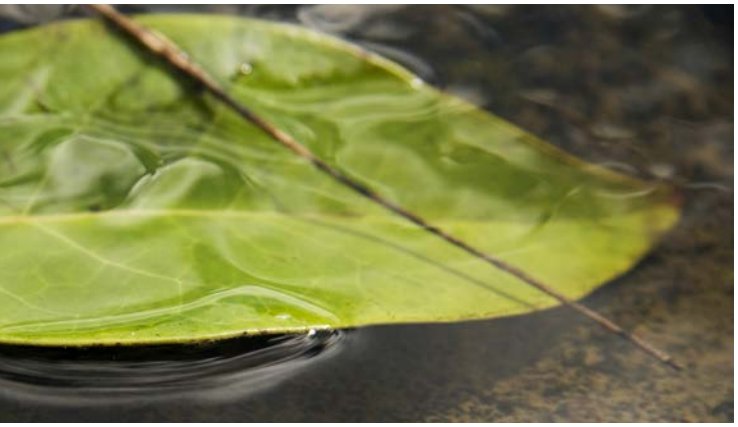

Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

NEW ENGLAND REGION 01

FINAL

August 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

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To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the New England Region, is part of a series of twenty-one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

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CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

NEW ENGLAND REGION 01

August 17, 2015

CDM Smith
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Water Resources Region 01: New England Region

1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty-one regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty-one Water Resources Regions included in this series of reports are shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and regional vulnerability assessment tools.

This report focuses on Water Resources Region 01, the New England Region, the boundaries for which are shown in **Figure 1.2**. The entirety of the region is within the New England USACE district.

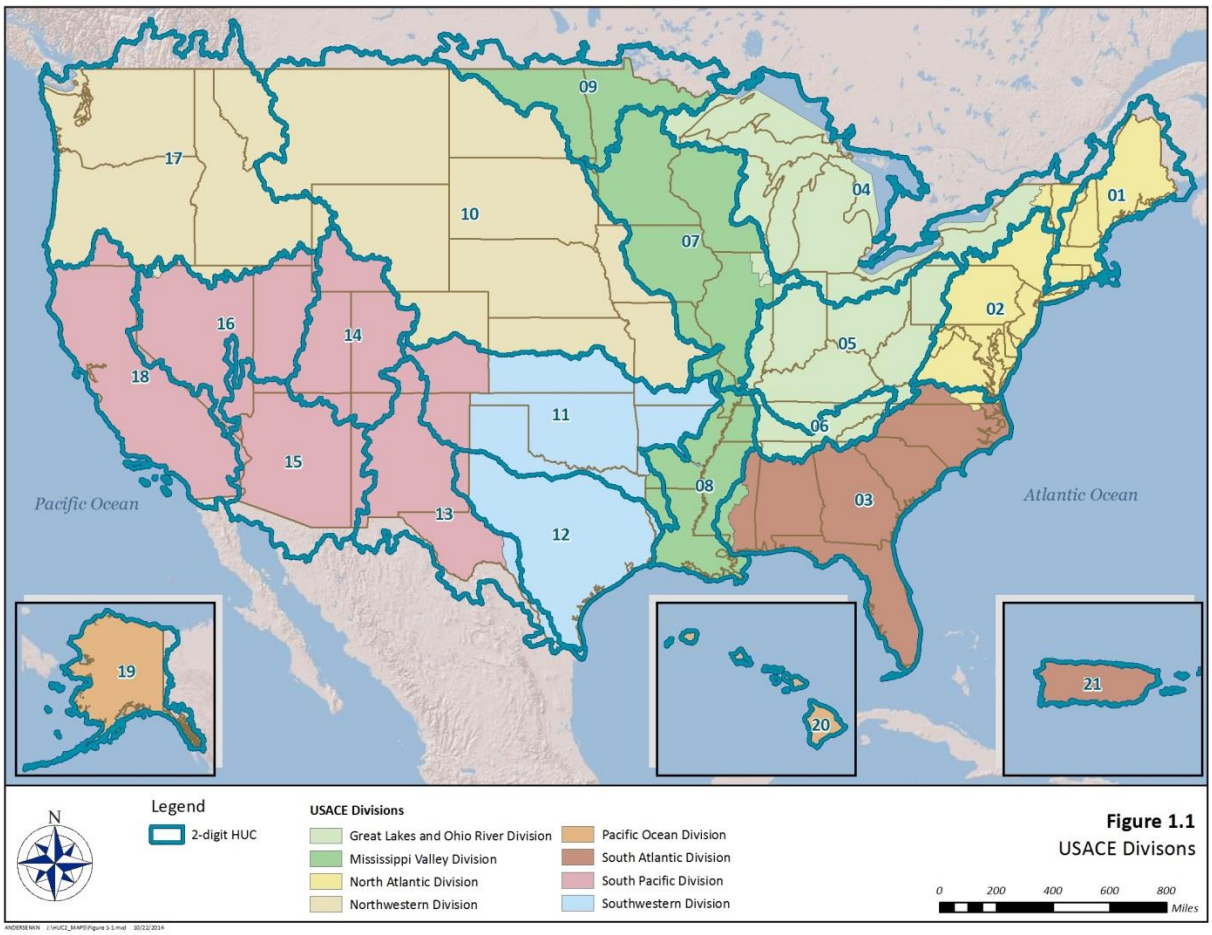


Figure 1.1. 2-digit Water Resources Regional Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

Figure 1.2. Water Resources Region 01: New England Region Boundary.

1.1 A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUCs (Water Resources Regions), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Region scale both to introduce relevant climate change literature and to support the vulnerability assessment USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 01, both the 2-digit and 4-digit HUC boundaries are shown in **Figure 1.2**.

2. Observed Climate Trends

Observed climate trends within the New England Region are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014) this section in not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed the reader is referred to the specific references cited, including the third National Climate Assessment (NCA) which includes not only regional assessments but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to the New England Region were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region or inclusive of the New England Region (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The results presented below indicate mild upward trending in both temperature and precipitation in the New England Region over the past 50 to 100 years as the region has gotten warmer and wetter. No such trends have been identified for streamflow, suggesting that the two climate trends may be offsetting.

2.1. Temperature

A number of studies focused on observed trends in historical temperature were reviewed for this report. These include both national-scale studies inclusive of the New England Region and regional studies focused more specifically and exclusively on the region. Results from both types of studies, relevant to the New England Region, are discussed below.

At a national scale, a 2009 study by Wang et al. examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive, statistically significant trends in recent observed mean surface air temperature for most of the U.S. (**Figure 2.1**). For the New England Region, results generally indicate

warming, up to 1.2 ºC (2.2 ºF) for the majority of the region for winter, spring, and summer but a cooling trend up to 1.2 ºC (2.2 ºF) for autumn (September – November). A cooling trend for winter (December – February) is also noted for northern Maine. The authors do not provide information on statistical significance of the presented observed trends. A later study by (Westby et al., 2013), using data from the period 1949 – 2011, showed a winter warming trend throughout the region of up to 0.008 ºC (0.014 ºF) per year, but the results were not significant at the 95% level.

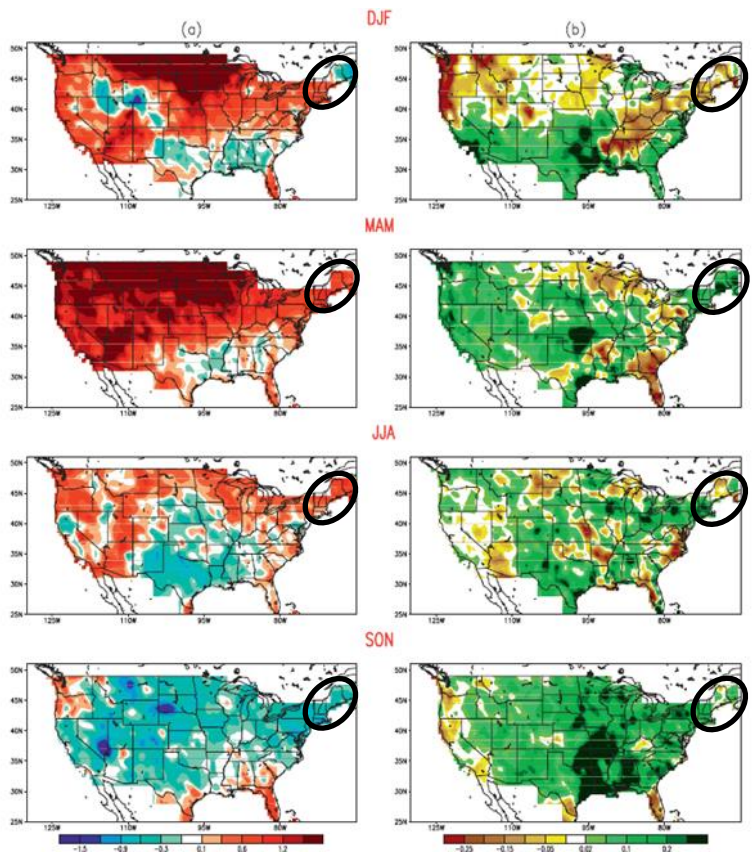


Figure 2.1. Linear trends in (a) surface air temperature in Kelvin and (b) precipitation in mm/day over the United States, 1950 – 2000. The New England Region is within the black oval (Wang et al., 2009).

Grundstein and Dowd (2011) investigated trends in one-day extreme maximum and minimum temperatures across the continental U.S. They used daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 – 2010. The researchers used a parameter called "apparent temperature", a metric which incorporates humidity and temperature in an attempt to better represent human sensation of heat, and defined extreme temperatures as exceeding the 85th percentile for historical data at each station. For the New England Region, they found statistically significant increasing trends in the number of one-day extreme minimum temperatures at four out of five stations within the region. However, no significant trends were found for one-day extreme maximum temperatures.

Meehl et al. (2012) used a combination of observed climate data and model calculations to analyze historical temperature changes across North America for the period 1950 – 1999. Results (**Figure 2.2**) show winter (December – February) cooling up to 0.75 ºC (1.4 ºF) per year, and summer (June – August) warming from 0.25 to 1.25 ºC (0.45 to 2.25 ºF) per year. Information on statistical significance was not provided. The winter cooling trend differs from the warming trends shown by Wang et al. (2009) and Westby et al. (2013), presented above. Differences may be attributable to differences in temporal and spatial scopes.

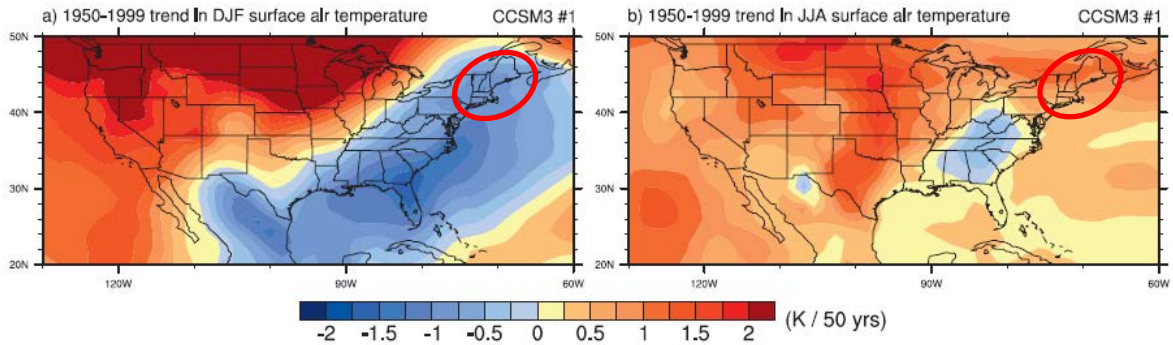


Figure 2.2. Seasonal mean air temperature trends, 1950 – 1999, winter (December – February, left panel) and summer (June – August, right panel). The New England Region is within the red oval (Meehl et al., 2012).

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the NCDC with periods of record extending through 2010. Their findings indicate that for most stations within the New England Region, spring onset is occurring at least a few days earlier for the current period (2001 – 2010) compared to an earlier baseline reference decade (1951 – 1960) (**Figure 2.3**). In other words, an apparent small shift in seasons has been identified, with spring warming occurring earlier than in the past. Information on statistical significance was not provided. These results seem to agree with the findings of Wang et al. (2009) (warmer winter and spring).

Figure 2.3. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The New England Region is within the red oval (Schwartz et al., 2013).

DeGaetano et al (2002) conducted a national study of temperature data at 361 stations for the period 1930 – 1996, including a review of trends in extreme maximum daily temperatures. They conducted a trend analysis on the number of days with a maximum temperature exceeding the 95th percentile. They performed a second analysis on the period 1960 – 1996 due to the influence of drought in the 1930s and 1940s when there were a large number of exceedance values, causing a greater number of decreasing trends for the period beginning in 1930. In the New England Region, the 1930 – 1996 trend analysis revealed five stations with increasing trends, of which three were statistically significant at the 95% level, and no stations with negative trends. The 1960 – 1996 analysis showed 13 stations with increasing trends, of which 11 were statistically significant, and four stations with negative trends that were not statistically significant.

The third NCA summarizes climate data by region (Horton et al., 2014). Water Resources Region 01 is contained in the NCA's Northeast Region, which includes all of New England as well as New York, Pennsylvania, New Jersey, Delaware, Maryland, and West Virginia. The NCA notes an increase of nearly 2 ºF (1.1 ºC) in average annual temperature between 1895 and 2011. Statistical significance was not provided.

Trombulak and Wolfson (2004) reviewed temperature data at 36 climate stations in the New England Region. Annual mean temperatures were calculated for each station for the period 1903 – 2000. They used a linear regression to calculate a temperature change per 100 years for each station (**Figure 2.4**). All stations within the New England Region showed increases, some exceeding 3 ºC (5.4 ºF) per 100 years. The average over the entire study area, which also included New York, was an increase of 1.11 ºC (2 ºF) per 100 years. Statistical significance on the temperature trend values was not provided.

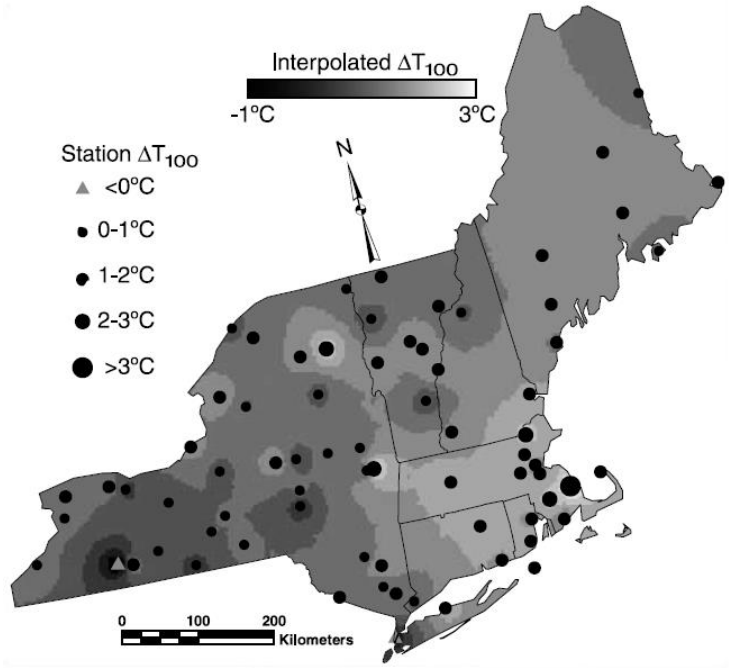


Figure 2.4. Temperature change trends, ºC per 100 years, at individual stations (circles) and interpolated across the entire region (shading) (Trombulak and Wolfson, 2004).

Hayhoe et al. (2007) evaluated observed trends as well as projected changes in a number of climatic variables in the northeastern U.S., including New England, New York, and Pennsylvania. Temperature data was analyzed for 73 stations from the United States Historical Climatology Network. Over the period 1900 – 1999, they observed increasing trends of 0.08 ºC (0.14 ºF) per decade in annual temperatures, 0.12 ºC (0.22 ºF) per decade in winter and 0.07 ºC (0.13 ºF) per decade in summer. Over the period 1970 – 2000, they observed increasing trends of 0.25 ºC (0.45 ºF) per decade in annual temperatures, 0.07 ºC (0.13 ºF) per decade in winter and 0.12 ºC (0.22 ºF) per decade in summer. Information on statistical significance was not provided. The authors note that seasonally, temperatures appear to be increasing most rapidly in winter, and annual temperatures have increased more rapidly in recent decades.

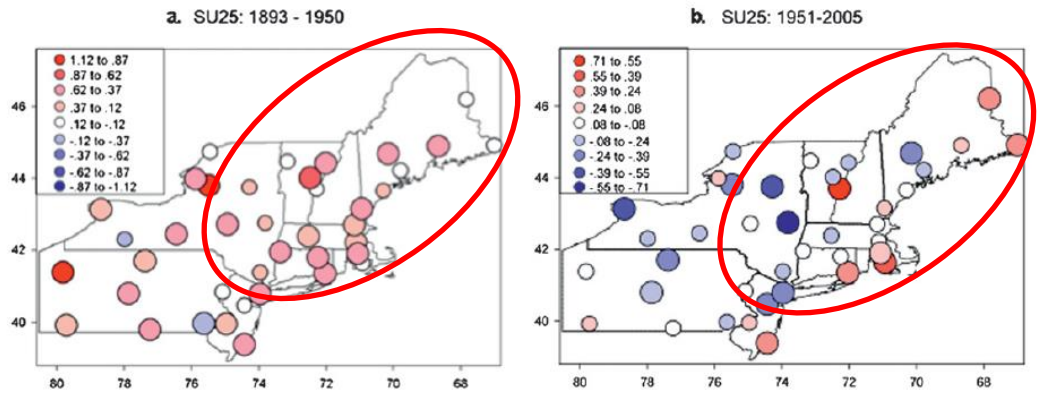
Burakowski et al. (2008) reviewed temperature and precipitation trends, with a focus on winter (December through March) climate, in a study area including the New England Region as well as New York, Pennsylvania, and New Jersey. They analyzed data from the United States Historical Climate Network at 138 stations over the period 1965 – 2005. The trend analysis found that winter mean, minimum, and maximum temperatures are all increasing at 0.42 to 0.46 ºC (0.76 to 0.83 ºF) per decade, with the greatest warming occurring during January and February, the coldest months of winter. Statistical significance of regional trends was analyzed using twelve 30-year windows within the longer study period. Trends in maximum, minimum, and mean temperature were significant for seven of the twelve windows.

The Northeast Climate Impacts Assessment (NCIA) (Frumhoff et al., 2007) presents an overview of changing climate and impacts to several sectors, based primarily on peer-reviewed literature. The study area includes the New England Region along with New York, Pennsylvania, and New Jersey. This report states that annual average temperatures in this region have risen 1.5 ºF (0.8ºC)

over the 20th century, with warming accelerating since 1970, after which the average warming rate is around 0.5 ºF (0.3 ºC) per decade. A doubling in the number of days per year exceeding 90 ºF (32 ºC) over the preceding 45 years is also noted. Information on statistical significance was not provided.

Brown et al. (2010) used an extended period data set (1893 – 2005) to investigate trends in climate extremes in the northeastern U.S., including New England as well as New York, New Jersey, and Pennsylvania (**Figure 2.5**). They divided the data set into two periods: 1893 – 1950 and 1951 – 2005. In the earlier part of the century, the New England Region showed an increasing trend in the number of summer heat days and a decreasing trend in the number of cold snap days. In the second half of the century, some stations showed increases in summer heat days while others showed decreases, while cold snap days continued to decrease throughout the region.

a) Summer extreme heat days (> 25 ºC or 77 ºF)



b) Cold spell duration indicator (annual count of days with at least six consecutive days with minimum temperatures below the 10th percentile)

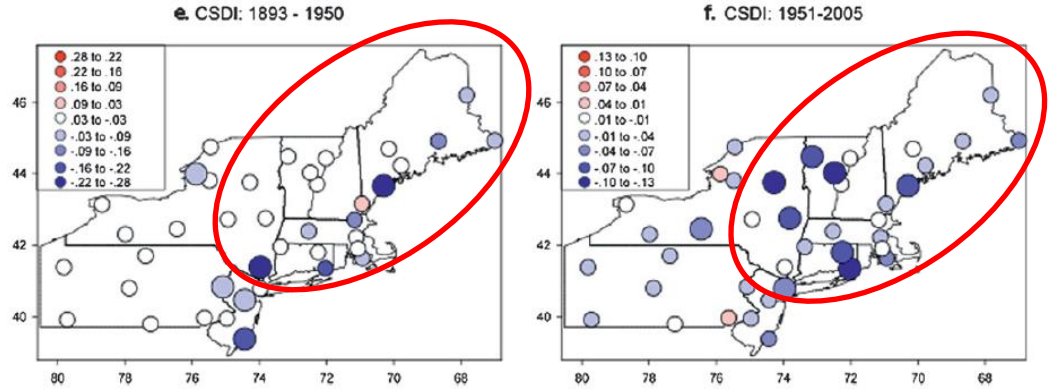


Figure 2.5. Observed trends (days/year) in climate-changes in extreme temperatures. 1893 – 1950 (left panels), 1951 – 2005 (right panels). Large circles indicate statistical significance ($p < 0.05$). The New England Region is within the red oval (Brown et al., 2010).

Huntington et al. (2009) conducted a survey of literature studying 20th century observed and 21st century projected climate change in New England and New York. The authors include several of the studies described here, with a focus on the potential impacts to forested and aquatic ecosystems. Based on their literature review, the authors conclude that temperatures have risen over the 20th century, with a particular increase in the winter months, and accelerated warming beginning in the 1970s.

Key points: Most studies agree that there has been an overall increase in average temperatures over the past century, although some indicate that there may be seasonal or localized cooling trends occurring. Some studies also indicate a greater temperature increase occurring during the winter months. Minimum temperatures also appear to be increasing, but there is no clear trend in high temperature extremes.

2.2. Precipitation

Palecki et al. (2005) examined historical precipitation data from across the continental United States. They performed a trend analysis on precipitation data, by season, for the period 1972 – 2002 using NCDC 15-minute rainfall data. For the New England Region, no statistically significant ($p < 0.05$) trends were found for storm magnitude, duration, or intensity for any season.

Grundstein (2009) identified statistically significant ($p < 0.05$) increasing trends in the Thornthwaite soil moisture index and total annual precipitation for the southern portion of the New England Region (**Figure 2.6**) over the period 1895 – 2006. Decreasing trends were identified at the two stations located in the northern portion of the region. The Thornthwaite soil moisture index is a function of both supply (precipitation) and demand (evapotranspiration [ET]).

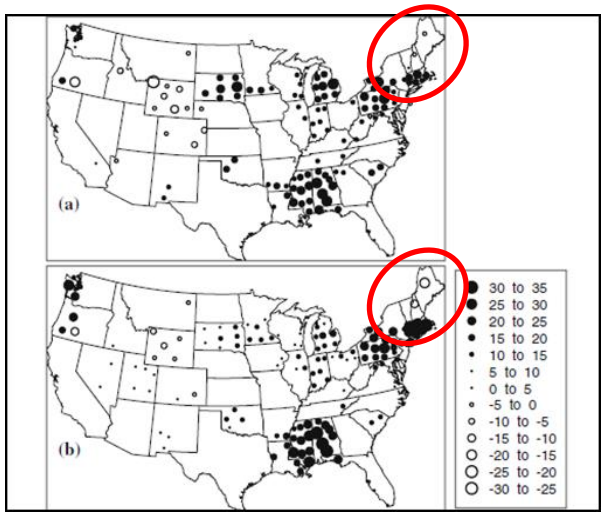


Figure 2.6. Statistically significant linear trends in (a) Thornthwaite soil moisture index (unitless) and (b) annual precipitation (cm per 100 years) for the continental U.S. The New England Region is within the red oval (Grundstein, 2009).

As described in Section 2.1, a study by Wang et al. (2009) focused on historical climate trends across the continental U.S., using gridded climate data and a shorter period of record (1950 – 2000). The authors identified positive trends in total seasonal precipitation for most of the U.S. (**Figure 2.1**). For the New England Region, increasing trends were identified for spring, summer and fall, while decreasing trends were identified in winter. Trends were slightly different in Maine, which had an increasing trend in summer precipitation and a mix of increasing, decreasing, or flat trends in fall. No information is provided with respect to statistical significance of the reported trends.

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous dataset to perform precipitation trend analyses for NCDC climate divisions across the United States. The data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S. (**Figure 2.7**). For the New England Region, increasing trends ranging from 5% to 20% per century were identified. Statistical significance on trend coefficients was not noted.

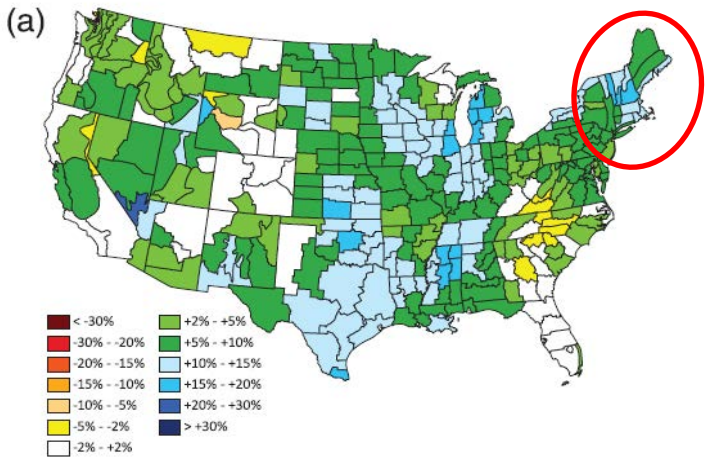


Figure 2.7. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The New England Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on intensity, frequency, or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled GCMs to investigate changes in extreme precipitation across North America. The authors examined trends in both historical data and future projections. They identified the 20-year maximum daily precipitation amount for the period from 1949 – 1976 and compared the return frequency of the same event magnitude over the period 1977 – 1999. Within the New England Region, the authors found that an event with the 20-year daily precipitation volume from 1949 – 1976 was anywhere from equally likely to twice as likely during the period 1977 – 1999, with a greater increase in frequency generally seen to the south and east.

Pryor et al. (2009) performed statistical analyses on 20th century rainfall data to investigate trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. For the New England Region, the analysis showed increasing, statistically significant ($p < 0.1$) trends in total annual precipitation, 90th percentile precipitation, precipitation intensity, and the number of precipitation days per year (**Figure 2.8**), for most stations in the

region. In other words, precipitation has increased across the board, with a greater increase seen in extreme events. The authors note that the trends identified are not necessarily linear, with an apparent increase in the rate of change in the latter part of the century for most stations.

a) Annual precipitation

b) 90th percentile daily precipitation

c) Precipitation intensity (annual total / number of precipitation days)

d) Number of precipitation days per year

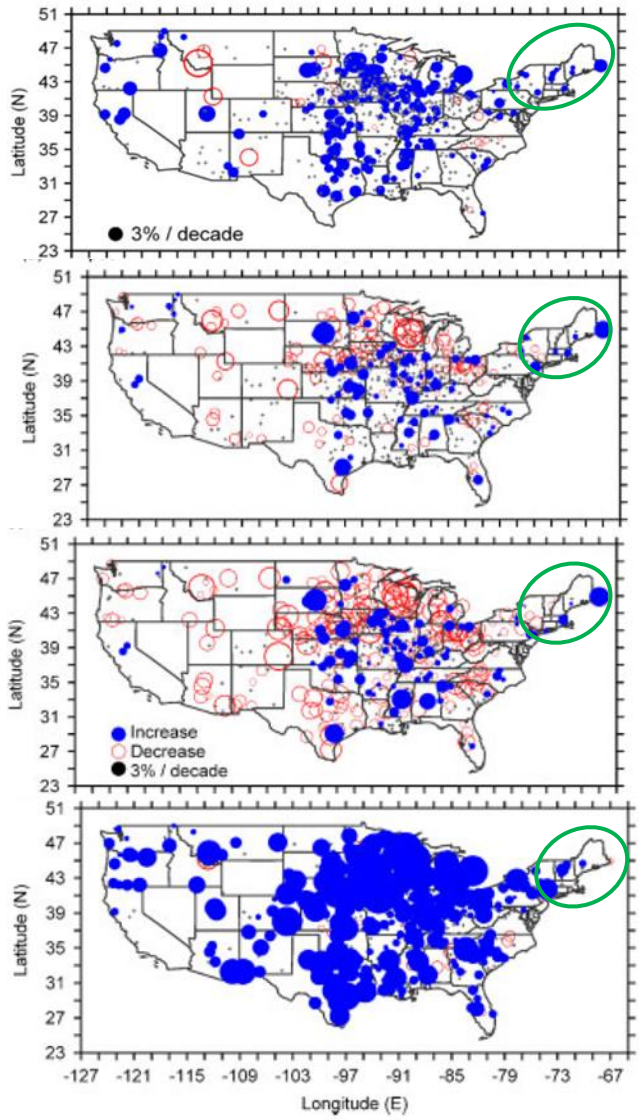


Figure 2.8. Historical precipitation trends in the 20th century. (a) Annual totals, (b) 90th percentile daily, (c) precipitation intensity (annual total/number of precipitation days), and (d) number of precipitation days per year. Blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The New England Region is within the green oval (Pryor et al., 2009).

A number of recent studies have focused more specifically on the northeast region of the U.S., including the New England Region. As above, regional investigations have targeted trends, or changes, in annual precipitation and the occurrence of extreme events. The third NCA report (Horton et al., 2014) cites an approximately 10% increase in average annual precipitation between 1895 and 2011 for the northeast region. Statistical significance was not noted. This

study also cites a substantial increase in the amount of precipitation received in the region from extreme heavy events.

The Hayhoe et al. (2007) study described above studied historical trends in annual, winter, and summer precipitation volumes in the northeastern U.S., including New England, New York, and Pennsylvania, using data from 93 stations from the United States Historical Climatology Network. Over the period 1900 – 1999, annual precipitation increased at a rate of 10 mm per decade, winter precipitation decreased by 0.5 mm per decade, and summer precipitation increased at 1 mm per decade. Over the period 1970 – 2000, trends were reversed in all three cases: annual precipitation decreased by 8 mm per decade, winter precipitation increased by 3 mm per decade, and summer precipitation decreased by 0.2 mm per decade. Total snowfall volumes and number of snowfall days decreased in the period 1950 – 1999 as well as 1970 – 2000, as more winter precipitation fell as rain rather than snow. Statistical significance values are not provided, but the authors note that these trends are not be robust due to the high inter-annual variability in precipitation values and the sensitivity of precipitation trends to the period of record analyzed.

The work of Small et al. (2006) included analysis of the New England Region for annual and fall (September through November) precipitation trends. These authors investigated trends in various precipitation and flow metrics based on U.S. Geological Survey Hydroclimatologic Data Network (HCDN) climate data from 1948 to 1997. One station within the region showed statistically significant ($p < 0.05$) increasing trends in both fall and annual precipitation, but the remaining stations within the region had no trend (**Figure 2.9**).

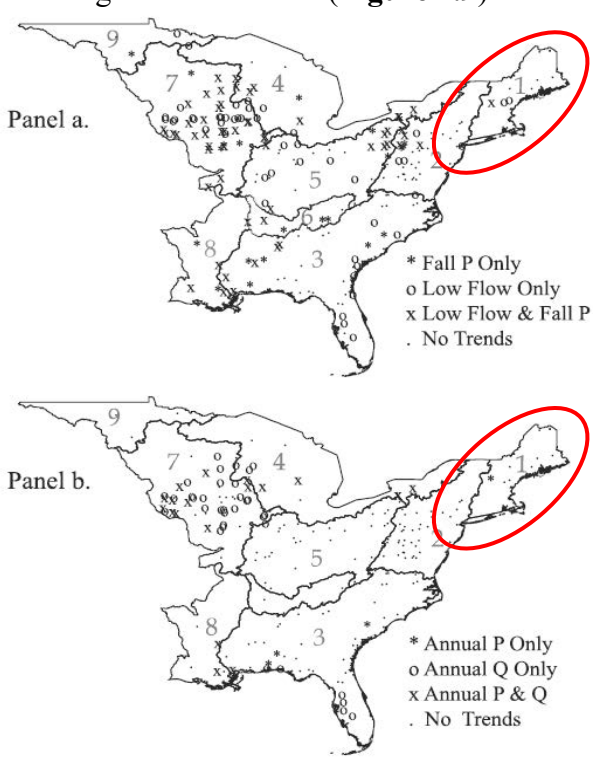


Figure 2.9. Historical trends in precipitation (P) and streamflow (Q), 1948 – 1997. The New England Region is within the red oval (Small et al., 2006).

Douglas and Fairbank (2011) reviewed precipitation data for 48 stations in Massachusetts, New Hampshire, and Maine, and performed trend analysis focused on extreme precipitation parameters. They used multiple kinds of trend analysis and evaluated trends significant at $p < 0.01$ as well as $p > 0.05$. They also evaluated four different time frames: 1954 – 2005, 1954 – 2008, 1970 – 2005, and 1970 – 2008. The different start dates allowed them to compare trends over a shorter, more recent period of record to trends found in the longer term, to determine whether trends have increased in the past several decades. The two different end dates were included to evaluate the impact of several extreme events that occurred during 2005 – 2008 on the overall trend analysis. (The authors note that from 1980 – 2005, four to six disaster events due to extreme precipitation occurred in New England. From October 2005 through April 2007, three extreme weather events took place. Comparing the periods through 2005 to those through 2008 allowed the authors to examine whether these events were indicative of longer-term precipitation trends rather than simply unlikely events that happened to occur in recent years).

The authors focused on two primary extreme precipitation metrics: annual maximum daily precipitation depth, and the number of days per year with daily precipitation depths exceeding 2 inches. For the period 1954 – 2005, the maximum daily precipitation showed no trends and the number of days with depths greater than 2 inches showed a trend at some stations. More trends in both were found for the period 1954 – 2008. When comparing 1954 – 2008 to 1970 – 2008, more trends were found in the maximum daily precipitation for the shorter period in southern New Hampshire and eastern Massachusetts. This is notable because in general, fewer statistically significant trend coefficients would be expected given the shorter period of record. An increase in frequency of events greater than 2 inches was also noted for a few stations. The authors conclude that trends since 1970 "are indeed unusual and may be indicative of change" and note that the large events after 2005 do appear to represent nonstationarity in precipitation volumes. Finally, the authors calculated 100-year storm volumes for the period 1954 – 2005 and compared them with National Weather Service values (NWS, 1961). The values calculated by the authors exceeded the National Weather Service values by 1 to 2 inches.

Kunkel et al. (2009) looked at trends in extreme snowfall seasons throughout the U.S. and present results for the NCDC northeast region, which includes the New England Region. They defined a "high extreme" snowfall season as one exceeding the 90th percentile volume of snowfall for the period 1937 – 2007, and a "low extreme" snowfall season as one less than the 10th percentile. No statistically significant trends were found in "high extreme" snowfall. However, the northeast region showed an increase in the chance of "low extreme" snowfall events for both the periods 1900 – 2006 ($p < 0.1$) and 1950 – 2006 ($p < 0.05$), indicating that winters with low snowfall volumes are occurring more frequently over time.

The NCIA (Frumhoff et al., 2007), in agreement with the majority of the studies presented above, noted an increasing trend in the annual average precipitation, for a total increase of 5-10% over the 20th century. Increases have been concentrated in spring, summer, and fall precipitation, although more recent records indicate that winter precipitation has been increasing, while a greater portion of winter precipitation falls as rain rather than snow. The NCIA also notes an increase in heavy precipitation events, defined as more than 2 inches of rain falling in 48 hours. Information on statistical significance was not provided.

Huntington et al. (2004) reviewed 21 precipitation stations in New England and examined the ratio of snow to total precipitation over the period 1949 - 2000 (**Figure 2.10**). Changes to this ratio could result in changes to magnitude or timing of streamflows, particularly spring runoff. Eleven stations showed a statistically significant ($p < 0.05$) decreasing trend in this ratio, with stronger trends in northern and coastal New England. The authors also analyzed aggregate data for the region. The ratio of snow to total precipitation, as well as total snowfall, showed statistically significant decreasing trends. There was no significant trend in annual rainfall. Therefore, the authors conclude that the trends in the ratio of snow to total precipitation is due primarily to a decrease in snowfall rather than to an increase in rainfall.

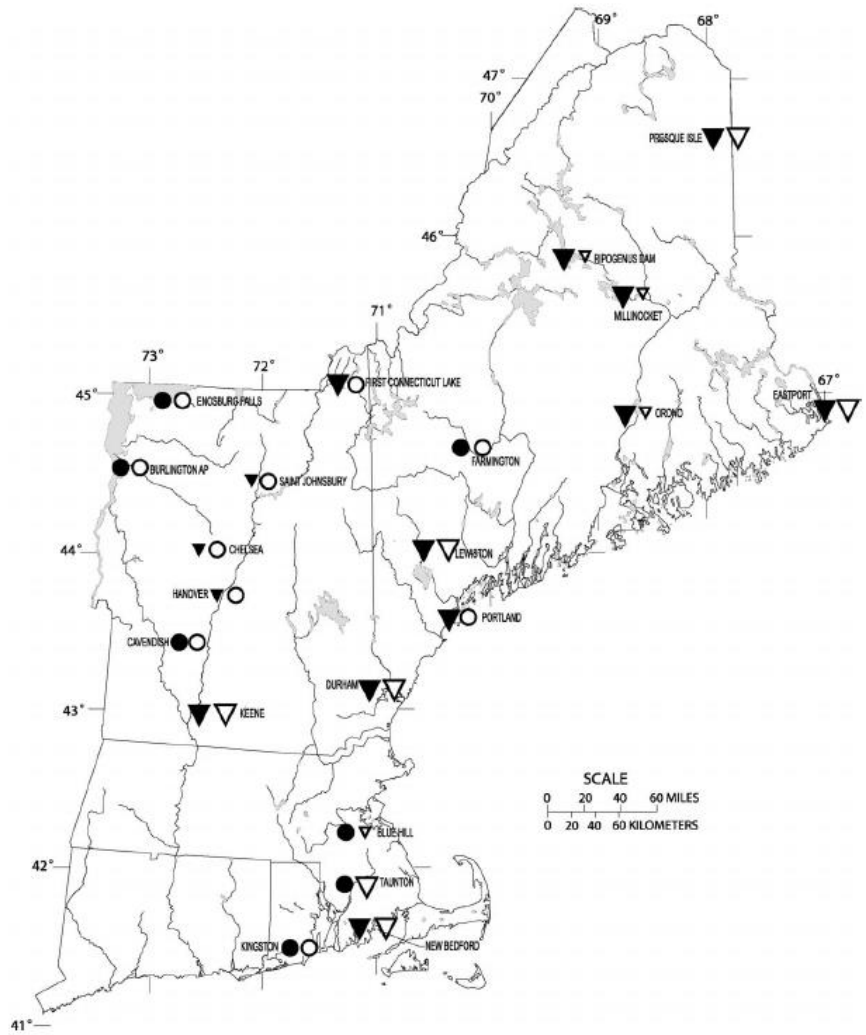


Figure 2.10. Trends in the ratio of snow to total precipitation at 21 stations in New England. Solid symbols indicate annual trends and hollow symbols indicate winter trends. Triangles indicate the direction of the trend; circles indicate no trend. Large triangles indicate significant trends ($p < 0.05$) (Huntington et al, 2004).

The survey by Huntington et al. (2009) described above indicates that overall precipitation volumes have increased, although snowfall has decreased. Precipitation intensity and the frequency of larger precipitation events have also increased. However, the authors noted that the

trends showed significant spatial variability. Temporal variability was also observed, with trends sometimes reversing for periods of time.

Key point: Most studies identified an increase in both average and extreme precipitation, although some studies identified that Northern New England may have experienced either no increase or a decrease. Snowfall appears to be decreasing as winter rainfall increases.

2.3. Hydrology

Studies of trends and nonstationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which include the New England Region. Kalra et al. (2008) analyzed historical streamflow (1952 – 2001) for over 600 flow stations throughout the U.S., including the New England Region. The authors found no statistically significant ($p < 0.05$) trend in the New England Region for either annual or seasonal streamflow.

A regional study by Small et al. (2006) (**Figure 2.9**, above) analyzed HCDN data for the period 1948 – 1997. The authors identified a statistically significant ($p < 0.05$) decrease in low flows for two stations in the New England Region, with no trends in annual flows at any station.

Armstrong et al. (2012) studied low-magnitude floods in New England. They selected 23 rivers throughout New England that have experienced minimal human impact and had streamflow records dating from at least 1948 to 2006. Each river has a specified threshold discharge, a value which is generally expected to be exceeded three to four times per year. The authors then looked for trends in the number of threshold discharge exceedances per year. They found that both the frequency and magnitude of low-frequency floods was increasing over time. Twenty-two of the 23 rivers showed increasing trends, with ten of those trends statistically significant at $p < 0.1$. Seventeen rivers showed positive trends in flood magnitude, with six of those trends statistically significant at $p < 0.1$.

The Hayhoe et al. (2007) study described above evaluated trends in the timing of spring peak flows as well as in 7-day low flow values. The spring peak flow was found to be trending earlier by 0.44 days per decade over the period 1950 – 1999 and by 0.21 days per decade over 1970 – 2000. The 7-day low-flow amount was found to increase by 2.8% per decade during 1950 – 1999, but decrease by 1.77% per decade during 1970 – 2000. Information on statistical significance was not provided. Additionally, runoff volume was found to increase by 0.032 mm per day per decade during 1950 – 1999, and decrease by 0.017 mm per day per decade during 1970 – 2000, but the runoff trends were not statistically significant.

Hodgkins et al. (2003) studied changes in peak flow timing at 27 stations in New England over the 20th century. They looked for trends in center of volume dates for winter/spring (January through May) and fall (October through December). A center of volume date is the date by which half of the total volume over the given period of time has flowed through the gaging station. It is a useful metric for trend analysis because it tends to be less variable than the peak streamflow date. 14 stations showed significantly ($p < 0.1$) earlier center of volume dates for winter/spring, with dates advancing by 1 – 2 weeks. 4 stations had significantly earlier fall center of volume dates.

The NCIA (Frumhoff et al., 2007) notes several hydrological changes in the northeastern U.S. over the 20th century. The date of spring thawing of lake ice has shifted earlier by 9 days in the northern part of the region and 16 days in the southern area. Peak streamflow has also shifted 7 – 14 days earlier. However, the timing and number of summer low flow events have remained fairly constant.

The literature review survey by Huntington et al. (2009), described above, notes variability among studies, but overall showed earlier spring snowmelt periods, resulting in a more even distribution of flow across the snowmelt season.

Key point: Most studies identified few or no trends in annual streamflow volumes, though some noted increases in both magnitude and frequency of peak flows throughout the region. However, several studies noted significant changes in the timing of both low and high flows, with particularly strong agreement that spring peak streamflows have shifted earlier in the season.

2.4. Summary of Observed Climate Findings

A strong consensus in the recent literature points toward an increase in annual temperature in the New England Region over the past century, particularly in the latter part of the century. Some studies indicate that there may be cooling during some seasons or cooling throughout the year in northern New England. Winter temperatures may be increasing at a faster rate than other seasons. The literature also points toward an increasing trend in the number and temperature of extreme heat days.

There is also good consensus in the literature that total precipitation and the occurrence of extreme storm events have increased over the past century in the study region. However, despite the increased precipitation in the region, there is little evidence of significant increases in streamflow over the same period. This paradox is discussed by Small et al. (2006) who attribute it largely to seasonal differences in the timing of the changes in precipitation vs. streamflow, and other studies note that snowfall is decreasing. Several studies indicate that seasonal streamflow timing is shifting even as annual volumes may not be changing. Results presented here also suggest that increasing temperatures may play an additional role in the lack of streamflow sensitivity to precipitation changes in the region.

3. Projected Climate Trends

While historical data is essential to understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2005). Consequently, the scientific and engineering communities are actively using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed GCMs, are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the New England Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview and, similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed the reader is referred to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that average and maximum temperatures will trend upward over the next century in the New England Region. There is less consensus on the future trending of precipitation and streamflow in the region. However, most studies project an increase in both average and extreme precipitation within the region.

3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. Results of studies including the New England Region typically fall in line with this generalization.

Maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case). The results of their study for the New England Region show a projected increase in fall, winter, and spring maximum air temperature of about 2 – 3 ºC (3.6 – 5.4 ºF) for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 3.1**). They project increases of 3 – 3.5 ºC (5.4 – 6.3 ºF) for summer temperatures.

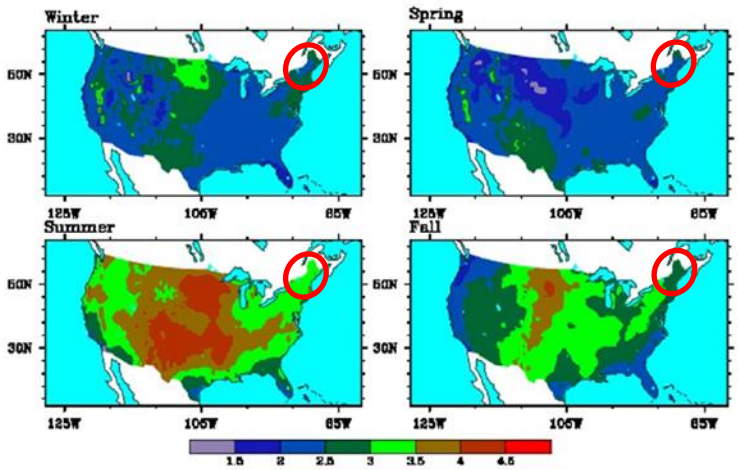


Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2055 vs. 1985. The New England Region is within the red oval (Liu et al., 2013).

Similar results are presented by Scherer and Diffenbaugh (2014). These authors apply a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. They present results by region, including a northeast region which covers the New England Region in addition to New York, Pennsylvania, West Virginia, New Jersey, Maryland, and Delaware. Model projections in this region indicate steadily increasing air temperatures throughout the 21st century for both summer and winter seasons (**Figure 3.2**). By 2090, projections show an expected increase of 5.2 ºC (9.4 ºF) in the summer and 1.7 ºC (3.1 ºF) in the winter, compared to a 1980 – 2009 baseline period.

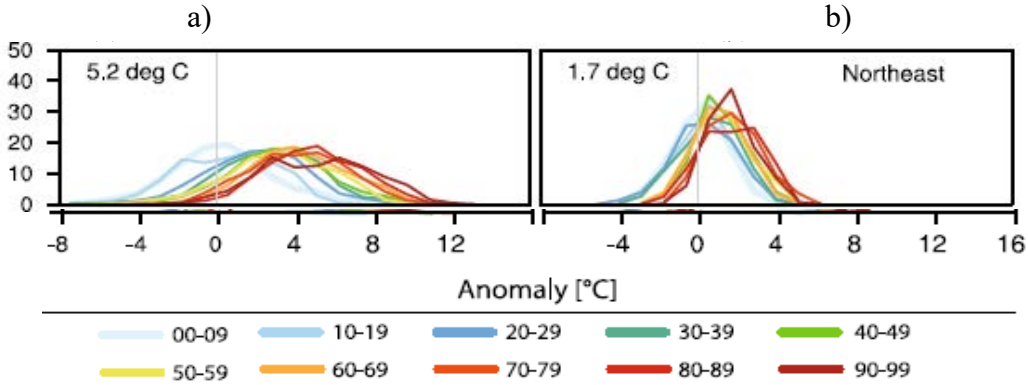


Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade, northeast region (a) summer months, June – August, (b) winter months, December – February (Scherer and Diffenbaugh, 2014).

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. For the New England Region, results show a shift from a mixture of cool wet and cold wet climate types in the latter decades of the 20th century to a predominantly cool wet climate type by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971 – 2000)

b) GCM projections (2041 – 2070)

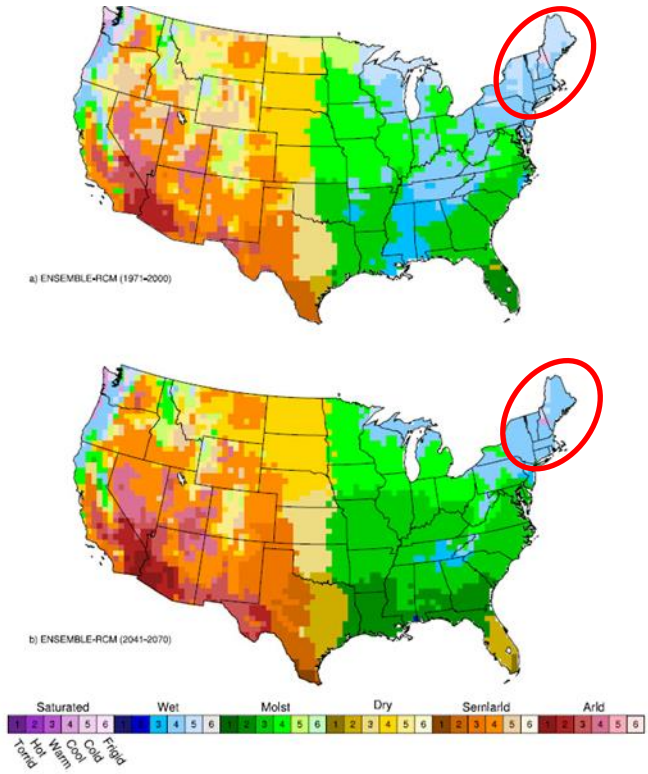


Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. The New England Region is within the red oval (Elguindi and Grundstein, 2013).

Projected changes in temperature extremes were the subject of a study by Kunkel et al. (2010). In this study, two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F). The authors focused on summer heat wave occurrence and intensity and compared a 2090 planning horizon with a recent historical baseline. For the New England Region, projections indicate a 3 to 4.5 ºC (5.4 to 8.1 ºF) increase in three-day heat wave temperatures for both emissions scenarios. Under the A1F scenario, the annual number of heat wave days may increase by 35 – 50 days (fewer in northern Maine), while the projected increase under the A2 scenario is 0 – 25 days.

At a regional scale, Gao et al. (2012) focused on future extreme climate events in the eastern U.S. They applied a single GCM downscaled to a high resolution grid (4 km x 4 km) and a single planning horizon centered on 2058, compared to a baseline period of 2001 – 2004. A single representative concentration pathway was simulated, representative of intensive future fossil fuel use and high greenhouse gas emissions. Results (**Figure 3.4**) are presented for all of the New England Region except for northern Maine, and show projected increases in heat wave intensity, duration, and frequency. Extreme heat wave temperatures are projected to increase by 2 – 5 ºC (3.6 – 9 ºF) and the frequency of heat waves is projected to increase by up to 3 days per year, except in coastal Maine where the frequency may be reduced by up to 2 days per year. Heat wave durations are also predicted to increase, by 4 – 8 events per year.

a) Intensity (ºC)

b) Duration (days/event)

c) Frequency (events/year)

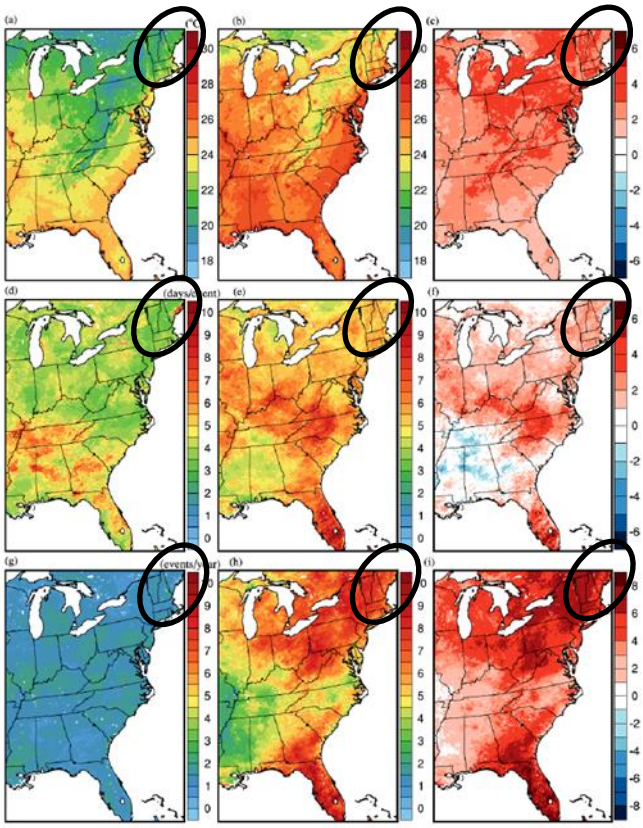


Figure 3.4. GCM projections of heat wave patterns in the eastern U.S. of intensity, duration, frequency, for a 2058 planning horizon (compared to 2002 baseline). Baseline (first column), future (second column), and difference between the two (third column). The New England Region is within the black oval (Gao et al., 2012).

The third NCA report (Horton et al., 2014) generally supports the findings presented above. This report states that, for the northeast region of the U.S., climate model projections predict an increase in the frequency, intensity, and duration of heat waves. Under the worst case (A2) greenhouse gas emissions scenario, model projections indicate an increase in annual average temperature of 4.5 to 10 ºF (2.5 to 5.5 ºC) for the region. The number of extreme heat days (over 90 ºF or 32 ºC) is projected to increase by more than 60 days per year by the middle of the 21st century, compared to the end of last century (**Figure 3.5**).

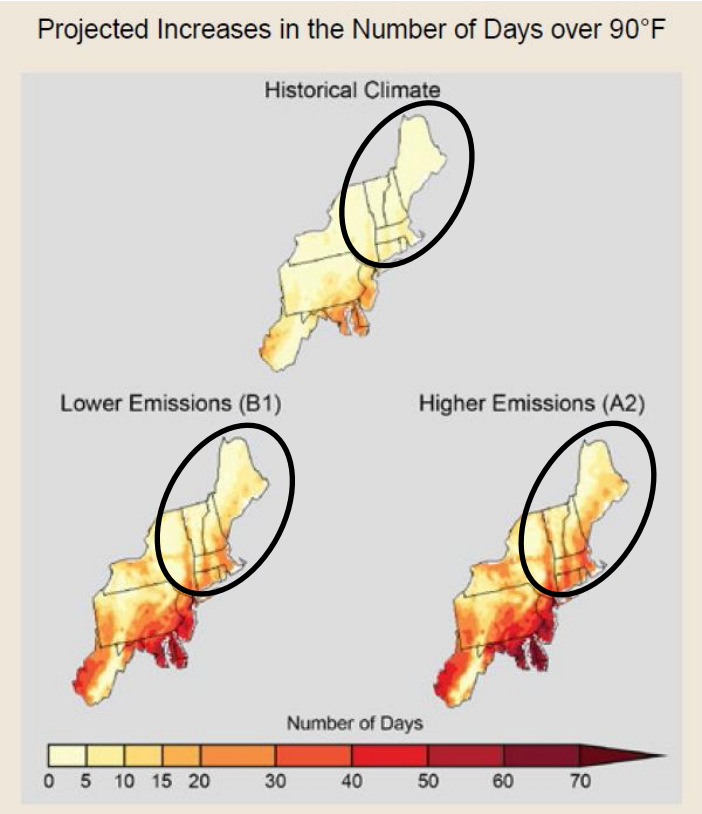


Figure 3.5. Projected increase in the number of days per year with a maximum temperature greater than 90 °F averaged between 2041 and 2070, compared to 1971 – 2000. The New England Region is within the black oval (Horton et al., 2014).

The NCIA (Frumhoff et al., 2007) notes that over the next century, winter temperatures are expected to increase at a greater rate than summer temperatures. By the end of the century, winter temperatures may rise by up to 8 ºF (4.4 ºC) under a lower emissions scenario, and up to 12 ºF (6.7 ºC) under a higher emissions scenario. Summer temperatures may rise by up to 7 ºF (3.9 ºC) under the lower emissions scenario and up to 14 ºF (7.8 ºC) under the higher emissions scenario. Extreme heat days are also expected to increase. Currently, cities in the northern portion of the study region experience around five days per year with temperatures exceeding 90 ºF (32 ºC), increasing to 20 days per year in the southern and inland areas. These values may increase to 30 days per year under a lower emissions scenario, and 60 days per year under a higher emissions scenario.

Rawlins et al. (2012) evaluated output from an ensemble of regional climate models to compare temperature and precipitation in the northeastern United States, including New England, New York, Pennsylvania, and New Jersey. They compared the period 1971 – 2000 to 2041 – 2070, using an A2 emissions scenario and nine model output datasets. All models showed an increase in temperature for all seasons, averaging 3 °C (5.4 °F) in winter, 2 °C (3.6 °F) in spring, 2.6 °C (4.7 °F) in summer, and 2.9 °C (5.2 °F) in autumn (**Figure 3.6**).

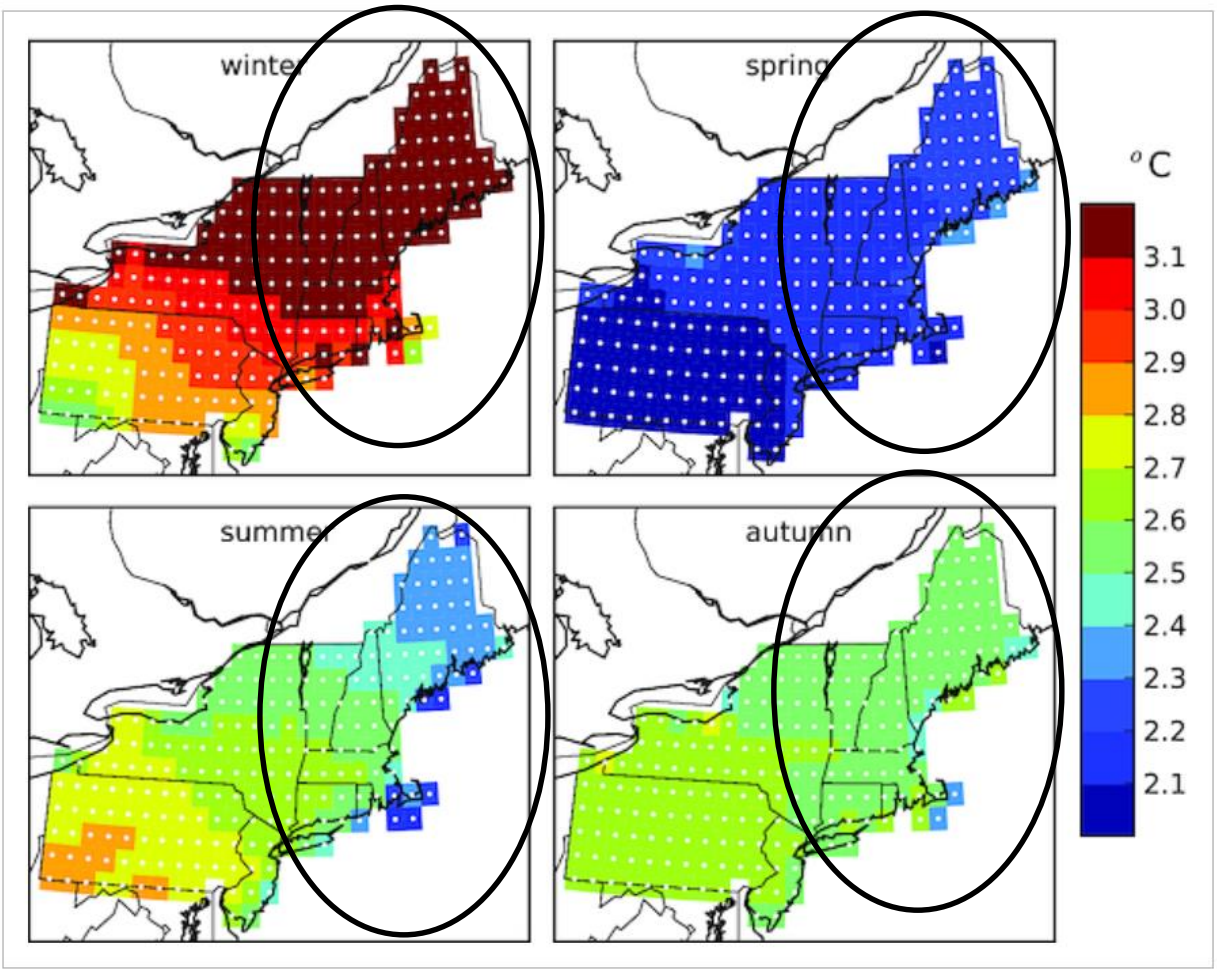


Figure 3.6. Projected changes in air temperature, 2041 – 2070 compared with 1971 – 2000 (Rawlins et al., 2012). The New England Region is within the black oval.

Hayhoe et al. (2007) evaluated projections for a number of climatic variables in New England, New York, and Pennsylvania, using a suite of nine GCMs using the A1F1 (higher), A2 (mid-high) and B1 (lower) emissions scenarios and comparing 2035 – 2064 and 2070 – 2099 to 1961 – 1990. By 2035 – 2064, annual temperatures are expected to rise by 2.9 °C (5.2 °F) under A1F1, 2.5 °C (4.5 °F) under A2, and 2.1 °C (3.8 °F) under B1. By 2070 – 2099, annual temperatures are expected to increase by 5.3 °C (9.5 °F) under A1F1, 4.5 °C (8.1 °F) under A2, and 2.9 °C (5.2 °F) under B1. Seasonal temperatures for winter and summer are also expected to increase under all scenarios.

A second study by Hayhoe et al. (2008) used three GCMs under the A1F1 and B1 emissions scenarios, over a study area including New England, New York, and parts of Pennsylvania and New Jersey. They used several methods to develop downscaled or regional models from the global models and compared the results. Annual temperatures are expected to continue rising through the end of the 21st century, with greater increase in summer temperatures versus winter. Extreme high temperatures are expected to increase as well, with the number of days exceeding the 1990 90th percentile temperature expected to double by the 2090s.

The Huntington et al. (2009) survey paper described above notes that modeled temperature projections are generally in line with historical trends, showing an increase in mean temperature of up to 5 °C (9 °F) over the 21st century.

Key point: Strong consensus exists in the literature that projected temperatures in the study region show an increasing trend through the next century in both average temperatures and high temperature extremes. Although no literature was reviewed studying projected extreme low temperatures, some studies indicate that seasonal winter temperatures are expected to rise at a faster rate than the annual average.

3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the New England Region are variable and generally lacking in consensus among studies or across models. The Liu et al. study (2013), described above, projected increases in winter and fall precipitation associated with a 2055 planning horizon, relative to a recent historical baseline (1971 – 2000), for the New England Region (**Figure 3.7**). Smaller increases, or even slight decreases, are projected for spring and summer. However, the authors also project slight increases in the severity of future droughts for the region, as projected temperature and ET impacts outweigh the increases in precipitation.

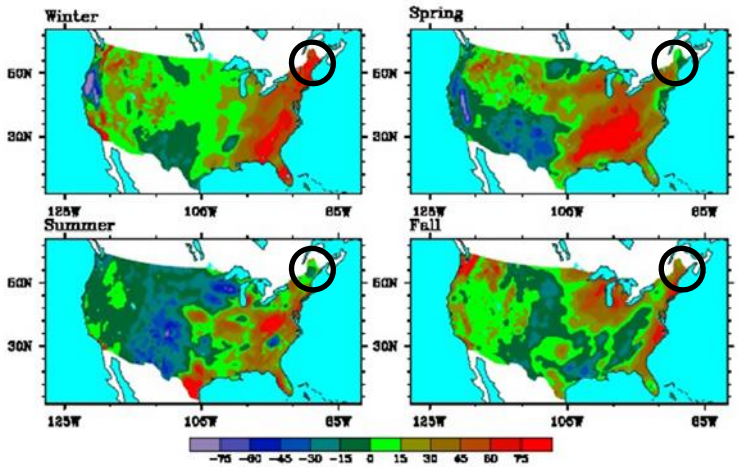


Figure 3.7. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The New England Region is within the black oval (Liu et al., 2013).

More regionally, Thibeault and Seth (2014) used a suite of five GCM models from the recently released Phase 5 Coupled Models Intercomparison Project (CMIP5) to evaluate projected summer precipitation changes for the northeastern U.S. They assume a high greenhouse gas emissions scenario (RCP 8.5) for all projections. When comparing 2081 – 2100 to 1981 – 2000, most models project a slight increase that was not statistically different from historical conditions. Some models show a statistically significant ($p < 0.05$) increase of up to 1.5 mm/day (**Figure 3.8**).

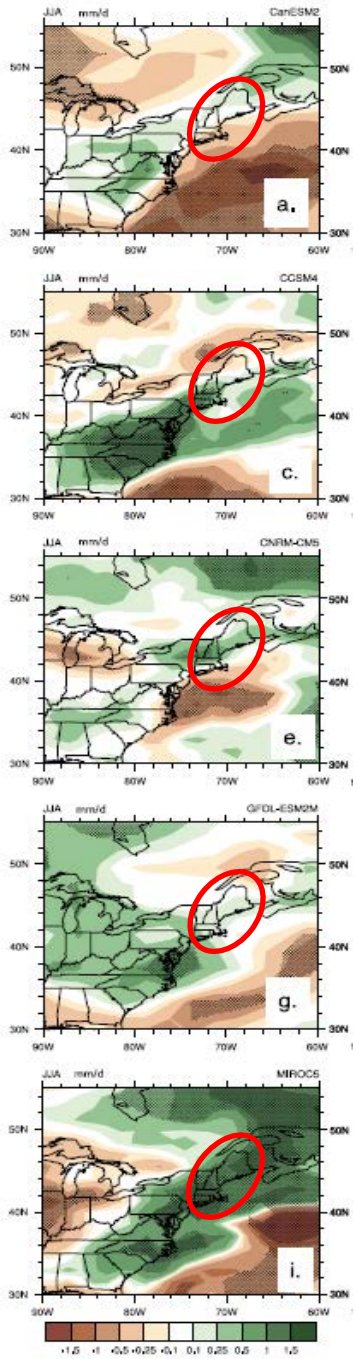


Figure 3.8. Projected changes in summer, Jun – Aug, mean precipitation (mm d-1) for eastern U.S., 2081 – 2100 vs. 1981 – 2000. Stippling indicates statistically significant ($p < 0.05$) differences. The New England Region is within the red oval (Thibeault and Seth, 2014).

The Rawlins et al. (2012) study, described above, noted an increase in precipitation for all seasons except summer when comparing the period 1971 – 2000 with 2041 – 2070 (**Figure 3.9**). Increases across the study region averaged about 12% in winter, 10% in spring, -2% in summer, and 3% in autumn. However, the authors note that there is little to no consensus between models

for all seasons except winter and that the bias in modeled precipitation during historical periods exceeds the change to the future, indicating that the projections may not be robust.

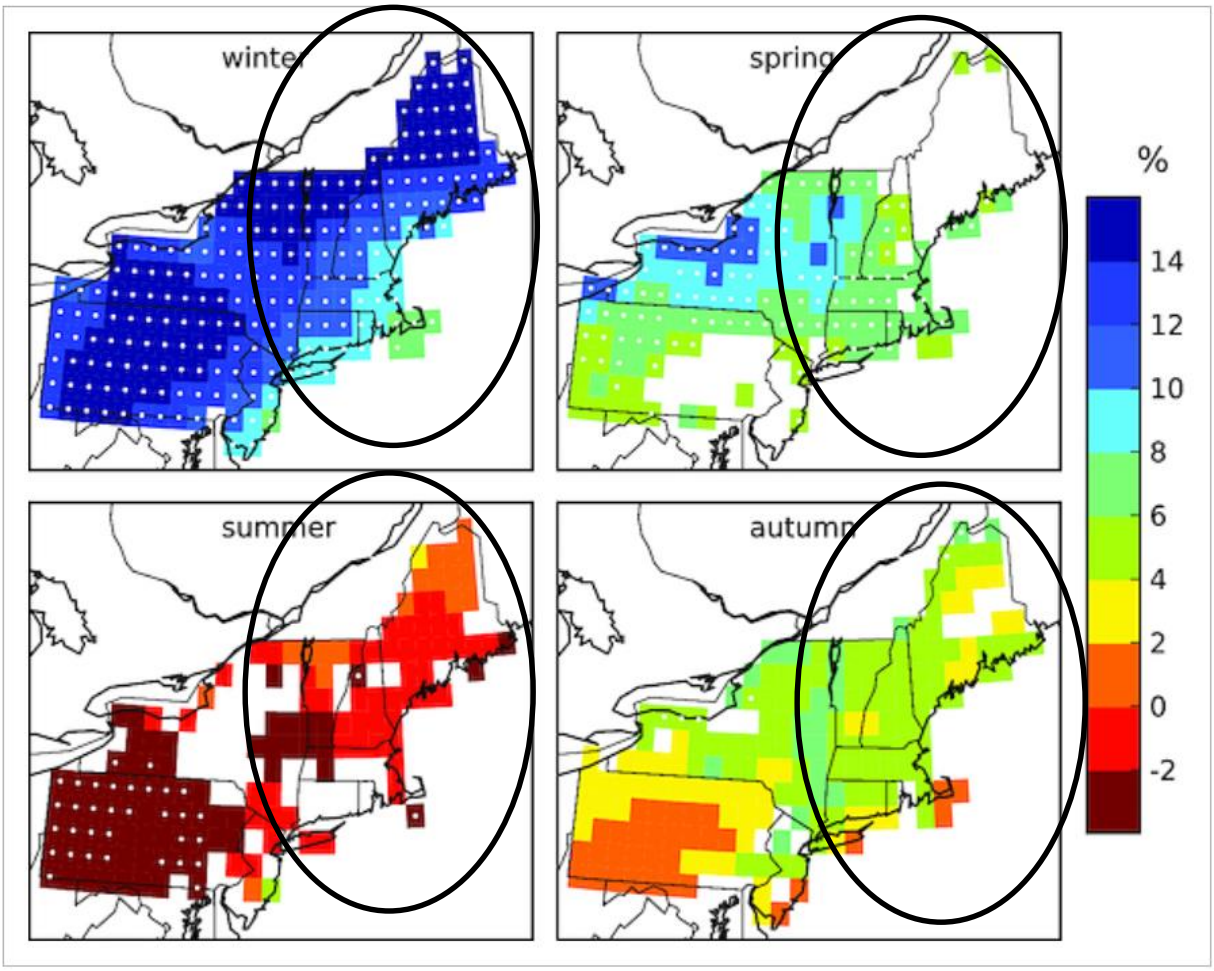


Figure 3.9. Projected changes in seasonal precipitation volumes, 1971 – 2000 compared with 2041 – 2070, as a percent of 1971 – 2000 precipitation volumes (Rawlins et al. 2012). The New England Region is within the black oval.

As noted above, Hayhoe et al. (2007) evaluated future climate projections for a study area including New England, New York, and Pennsylvania. When comparing 2035 – 2064 with 1961 – 1990, annual precipitation volume is expected to increase by 5% under B1, 6% under A2, and 8% under A1F1. By 2070 – 2099, annual precipitation is expected to increase by 7% under B1, 9% under A2, and 14% under A1F1. Winter precipitation is also expected to increase in all scenarios. However, summer precipitation is projected to remain steady or decrease in all cases except for A1F1 projections for 2035 – 2064. The authors note that these seasonal projections are in agreement with recent historical trends. Future projections also show a reduction in the number of snow days and in the proportion of total precipitation falling as snow.

The second study by Hayhoe et al. (2008) indicates an overall increase in annual precipitation volumes, with average daily rainfall expected to increase by about 5 mm form the 1990s to the 2090s. Projections showed larger increases (20-20%) in winter precipitation, but small decreases (around 3%) in summer precipitation volumes. The spatial distribution varied between the

various model outputs, though summer rainfall shows a greater decrease in the northern part of the study area. Variations in rainfall intensity also vary both spatially and between the various model output datasets, highlighting the greater uncertainty in precipitation projections as compared to temperature.

The NCIA (Fromhoff et al., 2007) projects a continued increase in annual precipitation, totaling around 10% by the end of the 21st century. A greater increase of 20-30% is expected for winter precipitation, with a significant increase in the proportion of winter precipitation falling as rain rather than snow. By contrast, summer rainfall is not expected to change significantly. Extreme precipitation is also expected to increase, as rainfall becomes more intense and heavy rainfall becomes more frequent. By the end of the 21st century, precipitation intensity is expected to increase 10-15%, the number of heavy-precipitation events is expected to increase 12-13%, and the volume of rain during the wettest annual 5-day period is expected to increase by 20%.

Future projections of extreme events, including storm events and droughts, are the subject of studies by Wang and Zhang (2008), and Gao et al. (2012). Wang and Zhang (2008) used downscaled GCMs to look at potential future changes in precipitation events across North America. They used an ensemble of GCMs and a single high emissions scenario (A2) to project up to a 30% increase in the recurrence of the current 20-year, 24-hour storm event for their future planning horizon (2075) in the New England Region (**Figure 3.10**).

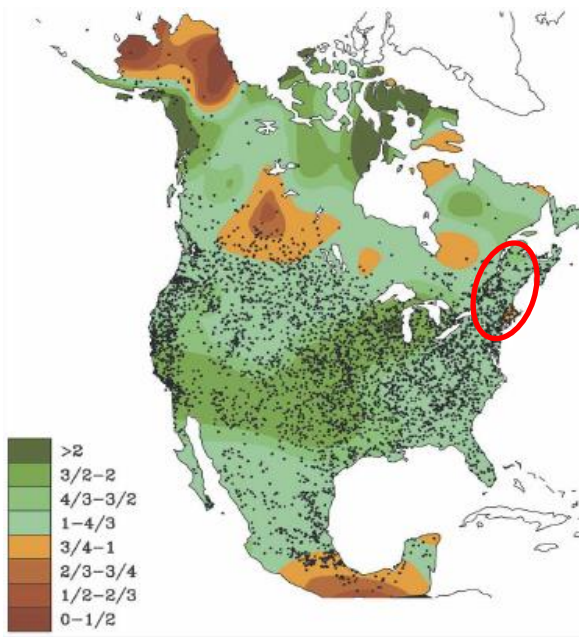


Figure 3.10. Projected risk of current 20-year, 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The New England Region is within the red oval (Wang and Zhang, 2008).

The GCM applied in the Gao et al. (2012) study for the eastern U.S. generally projects increases in the magnitude of annual total (up to 200 mm per year) and daily (up to 15 mm per day) extreme storm events and in the frequency of storm events (up to 5 days per yr), for their 2058

planning horizon compared to current conditions (2001 – 2004) (**Figure 3.11**). Extreme events are defined as those events equaling or exceeding the 95th percentile event.

a) Annual total of extreme events (mm/yr)

b) Daily extreme storms (mm/day)

c) Frequency of storm events (days/yr)

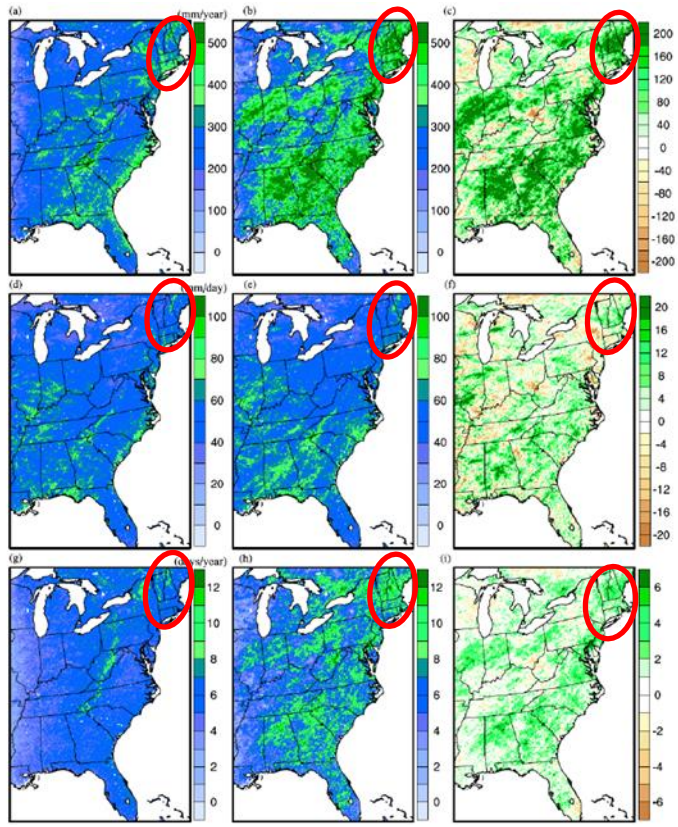


Figure 3.11. GCM projections of future precipitation patterns in eastern U.S. for annual extreme totals, daily extremes, frequency of events, for a 2057 – 2059 planning horizon (compared to 2001 – 2004 baseline); baseline (first column), future (second column), and difference between the two (third column). The New England Region is within the red oval (Gao et al., 2012).

Ahmed et al (2013) created two climate model ensembles, one based on six GCMs and another based on four Regional Climate Models (RCMs), all using an A2 emissions scenario. The authors performed bias correction and statistical downscaling on all models in order to review projections of extreme climate indicators in the northeastern U.S., comparing historical values from the period 1976 – 1995 with projections for the period 2046 – 2065 (**Figure 3.12**). Both the GCM and RCM ensembles predict an increase in the average number of days per year with precipitation exceeding 10 mm, with an increase between 0 and 4 days for most of the region. The projections for maximum 5-day total precipitation are variable within the region for both model ensembles, with some areas showing significant increases and others significant decreases.

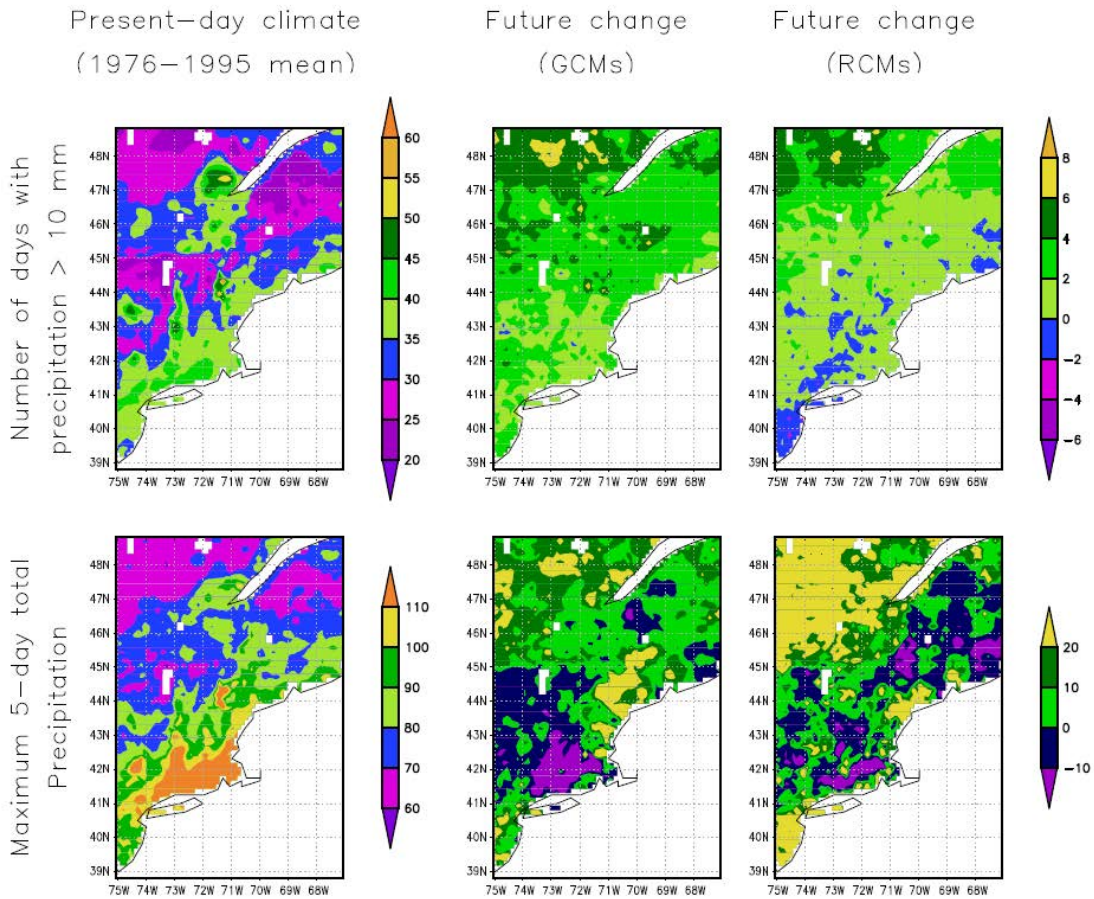


Figure 3.12. Historical (1976 – 1995) mean and difference from the projected (2046 – 2065) mean to the number of days with precipitation exceeding 10 mm (top row) and the maximum 5-day total precipitation (mm, bottom row). The left column shows the historical mean and the two right-hand columns show the projected changes based on two different model ensembles (Ahmed et al, 2013).

The Huntington et al. (2009) survey paper, described above, noted that annual precipitation is expected to increase by up to 10% by the end of the 21st century. However, the authors also noted that when compared to temperature projections, there is less consistency among precipitation projections and the projections don't follow historical trends as closely.

Key point: In general, average precipitation volumes are expected to increase along with the frequency and total precipitation volume of extreme events. However, there is low consensus in the literature as some studies show no trend or variability by season or by location within the region, while others note that projected precipitation trends vary between different model output datasets.

3.3. Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. These studies include projections of potential hydrologic changes in the New England Region. Thomson et al. (2005) applied two GCMs, across a range of varying input assumptions, in combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield across the United States. Results are presented for both continuous spatial profiles across the country (**Figure 3.13**) and for individual Water Resources Regions. For the New England Region, contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts significant decreases in water yield, the other projects significant increases in water yield.

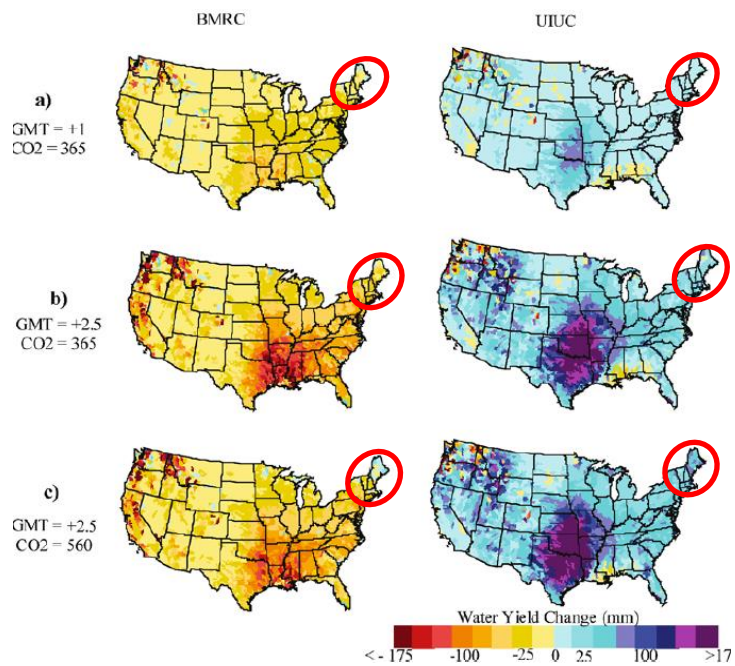


Figure 3.13. Projected change in water yield (from historical baseline), under various climate change scenarios based on 2 GCM projections. The New England Region is within the red oval (Thomson et al., 2005).

The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a study completed by Hagemann et al. (2013). In this study, the authors apply three GCMs, using two emissions scenarios, to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDM Smith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections for the general New England Region show an overall increase in runoff by anywhere from 60 to 200 mm per year for their future planning horizon (2071 – 2100)

compared to recent historical baseline (1971 – 2000) (**Figure 3.14**), assuming an A2 emissions scenario.

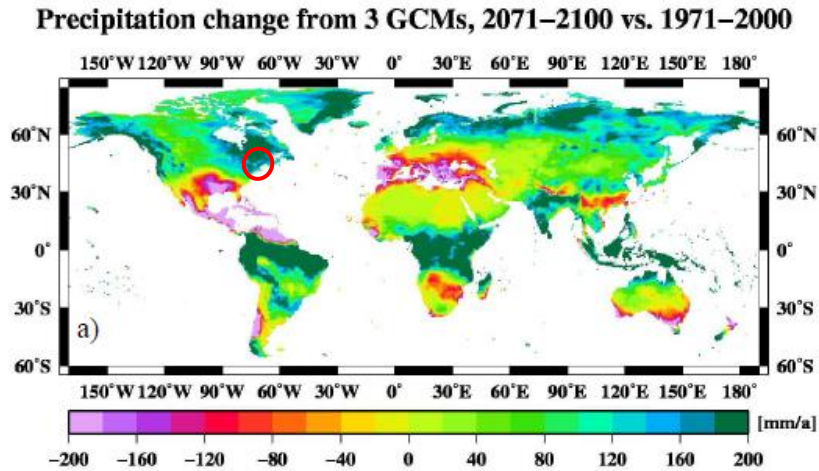


Figure 3.14. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The New England Region is within the red oval.

Tryhorn and Degaetano (2013) used a combination of GCM projections and empirical regression models to evaluate future snowpack conditions in the northeastern U.S. as a function of a changing climate. Their study domain includes six stations in the New England Region. They apply projections from a single GCM (HadCM3) and two assumed greenhouse gas emissions scenarios (A2 and B2). They compared projected annual maximum snowpack depth in the 2080s to the period 1971 – 2000. For the A2 scenario, decreases of up to 25% are expected, except for one station showing an increase of 7.9%. For the B2 scenario, decreases of up to 23% are shown for all stations.

The Hayhoe et al. (2007) study described above projects changes in the amount and timing of high and low flows. Increased variability is expected, low flows are expected to decrease while high flows increase. Annual streamflow volumes are expected to increase, but the seasonal distribution may change as streamflows decrease in in summer and fall and increase in winter and spring. Accordingly, advances in the peak spring streamflow date noted in historical trends are expected to continue, with spring peak flow dates projected to be 5 – 8 days earlier by mid-century.

Hayhoe et al. (2007) also analyzed projected drought intensity and frequency, as measured using soil moisture values. Short- (1 – 3 months), medium- (3 – 6 months) and long-term (6+ months) are all expected to occur more frequently.

The NCIA (Frumhoff et al. 2007) notes changes in the seasonal timing of runoff, particularly as rising winter temperatures cause earlier and larger spring runoff peak flows. By the end of the century, spring peak runoff could occur 10 days earlier by the end of the century under a lower emissions scenario, and more than two weeks earlier under a higher emissions scenario. The

probability of high-flow events may increase by up to 80%, especially in Maine, New Hampshire, and Vermont. However, increases in drought frequency are also expected under the higher emissions scenario as runoff and soil moisture decrease in the summer and fall, though only slight increases are expected under a lower emissions scenario. Low flows also are not expected to change significantly under a lower emissions scenario, but streamflow during the lowest week of the year may drop by more than 10% under a higher emissions scenario.

The Huntington et al. (2009) survey paper, described above, noted that summer streamflows are generally expected to decrease while snowmelt-driven spring peak flows move earlier in the season.

Key points: Several authors have emphasized the additional uncertainty introduced by the use of hydrologic models, reflected here in a lack of consensus about future streamflow volumes. Several studies noted the potential for earlier spring peak streamflows, as well as both increased peak flow volumes and decreased low flow volumes. Snowpack-dominated areas may see the most dramatic changes, as snowpack volumes decrease and warmer temperatures increase the rate of snowmelt.

3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study region, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of up to approximately 3 ºC (5.4 ºF) by the latter half of the 21st century for the New England Region. Some studies indicate that the largest increases will occur in summer, and others predict the greatest warming in winter. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past.

Projections of precipitation and hydrology in the New England Region are less certain than those associated with air temperature. However, in general the literature indicates increases in precipitation through the 21st century. Extreme high events (storms and floods), in particular, are projected to increase in the future. There is little consensus in the literature regarding future projections of annual streamflow volumes, but in general spring streamflow peaks are expected to arrive earlier in the year and may increase in volume. Simultaneously, summer low flow volumes may reduce and some studies indicate increased drought frequency.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.15**.

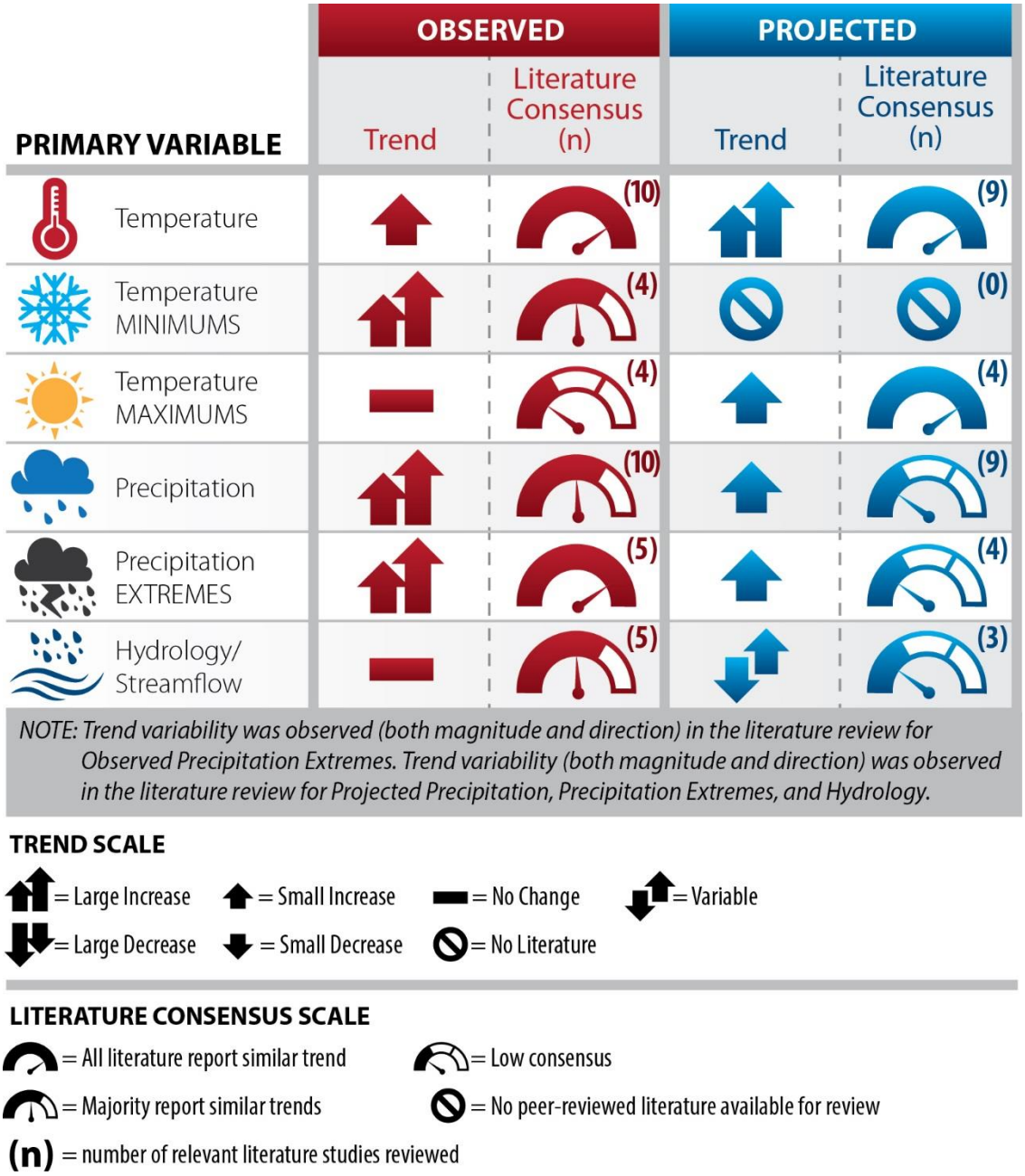


Figure 3.15. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The New England Region encompasses the New England states – Massachusetts, Connecticut, Maine, New Hampshire, Rhode Island, and the eastern half of Vermont. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Recreation
- Emergency Management
- Regulatory
- Military Programs

Millions of tons of cargo are transported to the ports in the New England Region. By the end of the century, the frequency and intensity of large storm events and associated flooding are also expected to increase. This may impact the ability of cargo ships to dock at ports. The New England Region may experience increases in ambient air temperature and a broader range of extremes in water availability, which has implications for water levels and thus the ability for vessels to navigate and dock at inland ports.

The region has experienced several historic flooding events, which impacted urban centers and local communities. USACE implements flood risk management projects in the region, which include structural projects such as storm and hurricane barriers. Annual precipitation and extreme storm events may increase in the region, making flood risk management projects very important for reducing the residual flooding impacts.

USACE also assists with fresh water supply projects. Managing competing water needs can be a challenge, especially when water demand is high and water supply is low. While this report does not highlight the impacts of sea level change, changes in coastal conditions can have impacts which penetrate to inland water bodies. Sea levels along the New England coastline of the United States are projected to increase and may exacerbate salt water intrusion into freshwater water supply. Tools and information related to sea level change can be found on the USACE Responses to Climate Change website (USACE, 2014). Water supplies may also be strained due to increased temperatures and heat waves in the summer months. Droughts are expected to slightly increase, despite an overall increase in precipitation. Maintaining necessary flows for competing sources such as ecosystem management, may present some significant, additional challenges to an already complex water resource system.

USACE implements several ecosystem restoration projects in the New England Region, such as examining existing ecosystems, developing watershed management plans, performing restoration feasibility studies, executing comprehensive river restoration, and preserving and maintaining natural habitats. Increased air temperatures and increased frequencies of drought, particularly in

the summer months, will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

Increased annual rainfall in the region may pose complications to planning for ecosystem needs and lead to higher peak flows and lower low flows. This may be particularly true during dry years, when water demands for conflicting uses may outweigh water supply. During wet years, flooding may raise particular ecological concerns and may threaten ecosystems.

Recreational facilities in the New England Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat waves in the summer months and the increased frequency of extreme storm events have the potential to decrease the number of visitors to USACE's recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal blooms and other water quality issues which may cause health risks for those involved in aquatic activities. An increase in extreme storm events may make recreational activity difficult, dangerous, or impossible.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. Extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the New England Region. These types of storms are capable of intense precipitation, winds, and storm surge in coastal areas. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulation or increase the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. Such interrelationships must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt.

Figure 4.1 summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
Increased Ambient Temperatures	Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region: • Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers. **BUSINESS LINES IMPACTED:**
Increased Maximum Temperatures	Air temperatures are expected to increase in the latter half of the 21st century, especially in the summer months. Heat wave day temperatures may increase between 3-9 °F (2-5°C) and there may be over 60 more days with temperatures reaching over 90°F (32°C). This is expected to create the following vulnerabilities on business lines in the region: • Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies. • Increased evapotranspiration. • Increased human health risk from extended heat waves, impacting recreational visitors and increasing the need for emergency management. **BUSINESS LINES IMPACTED:**
Increased Annual Precipitation	By the middle of the century, annual precipitation is expected to increase in the region which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**
Increased Storm Intensity and Frequency	Extreme storm events may become more intense and frequent over the coming century which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Change in engineering design standards to accommodate new extreme storms magnitudes. • Increased groundwater recharge rates, as residence times are shortened within areas where evapotranspiration takes place during high intensity events. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**
Streamflow Variability	Streamflow may have more variability's by the end of the century. This includes an increase in runoffs by 60-200mm and a decrease in snowpack of up to 25%. This may result in: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. • Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers. **BUSINESS LINES IMPACTED:**
Sea Level Rise	Sea level rise may exacerbate saltwater intrusion into fresh water supplies. **BUSINESS LINES IMPACTED:**

NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables

= Navigation = Flood Risk Management = Ecosystem Restoration = Hydropower = Recreation = Water Supply = Emergency Management

Figure 4.1. Summary of projected climate trends and impacts on USACE business lines

Appendix A: References Climate/Hydrology Summary Table

References	Observed										Projected									
	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Ahmed, K.F., Wang, G., Silander, J., Wilson, A.M., Allen, J.M., Horton, R., Anyah, R. (2013)														X	X					
Armstrong, W.H., Collins, M.J., Snyder, N.P. (2012)						X														
Brown, P.J., Bradley, R.S., Keimig, F.T. (2010)	X	X	X																	
Burakowski, E.A., Wake, C.P., Braswell, B., Brown, D.P. (2008)	X	X	X																	
CDM Smith (2012)																X				
DeGaetano, A.T., Alleen, R.J. (2002)		X	X																	
Douglas, E.M., Fairbank, C.A. (2010)				X	X															
Elguindi, N., Grundstein, A. (2013)											X			X						X
Frumhoff, P.C., McCarthy, J.J., Melillo, J.M., Moser, S.S., Wuebbles, D.J. (2007)	X		X	X	X	X	X	X			X		X	X	X	X	X	X		
Gao, Y., Fu, J.S., Drake, J.B., Liu, Y., Lamarque, J.F. (2012)													X	X	X					
Grundstein, A. (2009)				X				X												
Grundstein, A., Dowd, J. (2011)	X	X	X																	
Hagemann, S., Chen, C., Clark, D.B., Folwell, S., Gosling, S.N., Haddeland, I., Hanasaki, N., Heinke, J., ..., Wiltshire, A.J. (2013)																X				
Hayhoe, K., Wake, C.P., Huntington, T.G., Lifeng, L., Schwartz, M.D., Sheffield, J., Wood, E., Anderson, B., ..., Wolfe, D. (2007)	X			X		X	X	X	X		X			X		X	X	X	X	
Hayhoe, K., Wake, C., Anderson, B., Liang, X., Edwin, M., Zhu, J., Bradbury, J., DeGaetano, A., ..., Wuebbles, D. (2008)											X		X	X						
Hodgkins, G.A., Dudley, R.W., Huntington, T.G. (2003)						X														
Horton, R., Yohe, R., Easterling, W., Kates, R., Ruth, M., Sussman, E., Whelchel, A., Wolfe, D., Lipschultz, F., (2014)	X			X	X						X		X							
Huntington, T.G., Hodgkins, G.A. (2004)				X																
Huntington, T.G., Richardson, A.D., McGuire, K.J., Hayhoe, K. (2009)	X			X	X	X		X			X			X	X	X	X	X		
Kalra, A., Piechota, T.C., Davies, R., Tootle, G.A. (2008)						X														
Kunkel, K.E., Liang, X.-Z., Zhu, J. (2010)																				
Kunkel, K.E., Palecki, M.A., Ensor, L., Easterling, D., Hubbard, K.G., Robinson, D., Redmond, K. (2009)				X	X						X		X							
Liu, Y., Goodrick, S.L., Stanturf, J.A. (2013)											X		X	X			X			
McRoberts, D.B., Nielsen-Gammon, J.W. (2011)				X																
Meehl, G.A., Arblaster, J.M., Branstator, G. (2012)	X																			
Milly, P.C., Dunne, K.A., Vecchia, A.V. (2005)											X									
NSW, National Weather Service., (1961)				X																
Palecki, M.A., Angel, J.R., Hollinger, S.E. (2005)				X																
Pryor, S.C., Howe, J.A., Kunkel, K.E. (2009)				X	X															
Rawlins, M.A., Bradley, R.S., Diaz, H.F. (2012)											X			X						
Scherer, M., Diffenbaugh, N. (2014)											X	X	X							
Schwartz, M.D., Ault, T.R., Betancourt, J.L. (2013)	X								X											
Small, D., Vogel, R.M., Islam, S. (2006)				X		X														
Thibeault, J.M., Seth, A. (2014)														X						
Thomson, A.M., Brown, R.A., Rosenberg, N.J., Srinivasan, R., Izaurralde, R.C. (2005)																X				
Trombulak, S.C., Wolfson, R. (2004)	X			X																
Tryhorn, L., Degaetano, A. (2013)																X				
Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K.E., Stephens, G., Thorne, P., ..., Somerville, R., (2014)	X																			
Wang, H., Schubert, S., Suarez, M., Chen, J., Hoerling, M., Kumar, A., Pegion, P. (2009)	X			X																
Wang, J., Zhang, X. (2008)				X	X									X	X					
Westby, R.M., Lee, Y.-Y., Black, R.X. (2013)	X	X																		

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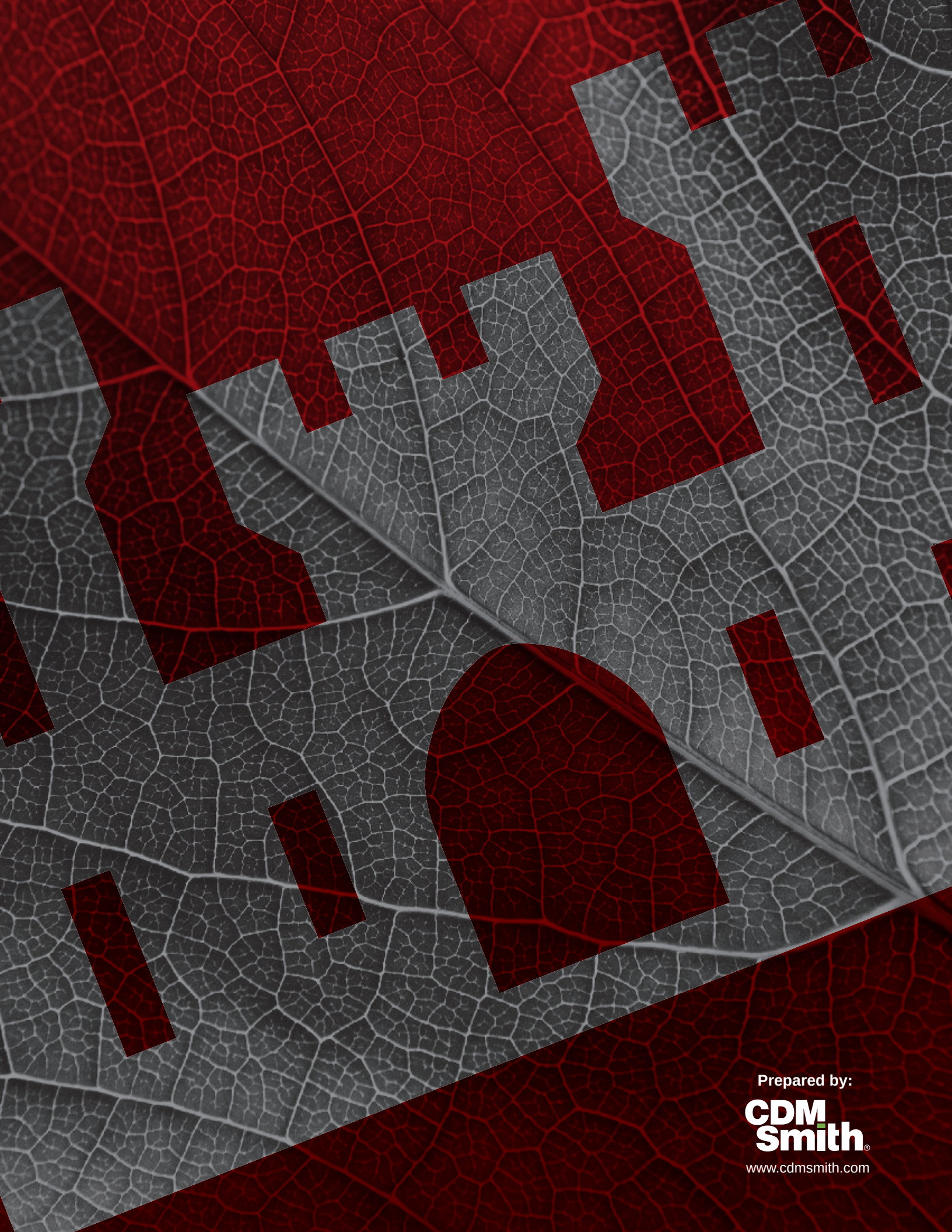

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