Trends in Extreme Precipitation Events
for the Northeastern United States 1948-2007

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Trends in Extreme Precipitation Events for the Northeastern United States 1948-2007

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Preface

IN THE YEARS since we published the first *Indicators of Climate Change in the Northeast* in 2005, the impacts of our changing climate on our infrastructure and ecosystems has become more apparent. One of the most obvious examples of these impacts is the increase in extreme precipitation events, which, combined with changes in land use, have led to an increase in freshwater flooding events across the region, exemplified by the "100-year" floods that have occurred in southern New Hampshire in 2005, 2006, 2007. And again in 2010, powerful nor'easters drenched the northeast with 3" to 8" of rain three times (late February, middle of March, and end of March) which resulted in significant flooding across the region.

Since an increase in the frequency of extreme precipitation events is one of the predicted impacts of a world warmed by heat-trapping gases, it seemed important to update this indicator for the Northeast, but to do so in a more rigorous fashion to improve the confidence in our results.

It was clear that flooding of the type we saw with alarming regularity in the first decade of the new millennium, if it were to continue, would require adaptation planning and new responses. It is also clear that precipitation that erodes the landscape, scours rivers, and carries pollutants in run off into water sources is a problem for communities in maintaining water of good quality. Both of these impacts areas are likely to require additional resources for study, planning, and engineering solutions. We hope that this report encourages discussions at local to regional levels regarding how our communities can develop and implement plans for adapting to our future climate.

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Figure 1. Photographs of flooding following recent extreme precipitation events in the Northeastern, U.S..

Introduction
Impacts of Extreme Precipitation

THE IMPACTS of heavy precipitation on ecosystems, agriculture, and infrastructure are particularly important for society. One of the most costly effects of extreme precipitation is flooding. During the 20th century, floods caused more loss of life and property damage than any other natural disaster in the United States.[1] Annual losses have increased from one billion dollars in the 1940s to six billion dollars during the 1980s and 1990s (based on the 1997 dollar).[2]

The growth in flood damage is partially due to an increase in impermeable surfaces in our watersheds, combined with more building in flood-prone areas. New England has experienced considerable development in many of its watersheds, with the consequent increase in impermeable surfaces such as asphalt resulting in more rapid runoff. Flooding is therefore 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, buildings), erosion and pollution from storm runoff (caused by the flooding of areas that contain sewage treatment facilities, farms, farm waste lagoons, chemical and petroleum storage facilities) with uncertain long-term consequences to fluvial and coastal ecosystems.

Flooding events are relatively rare but naturally occurring in the Northeastern United States. For example, New Hampshire has averaged about one major, destructive flood per decade since the early 20th century. A major concern is that New Hampshire has recently experienced three major flooding events that followed three major extreme precipitation events (October, 2005, May, 2006, and April, 2007)[2] (Table 1). As this report goes to press, major, but as yet unquantified, multiple flooding events are taking place here in March, 2010.

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 or current rainfall patterns.[3] To facilitate effective planning, decision makers also 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.[4] This study aims to provide a quantitative understanding of the current trends in extreme precipitation for the Northeast so that resource managers, municipal, county, state, and federal representatives, and other stakeholders have a baseline of information from which to prepare for and adapt to future climate change.

RANK	DATE	24 hour PRECIPITATION TOTAL (Inches)
1	September 11, 1954	6.49
2	October 21, 1996	6.30
3	April 2, 1973	6.28
4	**April 16, 2007**	5.46
5	August 19, 1991	5.23
6	**May 14, 2006**	4.70
7	June 13, 1998	4.65
8	May 9, 1954	4.59
9	February 25, 1981	3.93
10	October 7, 1962	3.93
11	October 6, 1962	3.81
12	September 12, 1960	3.72
13	**October 15, 2005**	3.71

Table 1. Top ranked 24 hour precipitation totals for Durham, N.H. The events of 2005, 2006 and 2007 are outlined in red boxes.

Study Methods

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://www7.ncdc.noaa. gov/CDO/cdo. 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. This study focuses on 219 stations in the Northeast United States (Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont). The time period analyzed is from 1948-2007 because most stations began collecting and recording continuous daily data in 1948. Stations with elevations greater than 3000 feet above sea level were excluded from analysis because of the significant differences in weather and climate at these locations compared to surrounding stations.

Each record was inspected individually to assess its completeness and reliability for use in trend analysis. If a station contained less than 80 percent of the daily precipitation measurements for the time period or had less than 50 years (out of 60 years studied) where there was 90 percent of daily data for each year, it was removed from further study. A spatial coherence analysis was also performed to remove any station data that contained non-climatic biases.[5]

To provide a broad examination of trends in extreme precipitation across the Northeast, several different types of extreme precipitation definitions are used. We examine the change in number of events over time in the accumulation of one or more inches of precipitation at a weather station 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). We also define extreme precipitation using event frequency thresholds where the top one percent of 24-hour precipitation measurements for each year is defined as extreme. Changes in the threshold of the 99th percentile of daily accumulations exemplify changes in precipitation intensity.

A third method is to define extreme precipitation events using recurrence intervals (or the average amount of time between events of a given magnitude). In other words, we look at the change in the amount of time between storms of a given magnitude. Here we examine the ten-, five-, and one-year recurrence intervals for each station for one day event durations across the Northeast.

Examining recent trends in extreme precipitation events of different magnitudes provides baseline data that can be used to inform a variety of decisions to enhance community resilience and reduce the impacts of future extreme precipitation events. For example, traditional practice in stormwater management has focused on flood events ranging from the 2-year to the 100-year storm. However, there has been an increased emphasis on addressing the quality of urban stormwater, resulting in the realization that small storms (i.e. up to 1.5 inches of rainfall) cause most water quality management issues. For instance, with the exception of eroded sediment, they are responsible for most pollutant wash-off from urban surfaces. These smaller storms are also responsible for most annual urban runoff and groundwater recharge. Therefore, the smaller storms are of significant concern for the stormwater management objectives of ground water recharge, water quality resource protection, and controlling thermal impacts (impacts from the temperature difference between rainfall and the ground surface).

Medium sized storms, defined as storms with a return frequency of 6 months to 2 years, are the dominant storms that determine the size and shape of the receiving streams. These storms are critical in the design of best management practices (BMPs) that protect stream channels from accelerated erosion and degradation. Larger, more infrequent storms (storms having a return frequency of 2 years to 100 years) have traditionally been used for the design of stormwater conveyance facilities such as storm sewers and

START YEAR – END YEAR	TREND (events per decade)	SIGNIFICANCE (p-value)
1948 – 1998	+ 0.20	0.02528
1949 – 1999	+ 0.21	0.01676
1950 – 2000	+ 0.20	0.02478
1951 – 2001	+ 0.17	0.0534
1952 – 2002	+ 0.20	0.02767
1952 – 2003	+ 0.26	0.00476
1953 – 2004	+ 0.29	0.00202
1954 – 2005	+ 0.31	0.0008
1955 – 2006	+ 0.36	0.00015
1956 – 2007	+ 0.35	0.00025
Average	0.26 ± 0.07	

Table 2. Decadal trends are determined from linear regression applied to ten 51-year time windows over the period 1948 – 2007. All of the individual trends for the one-inch regional average trends are significant because their p-values are less than 0.10. Therefore the average change is also statistically significant.

detention basins for peak discharge control; to prevent local over-bank flooding on urban streams and flooding of structures located in the floodplains of stream channels.[6]

Trend Analysis

For all of our measures of extreme precipitation, we have calculated trends over time in units of change-per-decade over the period of record. To account for a trend's sensitivity to the start and end year of the time-series, we calculate the mean of the decadal rate of change, or average change, determined from a least-squares linear regression of ten 51-year time windows. The time windows have 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, etc., up to 1957-2007). For example, the results of the individual trends (with varying start years and end years) of the regional average (weighted by the size of the climate divisions) for one-inch events are provided in Table 2. The mean of the individual trends is calculated to determine the average change. 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. A p value less than 0.10 means that there is only a 1 in 10 chance of this trend occurring by chance.
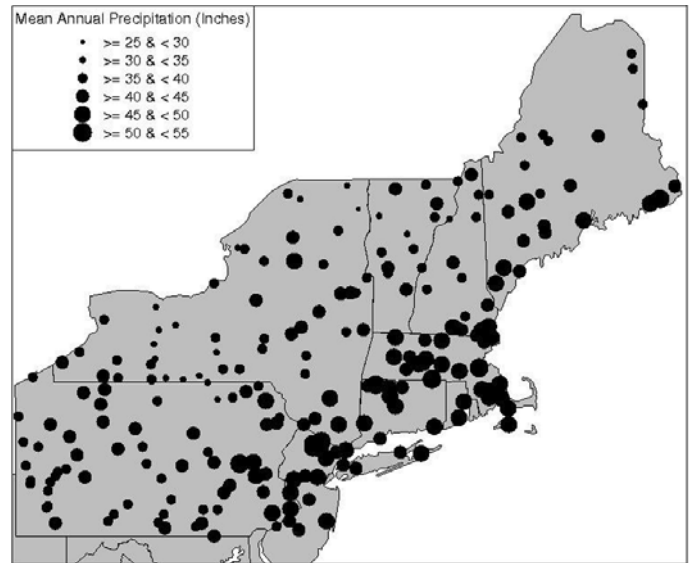

Figure 2. Mean annual precipitation for stations across the Northeast.

SEASON	PRECIPITATION BY SEASON (inches)	% OF ANNUAL PRECIPITATION
spring	6.0 ± 1.1	25.5%
summer	6.6 ± 1.1	28.1%
fall	6.1 ± 1.3	26.0%
winter	4.8 ± 1.2	20.4%

Table 3. The regional average amount of precipitation (with one standard deviation from the mean) and percent of annual precipitation by season.

Trends in Extreme Precipitation
Annual Precipitation

The National Climatic Data Center has subdivided the contiguous United States (U.S.) into 344 climate divisions, which represent nearly homogenous climatic regions within a climate division.[7] There are 38 climate divisions in the northeast U.S.; 37 of them are represented in the analysis.

Analysis of precipitation data for the Northeast shows that, over the period of 1948-2007, the mean annual precipitation was 40.8 in ± 4.5 in, calculated by taking an area weighted mean of the climate divisions represented in the region.

Coastal areas clearly show higher annual mean precipitation (Figure 2). Seasonally, mean annual precipitation is spread out over the entire year, with slightly more precipitation falling during the summer (6.6in ± 1.1in) and fall (6.1in ± 1.3in), compared to spring (5.9in ± 1.1in) and winter (4.8in ± 1.2in)(Table 3).

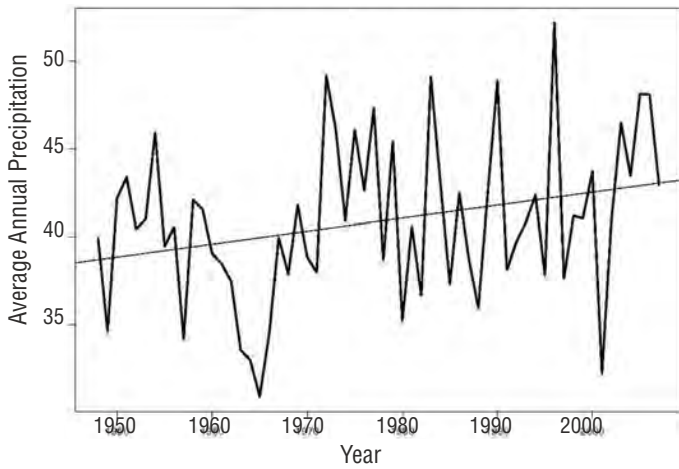## Regionally Averaged Annual Precipitation
1948-2007

Figure 3. Time series of regionally averaged annual precipitation from 1948 – 2007. Regional average is weighted by the size of each climate division in the Northeast.

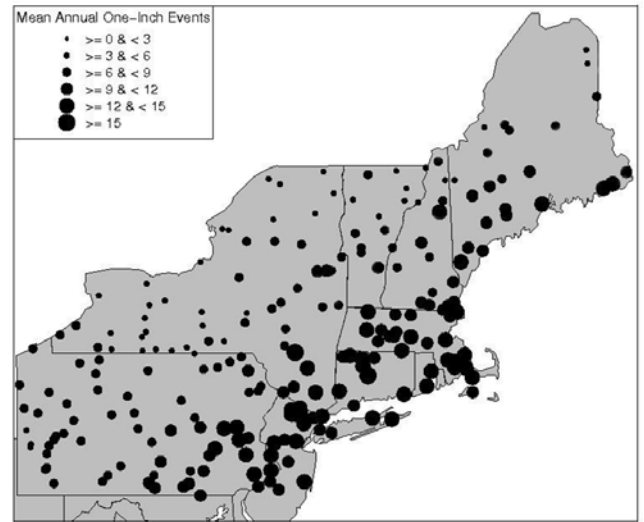## Mean Annual Number of 1-inch Events
1948-2007

Figure 4: Map showing the mean annual number of one-inch events at stations across the Northeast for the time period 1948-2007.

Mean Decadal Change in 1-inch Events
1948-2007

Figure 5. Mean rate of change for one-inch events per decade from 1948 – 2007. Increasing trends are shown in red, decreasing in blue. Trends were calculated from the linear regression of ten 51-year time series windows. Statistically significant trends are indicated by black diamonds.

The regional average annual precipitation for the 219 stations across the Northeast has an overall increasing trend (+0.73 ± 0.27 inches/decade) from 1948 - 2007 (Figure 3) or nearly three-quarters of an inch per decade, plus or minus a little more than a quarter inch. Apparent in the time series is a period in the mid 1960s with extremely low annual precipitation totals, which delineate the New England Drought of that period – the most severe and widespread drought to affect the northeastern United States since European settlement.[8] The low rainfall in 2001 also resulted in a drought across much of the region.

The trends for the regional average precipitation by season for the Northeast are also positive. Fall showed the greatest overall trend (+0.26 ± 0.04 inches/decade) followed by spring (+0.12 ± 0.06 inches/decade), summer (+0.11 ± 0.04 inches/decade) and winter (+0.01 ± 0.03 inches/decade) from 1948-2007.

One-inch Events

On average, stations in the Northeast experienced about five one-inch precipitation events annually from 1948-2007. However, stations located near the coastline tend to experience more events annually then stations in the interior (Figure 4).

Increasing trends were found in the occurrence of one-inch events at 201 stations (92 percent) , 30 of which were statistically significant (p<0.1)(Figure 5). The largest positive trends are found in Massachusetts and southern New Hampshire. Only 18 stations displayed negative trends, none of which were significant.
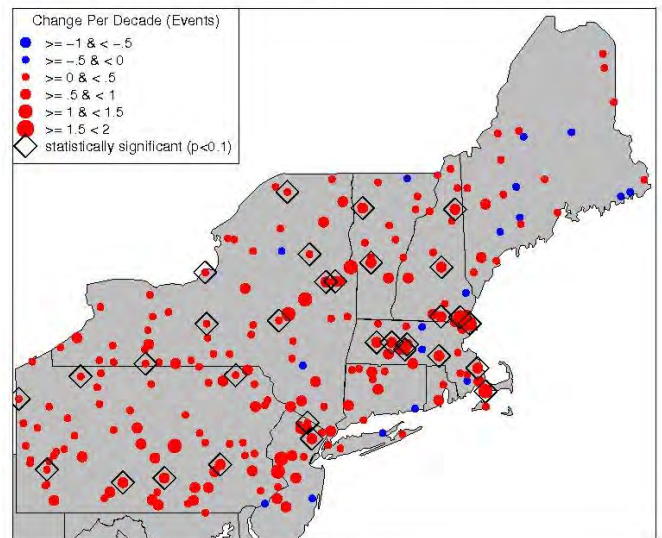
Mean Decadal Change in 2-inch Events
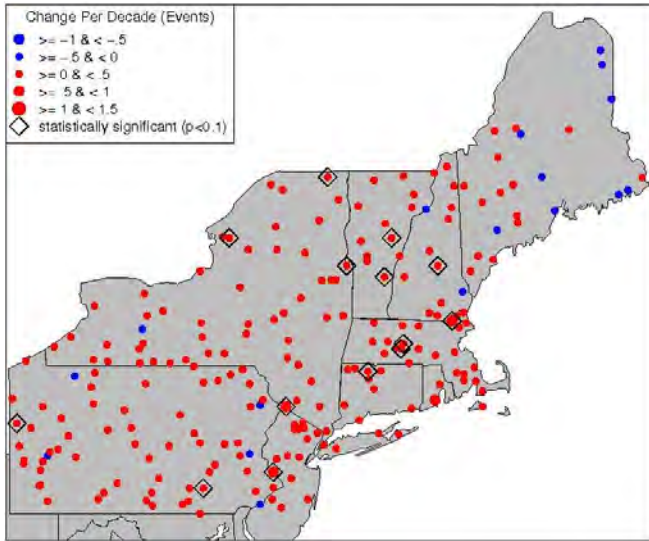## 1948-2007

Figure 6. Mean rate of change in two-inch events per decade from 1948 – 2007. Increasing trends are shown in red, decreasing in blue. Trends were calculated from the linear regression of ten 51-year time series windows. Statistically significant trends are indicated by black diamonds. Increasing trends are shown in red, decreasing in blue.

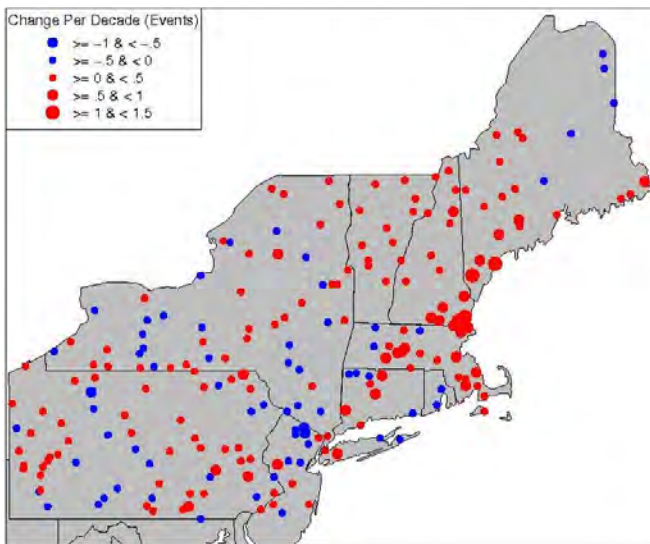## Mean Decadal Change in 4-inch Events
1948-2007

Figure 7. Rate of change in four-inch events per decade from 1948 -2007. Increasing trends are shown in red, decreasing in blue. Trends are calculated by the linear regression of the occurrence of four-inch events during discrete decades.

Seasonally, the overall mean trends in the number of one-inch events were all positive and greatest during the spring (+ 0.13 .02 events/decade) and summer (+ 0.08 ± 0.02 events/decade), compared to the fall (+0.01 ± 0.05 events/decade), and winter (+.01 ± 0.02 events/decade). West Buxton, ME recorded a significant mean trend of + 0.49 events per decade during the spring, which is the largest mean trend recorded for one-inch events. There were seven stations with significant increasing trends during the spring, one in the summer, six in the fall and three in the winter.

Two-inch Events

On average, precipitation accumulations of two inches or more in a 24-hour period occur about two times each year for the stations analyzed in the Northeast over the time period from 1948 - 2007. Most stations (92 percent) show increasing trends, with statistically significant ($p<0.1$) trends at 14 stations (Figure 6). The significant positive trends are apparent in Massachusetts, Vermont and the eastern New York area. Only 17 stations displayed negative trends and none of these trends were significant.

Four-inch Events

The less frequent four-inch events occur about two times a decade for the Northeast 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. This means that we cannot assume the normality needed to compute significance testing. 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 219 stations analyzed, 159 stations (73 percent) showed an increasing trend in the frequency of four-inch events (Figure 7). Positive trends are predominant in central New England, especially southern Maine, coastal New Hampshire and eastern Massachusetts. Positive and negative results are scattered throughout the New York and Pennsylvania regions

Changes in the 99th Percentile

The 99th percentile of 24-hour accumulations for each year averages 1.04 ± 0.11 inches of precipitation in the Northeast. Essentially, this means that, statistically, the top 1 percent of precipitation events in any given year are larger than 1.04 inches. Trends were predominantly positive with 86 percent of stations showing increasing trends in the 99th percentile of 24-hour accumulations each year, of which 19 were statistically significant (Figure 8). For example at Ipswich, MA, trend analysis showed an increase of 0.24

**Mean Decadal Change in the 99th Percentile
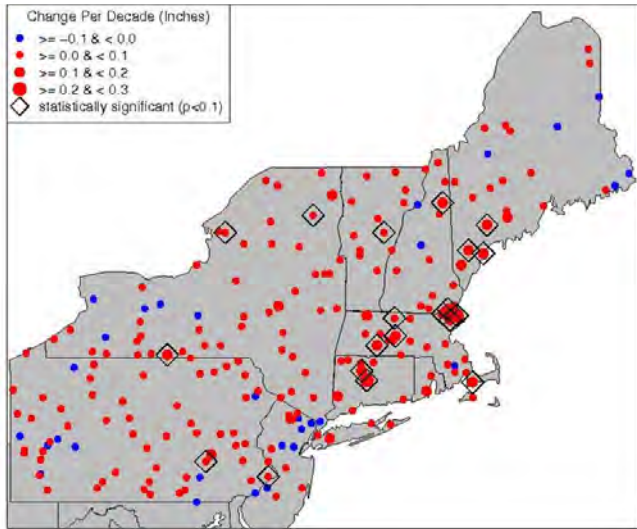of Daily Accumulations: 1948-2007**

Figure 8. Trends in the 99th percentile of daily accumulations per decade from 1948-2007. Increasing trends are shown in red, decreasing in blue. Trends were calculated from ten 51-year window time series. Statistically significant trends are indicated by black diamonds.
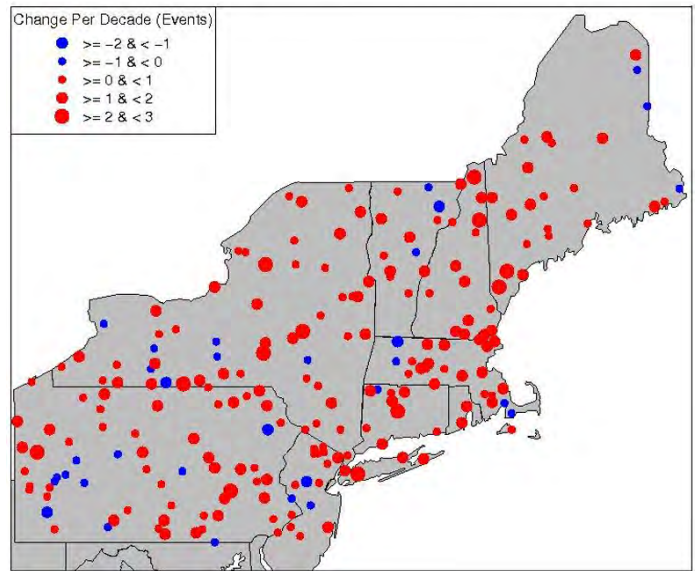
**Decadal Change in 1-yr Exceedences:
1948-2007**

Figure 9. Decadal change in the frequency of events that exceed the threshold for one-year. Increasing trends are shown in red, decreasing trends are in blue.

inches per decade, meaning that over five decades, there was an increase of 1.20 inches in the 99th percentile of events. No statistically significant negative trends were found. Similar to other definitions of extreme precipitation, predominately positive results are found in central and southern New England. The increasing trends in the 99th percentile represent increases in the intensity of precipitation because the top 1 percent of 24-hour events is delivering more precipitation.

Recurrence Intervals

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). To find the 24-hour, one-year (five-year, ten-year) recurrence interval for a particular station over a 60-year period (1948-2007) the 60 (12, 6) largest one-day accumulations at that station are identified. The smallest of the 60 (12, 6) one-day accumulation values is the threshold for that station, and the number of times the threshold is exceeded each year provides a measure of change over time.

The mean thresholds for the one-year, five-year, and ten-year recurrence intervals were 2.60 ± 0.87 inches, 3.92 ± 1.02 inches, and 4.52 ± 1.07 inches, respectively for the Northeastern United States. 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. This analysis should therefore be used as a supplement to the definitions with more rigorous testing.

Positive trends in the one-year recurrence intervals were found at 187 (85 percent) stations (Figure 9). For example, the largest trend in one-year recurrence intervals was found at Mineola, NY, which shows an increase of 2.54 events per decade. This means that over 50 years the number of times the one-year threshold event occurs at Mineola has increased by 12.7 events. For the five-year recurrence interval, 166 stations (76 percent) had positive trends. The less frequent 10-year events also had predominately positive results with 163 (74 percent) showing increasing trends.

Average Annual Precipitation:
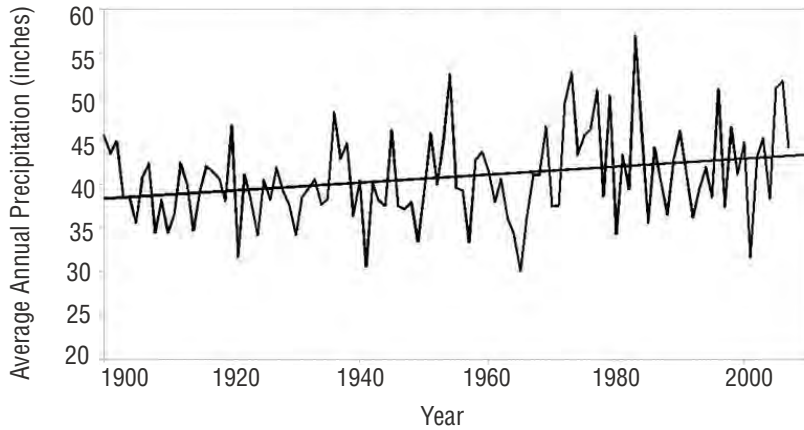**1948-2007**

Figure 10: Graph showing the average annual precipitation from 1900-2007 for the eleven long-term stations in the Northeast. The trend line shows an increase in the average annual precipitation since 1900.

Long-term Record

Data for eleven Northeast stations was available to analyze trends over the time period from 1900-2007. These stations were selected because their period of record began before 1900 and contained more than 90 percent of the daily precipitation measurements for each year for more than 90 of the years during the period (~85 percent of the years between 1900 and 2007).

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 the closest stations. Analysis of the 11 stations in the Northeast that had adequate precipitation measurements from 1900-2007 shows that increases in precipitation have been occurring since the start of the 20th century (Figure 10).

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 just the 11 stations with longer term data clearly shows that number of extreme precipitation events is increasing more rapidly in recent decades. The largest change was for the 1-year recurrence intervals with the rate of +0.38 events/decade from 1900-2007, increasing to +0.82 events/decade from 1948-2007 (Table 4).

DEFINITION	1900-2007	1948-2007
1-inch event (events/decade)	+ 0.16 ± 0.20	+ 0.26 ± 0.07
2-inch event (events/decade)	+ 0.11 ± 0.09	+ 0.17 ± 0.06
4-inch event (events/decade)	+ 0.13	+ 0.16
1-yr return interval (events/decade)	+ 0.38	+ .82
5-yr return interval (events/decade)	+ 0.12	+ 0.27
10-yr return interval (events/decade)	+ 0.05	+ 0.18
99th Percentile (inches/decade)	+ 0.01 ± 0.03	+ 0.06 ± 0.03

Table 4: The regional average trends for each definition of extreme precipitation at eleven stations across the region for the 1900-2007 and 1948-2007 time periods.

Extreme Precipitation and Temperature
Causes for Change

Changes in the amount and intensity of precipitation have long been key indicators of a changing climate. Several detailed studies published in peer reviewed literature conclude that the recent changes in precipitation patterns around the globe 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.[9] 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.[10] 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. [11]

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 long-wave 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 vapor in the atmosphere by 7 percent.[12]

Another potential cause of recent precipitation changes could be, in part, natural variability in the climate system. For example, one study 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 20th century.[13]

The increasing trends observed across all definitions of extreme precipitation over the past six decades corroborates this, as this is also a period that has experienced an increase in average temperatures both on a global and regional scale. Physical mechanisms support a causal link between extreme precipitation events and rising temperatures. The northern hemisphere temperature anomalies (relative to base period 1951-1980) showed an overall warming trend of +1.57 ± 0.33 °C per decade. Seasonally, the northern hemisphere temperature anomalies increased the most during the spring (+1.86 ± 0.33 °C/decade), followed by winter (+1.73 ± 0.33 °C/decade), then summer (+1.39 ± 0.29 °C/decade) and fall (+1.30 ± 0.40°C/decade).[14] Regression analysis was used

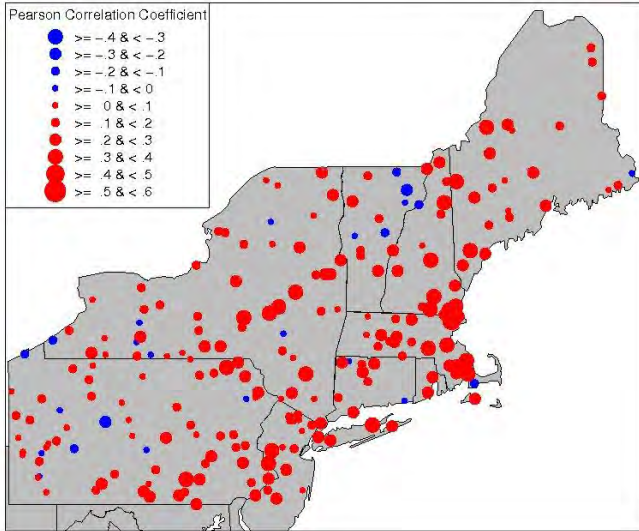| SEASON	REGIONAL MEAN CORRELATION COEFFICIENT (R)
spring	0.16 ± 0.13
summer	0.06 ±0.15
fall	0.18 ±0.17
winter	0.00 ± 0.13

Table 5. Table showing the regional mean correlation coefficients by season. The correlation coefficient measures the strength of the relationship between the Northern Hemisphere's Temperature Anomalies and the occurrence of one-inch events.

to investigate the extent to which seasonal northern hemisphere temperature anomalies are correlated with the number of seasonal one-inch events. We use northern hemisphere temperature anomalies instead of more regional temperature data because the analysis requires measures that provide an indication of the overall warming of the climate system that drive large scale precipitation patterns.
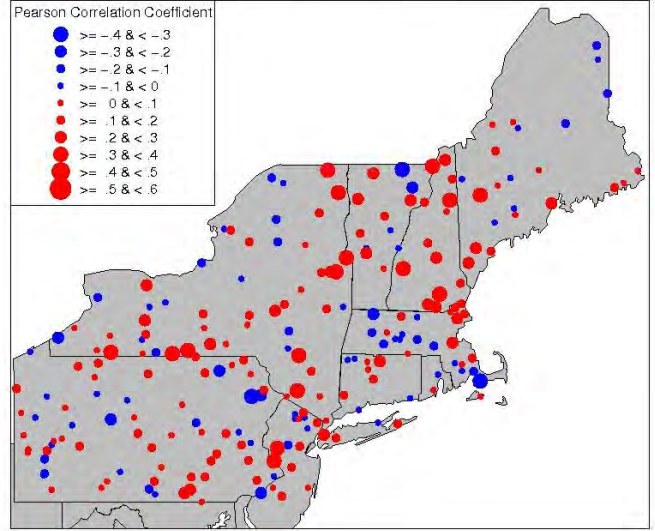
Temperature was found to be best correlated with one-inch events during the spring and fall (Figure 11 and Table 5), precisely the seasons where the rate of increase in extreme precipitation events is greatest. Regional averages of changes in extreme precipitation from 1948-2007 were greatest for one-inch events during the fall (+0.15 events/decade) and spring (+0.11 events/decade), compared to trends in summer (+0.08 events/decade) and winter (+0.02 events/decade). The results of this analysis for the northeast are consistent with the physical mechanism by which warmer hemispheric temperatures lead to more precipitation because a warmer atmosphere can hold more water vapor.

Our results are also consistent with several investigations of the impact of warmer temperatures on extreme precipitation using regional and global climate models. For example, global climate model projections forced by higher concentrations of greenhouse gases[15] in the atmosphere indicate an increasing probability of heavy precipitation events for many extratropical regions[16]. Detailed analysis of coupled atmospheric ocean general circulation models forced by a high greenhouse gas emissions scenario (A1fI) show that the annual temperature, annual precipitation, and extreme precipitation events will increase in the future under a scenario of increasing greenhouse gas emissions[17].
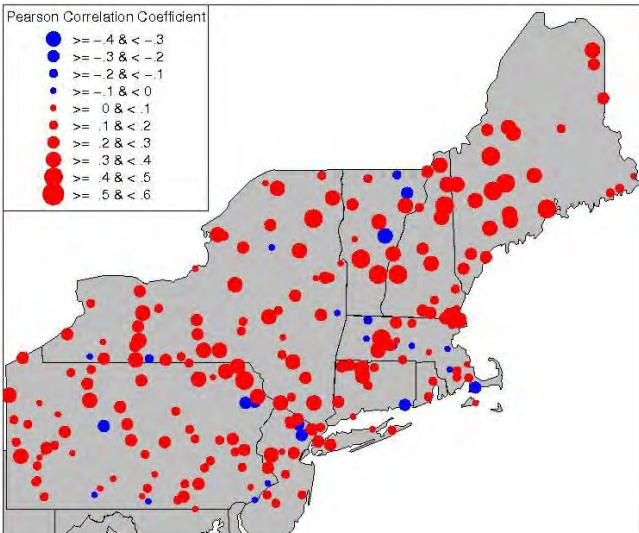
**Relationship Between Temperature and Occurence
of 1-in Events For Sprng: 1948-2007**

**Relationship Between Temperature and Occurence
of 1-in Events For Summer: 1948-2007**

**Relationship Between Temperature and Occurence
of 1-in Events For Fall: 1948-2007**

**Relationship Between Temperature and Occurence
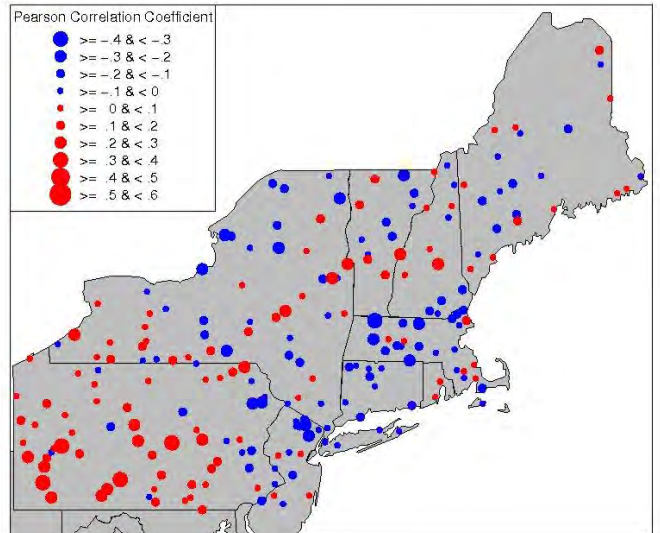of 1-in Events For Winter: 1948-2007**

Figure 11. Correlation between temperature and the occurrence of one-inch events for Spring (upper-left), Summer (upper-right), Fall (bottom-left) and Winter (bottom-right) from 1948 – 2007 in the Northeast. Positive R values are shown in red, negative R values are in blue. Significance of trends is not shown since the residuals were not normally distributed.

Conclusions

In this study, a range of definitions for extreme precipitation was examined to provide a robust indicator of climate change in the Northeastern United States. All of the definitions (frequency of accumulation, the 99th percentile of events, or recurrence intervals) indicate that the occurrences of extreme precipitation events, and the intensity of rainfall, are increasing. Annual precipitation also showed predominantly positive increases from 1948-2007, with the most significant increases occurring most recently. The increase in extreme precipitation events and in annual precipitation is occurring primarily during the spring and fall. Correlation between seasonal northern hemisphere temperature anomalies and the occurrence of seasonal one-inch events is also strongest during the spring and fall, suggesting that increasing temperatures play an important role in the increasing frequency of extreme precipitation.

As New England continues to develop and grow, more development and infrastructure infringe on the area's watersheds, rivers, and floodplains. This increases the potential severity of flooding in the future by decreasing the amount of permeable surface in watersheds as well as increasing the number of buildings and roads that are built in flood prone areas. Understanding extreme precipitation trends is important so that society can prepare for the potential of more frequent flooding.

Evidence is growing that the observed historical trends of increasing extreme precipitation are connected to greenhouse-gas-enhanced climate change, driven primarily by the burning of fossil fuels and land use changes. In 2007, the Intergovernmental Panel on Climate Change concluded that it was more likely than not that human influence contributed to the trend toward more extreme precipitation events and that future increases in extreme precipitation are very likely. This study provides further evidence of these trends.

These findings should be of value for a wide range of stakeholders to assist with efforts to reduce vulnerability to flooding in the future. It is difficult to directly link changes in extreme precipitation with flooding,[18] 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 77,000 square miles) have been found to be increasing in the 20th century[19], and are only amplified by increasing rainfall rates.

Requirements for how and where we build our homes, businesses, roads, wastewater treatment plants, power lines and other infrastructure need to be re-evaluated. For example, flood relief structures are constructed to a certain level of performance, in many cases, built to prevent flood impacts from the 100-year flood threshold (based on an outdated definition of the 100-year flood). 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.

Appendix A:
Methodology of Defining Extreme Precipitation

Extreme precipitation has been examined in previous studies using various criteria including: the accumulation of rain greater than two inches in a 48-hour time period[20]; hourly rainfall totals over one inch[21]; event frequency thresholds, where for a given location or season, extreme events are those that fall in the top 0.1 percent of all precipitation events[22]; and where the 24-hour precipitation total at one or more stations surpassed the 50-year recurrence level[23]. 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, 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 percent 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. Here, the top 1 percent of 24-hour precipitation measurements for each year is defined as extreme. Changes in the threshold of the 99th percentile of daily accumulations, which exemplify changes in precipitation intensity at stations in the Northeast, are examined over the 1948-2007 period. To calculate the annual 99th percentile accumulation for one-day precipitation totals at each station, the 24-hour 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.[24]

A third method to define extreme precipitation events is by using recurrence intervals. 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 the Northeast (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-hour 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 calculated 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, etc. to 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.

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