall totals when compared to observers that measure snowfall only once daily. In addition, the use of snowboards is not universal, and early instructions do not mention them, indicating that long-term records are probably not consistent. Other factors that may complicate trend analysis include compaction, gauge undercatch, and assumptions about snow density (Kunkel et al. 2007). It is common practice to assume that discrepancies in observing practices are random and canceled out when studying a large number of stations. In this study, errors in measuring snowfall would likely affect
northern New England stations more, where there is typically more snow, than stations in southern regions. The identification of biases introduced by such inconsistencies (both rain and snow) is critical when analyzing precipitation trends. To address this, we analyze the data using a spatial coherence method developed by Kunkel et al. (2007), discussed in the next section.

**Data Processing**

NCDC performs their own quality control on their data and provides the following statement in regards to the DSI-3200 dataset:

> These data have received a high measure of quality control through computer and manual edits. These data are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated against surrounding stations. Quality control "flags" are appended to each element value to show how they fared during the edit procedures and to indicate what, if any, action was taken. The historical data prior to 1982 were converted from existing files then placed in the element file structure format after being processed only through a gross value check. In November 1993 the entire historical period of record was processed through a stringent quality control. Another round of quality control in November 2000 increased the data set's quality still more.

It is important to note that on days where a precipitation measurement was missing but a snowfall measurement was recorded; the missing record was filled in by NCDC using the 10:1 (snow to rain respectively) conversion ratio. This practice may introduce additional errors in the record since the density of falling snow increases with increasing air temperature (Dube 2003).
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Kunkel et al. (2007) call attention to non-climate biases (i.e. change in an observer, observer practices, station location, exposure, instrumentation, etc.) contained in weather data that can significantly influence trends. They describe how to perform spatial coherence analysis on snowfall and snow depth data, a technique used to identify
stations containing non-climate biases so they may be removed from analysis. Burakowski et al. (2008) used the same method to remove bias from trends in wintertime climate for the northeastern United States. Here, the spatial coherence technique is used on precipitation data from stations in the 1948 - 2007 analysis.

The spatial coherence analysis consists of computing annual precipitation anomalies for each station (annual precipitation total minus the long-term annual precipitation mean) and evaluated by plotting the difference between each annual station anomaly and the annual anomalies of the five closest neighboring stations in a time series. If a station’s record agrees with the records of its five closest neighbors, the differences in anomalies will fluctuate near zero throughout the time series. A station that is not spatially coherent displays a large negative or positive shift in anomaly differences resulting from a manifestation of non-climatic influences. Shifts in the anomaly time series were identified visually by looking for prolonged time periods (on the order of 10 to 15 years) where the differences in anomalies remained above or below the zero line, followed by a relatively quick shift (over one to two year period) toward differences in anomalies of a different sign. The cause for the shift was investigated by looking at metadata and station histories; however in most cases the reason for the shift was not documented. This technique resulted in the rejection of eleven New England stations (out of the 94 stations that had already passed the previous criteria) in the 1948-2007 analysis. Spatial coherence analysis is not performed on the stations used in the 1900 - 2007 analysis because there are too few stations with a long enough data history for this time
period and the stations are spread out across New England and therefore do not have “close neighbors” as defined in our study.

This study concentrates on the 1948-2007 precipitation analysis because of the large number of stations for which reliable daily precipitation is available across New England. Out of the 144 stations in New England that had 80% of the daily precipitation measurements from 1948-2007, ninety-seven of them had 90% of the daily measurements for each year for at least fifty years of the time period. Two stations (Mt. Washington and Mt. Mansfield) were excluded because they had elevations greater than 1000m asl and would present misleading trends in extreme precipitation. Eleven stations failed the spatial coherence analysis and were therefore also removed from further study. Eighty-four stations (see Table A-1 in Appendix A for a complete list) were found to pass the quality control criteria and will be utilized in analysis (Figure 3-1).

Eleven New England stations were used for the 1900 – 2007 analysis (Figure 3-1). These stations were selected because their period of record began before 1900 and contained more than 90% of the daily precipitation measurements for each year for more than ninety of the years during the period (~85% of the years between 1900 and 2007). These eleven stations are also used in the 1948 – 2007 analysis with the exception of Johnbury, and Storrs, CT. Spatial coherence analysis was not performed on these stations due to the small number of stations that were available for this time period and because of the larger distance between closest stations. Trends in extreme precipitation events were examined at the eleven stations from 1900-2007 and also from 1948-2007.
Defining Extreme Precipitation

Extreme precipitation has been examined in previous studies using various criteria. For example, Hayhoe et al. (2007) defined extreme precipitation as the accumulation of rain greater than two inches in a 48 hour time period; Brooks and Stensrud (1999) looked at hourly rainfall totals over one inch; Groisman et al. (2005) used event frequency thresholds, where for a given location or season, extreme events are those that fall in the top 0.1% of all precipitation events; and Shumacher and Johnson (2004) studied events where the 24 hour precipitation total at one or more stations surpassed the 50-year recurrence level. To provide a broad examination of trends in
extreme precipitation across New England, three different types of extreme precipitation
definitions are used in this study.

We examine the change in frequency over time of the accumulation of one or
more inches of precipitation in a 24 hour period (referred to as a one-inch event), two or
more inches of rain in a 48 hour period (referred to as a two-inch event) and four or more
inches of rain in a 48 hour period (referred to as a four-inch event). The one and two-inch
events are common definitions of extreme precipitation events (Hayhoe et al. 2007; Wake
et al. 2006), whereas the four-inch event is a more severe, less frequent type of event.

If a station was retained in the analysis because it met the defined criteria, but still
contained years that did not have 90% of the daily precipitation measurements, then those
specific years of missing data were not included in the trend analysis for one and two-
inch events. When analyzing the trend for the much less frequent four-inch events, all the
years with missing data were examined closely to assess whether or not the missing days
coincided with extreme precipitation events in the area. For each station, every day that
did not have a daily precipitation measurement recorded was listed and compared with a
list of days where four-inch events had been measured at any of the five closest
neighboring stations. If any day during a four-inch event, which occurred at one or more
of the five closest stations, was missing a precipitation measurement at the reference
station, an average of the accumulations for that day at the five closest stations was
computed and filled into the reference station data to be included in the four-inch event
analysis.
Another way of defining extreme precipitation is to examine event frequency thresholds (e.g., Groisman et al, 2005). Here, the top 1% of 24-hr precipitation measurements for each year are defined as extreme. Changes in the threshold of the 99th percentile of daily accumulations, which exemplify changes in precipitation intensity at stations in New England, are examined over the 1948-2007 period. To calculate the annual 99th percentile accumulation for one day precipitation totals at each station, the 24-hr precipitation measurements greater than zero were ranked from smallest accumulation to largest accumulation for each year in the reference period. Percentiles are computed for each accumulation based on a sum polygon where the kth ranking measurement is the (k-1)/(n-1) percentile, where n is the number of measurements ranked, and intermediate percentiles are obtained by linear interpolation (Dalgaard 2002). Because the annual 99th percentile of daily accumulations are calculated and examined over time, this definition is not broken down seasonally or monthly in further analysis.

A third method to define extreme precipitation events is by using recurrence intervals (Schumacher and Johnson 2005; Kunkel et al. 1999). A recurrence interval is the average amount of time between events of a given magnitude. We examine the ten-, five-, and one-year recurrence intervals for each station for one day event durations across New England (The ten-, five- and one-year intervals were analyzed because they were intervals that could be sufficiently examined over time during the 1948-2007 time period). For example, to find the 24-hr one-year recurrence interval for station x, the 60 largest (1948-2007) one day accumulations at station x are identified. The smallest of the
60 one-day accumulation values will be the threshold for station x, and the number of times the threshold is exceeded each year will be examined over time.

**Trend Analysis**

To account for the trend's sensitivity to the start and end year of the time-series, we calculate the mean of the decadal rate of change determined from a least-squares linear regression of ten 51-year time windows with start years ranging from 1948 to 1957, and end years ranging from 1998 to 2007 (e.g. for a time window size of 51 years, trends were calculated for the time series 1948-1998, 1949-1999 ... 1957-2007). The significance of trends was evaluated by computing p-values, for which the assumption of normality was satisfied by inspecting residuals and associated Q-Q plots (quantile vs. quantile). Station trends with $p < 0.10$ for all ten 51-year trends were considered statistically significant.

For the four-inch events and the ten-, five-, and one-year recurrence intervals, trends were determined by computing the linear regression of the sum of the number of events that occurred in discrete ten year time intervals (1948-1957, 1958-1967, 1968-1977, 1978-1987, 1988-1997, 1998-2007). This method of trend analysis was utilized due to the rare nature of these events. No statistical significance tests were completed for the four-inch events or the ten-, five- and one-year recurrence intervals due to the non-normal distribution of the residuals for these definitions. These definitions without significance testing should be used as a supplement to the definitions with more rigorous testing. Due
to the longer period of record in the 1900-2007 analysis, trends were calculated with a single time window starting in 1900 and ending in 2007. To access the spatial variability of the trends for all the definitions used in this study, the decadal rate of change for each station was plotted by latitude. Stations located along the coast of New England were flagged to examine the variability between coastal and inland station trends.

**Correlations with Temperature and Atmospheric Circulation Indices**

The following correlations are a relatively simplistic approach to investigate why changes in precipitation patterns have been occurring in New England. One-inch events are correlated with temperature and large-scale atmospheric circulation patterns to determine if they are consistent with changes in extreme precipitation.

To study the relationship between temperature and extreme precipitation in New England, scatter plots were created comparing the number of events per month and the mean monthly temperature data from the National Climate Data Center (Monthly Surface Data DS3220). The temperature data was obtained for the same stations used in the 1948-2007 precipitation analysis, however only 55 out of the 84 stations had adequate temperature data for the regression, so the temperature – extreme precipitation analysis is limited to these 55 stations. For each definition of extreme precipitation described above, each station and during each season, the Pearson correlation coefficient was computed for the temperature vs. precipitation plots to evaluate the relationship. Seasonal trends in the northern hemisphere temperature anomalies (with the base period from 1951 to 1980,
available at http://data.giss.nasa.gov/gistemp/) were calculated from ten 51-year time series windows and compared to the seasonal trends in one-inch extreme precipitation events. Using seasonal northern hemisphere temperature anomalies will allow us to examine regional trends in temperature, rather than month to month variability at individual locations.

Regional changes in climate are often thought to be related to shifts in large scale atmospheric circulation patterns. Here, one-inch extreme precipitation events are correlated with the North Atlantic Oscillation (NAO) (Hurrell 1995), the Trough Axis Index (TAI) and the Jet Latitude Index (JLI) (Bradbury, personal communication), which have been observationally linked to winter precipitation anomalies in the northeastern United States (Bradbury et al. 2002, Bradbury et al. 2003)

Bradbury et al. (2002) suggests that the NAO is linked to storm-tracking patterns, primarily during the winter season. The NAO is defined as the sea level pressure difference between the Azores high and the Icelandic low. The NAO describes the steepness of the north-south atmospheric pressure gradient across the North Atlantic Ocean. It has two phases: a positive phase and a negative phase. When the NAO changes between opposite phases, the North Atlantic Ocean experiences changes in wind speed and direction, which affects heat and moisture transport to surrounding continents and seas (Hurrell et al. 2001). A winter (DJFM)] NAO index was provided by the Climate Analysis Section, NCAR, Boulder, USA, as defined by Hurrell (1995), using Stykkisholmur/Akureyri, Iceland, and Lisbon, Portugal as the sea level pressure (SLP) nodes. The NAO seasonal index was correlated with Fall (SON), Winter (DJF) and
Spring (MAM) one-inch events from 1948 - 2007, using Pearson R correlation coefficients. Trends in the winter-time NAO index (calculated from ten 51-year time series windows) was also compared to mean decadal trends in one-inch events from 1948 – 2007.

The Trough Axis Index (TAI) is a measure of the monthly mean longitudinal location of the East Coast pressure trough between 40°W to 100°W. Using gridded geopotential height fields, the TAI is calculated by identifying the longitudinal location (in degrees) of the grid point between 40°W to 100°W where the minimum 500mb geopotential height occurs at 40°N, 42.5°N, 45°N and 47.5°N latitude. Then, a monthly index value is calculated by averaging these four longitude values (Bradbury et al. 2002).

The Jets Latitude Index (JLI) is a measure of the monthly mean latitudinal position of the subtropical/polar front jet between 20°N and 60°N. The JLI is derived using gridded 200mb zonal wind fields by identifying the latitudinal location of the grid point (between 20°N and 60°N) at which the maximum 200mb zonal winds occur along each longitude between 65°W and 80°W, at 2.5° degree intervals. By averaging these seven latitude values, a monthly index value is calculated (Hayhoe et al. 2006). Both the TAI and the JLI values were provided to us by James Bradbury (pers. comm.).

In this study, the monthly TAI and JLI was correlated with December, January, February, and March one-inch events from 1948-2004. Again, Pearson correlation coefficients were used to access the relationships. The JLI is also correlated with monthly northern hemisphere temperature anomalies during the winter (DJFM).
Influence of Hurricanes on Extreme Precipitation

Studies of extreme precipitation in New England warrants the examination of the effect that hurricanes and their remnants have on the frequency of extreme precipitation in the region. To do this, seven stations in New England (Augusta ME, Burlington VT, East Milton Blue Hill Observatory, MA, Hartford CT, Plymouth NH, Plymouth Kingston RI, and Portland ME) were chosen to represent the New England region. The dates of all hurricanes (i.e., storm must have been classified as a hurricane during their lifetime) that affected New England since 1948 (Boose 2001, Donnelly 2001, and Roth 2008) were compared to the dates of all definitions of extreme precipitation events recorded at each representative station (tropical storms and depressions were also examined but there were only a few that had records of affecting New England). Time series for each station were then created to show the number extreme events caused by hurricanes compared with the annual number of extreme precipitation events.

Results

Annual Precipitation

Analysis of the detailed precipitation data sets for New England show that over the period of 1948 – 2007 the mean annual precipitation for New England was 42.5 in ± 5.7 in. Coastal areas (southern Maine, eastern Massachusetts, southern Connecticut, and
Rhode Island) show higher annual mean precipitation, as do areas with relatively higher elevations (northern New Hampshire, western Massachusetts, and southeastern Vermont) (Figure 3-2). Seasonally, mean annual precipitation is spread out over the entire year, with slightly more precipitation falling during the summer (12.6in ± 2.3in) and fall (12.4in ± 3.3in), compared to spring (11.1in ± 2.5in) and winter (9.8in ± 2.6in).

Figure 3-2. Mean annual precipitation for stations across New England.

The regional average annual precipitation for the eighty-four stations across New England has an overall increasing trend (+0.68 inches/decade) from 1948 - 2007, although most of the increase occurs over the last 30 years (Figure 3-3). Apparent in the time series are years with extremely low annual precipitation totals. These years coincide with the single-year drought of 2001 and the New England Drought of the 1960’s, which was the most severe and widespread drought to affect the northeastern United States since European settlement (NERA 2002).
Analysis of regional annual precipitation trends from 1948 – 2007 indicate increasing annual precipitation in New England, regardless of the start year and end year of the 51-year time series window (Figure 3-4). The magnitude of the 51-year regional trend remains positive for all ten 51 year windows. However the positive trend does decrease over the first four time periods (1948-1998, 1949-1999, 1959-2000 and 1951-2001), but then increases over the remainder of the 51 year windows. There is a significant jump in magnitude from the 1954-2004 trend (+0.26 inches/decade) to the 1955-2005 trend (+0.86 inches/decade), and increases greater than one inch per decade are found with the most recent two time intervals (1956-2006 and 1957-2007), both of which are statistically significant (p<0.1).
Figure 3-4. Time series showing the change in the slope of the regionally averaged annual precipitation as calculated from the linear regression of ten 51-year time series windows from the period 1948 – 2007. Statistically significant (p<0.1) trends are shown with red circles.

Stations in New England show a predominantly positive mean change in annual precipitation, with some stations showing increasing trends approaching two inches per decade (Figure 3-5). Out of the 84 stations analyzed in New England, seventy-one (85%) had mean increasing trends in annual precipitation, four of which were statistically significant (where all ten of the 51-year window trends had p-values less than 0.1). No stations had statistically significant decreasing trends in annual precipitation. Regional averages of seasonal precipitation trends from 1948 – 2007 show the greatest increase in precipitation during the fall (+0.5 inches/decade), followed by summer (+0.3
inches/decade), then spring (+0.02 inches/decade). Winter showed a decreasing trend in precipitation (-0.2 inches/decade).

(a) 
(b) 

Figure 3-5. Mean decadal rate of change in annual precipitation 1948 – 2007, plotted by a) location and b) latitude. Trends were calculated from the linear regression of ten 51-year time series windows. Statistically significant trends are indicated by black diamonds (a) and in red (b). In figure (a), increasing trends are shown in red, decreasing in blue. In figure (b), error bars represent one standard deviation on the mean.

Changes in the Frequency of Accumulation

On average, stations in New England experienced 10.0 ± 2.9 one-inch precipitation events annually from 1948-2007. Increasing trends were found in the occurrence of one-inch events at seventy-one stations (85%), fourteen of which were statistically significant (p<0.1) and are mostly clustered in coastal and western Massachusetts. Many of the stations with decreasing trends were located in Maine,
although no stations showed statistically significant decreasing trends (Figure 3-6a). Hatchville, MA had the greatest mean change of +1.4 one-inch events per decade. Stations located in southern New England show the greatest variability in the magnitude of the trend, as evidenced by the greater spread of trends in the latitude range south of 43°N (Figure 3-6b). Central New England (43°N to 45.5°N) shows slightly less variability and trends that are not as large as stations further south. The limited number of stations in the northern latitudes of the region (north of 45.4°N) show little to no trend in the frequency of one-inch events.

![Figure 3-6. Mean decadal rate of change for one-inch events from 1948–2007, plotted by a) location and b) latitude. Trends were calculated from the linear regression of ten 51-year time series windows. Statistically significant trends are indicated by black diamonds (a) and in red (b). In figure (a), increasing trends are shown in red, decreasing in blue. In figure (b), error bars represent one standard deviation on the mean, and coastal stations are indicated by solid circles.]

Precipitation accumulations of two inches or more in a 24-hr period occurs on average 7.4 ± 3.1 times each year for the stations analyzed in New England. Most stations
(88%) show increasing trends, with statistically significant (p<0.1) trends at seven stations (Figure 3-7). Only ten stations displayed negative trends (most north of 44 degrees) and none of these trends were significant. Similar to the results for the one-inch events, the variability in the trends magnitude was greater for southern New England, showing a decrease in trend moving north through central New England, and lacked any strong trend for the northernmost stations. The increase in the number of two inch events (0.5 to 1.0 events per decade) was similar to the trend for one-inch events, and significant trends were again found to be clustered in coastal and western Massachusetts. The largest trend occurs at Kingston, RI (+ 1.39 events per decade).

Figure 3-7. Mean decadal rate of change in two-inch events from 1948 – 2007, plotted by a) location and b) latitude. Trends were calculated from the linear regression of ten 51-year time series windows. Statistically significant trends are indicated by black diamonds (a) and in red (b). In figure (a), increasing trends are shown in red, decreasing in blue. In figure (b), error bars represent one standard deviation on the mean, and coastal stations are indicated by solid circles.
The less frequent four-inch events occur on average $2.5 \pm 1.8$ times a decade for the New England stations. Statistical significance was not computed for the trends in the frequency of four inch events due to the rarity of the events and the non-normal distribution of the residuals. The results do show an increase in the frequency of four inch events similar to the increase in one and two inch events. Of the 84 stations analyzed, 70 stations (83%) showed an increasing trend in the frequency of four-inch events (Figure 3-8). The largest increase was in Portland, ME and Newburyport, MA both showing +1.2 events/decade. Central New England shows consistently positive trends. The trends that were negative were clustered in Maine, Connecticut, and Massachusetts.

Figure 3-8. Decadal rate of change in four-inch events from 1948 -2007, plotted by a) location and b) latitude. Trends are calculated by the linear regression of the occurrence of four-inch events during discrete decades. In figure (a), increasing trends are shown in red, decreasing in blue. In figure (b), coastal stations are indicated in blue.
99th Percentile

The 99th percentile of 24-hr accumulations for each year average 1.9 in ± 0.3 in of precipitation in New England, but generally is higher for stations in the lower latitudes and along the coast (Figure 3-9). Trends were predominantly positive with 90% of stations showing increasing trends in the 99th percentile of 24-hr accumulations each year, of which fifteen were statistically significant (Figure 3-10). No statistically significant negative trends were found. Ipswich, MA shows the greatest change with +0.24 in/decade. The pattern of spatial variability observed with the other definitions of extreme precipitation is repeated here; there is more variability in the magnitude of the trends between the latitudes of 41°N and 43°N, a decrease in the trend for stations between 43°N and 45°N and no apparent trend for the limited number of stations north of 45° latitude.

Figure 3-9. Average annual 99th percentile of daily accumulations from 1948 – 2007
Figure 3-10. Decadal trends in the 99th percentile of daily accumulations from 1948-2007, plotted by a) location and b) latitude. Trends were calculated from ten 51-year window time series. Statistically significant trends are indicated by black diamonds (a) and in red (b). In figure (a), increasing trends are shown in red, decreasing in blue. In figure (b), error bars represent one standard deviation on the mean, and coastal stations are indicated by solid circles.

Recurrence Intervals

The mean thresholds for the one-year, five-year, and ten-year recurrence intervals were 2.2 in ± 0.4 in, 3.3 in ± 0.6 in, and 3.9 in ± 8.8 in, respectively. Thresholds were generally greater in the lower latitudes, coastal regions, and higher elevations of New England. All three intervals showed predominately positive trends in the frequency of events where the accumulation of precipitation exceeded the thresholds of the individual stations. Due to the non-normal distribution of the data used for the recurrence intervals,
statistical significance was not computed for these definitions of extreme precipitation events.

Positive trends in the one-year recurrence intervals were found at seventy-three (87%) stations. The strongest change was at First Connecticut Lake, NH with +2.5 events/decade as well as four other stations that showed trends greater than +2 events/decade. For the five-year recurrence interval, sixty-six stations (79%) had positive trends. The greatest change was for southern Maine (Lewiston and West Buxton), showing +1.1 events/decade. The less frequent 10-yr events also had predominately positive results with seventy nine (94%) showing increasing trends. The magnitude of the trends was smaller than the more frequent one-year and five-year events. The trends were strongest for Jonesboro, ME showing +0.8 events/decade (Figure 3-11 and Figure 3-12). The variability of the recurrence intervals is apparent in the lower latitudes of Connecticut, Rhode Island, and Massachusetts, but is more consistent through the southern and central areas of Vermont, New Hampshire, and Maine. The northernmost parts of Vermont and stations above 46°N in Maine (Caribou Municipal Airport, Houlton Internal Airport, and Presque Isle) show little to no trend in the frequency of one, five and ten-year recurrence interval events (Figure 3-12).
Figure 3-11. Decadal change in the frequency of events that exceed the threshold for one-year (left), five-year (middle), and ten-year (right) recurrence intervals. Increasing trends are shown in red, decreasing trends are in blue.
Figure 3-12. Decadal rate of change in the frequency of events that exceed the threshold for one (black), five (green) and ten (blue) year recurrence intervals from 1948 – 2007, by latitude. Trends are calculated by the linear regression of the occurrence of events that exceed the recurrence interval thresholds during discrete decades. Coastal stations are indicated with triangles.

**Seasonality**

Regional averages of changes in extreme precipitation from 1948-2007 were greatest for one-inch events during the spring (+0.14 events/decade), followed by fall (+0.12 events/decade), and essentially no change for summer (+0.01 events/decade); winter shows a slightly negative trend (-0.04 events/decade) (Figure 3-13). For the larger, rarer events (two-inch events, one, five and ten-year recurrence intervals), spring also showed the strongest increasing trends. For example, 4-in events showed an increase of
+.17 events/decade during the spring, followed by fall and summer (both averaging +0.09 events/decade) and winter showed a decrease of about -.04 events/decade (not shown).

Figure 3-13. Mean decadal rate of change in one-inch events for spring (top left), summer (top right), fall (bottom left), and winter (bottom right) from 1948 – 2007, by latitude as calculated from the linear regression of ten 51-year time series windows from the period 1948 – 2007. Significant trends are shown in red. Error bars represent one standard deviation of the mean.

1900 – 2007 Analysis

Analysis of the eleven stations in New England that had adequate precipitation measurements from 1900-2007 shows that increases in extreme precipitation have been
occurring since the start of the start of the 20th century. Regional trends were positive from 1900 – 2007 for all definitions of extreme precipitation used in this study. Comparison between the 1900-2007 trends and the 1948-2007 trends at the eleven stations shows that there are stronger positive trends for the more recent time period. The largest change was for the 1-yr recurrence intervals with the rate of +0.38 events/decade from 1900 – 2007, increasing to +1.01 events/decade from 1948 – 2007 (Table 4-1).

<table>
<thead>
<tr>
<th>Definition</th>
<th>1900 – 2007</th>
<th>1948 – 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-inch event</td>
<td>+ 0.16 ± 0.20</td>
<td>+ 0.31 ± 0.34</td>
</tr>
<tr>
<td>(events/decade)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-inch event</td>
<td>+ 0.11 ± 0.09</td>
<td>+ 0.21 ± 0.19</td>
</tr>
<tr>
<td>(events/decade)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-inch event</td>
<td>+ 0.13</td>
<td>+ 0.35</td>
</tr>
<tr>
<td>(events/decade)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-yr R.I. (events/decade)</td>
<td>+ 0.38</td>
<td>+ 1.01</td>
</tr>
<tr>
<td>5-yr R.I. (events/decade)</td>
<td>+ 0.12</td>
<td>+ 0.45</td>
</tr>
<tr>
<td>10-yr R.I. (events/decade)</td>
<td>+ 0.05</td>
<td>+ 0.27</td>
</tr>
<tr>
<td>99th percentile</td>
<td>+ 0.01 ± 0.03</td>
<td>+ 0.06 ± 0.03</td>
</tr>
<tr>
<td>(inches/decade)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-1. Summary of results from 1948 – 2007 compared to 1900 – 2007 using only the eleven stations in the 1900 – 2007 analysis.
Correlations with Temperature and Atmospheric Circulation Indices

The increasing trends seen across all definitions of extreme precipitation over the past five decades is also a period that has experienced an increase in average temperatures both on a global and regional scale. Physical mechanisms suggest that there may be a causal link between extreme precipitation events and rising temperatures. The regional average (weighted by climate division size) of mean monthly temperature data showed an overall warming trend in New England of +0.11°F per decade. Seasonally, regionally averaged temperature increased the most during the summer (+0.22°F/decade), followed by spring (+0.16°F/decade), then fall (+0.09°F/decade) and winter (+0.07°F/decade).

Scatter plots of mean monthly temperature vs. the occurrence of mean monthly one-inch events reveal a more positive correlation during the winter months, when compared with the summer months. For example, February shows positive correlations for 87% of the stations, thirteen of which were significant (Figure 3-14). The strongest positive correlations during the winter were between +0.4 and +0.5. However May showed the opposite, with negative correlations for 71% of the stations, ten of which were statistically significant. The strongest negative correlations were between -0.2 and -0.3. There were no significant negative trends during January, and there were no significant positive trends for May. There were also significant positive correlations found in the season-transition months of April and September, with six and ten statistically significant positive correlations, respectively. Trends in the seasonal northern
hemisphere temperature anomalies are most consistent with regional trends in one-inch event frequency during the spring (Figure 3-15), but present a poor relationship during the fall, winter, and summer (see Appendix).

Figure 3-14. Correlation between temperature and the occurrence of one-inch events for February (left) and May (right), from 1948 – 2007 in New England. Positive R values are shown in red, negative R values are in blue. Statistically significant (p<0.1) correlations are indicated with black diamonds.
Figure 3-15. Spring (MAM) northern hemisphere temperature anomaly trends (red) and seasonal one-inch event frequency trends (black) as calculated from ten 51-year time series windows.

A primarily wintertime phenomena (November through April), the NAO was correlated with one-inch precipitation events during the fall (SON), winter (DJF), and spring (MAM). Results indicate that the NAO is most positively correlated with spring extreme precipitation events, with 92% of stations showing positive R values, 25 of which were significant (p<0.1). The few negative relationships were for stations in Vermont and New Hampshire. For winter (DJF), 64% of the stations showed positive R values, of which seven were significant, and fall (SON) had only 41%, with two significant positive correlations. Most of the negative correlation coefficients were found
in Maine during the winter, and the positive correlations for winter are predominantly located in northern Vermont and New Hampshire. During the fall, the negative R values were found scattered throughout all areas of New England. No significant negative R values were found during the fall, winter or spring seasons (Figure 3-16). Trends in the seasonal (fall, winter, spring) northern hemisphere temperature anomalies display a poor relationship with seasonal trends in the frequency of one-inch events (see appendix).

The correlation between one-inch events and the TAI for December, January, February, and March had much stronger results. December and January had positive R values for all 84 stations in New England, of which 53 and 58 were statistically significant (p<0.1), respectively. February had 55 stations that had significant positive R values, and only had one negative R value for Presque Isle, ME which was not significant. March also showed a very positive correlation, with positive R values for 92% of the stations, eleven of which were significant. The negative R values for March were located in Vermont, Massachusetts and Connecticut, but all with weak negative correlations (Figure 3-17).
Figure 3-16. Correlation between one-inch events and the NAO during the fall (top left), winter (top right), and spring (bottom) from 1948 – 2007 in New England. Positive correlations are shown in red, negative in blue. Statistical significance is indicated with black diamonds.
Figure 3-17. Correlation between one-inch events and the TAI for December (top left), January (top right), February (bottom left), March (bottom right) from 1948 – 2004 in New England. Positive correlations are shown in red, negative in blue. Statistical significance is indicated with black diamonds.
The JLI correlation resulted in predominantly negative R values for all winter months. December had 76% negative R values, ten of which were significant, but also had one station with a significantly positive R value. January had negative correlations for all 84 stations and 37 of them were significant. February had 95% negative R values with 38 significantly negative. March also had predominately negative correlations with 85% of stations showing negative R values, 26 of which were significant. Also in March, inland stations of Vermont and New Hampshire show an area of positive R values that include four significantly positive correlations (Figure 3-18).
Figure 3-18. Correlation between the JLI and one-inch events in New England for December (top left), January (top right), February (bottom left), and March (bottom right) from 1948-2004. Positive correlations are in red, negative are blue. Statistically significant (p<0.1) correlations are indicated with black diamonds.
Influence of Hurricanes on Extreme Precipitation

Overall, the influence of hurricanes on extreme precipitation in New England is minor when compared to the total number of extreme precipitation events that occurred during the reference period (Table 4-2). At most, the representative stations across New England recorded two hurricanes in one season, compared to the average of about ten one-inch events, and seven two-inch events each year. For the more extreme definitions of extreme precipitation (e.g. four-inch events, 10-yr and 5-yr recurrence intervals), hurricanes have a greater influence on trends since these events are less frequent, but still relatively small when compared to the number of total events at each station during the reference period.

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<th>Reference Station</th>
<th>Total Events</th>
<th>Events Caused by Hurricanes</th>
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</tr>
<tr>
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<tr>
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<td>1124</td>
<td>47</td>
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<tr>
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<td>23</td>
</tr>
<tr>
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<td>34</td>
</tr>
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<td>Portland, ME</td>
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<td>34</td>
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Table 3-2. The number of hurricane-caused extreme precipitation events compared to the total number of events that occurred at reference stations in New England from 1948 - 2007. The numbers of events are a summation of events across all definitions used in this study.
Discussion

This study provides a rigorous examination of extreme precipitation trends in New England using a range of definitions from previous research. This analysis shows that for all of these definitions, New England is experiencing an increase in extreme precipitation event frequency and intensity. The one-inch events, two-inch events, changes in the 99th percentile, and the one-year recurrence intervals had largely positive trends, with limited negative trends characterizing a few stations in northern Maine. Trends in the larger four-inch events, five-year, and ten-year recurrence intervals show more spatial variability that is clearly not just a coastal or interior pattern. Negative trends are clustered in the southern latitudes of New England (Connecticut, Rhode Island, and Massachusetts), northern Vermont and New Hampshire, as well as in Maine, while positive trends are predominately located in central New England (southern New Hampshire, southern Vermont, and eastern Massachusetts). The increasing trends in the 99th percentile of daily accumulations are evidence that not only are the number of extreme precipitation events increasing, but so is the intensity of the precipitation that is falling in these events. This finding is consistent with previous studies of extreme precipitation (e.g. Groisman et al. 2005, Trenberth 2003, Easterling et al. 2000).

A decrease in the south to north magnitude of the trends is consistently found across all definitions of extreme precipitation in this study, and is clearly seen when the trends are plotted by latitude (figure 3-6b, 3-7b, 3-8b, 3-10b & 3-12b); from 41 °N to 43 °N there is a large range in the magnitude of trends, from 43 °N to about 45.5 °N the range in magnitude of trends narrows, and little to no trend in found for stations at
latitudes north of 45.5°N. This pattern of variability is not the result of a coastal signal in southern New England; coastal stations (indicated on the latitude plots) do show a large range in the magnitude of trends, but inland stations show a similar variability. The density or number of stations in each area also cannot explain the spatial variability in trends among central and southern New England because the number of stations located between 41°N and 43°N and 43°N and 45.5°N are similar with 39 and 38, respectively. Above 46°N, there are only seven stations and display considerably less variability and little to no trend in extreme precipitation event frequency or intensity. A possible explanation could be that because there is generally more snow accumulation for the northern stations, their trends have a greater potential to be influenced by errors in measuring snow. On average, northern New England is colder compared to southern parts of the region thus more precipitation will fall as snow. Areas of northwest Maine receive on average 140 inches of snow during the winter compared to less than 40 inches per winter along the southern coast of New England (Zielinski and Keim 2003). Perhaps the errors in snow measurement are responsible for the decrease in variability at higher latitudes. As mentioned, Brown (2000) reported an average increase of 3.9% per decade from 1915 – 1992 in snow water equivalent (SWE) over North America, an indication of more dense snow associated with increasing winter temperatures. However, NCDC has used the snow to rain ration of 10:1 (snow to rain respectively) conversion ratio throughout the time period for days when a precipitation measurement was missing but a snow measurement was recorded. Increasing snow density, which should lead to a higher SWE or precipitation measurements, is not being recorded by always using the 10:1
conversion ratio, resulting in a deflation of the actual precipitation trends. In addition, cooperative observers may have been inconsistent with using the 10:1 conversion ratio; Kunkel et al. (2007) reports that instructions to observers pertaining to snow measurement, may have varied between different administrative units and may of changed through time. They conclude that there may be negative biases in winter precipitation trends and/or positive biases in snowfall trends due to a decreasing trend in the frequency of 10:1 ratio reports by cooperative observers. These biases would likely have a greater affect on northern areas of New England and may be, at least in part, the reason that we observe decreases in the trend magnitude of extreme precipitation event frequency and intensity for central and northern latitudes.

Consistent with the seasonality of extreme precipitation events found in this study, Karl and Knight (1998) and Groisman et al. (2005) also found increases in extreme precipitation that are restricted to the spring, summer and fall, and decreases found during the winter. However, Hayhoe et al. (2007) reports an indication of a reversal of seasonal trends since 1970. Using USHCN data, they found decreases in annual precipitation including decreases in spring and fall, little change during the summer and slight increases in winter precipitation. They also report that almost all model-simulations (AOGCMs from the IPCC AR4 WG1 database) show increases in winter precipitation and no change to a decrease in summer rainfall. These winter precipitation increases are dynamically consistent with a projected westward shift in the seasonal mean position of the East Coast trough during the winter (Hayhoe et al. 2006).
Comparison of trends in extreme precipitation events from 1900 – 2007 to trends from 1948 – 2007 show that the frequency and intensity of extreme events have been increasing since 1900, with larger trends in the more recent time period (regardless of start and end years). The recent increase in the magnitude of extreme precipitation trends could be a result of recent warming trends in New England. Temperature trends in this study revealed a warming trend in New England of +0.11 °F/decade from 1948 - 2007, consistent with the results from other studies (e.g. Hayhoe et al. (2007), Keim et al. 2003, DeGaetano and Allen 2002). The IPCC reported that the eleven warmest years in the global instrumental temperature record (since 1850) have occurred since 1995 (IPCC 2007).

However, even though temperatures and extreme precipitation are observed to be increasing in New England, it is difficult to link them directly. The results of the correlation between one-inch events and mean monthly temperatures in New England are not consistently positive, although there were many significant positive trends during the winter and for the months of April and September. The positive correlation during the winter months may be associated with the increasing density of snow as air temperatures increase (Dube 2003), causing increases in winter snow-water equivalent (SWE). These findings are consistent with increasing winter temperatures resulting in increasing precipitation following the Clausius–Clapeyron relationship, depending on the slope of the snowfall-temperature relationship (Davis et al.1999).

Cloud cover may also be influencing the correlation between extreme precipitation and temperature. Clouds exert a dominate influence on the energy balance...
of earth's climate through the cooling effect of albedo and the greenhouse warming effect (Sun et al. 2000). In New England, clouds have a cooling effect on summer daytime temperatures because they block some of the shortwave radiation from the sun from reaching the surface of the earth. During the winter clouds act as a blanket, absorbing a large portion of energy that otherwise would escape to space (Aguado and Burt 2004). Also, surface observations suggest increased total cloud cover since the middle of the last century over many continental regions including the USA (Sun, 2003; Groisman et al., 2004; Dai et al., 2006), which is consistent with increasing extreme precipitation event frequency found in this study. Negative R values during the summer months may be related to the convective nature of summer precipitation events, which cause cloud formation and result in a cooling of daytime temperatures. Positive R values during the winter may be caused by warmer daytime temperatures associated with increased cloud cover during extreme precipitation events.

Trends in the seasonal northern hemisphere temperature anomalies do not show a strong relationship to trends in one-inch precipitation events for the summer, fall or winter but does show consistency with spring one-inch precipitation event frequency. Spring is also the season where one-inch precipitation event frequency increased the most from 1948 – 2007. Although the results of the correlations between temperature and one-inch events are not strong, the predominantly positive results for the winter season does provide evidence for increasing extreme precipitation in a warmer world. However, these correlations are a simplistic approach to linking temperature and extreme precipitation, and the use of a regional climate model and/or subsequent analysis of trends in air mass...
characteristics and/or synoptic circulation types would be needed to specify the relationship between temperature and extreme precipitation in New England.

Our results show that the TAI displayed the most significant positive correlation with one-inch events during the winter (DJFM). The positive correlation suggests that a westward displaced trough is associated with above average extreme precipitation events in New England, and the below average precipitation with an eastward positioned trough. A westward positioned trough would promote upper-level divergence downstream, which would be located over the northeastern United States and is a common area for midlatitude storms to occur. Drier conditions would be associated with an eastward positioned trough, because areas upstream of the trough would be experiencing upper-level convergence (Bradbury et al. 2002).

The JLI is known to be a strong control on temperature in New England because of its association with the polar front (Hayhoe et al. 2006). An inverse relationship between temperature and jet location was found during the winter, and positive correlations were found during the summer; consistent with the finding that the JLI is best correlated with region-wide summer temperatures when the mean jet location is overhead by Hayhoe et al. (submitted). Similarly, the correlation between the JLI and the one-inch events resulted in an inverse relationship during the winter (DJFM), except for some significant positive correlations found in March. This is evidence of a northerly shifting polar front, consistent with increasing temperatures, during the spring. The position of the polar front often determines the nature of prevalent storm tracks during the winter because the front is associated with a zone of very fast upper level winds. As the
polar front moves north toward New England the potential for extreme precipitation events increase because storm systems will tend to track closer toward New England.

Bradbury et al. (2005) found that winter precipitation in New England is not strongly controlled by the phase of NAO. This agrees with our finding that the correlation between one-inch events and the NAO do not display a consistent relationship, and that trends in the NAO index are weakly related to trends in one-inch precipitation event frequency. However, positive (negative) phases of the NAO have been linked to warmer (cooler) winter temperatures, increased (decreased) streamflow, and decreased (increased) regional snowfall in New England (Bradbury et al. 2002).

The influences of hurricanes, or remnants of hurricanes, do cause some extreme precipitation events in New England, although the influence on extreme precipitation event frequency is minor. The number of hurricane-caused extreme events is relatively small (about 2 - 4%) when compared to the total number of extreme precipitation events that have occurred at New England stations from 1948-2007. Landsea et al. (1996) found statistically significant decreases in intense hurricanes, and reported that landfalling Atlantic hurricanes have declined from 1944 to the mid-1990s. Therefore, results of the hurricane analysis show that, although hurricane-caused extreme precipitation events do influence the trends, they are too rare to be the sole driving force behind the increasing frequency of extreme precipitation events.

One of the most critical issues related to this study is the hypothesis that anthropogenic climate change is causing the hydrologic cycle to intensify, resulting in more frequent and intense extreme precipitation events. This study provides evidence
consistent with this hypothesis; however, like most other studies, observations are based on relatively short time periods and results cannot be considered unequivocal evidence of anthropogenically driven climate change. Therefore one of the biggest problems in studying indicators of climate change, such as extreme precipitation, is the lack of high-quality, long-term climate data. Without reliable data, it is difficult to rule out natural climate variability as a cause since we only have records that date back to the late 1800’s for New England, and much of the data we do have is inconsistent due to changes in procedures, instrumentation, location changes, etc. The climate data that we do have, however, confirms that the New England climate is changing, and this study verifies increases in extreme precipitation events as a robust indicator of climate change.

Conclusions

As New England continues to grow in population, more people and infrastructure infringe on the area’s rivers and floodplains. Understanding extreme precipitation trends is important so that society can prepare for the potential of more frequent flooding.

Trend analysis of climate data is complicated by missing data and incomplete documentation of station moves, observer changes, and instrument changes. Therefore, extensive quality control procedures were employed in this study to ensure that only the most complete and reliable precipitation data were used to determine trends in extreme precipitation in New England. Long-term consistent operational practices among
observing stations would greatly improve the certainty of trends derived from the observational record.

To present even more reliable results, a range of definitions for extreme precipitation were examined to provide a robust indicator of climate change in New England. It turns out that no matter which definition is used (frequency of accumulation, the 99th percentile of events, or recurrence intervals) there is a consistent finding that the occurrence of extreme precipitation events, and the intensity of rainfall, are increasing in New England. We also found evidence that the trends of increasing extreme precipitation are stronger for more recent times, consistent with previous research (e.g. Groisman et al. 2005, Alexander 2006). Annual precipitation also showed predominantly positive increases from 1948 – 2007, with the most significant increases occurring more recently. The increase in extreme precipitation events and in annual precipitation is occurring during spring, summer, and fall, with weak decreasing trends during the winter.

Spatially, all definitions showed the general pattern of relatively consistent positive trends in extreme precipitation for central New England, more variability in the trends for the southern latitudes of Connecticut, Rhode Island, and Massachusetts, and little to no trend in the northernmost areas of Maine. This pattern may be the result of increased errors in snowfall measurement influencing the trends of stations in the northern latitudes, where more snow accumulation generally occurs, compared to southern stations that typically receive less snowfall.

Correlations between one-inch events and mean monthly temperatures show that temperature is not a consistent control on extreme precipitation, but negative correlations
during the winter and positive correlations during the summer may be the result of cloud cover and its influence on daytime temperatures. Seasonal trends in the northern hemisphere temperature anomalies also display a weak relationship with trends in one-inch events, except during the spring, when one-inch event frequency has been increasing most drastically.

Atmospheric circulation patterns do show some correlation with extreme precipitation events. Changes in one-inch event frequency are positively correlated with the monthly winter TAI and with the NAO seasonal index during the spring. Trends in one-inch event frequency in New England are best correlated with the JLI during warmer months when the jet is located overhead, causing storms to track through New England. However, exactly how large scale atmospheric circulation patterns influences climate in New England is a topic of major research and future analysis is needed to fully understand how the North Atlantic Oscillation (NAO), the Trough Axis Index (TAI) and the Jet Latitude Index (JLI) affect extreme precipitation in New England.

Evidence is growing that the observed historical trends of increasing extreme precipitation are connected to greenhouse gas-enhanced climate change. In 2007, the Intergovernmental Panel on Climate Change concluded that it was more likely than not (more than 50% confidence) that human influence contributed to the trend toward more extreme precipitation events and that future increases in extreme precipitation are very likely (more than 90% confidence). This study provides further evidence of these trends. These findings should be of value for emergency managers and for weather forecasters, in efforts to allocate resources and plan for the inevitable flooding events associated with
extreme precipitation. It is difficult to directly link changes in extreme precipitation with flooding (e.g. Kunkel 2003) since records are often confounded by changes in land use and increasing human settlement in flood plains. However, great floods (defined as floods with discharges exceeding 100-year levels from basins larger than 200,000km) have been found to be increasing in the twentieth century (Milly et al. 2002), and are only amplified by increasing rainfall rates. Changes in how and where we build our homes and businesses may need to be considered. Flood relief structures are constructed to a certain level of performance; In many cases, they are built to prevent flood impacts from the 100-year flood threshold. The problem with increasing frequency and intensity of extreme precipitation is that the 100-year flood is now occurring much more frequently. It may be necessary to alter building codes to withstand even larger events and adopt floodplain ordinances to exclude/restrict construction in high risk areas. Knowing the trends will assist society in becoming more prepared and possibly help prevent the worst-case scenarios projected for our future, if current trends in climate change indicators continue.
CHAPTER V

CONCLUSIONS AND FUTURE WORK

As New England continues to grow in population, more people and infrastructure infringe on the region's rivers and floodplains. Understanding extreme precipitation trends is important so that society can prepare for more frequent flooding and work towards preventing more costly damage. Tracking how extreme precipitation is currently changing will help society prepare for the potential of even more severe and frequent extreme precipitation events in the future.

Trend analysis of climate data is complicated by missing data and incomplete documentation of station moves, observer changes, and instrument changes. Therefore, extensive quality control procedures were completed in this study to ensure that only the most complete and reliable precipitation data were used to determine trends in extreme precipitation in New England. Long-term consistent operational practices among observing stations would greatly improve the certainty of trends derived from the observational record.

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Currently, atmosphere-ocean general circulation models (AOGCMs) are depended on to reproduce key processes responsible for regional climate trends, however they often lack the spatial resolution needed to replicate observed regional trends. Regional climate model simulations, although limited, have had some success in capturing regional surface climate that is similar to observed, and are the most promising tools available to examine future trends (Hayhoe et al., submitted). However, more sophisticated simulations of finescale heavy precipitation, which depends on small-scale topographical and dynamic features, is needed to output more accurate trends in extreme precipitation, and to specify the link between extreme precipitation, temperature and large-scale atmospheric circulation patterns. The development of more regional climate models such as the North American Regional Climate Change Assessment Program (http://www.narccap.ucar.edu/) may help define those relationships (Hayhoe et al. submitted).

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<th>LON</th>
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Table A-1. List of stations included in the 1948 – 2007 Analysis. Stations denoted with an * were also used in the 1900 – 2007 analysis. Two stations (Johnsbury, and Storrs, CT) were not used in the 1948 – 2007 analysis but included in the 1900-2007 analysis.
Figure A-1. Trends in the northern hemisphere temperature anomalies (red squares) and regional one-inch precipitation event frequency (black diamonds), as calculated from the linear regressions of ten 51-year time series windows for a) spring, b) summer, c) fall and d) winter.
A) Spring (MAM)

B) Fall (SON)
Figure A-2. Trends in the NAO Index (blue squares) and one-inch precipitation events (black diamonds) for a) spring, b) fall, and d) winter, as calculated from the linear regression of ten 51-year time series windows.
LIST OF REFERENCES


Dube, I. 2003. From mm to cm: Study of snow/liquid ratio over Quebec. Extended Abstracts, 60th Eastern Snow Conf., Sherbrooke, QC, Quebec, ERDC-CREEL, 42.


