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Climate Change in the Piscataqua/Great Bay Region: Past, Present, and Future

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Climate Change in the Piscataqua/Great Bay Region: Past, Present, and Future

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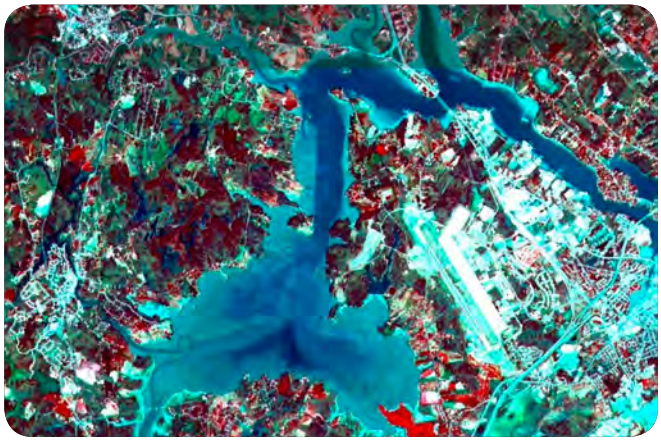


Contents

Executive Summary i
I. Introduction 1
II. Historical Climate Change
Temperature 5
Extreme Temperature 8
Precipitation 10
Extreme Precipitation 13
Snowfall 15
Snow Cover 16
River Flow: Lamprey River and Oyster River 17
Lake Ice Out: Winnipesaukee, NH and Sebago, ME 20
Sea Surface Temperature 21
III. Future Climate Change
Overview of Global Climate Models 23
Why Use Statistical Downscaling? 23
Temperature 24
Extreme Temperature 27
Precipitation 31
Extreme Precipitation 31
Snow Cover 34
IV. Sea Level Rise
Historical Sea Level Rise 35
Future Changes in Sea Level and Coastal Flooding 36
V. Conclusions 38
Appendix A: Durham Minimum Temperatures 40
Appendix B: Modified Statistical Asynchronous Regression Downscaling Method 42
Endnotes 44

Executive Summary

EARTH'S CLIMATE CHANGES. It always has and always will. However, an overwhelming body of scientific evidence indicates that human activities – including the burning of fossil fuel for energy, clearing of forested lands for agriculture, and raising livestock – are now a significant and growing force driving change in the Earth's climate system. This report describes how the climate of the Piscataqua/Great Bay region has changed over the past century and how the future climate of the region will be affected by human activities that are warming the planet.

Overall, the region has been getting warmer and wetter over the last century, and the rate of change has increased over the last four decades. Detailed analysis of data collected at four meteorological stations (Durham and Concord NH; Lawrence, MA; and Portland, ME) in and around the Piscataqua/Great Bay region show that since 1970, mean annual temperatures have warmed 1.3 to 1.7 °F, with the greatest warming occurring in winter (2.7 to 4.2 °F). Average minimum and maximum temperatures have also increased over the same time period, with minimum temperatures warming faster than mean temperatures. Both the coldest winter nights and the warmest summer nights are warming as well. Over the past four decades, annual precipitation has increased 5 to 20%, and extreme precipitation events (more than one inch of precipitation in 24 hours and more than four inches of precipitation in 48 hours) have increased across the region. While the amount of snowfall and the number of snow-covered days does vary on decadal time scales over the past six decades, there are no significant trends. Annual discharge has increased in the Lamprey and Oyster rivers, due primarily to increases in flow during the fall. More than a century of observations shows that lake ice-out dates on Lake Winnipesaukee and Sebago Lake are occurring earlier today than in the past. Data collected from ships, buoys, and other observational platforms show that the rate of warming of sea surface temperatures in the Gulf of Maine has quadrupled over the last four decades.

To generate future climate projections for Durham, Concord, Lawrence, and Portland, simulated temperature and precipitation from four atmosphere-ocean general circulation models were fitted to local, long-term weather observations. Unknowns regarding future fossil fuel consumption were accounted for by using two future emissions scenarios, each of which paints a very different picture of the

future. In the "lower emissions" scenario, improvements in energy efficiency combined with the development of renewable energy reduce our emissions below those of today by 2100. In the "higher emissions" scenario, fossil fuels are assumed to remain a primary energy resource, and our emissions grow to three times those of today by 2100. The scenarios describe climate in terms of temperature and precipitation for three future periods: the near-term (2010-2039), mid-century (2040-2069), and end-of-century (2070-2099). All changes are relative to a historical baseline, 1970-1999.

As greenhouse gases continue to accumulate in the atmosphere, seasonal and annual temperatures will rise in the Piscataqua/Great Bay region. Depending on the scenario, mid-century temperatures increase by 3 to 6°F, and end-of-century temperatures increase as much as 4°F to 9°F. Summer temperatures experience the most dramatic change, up to 11°F warmer under the higher emissions scenario. Extreme heat days are projected to occur more often, and to be hotter. At end-of-century, under a lower emissions scenario, days where temperatures rise above 90°F increase to more than 20 per year from their current average of 9 per year. Under a higher emissions scenario, these hot days increase to more than 60 days each year in Durham, Concord, and Lawrence, raising concerns regarding the impact of extreme, sustained heat on human health, infrastructure, and the electricity grid. These concerns are further exacerbated by projections of increases in very hot days, where temperatures climb above 95°F. Under higher emissions, these may increase to more than 30 days per year from their current average of just one day each year.

Extreme cold temperatures are projected to occur less often, and cold days will be warmer than in the past. By the end of the century, under lower emissions, Durham could experience 25 fewer days with minimum temperatures below 32°F (a 15% decline), or under the higher emissions scenario 50 fewer days with minimum temperatures below 32°F (a 30% decline). Very cold days, where minimum temperature falls below 0°F, are projected to drop from their current average of 12 days per year in Durham, to 4 days per year under lower emissions and less than one day per year on average under higher emissions before the end of the century. Coldest temperatures of the year are also expected to warm. As an example, by the end of the century, the lowest temperatures on the coldest day of the year in Durham under the lower emissions scenario will on average be 8 to 9°F warmer and under the high emissions scenario will be 19 to 20°F warmer. These changes will reduce winter heating bills and the risk of cold-related accidents and injury. However, they may also lift the cold temperature constraints currently limiting some pest and invasive species to more southern states, and simultaneously reduce the number of chilling hours experienced each year required for iconic crops such as berries and fruit.

Annual average precipitation is projected to increase 12 to 17% by end-of-century. Larger increases are expected for winter and spring, exacerbating concerns regarding rapid snowmelt, high peak stream flows, and flood risk. In addition, the Piscataqua/Great Bay region can expect to see more extreme precipitation events in the future, and more extreme precipitation events under the higher emissions scenario relative to the lower emissions scenario. Frequency of drought, a precipitation deficit more than 20% below long-term historical averages for a month, is projected to remain the same in Durham and Lawrence under the higher emissions scenario, while Portland can expect the number of months in drought conditions to double by 2070-2099. Under the lower emissions scenario, all three stations are projected to experience a slight decrease in the number of months in drought.

Tidal gauge data indicates relative sea level at Portsmouth is rising at about 0.7 inches per decade over the past eight decades. To generate future projections of coastal flooding on the New Hampshire seacoast, projected increases in global and regional sea level were combined with current 100-year flood elevations, also using two future emissions scenarios. Coastal flooding projections, not including wave effects, were generated for 2050 and 2100, relative to 1990. Flood maps showing the spatial extent of these estimates of future coastal flooding elevations for the New Hampshire seacoast will be developed once the new digital elevation model has been generated from the recently acquired LiDAR (Light Detection And Ranging) data. A review of the most recent analyses suggests that global sea level rise by 2100 will range from 1.7 to 6.3 feet, not including wave effects. Our analysis shows that this results in 100-year flood stillwater elevations at Fort Point (at the mouth of the Piscataqua River) will range from 9.4 to 12.9 feet by 2050 and 10.9 to 17.5 feet by 2100. These estimated stillwater elevations do not include wave effects, which can be significant.

The changes in climate over the past several decades are already having a significant impact on New Hampshire's coastal watershed. The projected changes in the climate of the Piscataqua/Great Bay region over the next century will continue to impact ecosystems and society in a range of ways. Because some future changes are inevitable, smart choices must be made to ensure our society and our environment will be able to adapt. But with prompt action that improves the efficiency with which we use energy and significantly enhances sources of renewable energy, many of the most extreme consequences of climate change can be avoided and their worst impacts reduced. Our hope is that the focused information presented in this report provides local and regional stakeholders with decision relevant information and serves as a foundation for the development of local climate change adaptation plans.

Introduction

OVER MOST OF EARTH'S 4.5 billion year history, large-scale climate variations were driven by natural causes including gradual shifts in the Earth's orbital cycles, variations in solar output, changes in the location and height of continents, meteorite impacts, volcanic eruptions, and natural variations in the amount of greenhouse gases in the atmosphere[1].

Today, however, the story is noticeably different. Since the Industrial Revolution, atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have been rising because of increasing emissions from human activities[2]. The primary source of CO_2 comes from the burning of fossil fuels such as coal, oil, and natural gas. Emissions and Carbon dioxide are also produced by land use changes, including tropical deforestation. Agricultural activity and waste treatment are critical sources of CH_4 and N_2O emissions. Atmospheric particles released during fossil fuel combustion, such as soot and sulfates, also affect climate.

Atmospheric levels of carbon dioxide are now higher than they have been at any time in at least the last 800,000 years.[3] As human-derived greenhouse gas emissions continue to rise[4] , analysis of data collected around the globe clearly shows ongoing and often dramatic changes in our climate system such as increases in global atmospheric and sea surface temperatures, increases in atmospheric water vapor, precipitation, and extreme precipitation events, rising sea levels, reductions in the extent of late summer Arctic sea ice and northern hemisphere snowcover, melting of mountain glaciers, increases in the flux of ice from the Greenland and West Antarctic ice sheets into the ocean, and thawing permafrost and methane hydrates[2,5] . An overwhelming body of scientific evidence[2,6] shows that it is very likely that most of the climate changes observed over the last fifty years have been caused by emissions of heat-trapping or greenhouse gases from human activities.

The northeast United States has already experienced an overall warming over the past century, with an increase in the rate of warming over the past four decades.[7] This regional climate change has been documented in a wide range of indicators that include increases in temperature (especially in winter), increase in overall precipitation and an increase in the nubmer of extreme precipitation events, an increase in the rain-to-snow precipitation ratio, a decrease in snow cover days, earlier ice-out dates, eariler spring runoff, earlier spring bloom dates for lilacs, longer growing seasons, and rising sea levels.

Over the coming century, New Hampshire's coastal climate is expected to continue to warm in response to increasing emissions of heat-trapping gases from human activities. At the global scale, temperature increases anywhere from 2°F up to 13°F are expected. This range is due to two important sources of uncertainty: future emissions of heat-trapping gases; and the response of the Earth's climate system to human-induced change. The first source of uncertainty is addressed through generating climate projections for two very different pictures of the future: a "higher emissions" future where the world continues to depend on fossil fuels as the primary energy source, and a "lower emissions" future where we focus on sustainability and conservation. The second source of uncertainty is addressed by using four different atmosphere-ocean general circulation models to simulate the climate changes that would result from these two very different futures. The climate models used here cover the accepted range of how the climate system is likely to respond to human-induced change.

Global climate models operate on the scale of hundreds of miles, too large to resolve the changes over New Hampshire's coastal watershed (Figure 1) also referred to as the Piscataqua/Great Bay region in this report. State-of-the-art statistical techniques were used to "downscale" or match the regional temperature and precipitation simulations generated by the global climate models[8] to observed conditions at four individual long-term weather stations in the Piscataqua/Great Bay region: Durham and Concord, NH; Lawrence, MA; and Portland, ME (Figure 2).

The research results presented in this report describe the changes in climate that have already occurred over the past century and the changes that might be expected over the coming century. Section II shows how the climate across the Piscataqua/Great Bay region has changed over the past century using a number of different indicators that include annual and seasonal temperature, precipitation, extreme precipitation events, ice-out dates, snowfall and snowcover, and sea surface temperatures. Section III describes: (1) how climate model simulations are downscaled using a state-of-the-art asynchronous statistical regression method based on long-term daily observations at those sites; (2) discusses how average and extreme temperatures are

Figure 1. New Hampshire coastal watershed communities.
Map provided by the Piscataqua Region Estuaries Project (PREP).

likely to be affected by climate change in the near future (2010-2039), by mid-century (2040-2069) and towards the end of the century (2070-2099) relative to a historical baseline of 1970-1999; and (3) describes projected changes in annual and seasonal rain and snow, as well as heavy rainfall events, for those same future time periods. Section IV discusses historical sea level rise over the past eight decades measured at the mouth of the Piscataqua River and describes the potential impacts of increased coastal flooding as sea levels continue to rise. Finally, Section V concludes with a discussion of the implications of climate change for the future.

The implications of the results presented here – of warmer temperatures and shifting precipitation patterns and increased coastal flooding – for the Piscataqua/Great Bay region are pervasive[9]. For example, warmer temperatures affect the types of trees, plants, and even crops likely to grow in the area. Long periods of very hot conditions in the summer are likely to increase demands on electricity and water resources. Hot summer weather can also have damaging effects on agriculture, human and ecosystem health, and outdoor recreational opportunities. Less extreme cold in the winter will be beneficial to heating bills and cold-related injury and death; but at the same time, rising minimum temperatures in winter could open the door to invasion of cold-intolerant pests that prey on the region's forests and crops. Warmer winters and a reduction in snow-covered days will also have an impact on winter recreation opportunities. Rising winter and spring precipitation could increase the risk of spring riverine flooding. Coastal flood elevations will continue to increase due to sea level rise, leading to increasingly larger areas of flooding during coastal storms. These changes will have repercussions on the region's environment, economy, and society. However, if we respond to the grand challenge of significantly reducing our emission of greenhouse gases we can avoid the more catastrophic climate change, begin to adapt to changes that are already in the pipeline, and, in the process, develop a new sustainable society for the remainder of the 21st century.

What about weather data from Portsmouth, NH and Greenland, NH?

Figure 2 shows the location of the four stations where the weather data used in this report was collected. Weather observations have also been collected since 1933 in Portsmouth, which lies at the mouth of the Piscataqua River that connects the Great Bay to the Gulf of Maine. However, three different issues have introduced non-climatic influences on the data from Portsmouth that significantly reduce our confidence in using the records to track changes in climate over time. First, the site of the station has moved three times since its inception, in the 1940s, 1956, and finally in 1957 to current location at Pease International Tradeport. Changing weather observation sites introduces biases and discontinuities into the time series that can be difficult to correct. Second, a four-year gap of missing data exists between 1973-1976. Third, the observations made between 1977 and 2001 are not yet digitized. This period of observations only exists on paper and many months of work are needed to digitize these data to make them ready for statistical analysis.

There is also a cooperative weather observation site at Greenland, NH just south of Great Bay whose records were initially considered for this study. The observations are of good quality and have been collected at the same location by the same observer for the entire length of the record. Unfortunately, the record only goes back to 1974, which is too short for an accurate assessment of long-term climate change.

Historical Climate Change

Annual and Seasonal Temperature Trends: Records from New Hampshire's Coastal Watershed and Beyond

Temperature records are one of the most commonly used indicators of climate change. In a modern world warmed by greenhouse gases originating from the burning of fossil fuels and land use change, temperatures have risen and will likely continue to rise in the Piscataqua/Great Bay region.

The temperature record from Durham, NH provides the longest, most continuous, record of temperature change within the Great Bay watershed. The United States Historical Climatology Network (USHCN) performs numerous quality assurance and quality control checks on all historical climatology data sets and corrects temperature records for time-of-observation biases and other non-climatic changes such as station relocations, instrument changes, changes in observer, and urban heat island effects through homogeneity testing[10]. We have also included analysis of the two nearest high-quality USHCN stations, Lawrence, MA and Portland, ME (Figure 2).

All historical climate trends are calculated using Sen's slope[11] and expressed as change in units per decade (e.g., °F/decade). Sen's estimation of slope is succinctly described as the median slope of all possible slopes in an evenly spaced time series. As such, it provides a more robust trend estimation than the commonly used least squares linear regression, which may be sensitive to the start and end dates in a time series. The statistical significance of the slope is evaluated using the Mann-Kendall non-parametric test. Trends are considered statistically significant if $p<0.05$. All time series figures presented in this report also include locally weighted scatter plot smoothing (LOWESS) to illustrate decadal-scale variability that may not otherwise be apparent by looking at the annual time series alone.

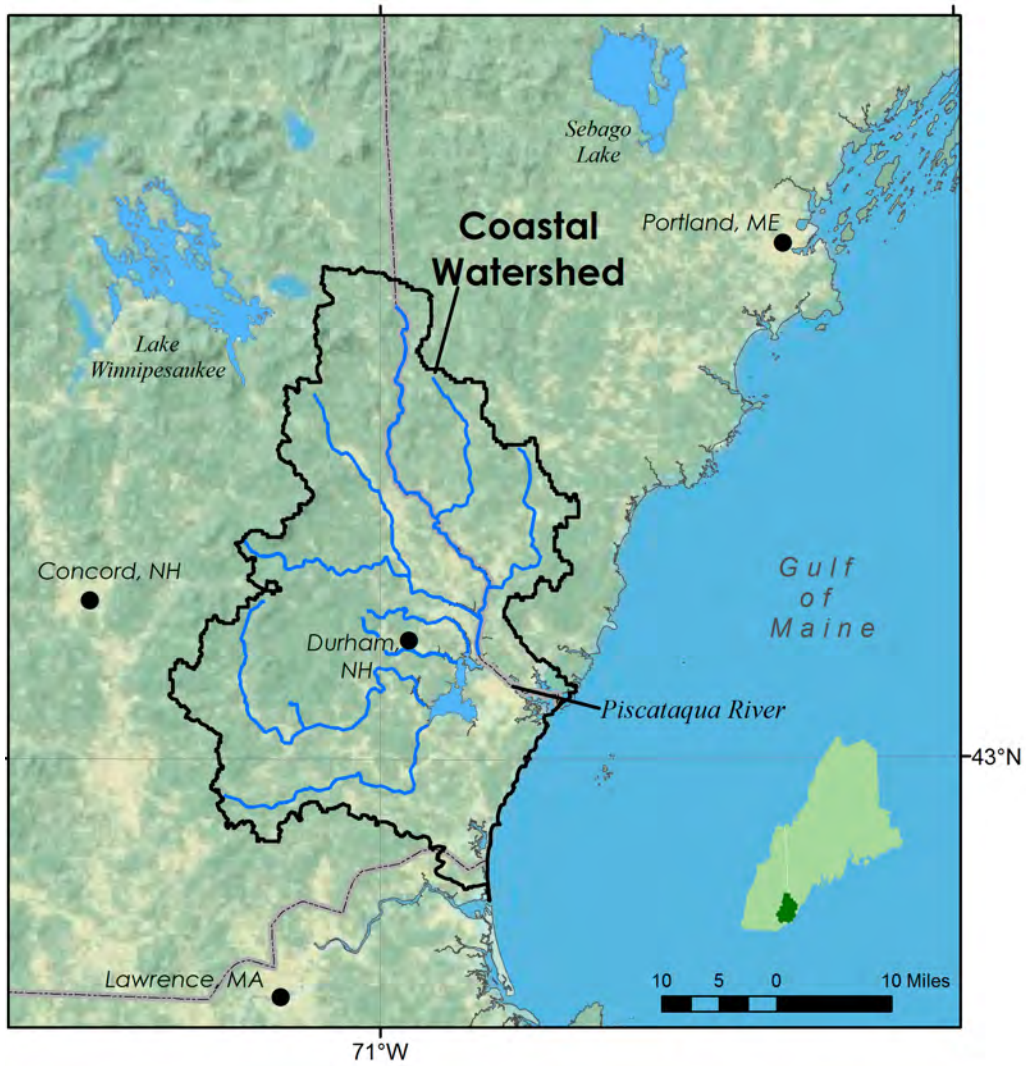


Figure 2. Map of the Piscataqua region and Great Bay watershed showing the location of United States Historical Climate Network stations (Durham, NH, Lawrence, MA, and Portland, ME) and Global Historical Climate Network stations (Concord, NH)(black dots). These stations provide historical climate data within and around the Great Bay watershed over the time period 1895-2009.

Long Term Temperature Trends: 1895-2009

Despite the extensive quality assurance and quality control checks carried out on USHCN records, we remain concerned with the quality of the Durham minimum temperature record, which exhibits a moderate decreasing trend from 1895-1948. This decreasing trend is not apparent in the Durham maximum temperature record (Appendix A). Neither Lawrence nor Portland show decreasing trends in minimum or maximum temperature over the 1895-1948 period, suggesting that the Durham minimum temperature may be affected by non-climatic biases unresolved by USHCN Quality Assurance/ Quality Control methodologies. For this reason, the Durham minimum temperature record has been excluded from our analysis.

Overall, both maximum and minimum temperatures show increasing trends over the period of record (Figures 3 and 4). As is common in New England, significant year-to-year variability is evident at all three stations. Cool temperatures dominate the first half of the 20th century, followed by a warm period in the 1940s to 1950s. Temperatures cool slightly through the 1960s and 1970s, followed by the current warm period of increasing temperatures from 1980-present. In Lawrence and Portland, seven of the ten warmest years occur after 1990 (Table 1).

Significant warming trends are detected using Sen's slope on annual maximum temperature records at all three USHCN stations over the period 1895-2009 (Table 2). In Durham NH, maximum temperatures warmed by +0.11°F/decade while Lawrence and Portland show warming of +0.16°F/decade and 0.21°F/decade, respectively. Significant warming trends are apparent in the Lawrence and Portland minimum temperature records that are

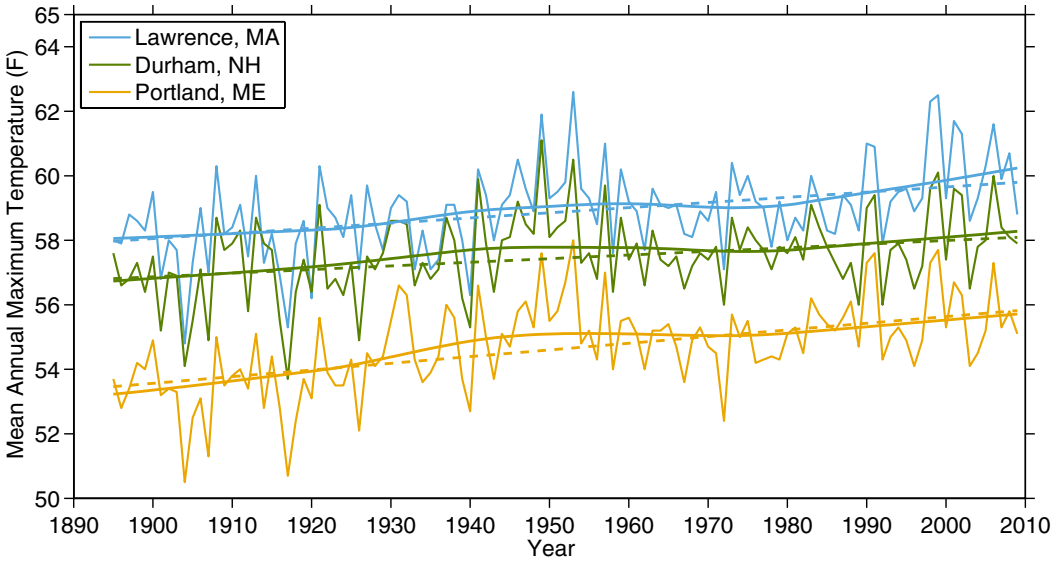


Figure 3. Annual maximum temperature records with LOWESS smooths (solid) and Sen's slope (dashed) for Durham, NH, Lawrence, MA and Portland, ME, 1895-2009.

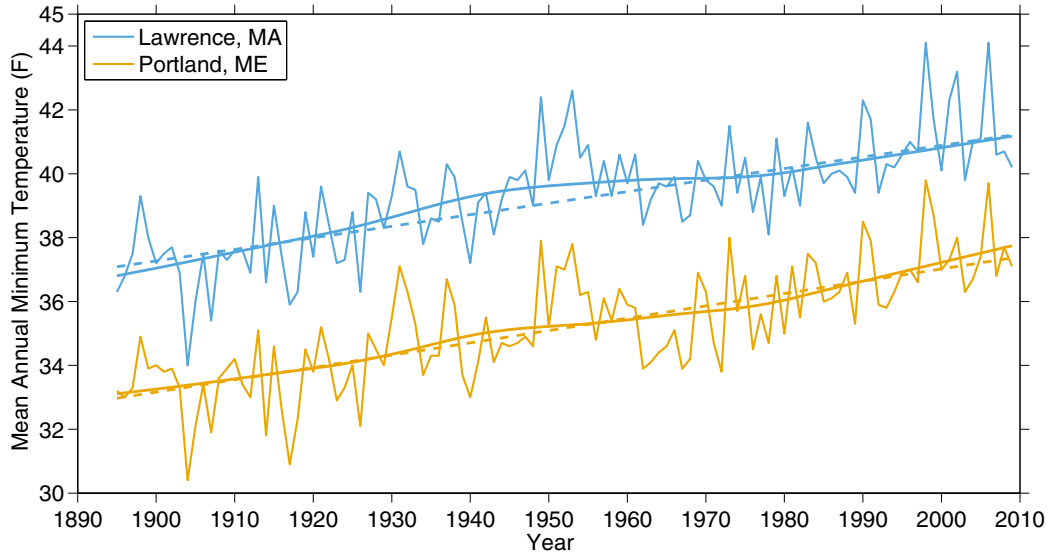


Figure 4. Annual minimum temperature time series, LOWESS smooths (solid), and Sen's slope (dashed) for Lawrence, MA and Portland, ME, 1895-2009.

double the rate of their respective maximum temperature warming trends. In Portland and Lawrence the annual minimum, maximum, and mean temperature trends were found to be statistically significant. In Durham, the trend in maximum temperature was also statistically significant.

Over the long-term record 1895-2009, every season at all three stations displays a warming trend (Table 2) even while seasonal rates of warming vary across the region. In Durham, spring maximum temperatures exhibit the greatest seasonal rate of warming (+0.21°F/decade). Interestingly, winter maximum temperatures have warmed the fastest in Lawrence, MA whereas summer temperatures have warmed the fastest in Portland, ME. In Portland and Lawrence, all annual and seasonal minimum and maximum temperature trends are statistically significant, with the exception of Lawrence springtime maximum temperatures. Statistically significant warming trends in Durham's annual, spring and summer maximum temperature records were also detected. Regardless of the wide range in seasonal rates of warming, the message from the long-term USHCN temperature records is very clear: the region encompassing the Great Bay National Estuarine Research Reserve has been warming over the past century.

Recent Temperature Trends: 1970-2009

We repeat the temperature trend analysis for the same three stations over the last four decades, 1970-2009. This period coincides with the marked increase observed in global

PORTLAND, MAINE		LAWRENCE, MA	
1998	53.2	1998	48.6
2006	52.9	2006	48.5
1953	52.6	1999	48.2
2002	52.3	1953	47.9
1949	52.2	1990	47.9
1999	52.1	1949	47.8
2001	52.0	1991	47.8
1990	51.7	2002	47.2
1991	51.3	2001	47.0
1973	51.0	1931	46.9

Table 1. Top ten annual mean temperature rankings, in °F.

°F/decade (1895-2009)	DURHAM, NH	LAWRENCE, MA	PORTLAND, ME
Maximum Temperature	**+0.11**	**+0.16**	**+0.21**
Winter	+0.11	**+0.32**	**+0.19**
Spring	**+0.21**	+0.12	**+0.20**
Summer	**+0.18**	**+0.13**	**+0.33**
Fall	+0.02	**+0.15**	**+0.17**
Mean Temperature	--	**+0.27**	**+0.29**
Winter	--	**+0.45**	**+0.31**
Spring	--	**+0.24**	**+0.31**
Summer	--	**+0.21**	**+0.40**
Fall	--	**+0.22**	**+0.22**
Minimum Temperature	--	**+0.36**	**+0.39**
Winter	--	**+0.56**	**+0.41**
Spring	--	**+0.38**	**+0.42**
Summer	--	**+0.30**	**+0.49**
Fall	--	**+0.28**	**+0.29**

Table 2. Annual and seasonal temperature trends (in °F/decade) for the period *1895-2009* for three USHCN stations located within or near the New Hampshire coastal watershed. The trends were estimated using Sen's slope; trends that meet the Mann-Kendall non-parametric test for statistical significance ($p<0.05$) are highlighted in **bold and underlined**.

Portsmouth Harbor Frozen – 1918

Collection Thomas C. Wilson Photograph Collection.
Photograph provided courtesy of Portsmouth Athenaeum

This photograph of the Piscataqua River, which separates Portsmouth from Kittery, Maine, shows ice covering Portsmouth Harbor. The winter of 1918 remains the coldest winter during the period of record from 1895 to 2009. The mean wintertime temperature was 17.4ºF, or 7.1ºF below the long-term average.

The caption on the back of the photograph states "The picture taken 30 years ago on February 11, 1918 shows the Government Ferry boat No 1048 stuck in the middle of the river because of an ice jam and employees of the Navy Yard shown walking to the Portsmouth shore on planks laid down on the ice. In the left of the picture can be seen the old wooden toll bridge of the Boston & Maine Railroad, now replaced by the present Maine-New Hampshire Interstate Bridge. "

temperatures that are very likely caused by anthropogenic activities, including the burning of fossil fuels and land use changes that have led to increases in greenhouse gas concentrations in the atmosphere[12]. The 1970-2009 trend analysis includes minimum, maximum, and mean temperature records from all three stations as the Durham station does not show the inconsistencies in minimum temperature over this time period (Appendix A).

All three USHCN stations over the period 1970-2009 show marked increases in warming rates for annual and seasonal minimum, maximum, and mean temperature (Table 3) relative to the long-term 1895-2009 trends, consistent with recent increases in global temperature. All stations show significant warming trends in annual mean and minimum temperatures. Lawrence and Portland also show significant warming trends in annual maximum temperature. Durham annual maximum temperature warmed at a rate of +0.13ºF/decade, but was not statistically significant.

At the seasonal level, most notable are the dramatic increases in the rate of winter warming, which surpass all other seasonal rates of warming over the last four decades at all three stations. Significant warming trends in winter minimum temperatures are identified at all three stations. Lawrence and Portland also exhibit significant warming trends in winter maximum temperature. The rate of warming in Durham winter maximum temperatures nearly quadrupled relative to the 1895-2009 trend. The large increases in winter temperature may be linked to decreasing snow cover through changes in surface albedo, or reflectivity. Significant warming trends in summer and fall minimum temperature were also apparent at all three stations in the Great Bay region.

Extreme Temperature Trends

The trends observed in annual and seasonal temperature may be too subtle for the average person to detect via personal experience. However, temperature extremes may provide more apparent clues to warming trends. Changes in the distribution of extreme temperatures can lead to increased duration and frequency of heat waves[13], lengthening of the growing

season[12], and northward expansion of invasive insects like the woolly adelgid (*Adelges tsugae*), an aphid-like insect that has decimated stands of eastern hemlock from Georgia to Connecticut since the 1950s[14]. Increasing trends in minimum daily temperature are indicators of nighttime warming while trends in maximum daily temperature provide insight to daytime processes.

Durham, Lawrence, and Portland all have daily temperature records that have been homogenized back to 1949[15]. Here, we use a metric known as "percentile exceedances" to evaluate trends in extreme temperatures. For example, the 99th percentile value is the temperature below which 99% of all daily temperature values recorded between 1949 and 2009 fall (and above which only 1% of the values fall). The 1st percentile is the value below which 1% of the daily values fall.

°F/decade (1970-2009)	DURHAM, NH	LAWRENCE, MA	PORTLAND, ME
Maximum Temperature	+0.13	**+0.38**	**+0.30**
Winter	+0.42	**+1.02**	**+0.70**
Spring	+0.24	+0.23	+0.25
Summer	+0.12	+0.18	+0.05
Fall	+0.08	+0.51	**+0.3**8
Mean Temperature	**+0.33**	**+0.43**	**+0.42**
Winter	+0.67	**+1.04**	**+0.89**
Spring	+0.11	+0.25	+0.18
Summer	+0.35	+0.86	+0.23
Fall	+0.36	**+0.59**	**+0.56**
Minimum Temperature	**+0.54**	**+0.47**	**+0.64**
Winter	**+0.88**	**+0.99**	**+1.13**
Spring	no change	+0.33	+0.08
Summer	**+0.67**	**+0.33**	**+0.57**
Fall	**+0.79**	**+0.58**	**+0.69**

Table 3. Annual and seasonal temperature trends (in °F/decade) for the period *1970-2009* for three USHCN stations located within or near the New Hampshire coastal watershed. Trends that meet the Mann-Kendall non-parametric test for statistical significance ($p<0.05$) are highlighted in **bold and underlined**.

Metric	Metric description	DURHAM, NH	LAWRENCE, MA	PORTLAND, ME
1st percentile TMIN	Coldest winter nights	**-0.04**	no change	**-0.10**
99th percentile TMIN	Warmest summer nights	**+0.08**	**+0.09**	**+0.04**
1st percentile TMAX	Coldest winter days	no change	no change	no change
99th percentile TMAX	Warmest summer days	no change	no change	no change

Table 4. Annual and extreme temperature trends (in days/decade) for three USHCN stations located within or near the New Hampshire coastal watershed for the period *1949-2009*. Trends are estimated using Sen's slope; statistically significant trends ($p<0.05$) are highlighted in **bold and underlined**.

We calculate the 99th and 1st percentile minimum and maximum temperature values independently for each of the three stations in and around the Great Bay watershed. In order to calculate the 99th and 1st percentile exceedances, we tally up the number of days per year with temperaures that are greater than the long-term 99th percentile and the number of days per year that the temperatures are less than the long-term 1st percentile. One can think of the 99th percentile as the 'hottest of the hot' and the 1st percentiles as the 'coldest of the cold'. Exceptionally cold years will have a large number of days per year that are less than the 1st percentile ranking while exceptionally warm years will have a large number of days per year that are greater than the 99th percentile. Since daily minimum temperatures (TMIN) typically occur at night and daily maximum temperatures (TMAX) typically occur during the day, we present trends in Table 4 for the following four metrics: (1) coldest winter nights or 1st percentile TMIN, (2) warmest summer nights or 99th percentile TMIN, (3) coldest winter days or 1st percentile TMAX, and (4) warmest summer days or 99th percentile TMAX.

Significant increasing trends in 99th percentile minimum temperatures are observed at all three stations (Table 4). This means the Great Bay and the surrounding region is experiencing an increase of 0.2 – 0.6 days over the past six decades in the number of days with extreme warm nighttime temperatures in summer, a strong indicator of heat waves. During heat waves, warmer nighttime temperatures do not offer cooling relief and contribute to greater threats to human health, especially for those who are most vulnerable, such as elderly individuals who live by themselves[16]. The results obtained in this report are consistent with a nationwide analysis[6], indicating that warmer nighttime minimum temperatures are occurring throughout the Northeastern US, not just in the Piscataqua region. Durham and Portland also exhibit significant decreasing trends in 1st percentile minimum temperatures. These stations are therefore seeing fewer days (on the order of 0.2 – 0.6 days) with extreme cold nighttime temperatures in winter.

Annual and Seasonal Precipitation Trends

Temperature and precipitation trends are linked in Earth's climate system by the hydrological cycle. Increases in precipitation may accompany increases in temperature because warmer air masses can hold more moisture. Regions with abundant moisture sources, such as New England, can therefore expect to see increases in the total amount and intensity of precipitation as temperatures continue to rise[17].

Durham provides the longest and highest quality precipitation record within the Great Bay watershed. Over the 1895-2009 historical record, Durham receives on average 40 inches of precipitation per year. The data quality issues that affect Durham's minimum temperature record do not appear to impact precipitation records. Lawrence, MA and Portland, ME records are also included to provide a more regional view of trends in annual and seasonal precipitation. Precipitation records have undergone rigorous quality checks for outliers and missing values. The three stations generally show coherent patterns of dry years and wet years, including a consistent record of the region-wide drought in the mid 1960's (Figure 5). Other periods, such as 1930-1940 show greater variability among stations. The USHCN stations represent the best available long-term instrumental precipitation records for the Great Bay watershed and surrounding region.

Long-term Precipitation Trends: 1895-2009

Over the period 1895-2009, all three stations in the region exhibit significant increasing trends in annual precipitation (Figure 5; Table 5). In Durham, annual precipitation increased at a rate of +0.59 inches/decade, or +6.73 inches over the past 114 years. This means that on an annual basis the Piscataqua region receives six more inches of precipitation today than it did at the end of the 19th century, an increase of about 8%. In the surrounding region, Portland saw increases of +0.49 inches/decade while Lawrence increased by +0.75 inches/decade.

At all three stations, the increases in annual precipitation are driven primarily by significant increases in precipitation during the fall season. Durham and Lawrence showed similar trends at +0.31 inches/decade and +0.35 inches/decade, respectively. Portland showed the greatest increase in fall

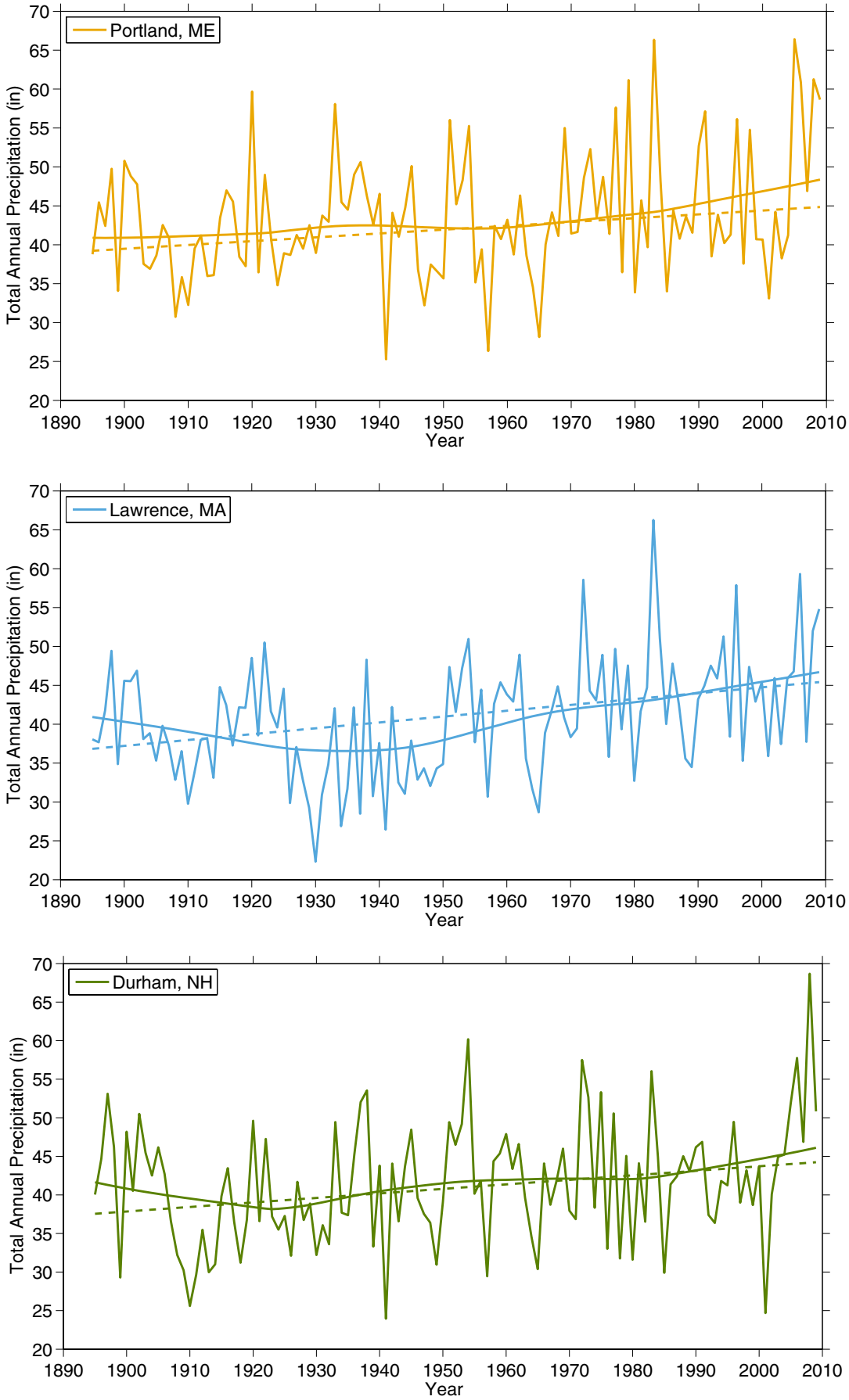


Figure 5. Annual precipitation for Portland (top), Lawrence (middle), and Durham (bottom) showing Sen's slope (dashed) and LOWESS smooths (solid), 1895-2009.

precipitation at +0.45 inches/decade. Lawrence also showed significant increases in spring precipitation (+0.21 inches/decade). We detect no significant long-term trends in winter or summer precipitation at any of the stations.

Recent Precipitation Trends: 1970-2009

Since the 1970s, annual precipitation trends in the Great Bay and surrounding region have continued on an upward trend (Figure 5), though none were found to be statistically significant (Table 6). It would appear the increasing trends in precipitation are being driven by higher than average precipitation totals over the past five years. The Mother's Day storm of May 13th-16th 2006 (10.3 inches in 4 days in Durham) and the April 16th, 2007 Patriot's Day storm (4.5 inches in 1 day in Durham) no doubt contributed to record precipitation totals visible at the tail end of the 114-year time series (Figure 5).

Seasonal precipitation is increasing in spring, summer, and fall but decreasing during winter. Decreases in winter precipitation at all three stations are primarily the result of decreasing snowfall between December and February (see *Snowfall* section). Durham summer precipitation has increased significantly at a rate of +1.04 inches/decade. Summer precipitation trends at Lawrence and Portland are considerably weaker, at +0.07 inches/decade and +0.31 inches/decade, respectively. In Portland, fall precipitation has increased at more than double the rate of spring trends. The opposite is true in Lawrence where spring precipitation trends are more than double fall precipitation trends. In Durham, fall trends are only slightly weaker than spring trends. The variability in seasonal trends in precipitation reflects the overall well-acknowledged greater spatial variability in precipitation compared to spatial variability in temperatures.

Inches /decade (1895-2009)	DURHAM, NH	LAWRENCE, MA	PORTLAND, ME
Annual Precipitation	**+0.59**	**+0.75**	**+0.49**
Winter	no change	+0.04	-0.10
Spring	+0.19	**+0.21**	+0.14
Summer	+0.12	+0.07	+0.09
Fall	**+0.31**	**+0.35**	**+0.45**

Table 5. Annual and seasonal precipitation trends (in inches/decade) for three USHCN stations located within or near the New Hampshire coastal watershed for the period *1895-2009*. Trends are estimated using Sen's slope; statistically significant trends ($p<0.05$) are highlighted in **bold and underlined**.

Inches /decade (1970-2009)	DURHAM, NH	LAWRENCE, MA	PORTLAND, ME
Annual Precipitation	+2.11	+1.11	+0.56
Winter	-0.66	-0.76	-0.91
Spring	+0.47	+0.65	+0.27
Summer	**+1.04**	+0.07	+0.31
Fall	+0.57	+0.23	+0.88

Table 6. Annual and seasonal precipitation trends (in inches/decade) for three USHCN stations located within or near the New Hampshire coastal watershed for the period *1970-2009*. Trends are estimated using Sen's slope; statistically significant trends ($p<0.05$) are highlighted in **bold and underlined**.

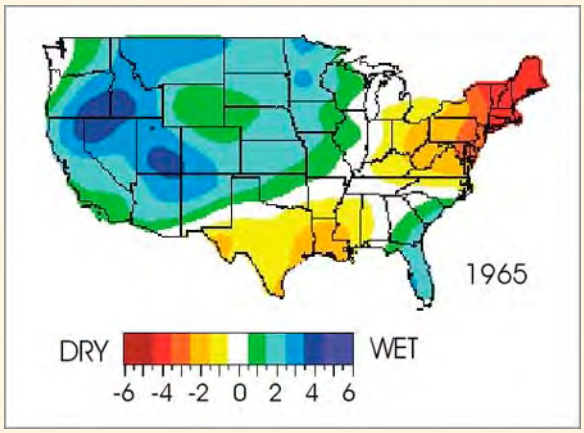
Extreme Precipitation Trends

There are potential benefits that result from an increase in total annual precipitation - alleviation of scarce water resources, less reliance on irrigation, increased resilience to drought. However, those benefits may not occur if the increase in precipitation is primarily the result of an increase in extreme precipitation events which can lead to flooding, damage to buildings, roads, dams, and culverts, increased erosion, and degradation of water quality. Climatologists have many metrics for defining a precipitation event as extreme. Using the same three meteorological stations from the annual and seasonal precipitation analysis, we present trends in three categories of extreme precipitation events; (1) greater than one inch in 24 hours, (2) greater than two inches in 24 hours, (3) greater than two inches in 48 hours, and (4) greater than four inches in 48 hours. Additionally, the percentage of annual precipitation delivered in events greater than one inch in 24 hours is calculated for each year and analyzed for statistical trends.

All three stations show increasing trends in the number of events greater than one inch in 24 hours over the period 1949-2009, though none were found to be statistically significant (Figure 6). The lack of significant trends may be related to the proximity of the meteorological stations to the coast; a similar analysis of precipitation records across New England indicates that the strongest increasing trends in one-inch events are occurring inland.[19] No significant trends in two-inch events or four-inch events were detected. However, when four-inch events are summed by decade, it becomes clear that four inch events are occurring more frequently in the past two decades than in the previous four decades (Figure 7).

Historically averaged over the period 1949-2009, stations in the Great Bay region typically receive about 5%-6% of annual precipitation in events greater than one inch. The percentage of annual precipitation being delivered in events of one inch or greater has only increased slightly in Durham by <1%; Lawrence and Portland each increased 3.6% over the period 1949-2009, with Portland's trend determined to be statistically significant (p=0.0263).

The 1960s Drought in the Northeastern United States



The Palmer Drought Severity Index (PSDI) uses temperature and rainfall data to determine dryness. It is most effective in determining long term drought (several months to years). Zero is normal; minus 4 is extreme drought. Note the values below minus 4 for all of New England in 1965. Image from the NOAA National Climatic Data Center.

The drought of the 1960s was the most severe drought the Piscataqua/Great Bay Region and New Engalnd has experienced over the past several hundred years. The drought had numerous negative impacts including severe water shortages, degradation of water quality, fish kills, increases in the number and severity of forest fires, and severely degraded pasture conditions. Extreme drought conditions affected over 60,000 square miles by summer 1965, when the drought reached its peak. Precipitation shortfalls during spring and summer were the proximal cause of the drought, but what caused the decrease in precipitation? Prevailing circulation patterns indicated an unusually deep mid-tropospheric trough positioned just off the Atlantic Seaboard that pulled northerly, cold, dry air masses over the Northeastern US. The exact causes of the unusual jet stream pattern remain a bit of a mystery, but some scientists have concluded that colder than average sea surface temperatures along the continental shelf triggered the drought pattern of the 1960s.[18]

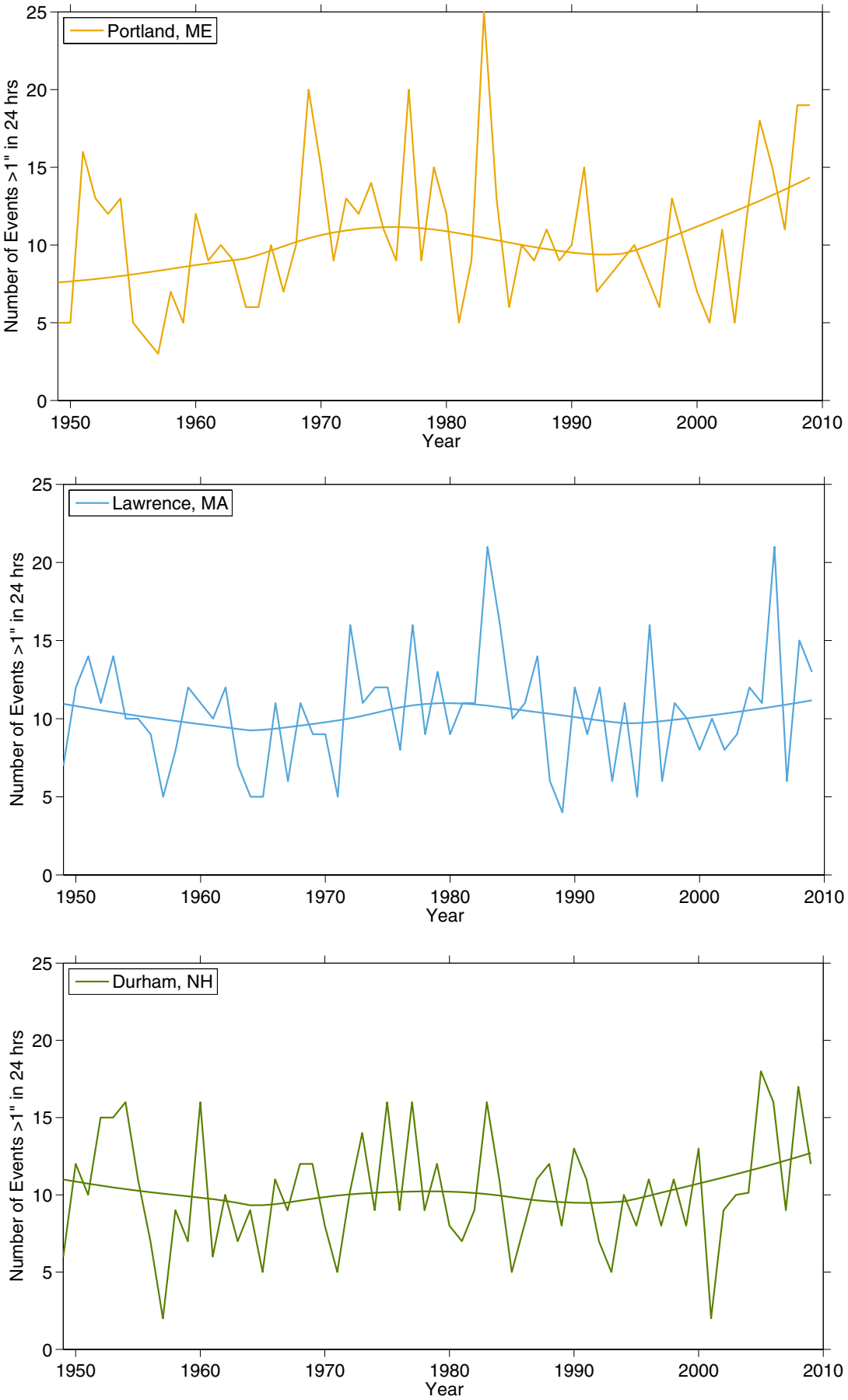


Figure 6. Number of events per year with greater than one inch of precipitation in 24 hours for Portland (top), Lawrence (middle), and Durham (bottom).

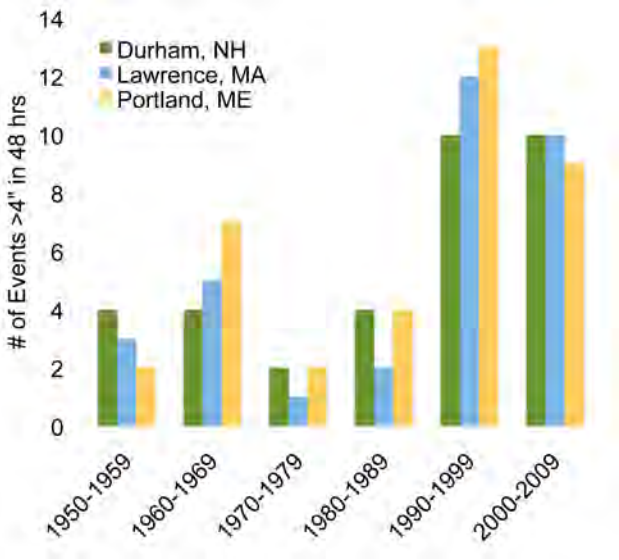


Figure 7. Total number of events with greater than four inches of precipitation in 48 hours per decade.

Snowfall Trends

The response of snowfall trends to warmer winter temperatures is not as straightforward as one would think. Warmer air masses hold more moisture; as long as temperatures remain below freezing, snowfall can be expected. Only when temperatures rise above the freezing point can the region expect to see less snowfall in response to winter warming. As such, there remains large spatial variability in snowfall trends throughout the northeastern US[20].

We report monthly snowfall totals as the sum of all daily snowfall values for a given winter month for the months of December, January, February, and March for all months with less than 10% of daily values reported as missing values.

Though traditionally designated as a *spring* month, we also include March in the winter analysis because snowfall and snow depth totals in March typically exceed those observed in December. The Durham snowfall record is missing five of the last ten years of data and therefore is not be included in this analysis. The Lawrence record is equally as poor, with thirteen winters flagged as missing considerable data between 1984 and 2009. The Concord, NH and Portland, ME records therefore provide the most complete and reliable records of changing snowfall near the Piscataqua/Great Bay region over the period 1949-2009.

A comparison of the smoothed time series of winter snowfall at Concord and Portland reveals similar patterns of decreasing and increasing periods of snowfall. Winter snowfall totals trended upward from 1949-1965, followed by declines over the following 30 years from 1965-1995, concluding with another period of modest increases from 1995-2009 (Figure 8), though no statistically significant trends in seasonal or monthly snowfall over the entire period of record were detected (Table 7).

Concord, NH shows a weak increasing trend in total winter snowfall of +0.2 inches/decade, while Portland shows a strong but not statistically significant decreasing trend of -2.0 inches/decade. At the monthly level, Portland shows overall decreasing trends in total snowfall for all winter months, December through March, yet Concord, NH reveals weak increasing trends for all winter months except February, which showed no detectable change. The inconsistent snowfall trends at Concord and Portland reflects the broader regional scale heterogeneity in snowfall responses to warmer winter temperatures across the Northeastern US[8].

Inches /decade (1949-2009)	CONCORD, NH	PORTLAND, ME
Winter Snowfall	+0.2	-2.0
December	+0.4	-0.1
January	+0.2	-0.3
February	no change	-0.9
March	+0.3	-0.4

Table 7. Seasonal and monthly snowfall trends (inches/decade) for two stations located within or near the Great Bay watershed for the period *1949-2009*. Trends are estimated using Sen's slope; there are no statistically significant trends ($p<0.05$).

Snow Cover Trends

The number of snow-covered days in winter is closely tied to temperature trends through feedback processes related to the high reflectivity (albedo) of freshly fallen snow (think of how bright it is after a snowstorm). Following a fresh snowfall event, the overall reflectivity of the ground decreases as the overlying snow pack ages, melts, and retreats. The retreat exposes bare ground that has a significantly lower albedo. The decrease in reflectivity causes a surface to warm as it absorbs more and reflects less of the sun's energy. In the Piscataqua/Great Bay region, few stations provide snow depth records complete enough to analyze trends in snow-covered days. At the Durham, NH station, a considerable number of snow-depth values are flagged as missing during the winter months December through March over the period 2001-2010, rendering the only long-term record within the Great Bay watershed useless for analysis in recent years. The Lawrence record suffers the same data quality issues as Durham. Fortunately, Concord, NH and Portland, ME provide temporally complete snow-depth records with less than 10% of daily values missing from any given month between 1948 and 2009. Here, a day is considered 'snow-covered' if the daily snow depth value is greater than three inches. Monthly snow-covered days for December-March are summed to calculate the total number of snow-covered days in a given winter.

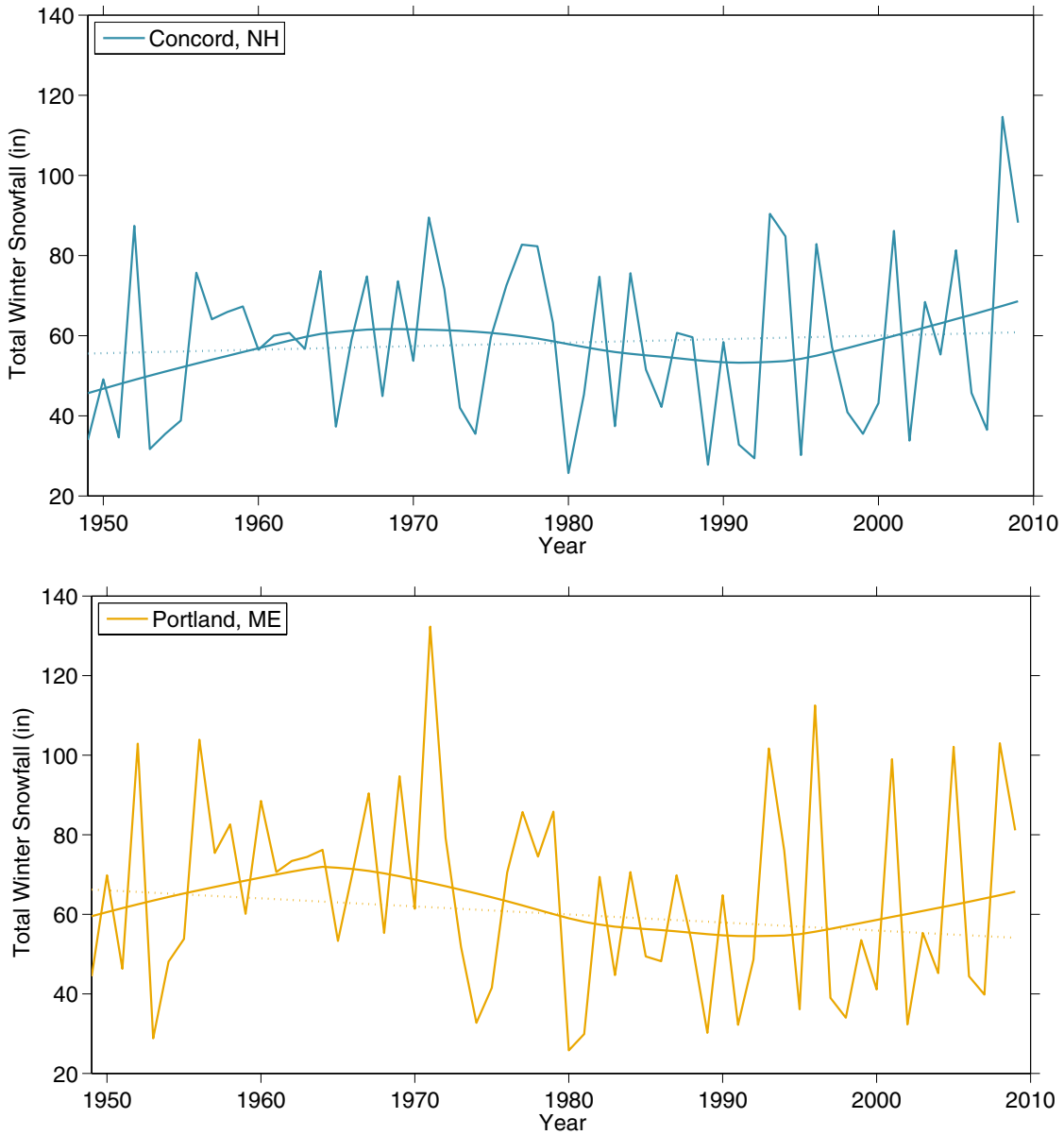


Figure 8. Time series and LOWESS smoothes of total winter snowfall (inches) at Concord, NH (top) and Portland, ME (bottom), 1949-2009. Winter includes the months off December, January, February, and March.

Snow-cover trends follow a similar pattern to snowfall trends, showing a substantial increase in the number of snow-covered days from 1949-1965, followed by an equally large decline through 1995, and a slight increase from 1995-2010 (Figure 9). Still, the average number of snow-covered days in the past decade has not rebounded to match the 1965-1975 average. Over the period 1948-2009, declining trends in snow-covered days are detected at Concord, NH (-1.9 days/decade, or 12 days total) and Portland, ME (-0.5 days/decade, or 3 days total). Though the trends are not statistically significant, they are consistent with broader scale declines in North American mid-latitude snow cover extent observed from satellite records[21].

River Flow in the Great Bay Watershed: Lamprey River and Oyster River

Rivers contribute to flooding and nitrogen pollution in the Piscataqua/Great Bay region, especially during the snowmelt season and during extreme precipitation events. Flooding in recent years has led to hundreds of roads closures, resident evacuations, and cost the state of New Hampshire tens of millions of dollars in damages. The Mother's Day Flood of 2006 recorded the highest maximum discharge (8400 cubic feet per second, cfs) on the Lamprey River, followed by the Patriot's Day Flood of 2007 (7590 cfs). Flooding in 2010 during February (4640 cfs), March (6550 cfs), and April (5240 cfs) are also in the top ten highest

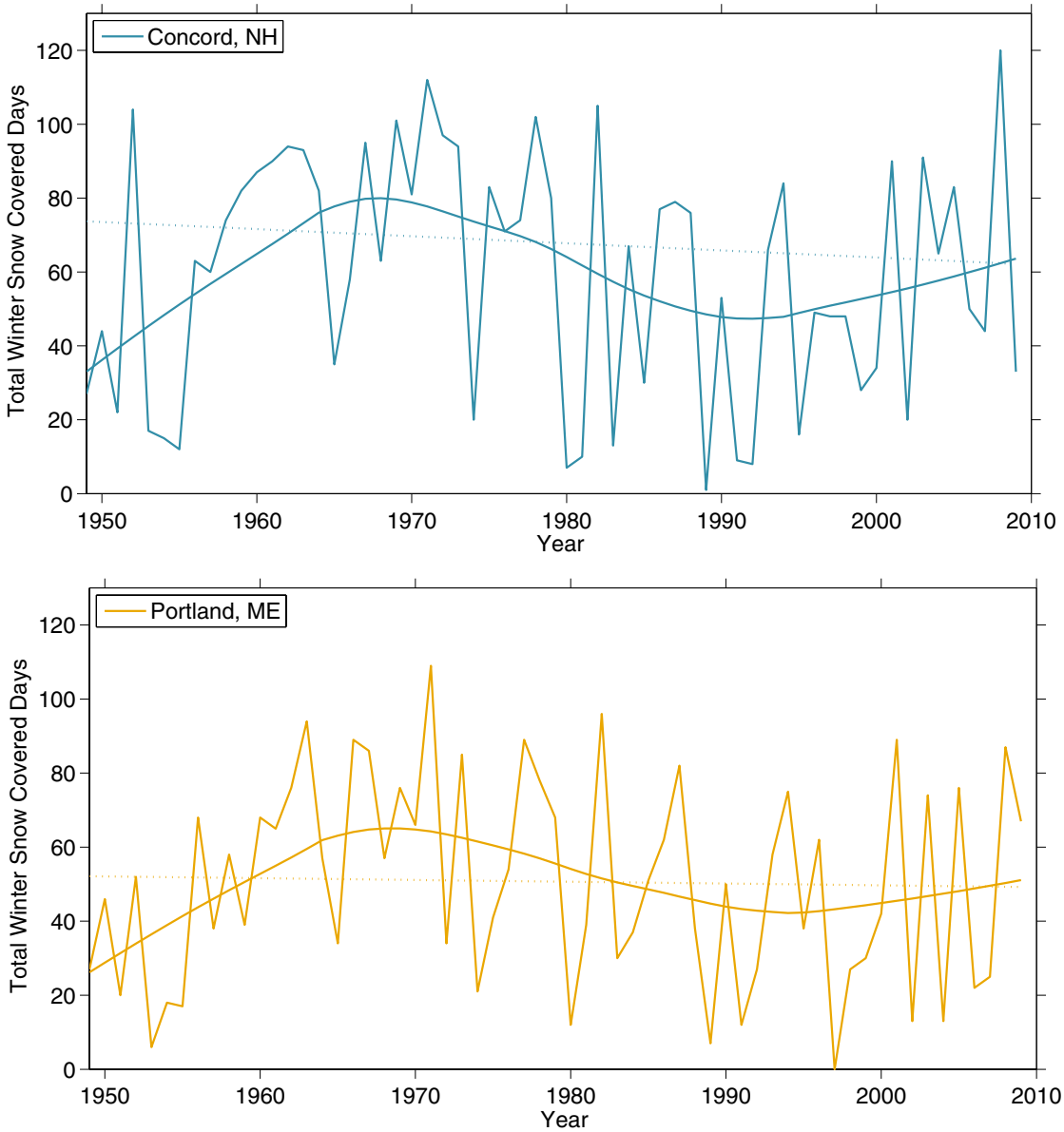


Figure 9. Total number of winter snow-covered (snow depth > 3 inches) days for Concord, NH (top) and Portland, ME (bottom), 1949-2009. Winter includes the months of December, January, February and March. Winter 1949 includes December 1948 and January-March 1949.

daily discharge events on the Lamprey River. During periods of heavy precipitation, excessive runoff and flooding increase nitrogen levels in the bay, exacerbating pollution problems in the Great Bay[23]. While Great Bay has not yet reached critical hypoxic (low oxygen) levels[22], it is clear that the watershed is vulnerable and heading in that direction. It is therefore critical to monitor river flow on the major tributaries to Great Bay.

Of the seven major rivers that drain into the Great Bay estuary (Figure 10), daily water discharge records extending back to 1935 are only available for the Lamprey and Oyster Rivers. The Cocheco and Exeter Rivers also have gauging stations but the records are much shorter, extending from 1995-present and 1996-present, respectively. The gauging station on the Salmon Falls River, which had been collecting data since 1968, was closed in 2005 due to lack of funding[24]. The Oyster River provides a

Figure 10. The Great Bay Watershed and major rivers that drain into the Bay. Long-term stream flow gages (black and white circles) have been collecting daily discharge data on the Lamprey and Oyster River since 1935.

particularly valuable river flow record in that it belongs to a unique list of gauging stations in the United States that are relatively free of anthropogenic influences such as regulation, diversion, land use change, and/or extreme groundwater pumpage.

Trends in river flow are calculated for annual and seasonal discharge by summing daily discharge over the calendar year and for the four seasons. In addition, the timing of high river flow is evaluated using trends in peak flow volume, peak flow date, and center-of-volume date calculated for the snowmelt (late winter/early spring) season and the autumn. *Peak flow volume* is defined as the maximum daily discharge (in cubic feet per second [cfs]) recorded in a given season, and the *peak flow date* is the Julian date (number of days past Jan 1st) on which peak flow was recorded. The *center-of-volume date* is the Julian date on which half of the total seasonal flow volume passed the gauging station. The center-of-volume date is considered a more robust indicator of climate change, since peak flow resulting from a rain-on-snow event or extreme precipitation event may occur well before or after the bulk of seasonal high flows. Trends in river flow are evaluated using the non-parametric Mann-Kendall test, a rank-based procedure that is resistant to the influence of extremes and thus good for use with time series that may have skewed variables (e.g., exceptionally high flow after a snowmelt event)[25]. Trends are considered statistically significant if the p-value (a measure of statistical significance) is less than 0.05.

Annual discharge exhibits increasing trends in both the Lamprey River and Oyster River, driven largely by statistically significant increases in fall discharge (Table 8). Summer discharge on the Lamprey River showed a weak decreasing trend while spring, and to a greater extent, winter, show increasing trends. All seasonal trends in Oyster River discharge are positive, indicating increased flow year-round. Note that the large differences between the Lamprey and Oyster River in terms of the trend magnitude are related to the overall size of the river, not a climatic difference. Average annual discharge on the Lamprey River is 105,970 cubic feet per second (cfs) (94 km^3/yr) versus 7,336 cfs (6.6 km^3/yr) on the Oyster River. Significantly later trends in winter-spring peak flow date were found for both the Lamprey and Oyster Rivers (Table 9), in contrast to the significantly earlier peak flow dates identified on northern New England rivers in a separate study[26]. However, the contrasting trends are not surprising since snowmelt tends to dominate northern inland rivers, whereas spring precipitation dominates southern coastal rivers[18]. The shift towards later winter-spring peak flow dates on the Oyster River is most highly correlated with increasing April-May precipitation (r^2=0.52). Winter-spring center-of-volume dates have also been occurring later, though the trends are not significant.

Total Discharge (cfs/yr)	Lamprey River	Oyster River
Annual	+212.8	+15.2
Winter	+99.8	+3.6
Spring	+14.5	+0.9
Summer	-11.6	+3.0
Fall	**+127.7**	**+7.5**

Table 8. Total annual and seasonal discharge trends (cfs/yr) for the period from 1935 to 2009. Trends are estimated using Sen's slope; statistically significant trends (p<0.05) are highlighted in **bold and underlined.**

Seasonal Discharge	Lamprey RIver	Oyster RIver
Winter/Spring (Jan 01-May 31)		
Peak Flow (cts)	+8.0	+1.1
Peak Flow Date (days/decade)	**+0.25**	**+0.38**
CV Date (days/decade)	+0.02	+0.07
Fall (Oct 01-Dec 31)		
Peak Flow (cts)	+3.86	+0.35
Peak Flow Date (days/decade)	**-0.28**	-0.08
CV Date (days/decade)	**-0.15**	-0.11

Table 9. Trends in seasonal discharge for the Lamprey and Oyster Rivers over the period from 1935 to 2009. Trends are estimated using Sen's slope; statistically significant trends (p<0.05) are highlighted in **bold and underlined.**

Lake Ice-Out Trends: Lake Winnipesaukee, NH and Sebago Lake, ME

Lake ice-out dates are frequently used as an indicator of late winter/early spring climate change due to the close correlation with surface air temperature in the months before ice break up. Earlier lake ice-out can increase phytoplankton productivity[27] and subsequently deplete summer oxygen levels[28] as the phytoplankton blooms are decayed through bacterial respiration. Earlier ice-out dates also impact the ice-fishing and snowmobiling industry by shortening the winter recreation season, or worse, eliminating it altogether during years when lakes do not ice over completely.

While there are no long-term records of lake ice-out in the Great Bay watershed, records of lake ice-out on Lake Winnipesaukee (located only 4 miles northwest of the watershed boundary, Figure 1) have been meticulously kept since 1887. Less than 40 miles to the northeast, Sebago Lake (Figure 1) ice-out records start in 1807, but over 50% of the values between 1807 and 1870 are missing. To facilitate comparison between the two lakes, we use the period of overlap 1887-2010. For Lake Winnipesaukee, the criteria used to determine the official date of lake ice-out has varied over the years, but the vast majority of the record has been declared when the 230-ft *M/S Mount Washington* can safely navigate between her port stops of Alton Bay, Center Harbor, Weirs Beach, Meredith, and Wolfeboro. The criteria for the official declaration of lake ice-out on Sebago has similarly varied throughout the years.

In 2010, a new record for earliest declared lake ice-out on Winnipesaukee was set on March 24th, breaking the previous record set on March 28th, 1921(Julian Day 137) by four days. The latest ice-out ever declared on Lake Winnipesaukee occurred on May 12th, 1888 (Julian Day 133). Sebago shows a number of years when the lake did not develop complete ice-cover; not surprisingly, these years coincide with the warm periods identified

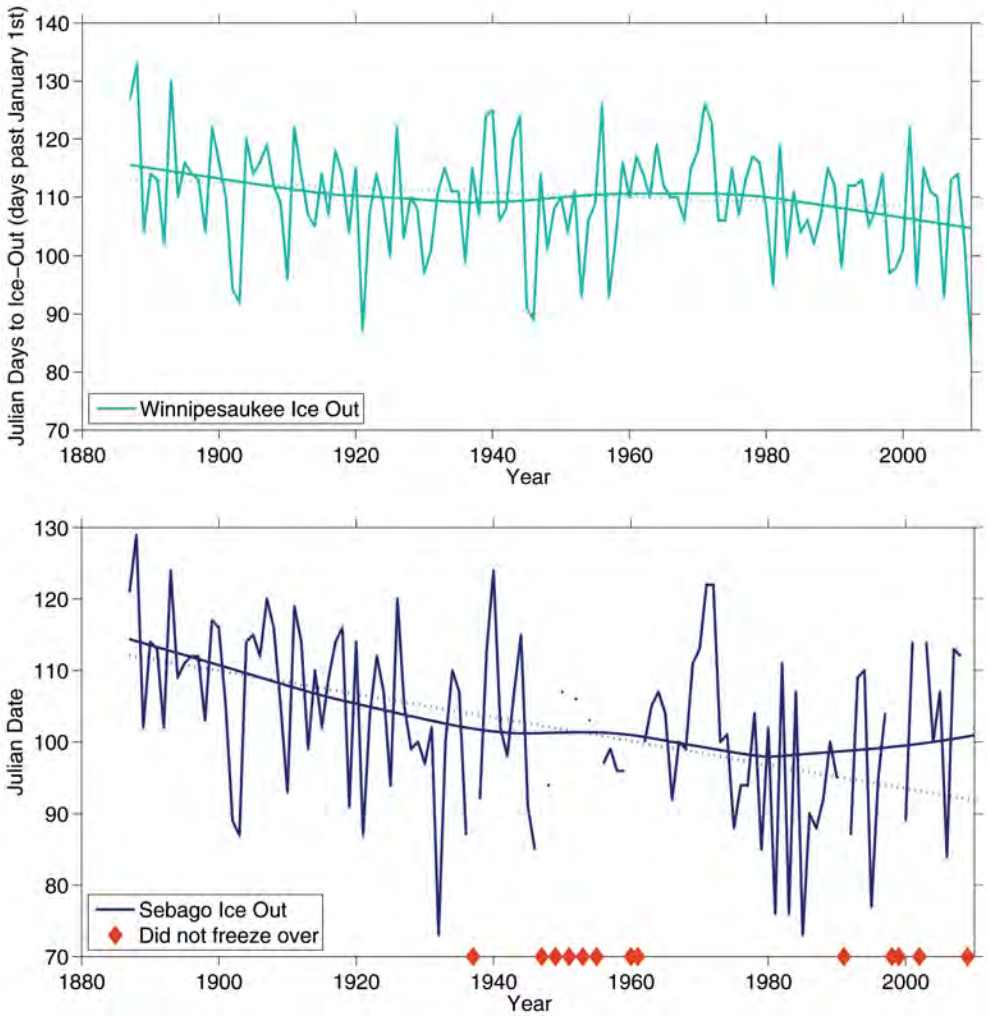


Figure 11. Ice out dates, in Julian days (number of days past January 1st) for Lake Winnipesaukee (top) and Sebago Lake (bottom), 1887-2010. Red diamonds indicate years when Sebago did not freeze over completely.

in temperature records between 1940-1960 and 1990-2010 (Figure 11). The overall long-term trends of -0.4 days/decade for Winnipesaukee and -1.6 days/decade for Sebago (not including years when the lake did not ice over) are consistent with 28 other long-term ice-out records from New Hampshire, Maine, and Massachusetts[29].

Sea Surface Temperature: Ship and Buoy Observations Since 1887

The vast heat capacity of the ocean serves to warm coastal regions in winter and cool them in summer. The ocean's ability to absorb heat has also served to mitigate the warming effects of increasing concentrations of greenhouse gases in the atmosphere. Over the past 40 years, scientists estimate that the ocean has absorbed almost 80% of the excess heat generated from human driven global warming[30]. The increase in sea surface temperature causes thermal expansion of sea water, which accounts for about half of global sea level rise (the other half coming primarily from glacial melt)[31].

Changes in monthly to annual sea surface temperature play an important role in monitoring the climate and vulnerability of coastal areas to sea level rise. The National Oceanic and Atmospheric Administration (NOAA) provides gridded sea surface temperature (SST) records collected from ships and buoys for the Gulf of Maine dating back to the late 1800s[32]. Sea surface temperatures for the Gulf of Maine are the average of three grid cells centered on 70W x 42N, 68W x 42N, and 68W x 44N (Figure 12).

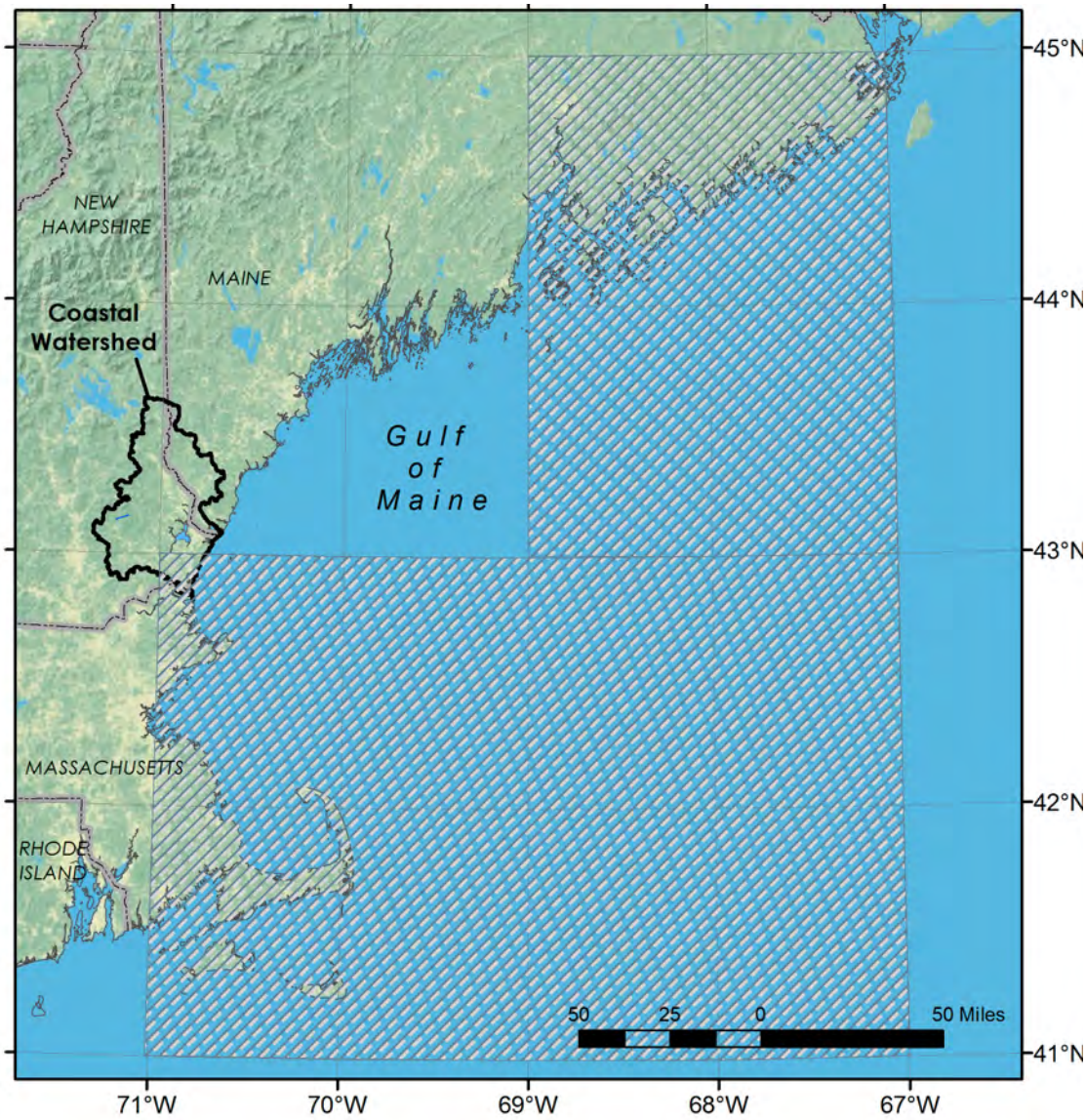


Figure 12. Sea surface temperature for the Gulf of Maine are provided by the Extended Reconstruction Sea Surface Temperature (ERSST) version 3b gridded data centered on grid cells at 70W x 42N, 68W x 42N, and 68W x 44N [32].

The Gulf of Maine SST time series show significant variability between 1887 and 2008 (Figure 13). Warm periods are evident during the 1940s and from the mid-1980s to present. Note the precipitous decline in sea surface temperatures during the 1960s that coincided with cooler than average air surface temperatures, decreased precipitation over land, and a multi-year drought that extended across much of the northeast United States. Record warmth occurred in 1999 (53.1°F), exceeding previous maximum values in the 1940s and 1950s by almost 1.0°F. Trends in Gulf of Maine SSTs are significant at the annual and seasonal level for all seasons. Over the period 1887-2008, spring SSTs have risen the fastest at 0.13 °F/decade (Table 10). As with surface air temperature records, rates of warming have increased markedly since 1970. Annual sea surface temperature warming has more than quadrupled over the period 1970-2008 relative to the 1887-2008 trend. The rates of warming at the seasonal level have increased three-fold in winter, more than four-fold in spring, over six-fold in fall, and alarmingly seven-fold in summer (Table 10).

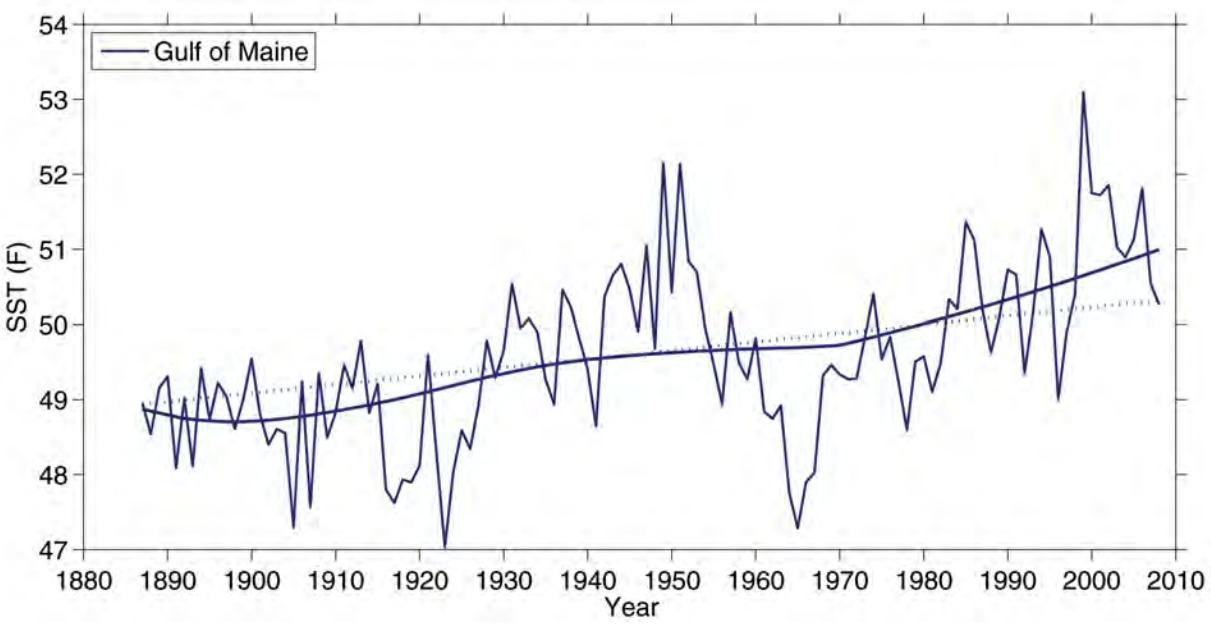


Figure 13. Mean annual sea surface temperature (°F) in the Gulf of Maine, 1887-2008. Data from the National Oceanic and Atmospheric Administration Extended Reconstructed Sea Surface Temperature (ERSST) V3b ship and buoy observational gridded dataset using grids centered on 290E x 42N, 290E x 42N, and 292E x 44N (Smith et al. 2008).

°F/decade	1887-2008	1970-2008
Annual Sea Surface Temperature	**0.11**	**0.52**
Winter	**0.11**	**0.33**
Spring	**0.13**	**0.55**
Summer	**0.11**	**0.77**
Fall	**0.09**	**0.60**

Table 10. Annual and seasonal sea surface temperature trends (°F/decade) for the Gulf of Maine for two time periods (1887-2008 and 1970-2008). Trends are estimated using Sen's slope; statistically significant trends ($p<0.05$) are highlighted in **bold and underlined.**

Future Climate Change

Overview of Global Climate Models

To evaluate possible future changes in climate, scientists use atmosphere-ocean general circulation model (a.k.a. global climate model) simulations driven by future emission scenarios. An emissions scenario incorporates assumptions about population, energy use, and technology to build pictures of how the future might look. Each scenario is associated with a unique "signature" of greenhouse gases emissions. Here, we use the high (A1fi) and a low (B1) emissions scenarios from the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES)[33] (Figure 14). Under the A1fi "higher-emissions" scenario, SRES assumes a world with fossil fuel-intensive economic growth and a global population that peaks mid-century and then declines. New and more efficient technologies are introduced toward the end of the century. In this scenario, atmospheric carbon dioxide (CO_2) concentrations reach 940 parts per million (ppm) by 2100—more than triple pre-industrial levels (red line in Figure 14). The B1 "lower-emissions" scenario also represents a world with high economic growth and a global population that peaks mid-century and then declines. However, this scenario includes a shift to less fossil fuel-intensive industries and the introduction of clean and resource-efficient technologies. Emissions of greenhouse gases peak around mid-century and then decline. Atmospheric carbon dioxide concentrations reach 550 ppm by 2100—about double pre-industrial levels (purple line in Figure 14). As diverse as they are, the SRES scenarios still do not cover the entire range of possible futures. By choosing a high CO_2 and a low CO_2 scenario, we hope to create an envelope of future climate change that the Piscataqua/Great Bay region may fall within by the end of the 21st century.

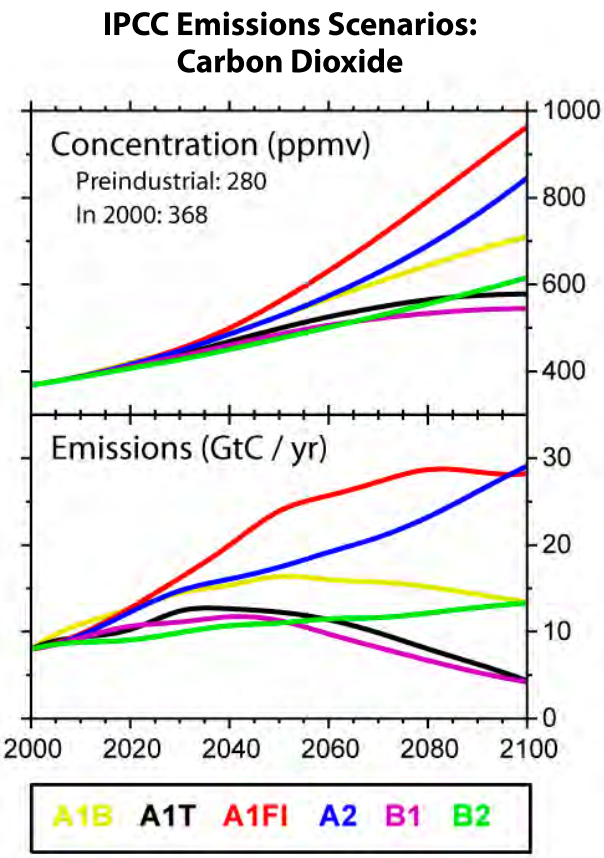


Figure 14. Projected future concentrations (top) and emissions (bottom) of carbon dioxide, 2000-2100. [Image by Robert A. Rohde/Global Warming Art.]

The future emission scenarios such as those described above are used as input to atmosphere-ocean general circulation models (AOGCMs)[2]. These large, three-dimensional coupled models incorporate the latest understanding of the physical processes of the atmosphere, oceans, and Earth's surface. As output, AOGCMs produce geographic grid-based projections of precipitation, temperature, pressure, cloud cover, humidity, and a host of other climate variables at daily, monthly, and annual scales. Historical simulations by AOGCMs used here were driven by the Coupled Model Intercomparison Project's "20th Century Climate in Coupled Models" scenario[34]. The intent of those simulations was to reproduce the climate conditions observed over the past century as closely as possible. Hence, they included observed changes in solar radiation, volcanic eruptions, human emissions of greenhouse gases, emissions of other gases and particles that interact with the energy emitted by the Earth and the sun, and secondary changes in lower-atmosphere ozone and water vapor from the 1800s to 1999.

Why Use Statistical Downscaling?

The spatial resolution of AOGCMs limits them from providing information on climate change on scales smaller than hundreds of miles. To address this issue, we use advanced statistical downscaling methods to relate projected large-scale changes in climate to local conditions on the ground. Local-scale climate

projections are generated for the four reliable long-term weather stations located within or around the Piscataqua/Great Bay region. (Durham, NH, Concord, NH, Lawrence, MA, and Portland, ME; Figure 1). Appendix B provides a more detailed description of the advanced statistical downscaling methods used in this study.

For this study, we relied on simulations from four different AOGCMs (Table 11): the U.S. National Atmospheric and Oceanic Administration's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1; the United Kingdom Meteorological Office's Hadley Centre Climate Model, version 3 (HadCM3); and the National Center for Atmospheric Research's Community Climate System Model version 3 (CCSM3), and Parallel Climate Model (PCM). These models were chosen based on several criteria. First, only well-established models were considered, those already extensively described and evaluated in the peer-reviewed scientific literature. The models must have been evaluated and shown to adequately reproduce key features of the atmosphere and ocean system[2]. Second, the models chosen must encompass the greater part of the IPCC range of uncertainty in climate sensitivity. Climate sensitivity is defined as the temperature change resulting from a doubling of atmospheric carbon dioxide concentrations relative to pre-industrial times, after the atmosphere has had years to adjust to the change. Climate sensitivity determines the extent to which temperatures will rise under a given increase in atmospheric concentrations of greenhouse gases. The last requirement was that simulations of temperature, precipitation, and other key variables had to be available at daily resolution for both the SRES A1fi and B1 emission scenarios. The AOGCMs selected for this analysis are the only four for which daily output from A1fi and B1 simulations are available. Unfortunately, we are not able to produce future trends for all of the historical indicators presented in the previous section, such as the date of lake ice-out, river flow, and snowfall.

Future Temperature

Temperatures in the Piscataqua/Great Bay region and surrounding areas will continue to rise regardless of whether or not the future follows a lower or higher emissions scenario. However, it is clear that the magnitude of warming that can be expected will depend on which emissions pathway is followed (Table 12; Figure 15). During the first part of the 21st century (2010-2039), temperature increases are similar for the lower (B1) and higher (A1fi) emissions scenarios for annual, winter, and summer temperature. The magnitude of warming begins to diverge during the middle part of the century (2040-2069), with the higher emissions scenario resulting in warming that is 1.5 times greater than the lower emissions scenario warming. Temperature increases under the higher emissions scenario will be nearly twice that expected under the lower emissions scenario by the end of the 21st century (2070-2099). Overall, the NH Coastal watershed can expect to see increases in annual maximum and minimum temperature ranging from +4.5°F to +9.0°F over the next 100 years.

Historically, average winter maximum and minimum temperatures were warming at the greatest seasonal rate over the period 1970-2009, but that isn't necessarily the case for future scenarios. By 2070-2099, winter minimum temperature increases will be only slightly greater than summer, ranging from +5.3°F to +9.9°F for winter and +4.7°F to +9.0°F for summer (Table 12). Summer maximum temperature increases (+5.4°F to +10.7°F) will be substantially higher than winter (+3.9°F to +6.7°F).

MODEL	HOST INSTITUTION	HORIZONTAL RESOLUTION
CCSM3[35]	National Center Atmospheric Research (USA)	1.4 degrees
GFDL CM2.1[36]	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA)	1.8 degrees
HadCM3[37]	United Kingdom Meteorological Office, Hadley Center (UK)	2.5 x 3.75 degrees
PCM[38]	National Center for Atmospheric Research (USA)	2.8 degrees

Table 11. Atmosphere-Ocean Coupled General Circulation Models AOGCMs) used for generating projections of future climate change.

With regard to climate impacts, the projected increases in Durham, NH winter maximum and minimum temperature will very likely push regional average winter temperatures *above* the freezing point. With average winter temperatures above freezing, the region can expect to see a greater proportion of winter precipitation falling as rain (as opposed to snow), earlier lake ice-out dates, and a decrease in the number of days with snow cover. Warmer summer temperatures will likely lead to increased drought, heat waves, more frequent and extreme convective precipitation events, and an increase in invasive pests and weeds.

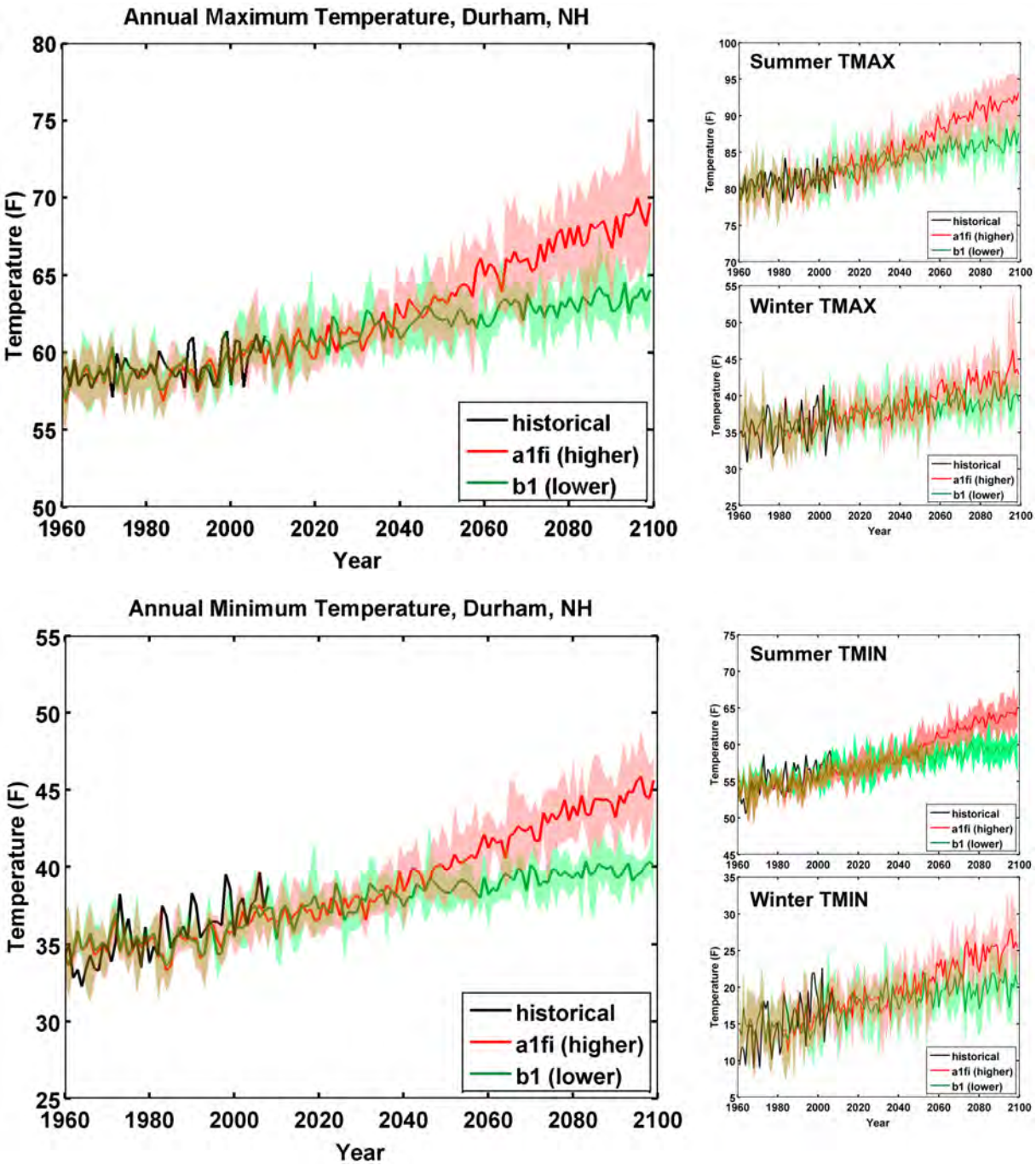


Figure 15. Projected annual maximum (top) and minimum (bottom) temperature for Durham, NH, 1960-2099. Historical record in black; projected temperature from the higher emission scenario (A1fi) in red and lower mission scenario (B1) in green. Projected values represent the average of four AOGCM simulations (see text for additional explanation); shaded area represents range in output from the four AOGCMs that were used.

		Minimum Temperature (°F)		Maximum Temperature (°F)	
DURHAM, NH		**low (B1)**	**high (A1fi)**	**low (B1)**	**high (A1fi)**
2010-2039	**Annual**	+2.4	+2.5	+2.3	+2.3
	Winter	+3.0	+3.1	+2.2	+2.0
	Summer	+2.4	+2.7	+2.5	+2.2
2040-2069	**Annual**	+3.6	+5.6	+3.7	+5.6
	Winter	+4.3	+6.2	+3.2	+4.1
	Summer	+3.8	+5.8	+4.4	+6.8
2070-2099	**Annual**	+4.5	+8.9	+4.6	+9.0
	Winter	+5.3	+9.9	+3.9	+6.7
	Summer	+4.7	+9.0	+5.4	+10.7
LAWRENCE, MA					
2010-2039	**Annual**	+1.9	+2.0	+2.2	+2.1
	Winter	+2.5	+2.6	+2.3	+2.0
	Summer	+1.7	+2.0	+2.3	+2.6
2040-2069	**Annual**	+2.8	+4.5	+3.4	+5.2
	Winter	+3.5	+5.1	+3.2	+4.1
	Summer	+2.9	+4.5	+4.1	+6.1
2070-2099	**Annual**	+3.6	+7.3	+4.3	+8.5
	Winter	+4.3	+8.2	+3.9	+6.8
	Summer	+3.6	+7.2	+5.0	+9.7
PORTLAND, ME					
2010-2039	**Annual**	+2.0	+2.1	+2.1	+2.1
	Winter	+2.9	+3.0	+2.2	+1.9
	Summer	+1.7	+2.0	+2.5	+2.7
2040-2069	**Annual**	+3.0	+4.8	+3.4	+5.1
	Winter	+4.0	+5.9	+3.0	+4.0
	Summer	+2.8	+4.3	+4.4	+6.7
2070-2099	**Annual**	+3.8	+7.7	+4.3	+8.5
	Winter	+5.0	+9.4	+3.8	+6.5
	Summer	+3.5	+6.9	+5.4	+10.8

Table 12. Future changes in annual and seasonally averaged minimum and maximum temperature for Durham, Lawrence, and Portland to the period 2010-2099. Warmer colors indicate stronger warming trends.

Future Extreme Temperature

As temperatures increase in the Piscataqua/Great Bay region, extreme heat is expected to become more frequent and severe while extreme cold is expected to become less frequent and less severe.

Extreme Heat

Increases in extreme heat are calculated using three metrics: (1) number of days above 90°F, (2) number of days above 95°F, and (3) average temperature on the hottest day of the year. The metrics are summarized in four 30-year periods: (1) historical, 1970-1999, (2) early century, 2010-2039, (3) mid-century, 2040-2069, and (4) late-century, 2070-2099.

During the historical baseline period 1970-1999, Durham experienced about 9 days above 90°F each year, comparable to Concord and Lawrence (Figure 16). Portland's location directly on the coast benefits more from cooling sea breezes and historically sees about 3-4 days per year above 90°F. By 2070-2099, Durham can expect 30 days per year with daytime maximum temperatures above 90°F under the lower emissions scenario and over 70 days per year under the higher emissions scenario, nearly eight times the historical average. Concord and Lawrence show comparable results to Durham. Portland is expected to see the number of days above 90°F triple by the end of the century under the higher emissions scenario such that nearly a month and a half of summer will be above 90°F.

Between 1970-1999, extreme daytime maximum temperatures above 95°F were historically rare, occurring on less than two days per year at all stations (Figure 17). Under the lower emissions scenario, Durham and Concord can expect to see between 5 and 10 days per year above 95°F. Under the higher emissions scenario, the number of days above 95°F is expected to increase to 30 days, more than 10 times the historical average. The number of days above 95°F in Portland is expected to increase from an historical average of less than one day per year to 2-12 days per year under lower and higher emissions scenarios, respectively.

As the number of extremely hot days per year increases, the average daytime maximum temperature on the hottest day of the year is also expected to increase. Near-term increases are slightly higher under the lower emissions scenario than higher emissions scenario, but by mid- to late-century the emissions pathways diverge with higher emissions resulting in much higher temperatures on the hottest day of the year. In Durham, the average maximum temperature on the

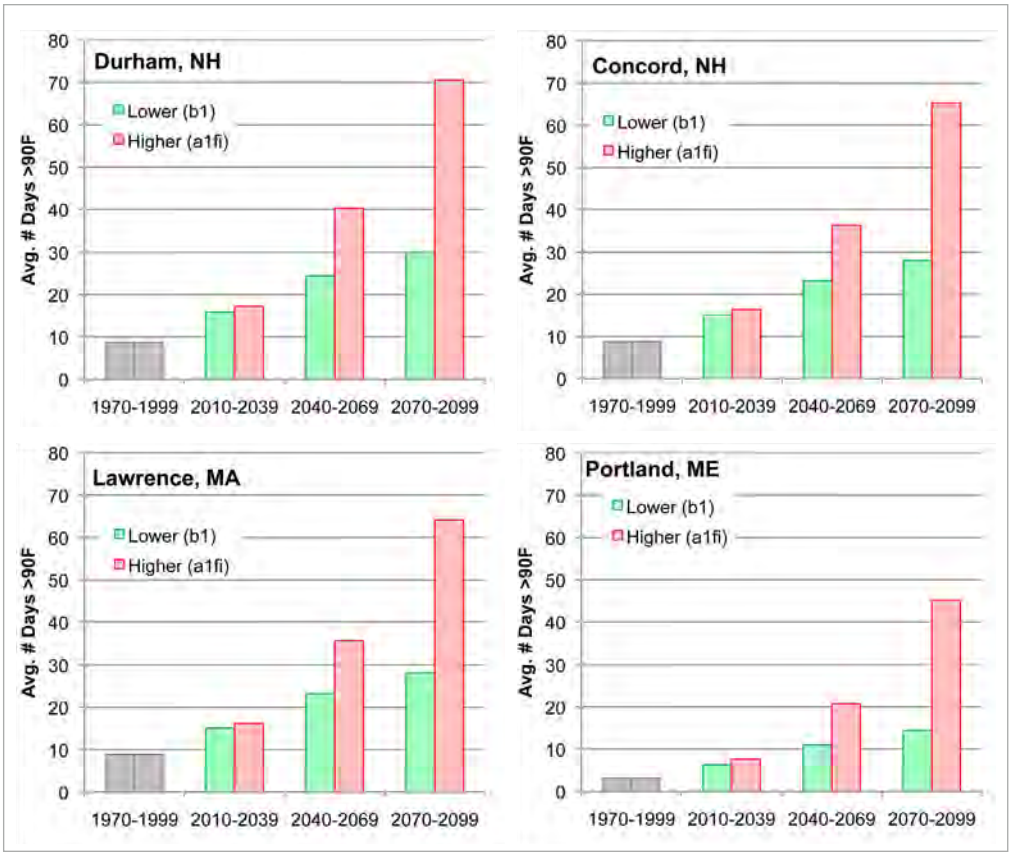


Figure 16. Historical (grey) and projected lower emissions (green) and higher emissions (red) average number of days above 90°F per year, shown as 30-year averages. Projected values represent the average of four AOGCM simulations.

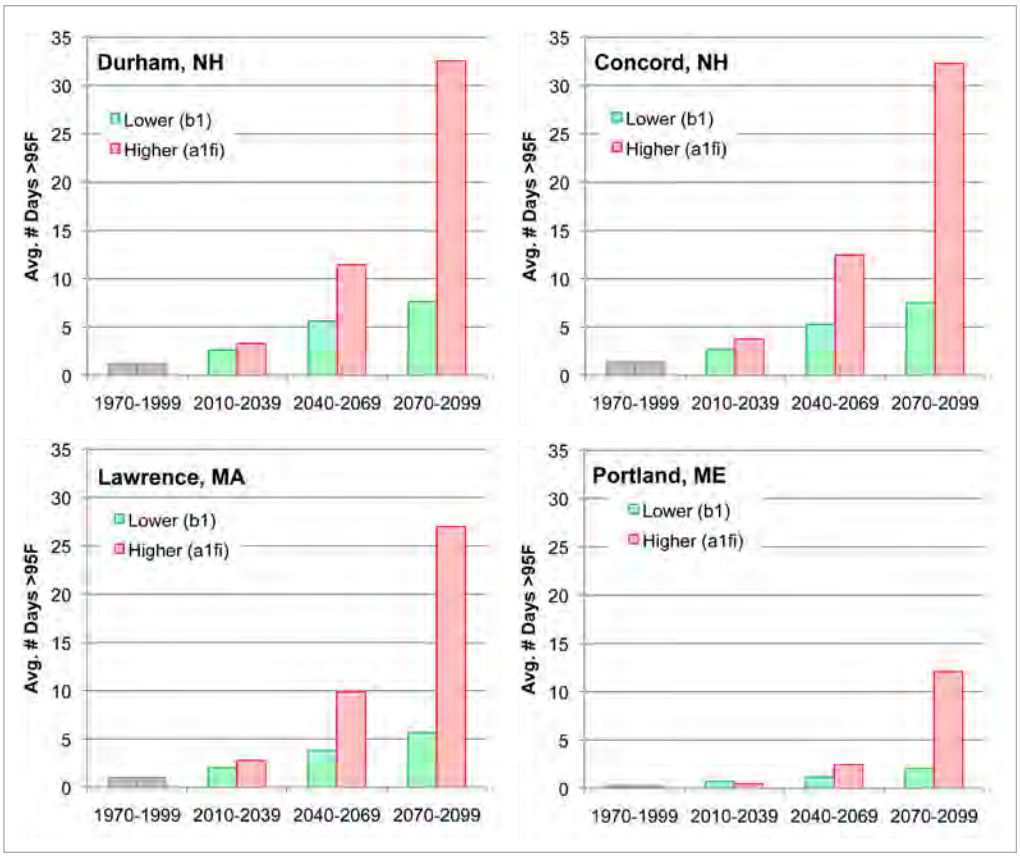


Figure 17. Historical (grey) and projected lower (green) and higher emissions (red) average number of days above 95°F per year, shown as 30-year averages. Projected values represent the average of four AOGCM simulations.

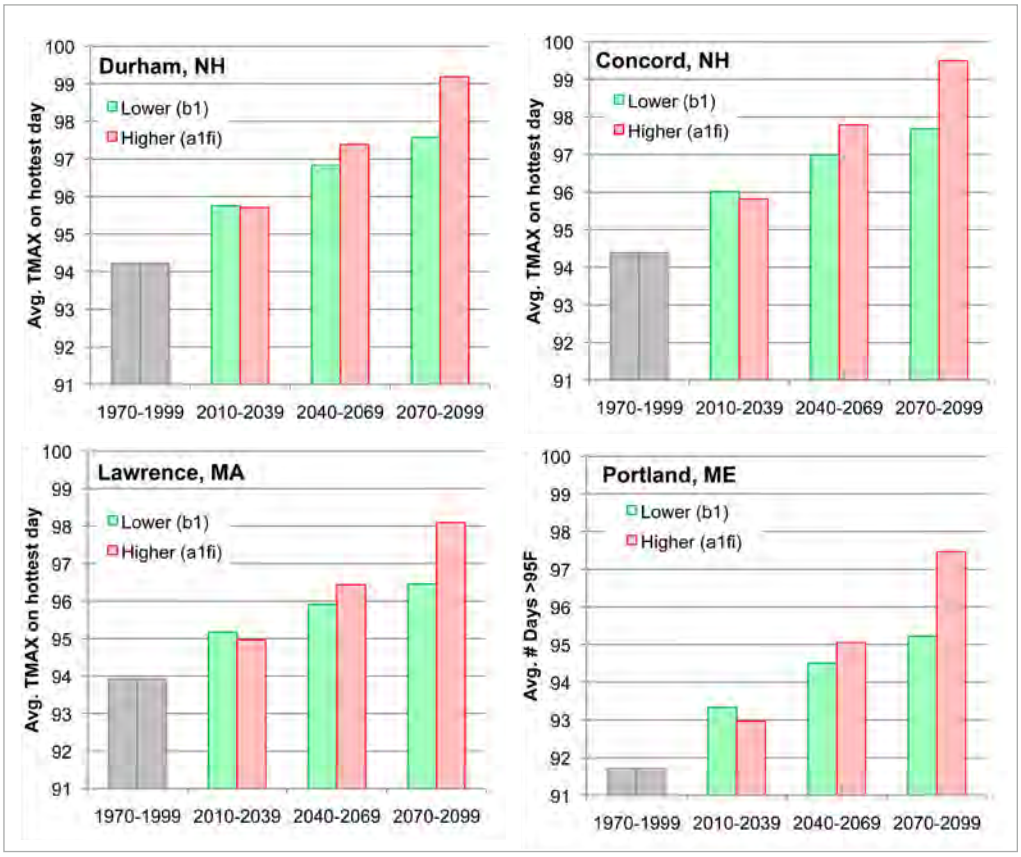


Figure 18. Historical (grey) and projected lower (green) and higher emissions (red) average maximum temperature on the hottest day of the year, shown as 30-year averages. Projected values represent the average of four AOGCM simulations.

hottest day of the year over the period 1970-1999 was typically around 94ºF. Over the next 100 years, the temperature on the hottest day of the year could climb to 97.5ºF under the lower emissions scenario and upwards of 99ºF under the higher emissions scenario (Figure 18).

Extreme Cold

Increases in extreme cold are calculated using three metrics: (1) number of days below 32ºF, (2) number of days below 0ºF, and (3) average nighttime minimum temperature on the coldest day of the year.

Over the period 1970-1999, Durham experienced on average between 150-160 days per year with nighttime minimum temperatures below 32ºF, roughly the length of the winter season from mid-Nov through mid-April. Over the next century, these numbers are expected to decrease gradually (Figure 19). By the end of the century, Durham could experience 50 fewer days per year under the higher emissions scenario, or about a 30% decline. Under the lower emissions scenario, 25 fewer days per year are expected, or about a 15% decline. Decreases in the number of extreme cold days below 0ºF are more severe compared to days below 32ºF. Durham currently experiences between 10-12 days per year when minimum temperatures fall below 0ºF (Figure 20). That number will be halved by 2010-2039 to about 6 days per year under both lower and higher emissions scenarios. By mid-century, the higher emissions scenario will result in only 2 days per year on average, and 4 days per year under the lower emissions scenario. By the end of the century, Durham can expect less than one day per year on average with minimum temperatures below 0ºF.

The average nighttime minimum temperature on the coldest day of the year in the Great Bay region will gradually warm over the next 100 years. Historically, extreme low temperatures in Durham dip just below -15ºF. By mid-century (2040-2069), the lowest temperatures on the coldest day of the year under the lower emissions scenario will be almost 10ºF warmer than it was during the historical baseline period from 1970-1999, and nearly 12ºF warmer under the higher emissions scenario. By the end of the century, temperatures are expected to warm 8ºF to 9ºF under lower emissions and 19ºF to 20ºF under higher emissions (Figure 21).

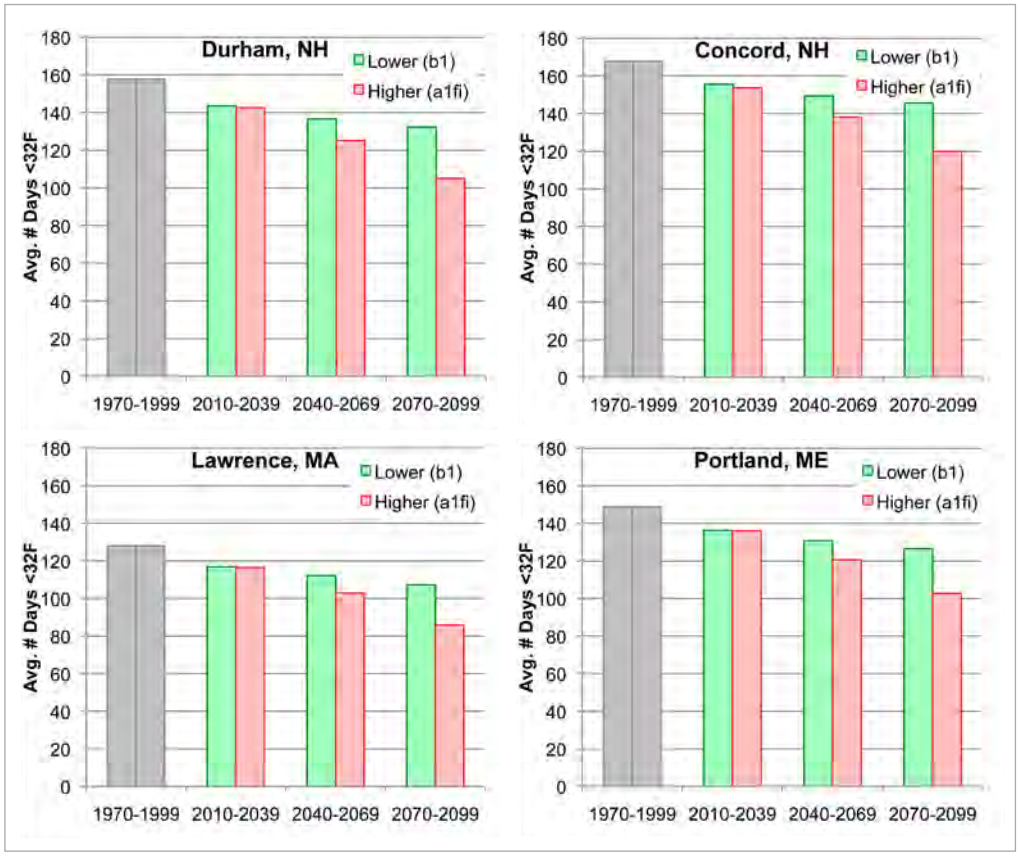


Figure 19. Historical (grey) and projected B1-lower emissions (green) and A1-higher emissions (red) average number of days below 32ºF per year, shown as 30-year averages. Projected values represent the average of four AOGCM simulations.

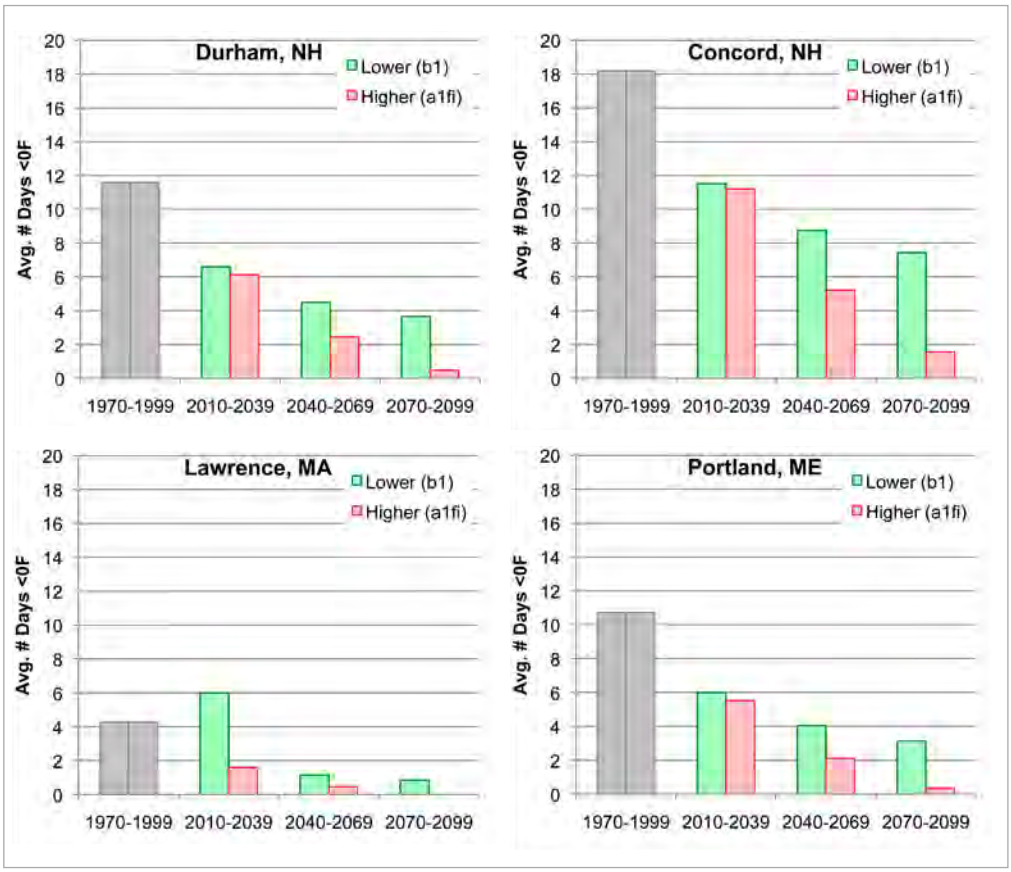


Figure 20. Historical (grey) and projected lower emissions (green) and higher emissions (red) average number of days below 0ºF per year, shown as 30-year averages. Projected values represent the average of four AOGCM simulations

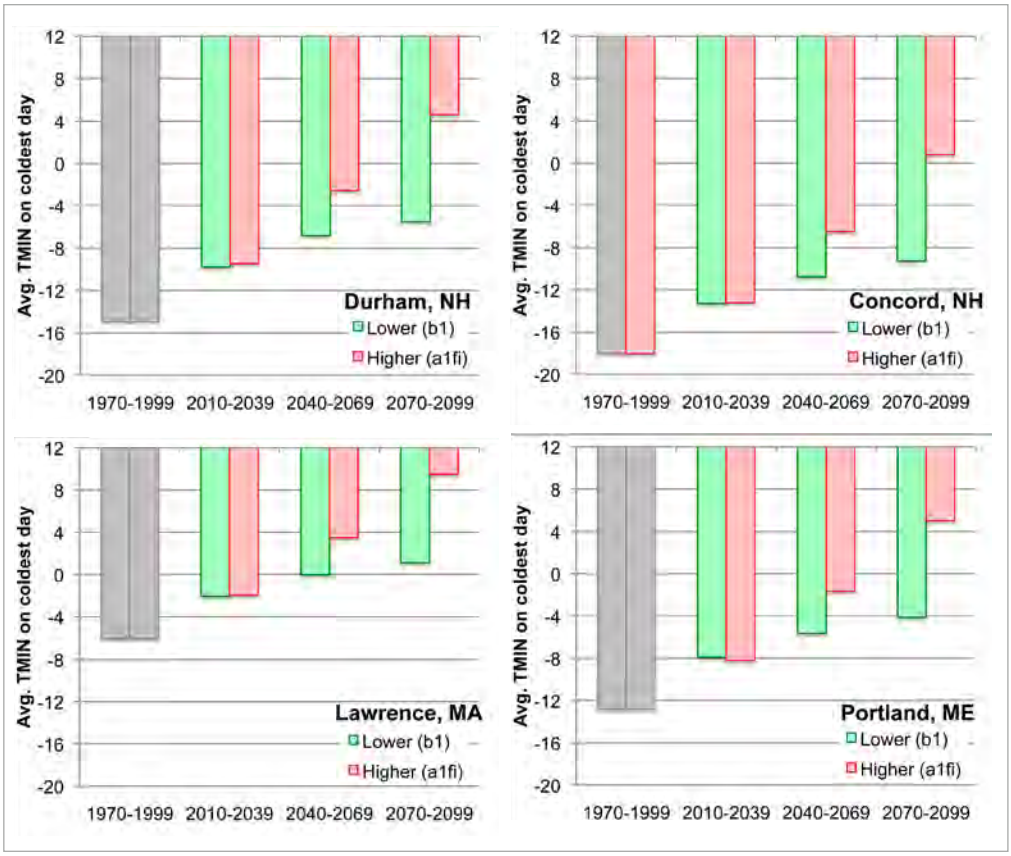


Figure 21. Historical (grey) and projected lower emissions (green) and higher emissions (red) average minimum temperature on the coldest day of the year, shown as 30-year averages for time periods shown. Projected values represent the average of four AOGCM simulations.

Future Precipitation

Annual precipitation is expected to increase slightly more under the higher emissions scenario compared to the lower emissions scenario by the end of the century. Under the higher emissions scenario, Durham's annual precipitation is projected to increase over 17% by 2070-2099, relative to the historical baseline period 1970-1999 (Figure 22a). Neighboring stations can expect to see similar increases in annual precipitation, ranging from 12%-16%. The expected increase in annual precipitation under the lower emissions scenario is only slightly less, about 13% for Durham and ranging from 12%-13% for neighboring stations (Figure 22b).

The seasonal distribution of future precipitation differs for the higher and lower emissions scenarios (Figure 22). Under the higher emission scenario precipitation increases are largest during winter, spring, and summer, whereas very little change is expected for fall (Figure 22a). Lawrence, MA may even expect to see a slight decrease in fall precipitation by the end of the 21st century. Under the lower emissions scenario, changes in fall precipitation are greater, ranging from 6%-12%, but with a range of positive and negative trends (Figure 22b). Winter and spring precipitation changes are about 5% less for the lower emissions scenario compared to the higher emissions scenario. Overall the higher emissions scenario shows a much wider range of variabilty across models illustrating the uncertainty of how precipitation will respond to increases in greenhouse gases. The projected changes in the Piscataqua/Great Bay region precipitation are in contrast to broader regional studies that indicate there will be very little to no change in summer precipitation across most of the northeast United States.[39]

Future Extreme Precipitation and Drought

Future trends in annual and seasonal precipitation point toward wetter conditions in the Piscataqua/Great Bay region over the next 100 years. With regard to drought and flood risk, it is also important to examine changes in the magnitude and frequency of precipitation events. The same four metrics described in the historical analysis are presented for late-century (2070-2099) higher and lower future emissions scenarios (Figure 23). In addition to the four metrics analyzed above, changes in the amount of rainfall on the wettest day of the year are examined. To evaluate future drought projections, the number of months in drought conditions is calculated for the historical and late-century 30-yr periods. For any given month, drought conditions are met if the monthly precipitation is 20% below the long-term (1895-2009) monthly average.

Regardless of the metric analyzed, it is clear that the Piscataqua/Great Bay region can expect to see more extreme precipitation events in the future, and more extreme precipitation events under the higher emissions scenario relative to the lower emissions scenario. Historically, Durham experienced about 11 events per year with greater than one inch of precipitation in 24 hours (Figure 23a). By 2070-2099, that will increase to 13 events under the lower emissions scenario and to just over 14 events for the higher emissions scenario. For events with greater than two inches in 24 hours, Durham averaged 1-2 days per year, but that will increase to 2-3 days per year depending on the emissions

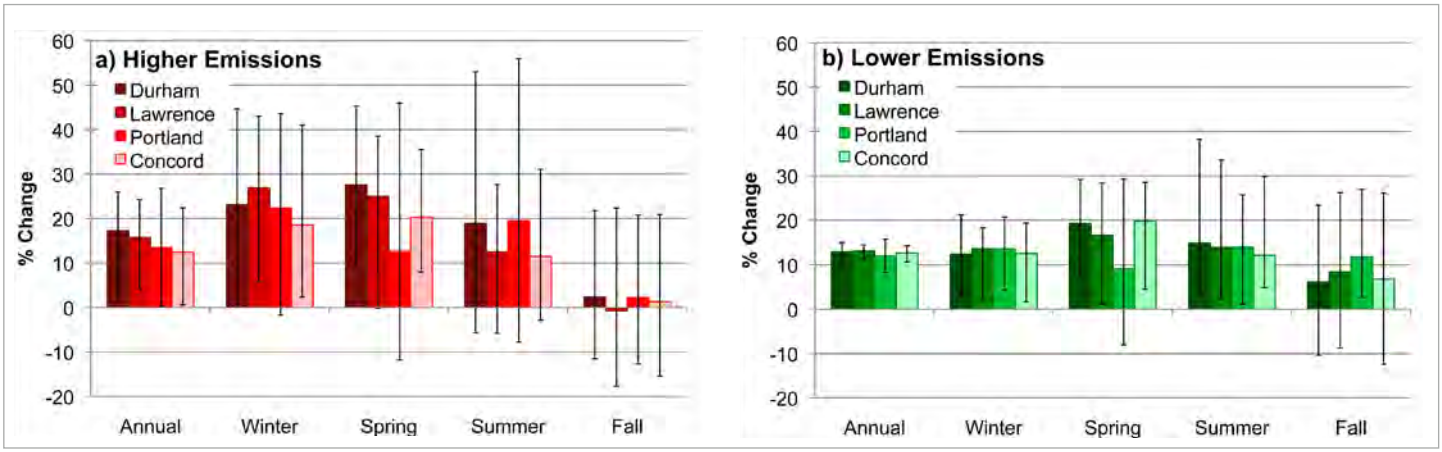


Figure 22. Percentage change in 2070-2099 annual and seasonal precipitation relative to the 1970-1999 historical average for (a) higher and (b) lower emissions scenarios. Projected values represent the average of four AOGCM simulations. Error bars indicate the range of projections from the four model simulations for each scenario.

pathway (Figure 23b). The same pattern of increasing extreme precipitation events under lower emissions and even greater increases under higher emissions scenarios emerges for events greater than two inches in 48 hours (Figure 23c) and greater than four inches in 48 hours (Figure 23d).

Historically, Durham received on average 2.8 inches of rain on the wettest day of the year over the period 1970-1999. By late-century, the wettest day of the year will deliver on average 3.7 inches of rain under the higher emissions scenario and 3.6 inches of rain under the lower emissions scenario. This represents about a 30% increase in the amount of rain on the wettest day of the year. Portland will see a substantially larger change, from an historical average of 3.2 inches in 1970-1999 to 4.5 inches in 2070-2099 under the higher emissions scenario, representing an increase of greater than 40% (Figure 24).

Over the period 1970-1999 Durham and Lawrence experienced 11-14 months in drought conditions (20% or more below average) while Portland only saw about five months in drought conditions (Figure 25). Under the higher emissions scenario, little relief from drought is expected for Durham or Lawrence. Portland can expect the number of months in drought conditions double by 2070-2099 (Figure 25). Under the lower emissions scenario, all three stations are projected to see decreases in the number of months in drought. A more sophisticated analysis based on output from nine AOGCMs and an advanced hydrological model that accounts simultaneously for projected increases in temperature and evapotranspiration (water loss through vegetation) indicates that more frequent short and medium-term droughts can be expected by 2070-2099 in the northeast US[39].

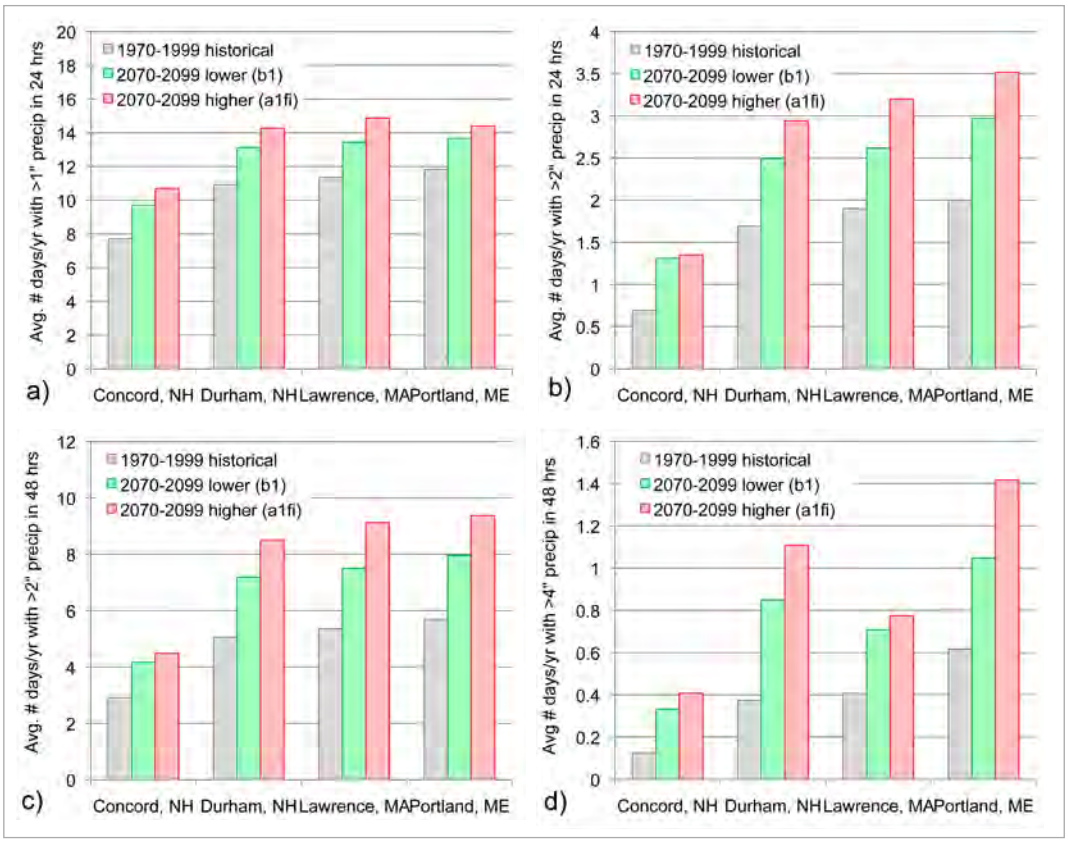


Figure 23. Historical (grey) and projected lower emissions (green) and higher (red) emissions average number of days per year with (a) greater than one inch of precipitation in 24 hours, (b) greater than two inches of precipitation in 24 hours, (c) greater than two inches of precipitation in 48 hours, and (d) greater than four inches of precipitation in 48 hours, shown as 30-year averages. Projected values represent the average of four AOGCM simulations.

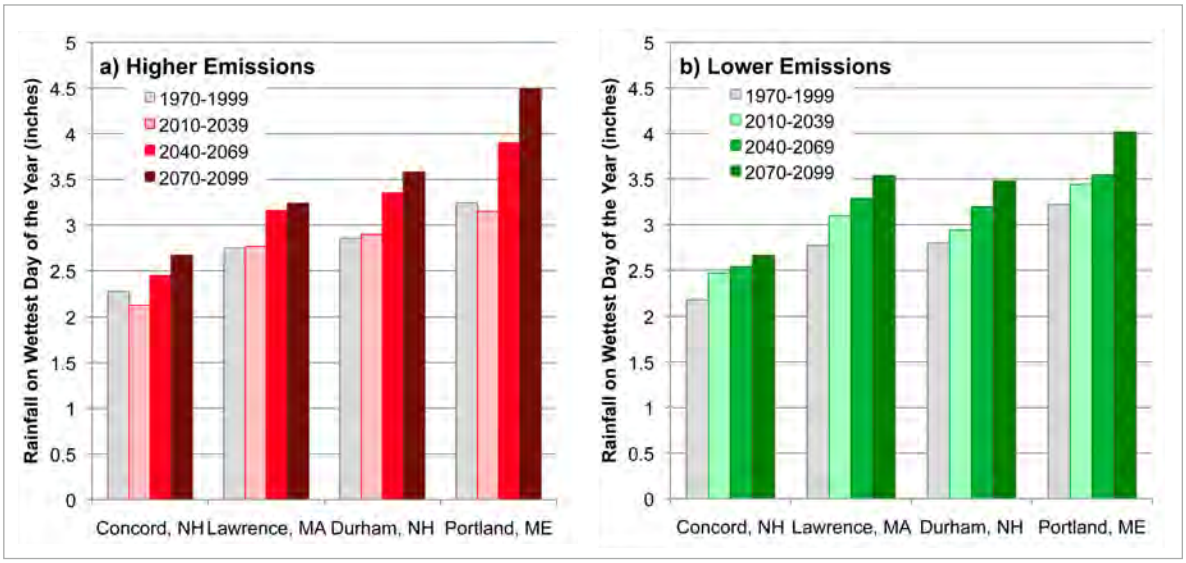


Figure 24. Historical (grey) and projected change in average total rainfall on the wettest day of the year for (a) higher emissions and (b) lower emissions, shown as 30-year averages. Projected values represent the average of four AOGCM simulations.

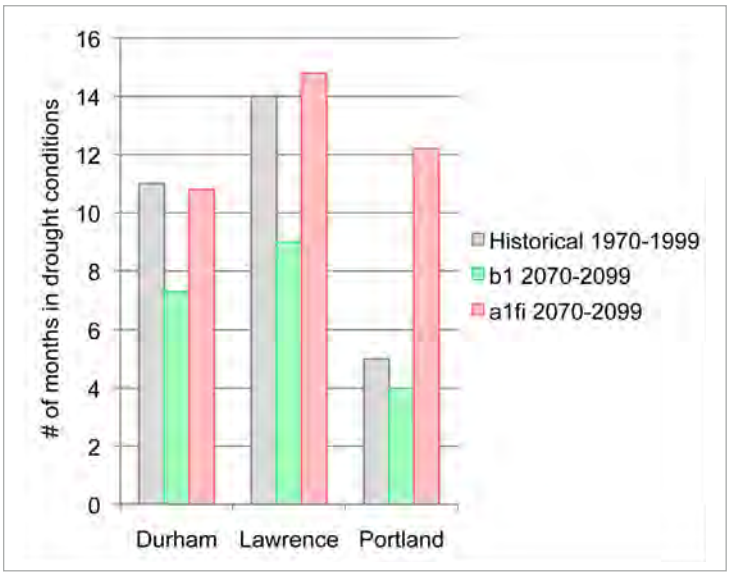


Figure 25. Historical 1970-1999 (grey) and projected change in the number of months in drought conditions for the (red) A1Fi higher emissions scenario and (green) B1 lower emissions scenario. A month is considered to be in drought conditions if the monthly total precipitation is less than 20% of the long-term (1895-2009) historical average for that month.

Future Snow Cover

Changes in future snow cover will depend on two factors described above – temperature and precipitation. As shown earlier, the projected increases in Durham, NH winter maximum and minimum temperature will very likely push the Piscataqua/Great Bay regional average winter temperatures *above* the freezing point by the end of the 21st century. This suggests that a greater proportion of winter precipitation is more likely to fall as rain as opposed to snow. At the same time, precipitation is expected to increase in winter and spring, potentially increasing total snowfall in the near future as long as below-freezing temperatures occur. Projected changes in the number of winter days with snow cover (greater than one inch) are examined for early (2010-2039), mid (2040-2069), and late (2070-2099) century to evaluate when which factor will dominate: temperature increases (which will decrease snow cover days) or precipitation increases (which would potentially increase snow cover days if the temperature remains below freezing).

For the Piscataqua/Great Bay region and surrounding areas, it is clear that the influence of warming winter and spring temperatures will win out over expected increases in winter precipitation – all stations project decreasing number of days with snow cover (Figure 26). Historically, Durham experiences on average between 70-80 days per year with snow cover. During the early part of the century, decreases in snow-covered days are nearly the same for higher and lower emissions scenarios, -27% to -27%, respectively. By mid-century, the emissions pathway followed will determine the magnitude of snow loss. Under the lower emissions pathway, Durham can expect 32% fewer snow-covered days (about 22-25 days) relative to the 1970-1999 average. Under the higher emissions scenario, mid-century snow-covered days will decrease by almost 50% relative to historical values, shortening the snow cover season by over a month. End of century snow-covered day estimates for the lower emissions scenario are 40% of historical values. Under higher emissions scenario, the number of snow-covered days in Durham is expected to plummet to 60% of the historical value, leaving the Great Bay watershed with just over one month (32 days) of snow cover per year. The surrounding stations – Portland, Lawrence, and Concord, exhibit similar decreasing patterns as Durham with little to no difference in scenarios during the early part of the century and more dramatic decreases under the higher emissions scenario by mid- to late-century.

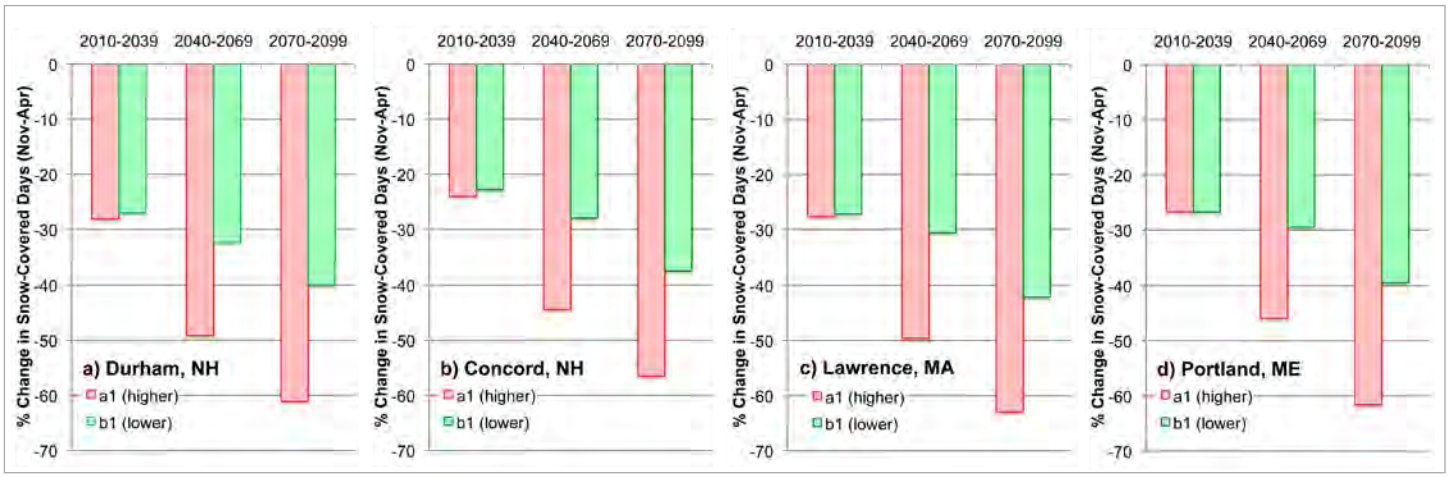


Figure 26. Projected percentage change in number of November-April snow covered days for (a) Durham, NH, (b) Concord, NH, (c) Lawrence, MA, and (d) Portland, ME for higher emissions (red) and lower emission (green). Percentage change is calculated relative to the 1970-1999 historical modeled mean.

Sea Level Rise

Historical Sea Level Rise

An overwhelming body of scientific evidence indicates that "most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations"[2]. One of the impacts of this warming has been an increase in sea level resulting from melting of land-based ice (i.e., glaciers and ice sheets) combined with thermal expansion of the ocean. The sum of these two effects is known as *eustatic* sea level rise (SLR)[40]. The long-term average rate of this eustatic global SLR has been estimated to be on the order of 0.67 inches per decade during the 20th century[41]. Sea level rise during the latter half of the 20th century was estimated at 0.7 ± 0.1 inches per decade [42]. One study suggested that the rate of eustatic coastal SLR in the late 20th century was greater than the average eustatic SLR in the second half of the 20th century[43]; this was later confirmed by sea level rise estimates of 1.2 inches per decade for the period 1993 to 2003[4] and 1.3 ± 0.2 inches per decade from 1993 to 2009[44] using satellite altimetry.

Rates of total or relative sea level rise (RSLR) which includes both climate and geologic influences measured at tide gauges along the United States coastline range from <0.4 to 3.9 inches per decade[45]. Differences in RSLR are due to local variations in vertical land motion, which are related to regional-specific processes such as tectonic uplift and down dropping, isostatic rebound and depression, coastal subsidence, land surface changes due to compaction, dewatering, fluid extraction, and diagenetic processes. Specifically, along the northeastern U.S. coast, vertical land movement ranges from < 0.3 inches per decade along the Maine coast to 0.67 inches per decade in Delaware[46], a range that is consistent with other estimates[47].

The combined effects of thermal expansion, increases in meltwater, a subsiding coast, and potential changes in ocean circulation make coastal New Hampshire particularly vulnerable to rising sea level. Increases in relative sea level contribute to enhanced flooding of coastal infrastructure, increased coastal erosion, saltwater contamination of freshwater ecosystems and loss of salt marshes. Low-lying shorelines such as sandy beaches and marshes are likely to be the most vulnerable to rising seas.

Relative sea level has been rising on the New Hampshire coast for the past 10,000 years[48]. However, relative sea level has been recorded at the Portsmouth Harbor (Seavey Island) tidal gauge only since 1926[49]. For the period 1926 to 2001, sea level rose nearly half a foot (5.3 inches), at a rate of about 0.693 inches per decade (Figure 27). In 2003, the Fort Point tide gauge replaced the Seavey Island gauge, but this new gauge does not have a long enough record from which to examine changes in relative sea level. Analysis of recent trends in tidal gauge records in Portland and Boston suggest that trends of the late 20th century are similar to trends over the past decade. Here we assume that the rate of SLR at Fort Point over the past decade is the same as has been measured at the Seavey Island tide gauge over the time period from 1926 to 2001 - about 0.7 inches per decade.

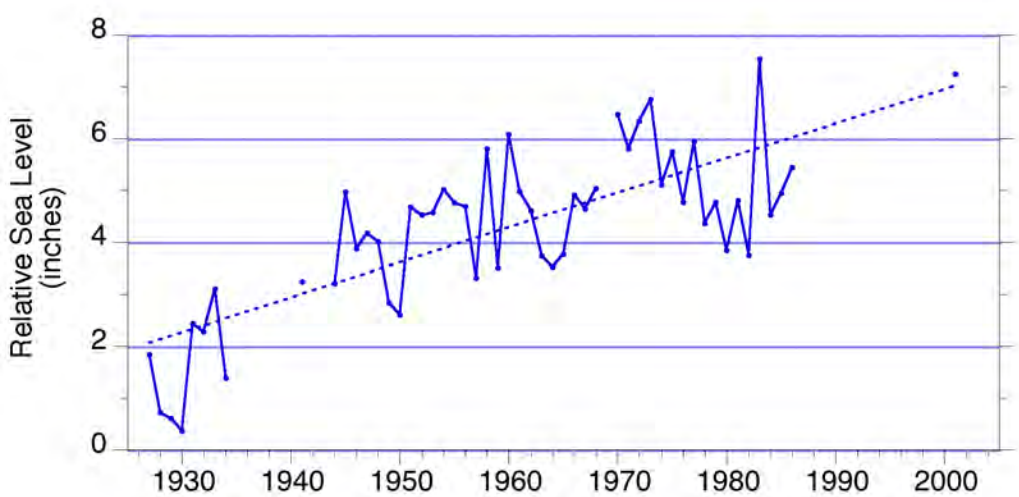


Figure 27. Annual mean sea level measured at the Seavey Island tidal gauge, 1927-2001. Data from NOAA[49]. The annual values represent the annual mean of the monthly mean sea level data. The dashed blue line is the linear regression applied to the time series. The gaps represent years with missing data.

Future Changes in Sea Level and Coastal Flooding

As sea level increases due to global and regional influences, coastal flood elevations will also increase, leading to increasingly larger areas of flooding during coastal storms. To generate future projections of coastal flooding in Portsmouth, projected increases in global and regional sea level were combined with an estimate of the current 100-year flood (stillwater) elevations using two emissions scenarios (B1 and A1fi)[33]. Coastal flooding projections, not including wave effects, were generated for mid-century, 2050, and end-of-century, 2100, relative to 1990

Analysis of Changes in the 100-Year Coastal Flooding Event

The results of the coastal flooding analysis for Portsmouth Harbor, New Hampshire, were based on methods previously developed[50] and updated to incorporate more recent SLR projections[51].

Historical hourly water-level data from the Seavey Island tide gauge are only available from 1985 through 2002 on the Tides and Current web site of the National Oceanic and Atmospheric Administration / National Ocean Service (NOAA/NOS) Center for Operational Oceanographic Products and Services. However, based on discussions with NOAA staff, hourly water-level data for Seavey Island are available for 1926 through 2002[52]. These data were requested from, and provided by, NOAA staff. This dataset contains several large gaps, specifically in the late 1930s, and from 1986 through 2001 (Figure 27). As mentioned above, the Fort Point tide gauge replaced the Seavey Island gauge, and has been operating since 2003.

Coastal flooding anomaly heights and the future change in recurrence intervals of today's 100-year coastal flooding event in Portsmouth were calculated for both datasets: Seavey Island (1926 through 2002) and Fort Point (2003 through 2010). As mentioned above, there is no published sea level rise trend for Fort Point, so the Seavey Island trend was used for these calculations. Recurrence intervals were then determined for the period 1926 through 2010, excluding data gaps, combining the anomalies from both datasets.

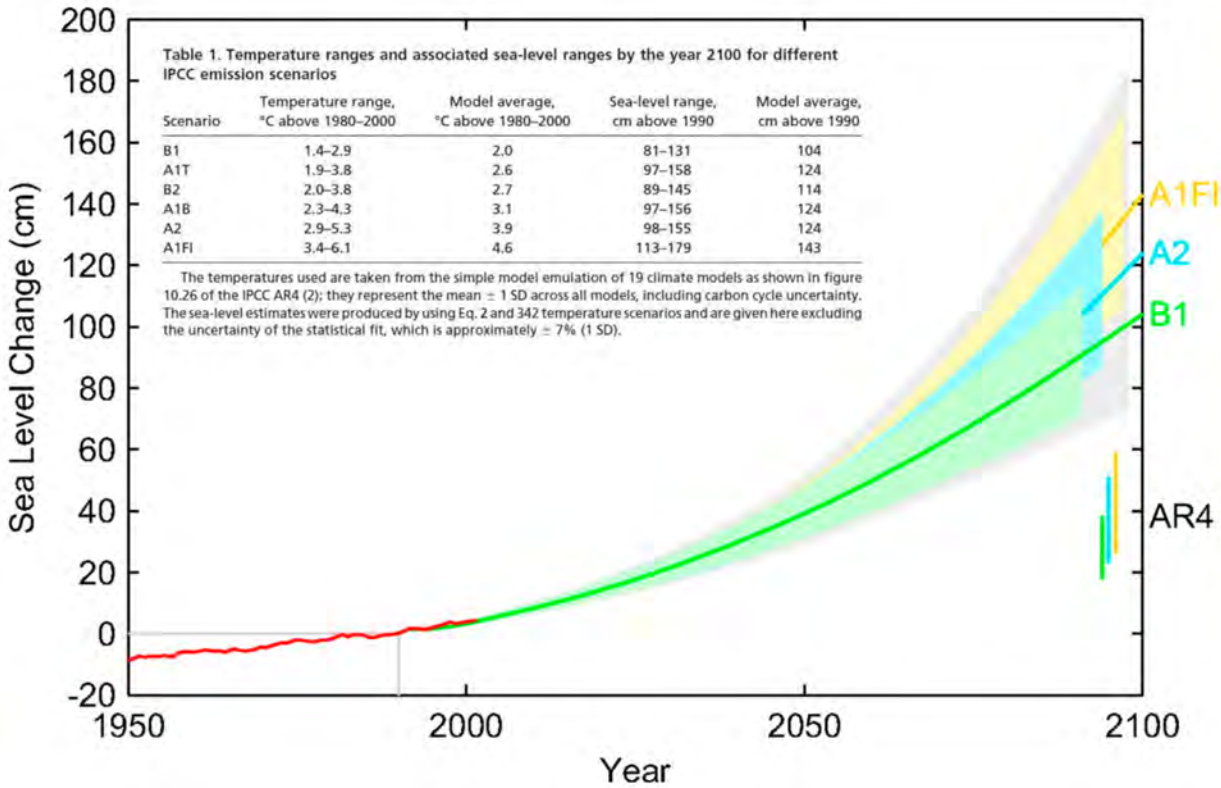


Table 1. Temperature ranges and associated sea-level ranges by the year 2100 for different IPCC emission scenarios

Scenario	Temperature range, °C above 1980–2000	Model average, °C above 1980–2000	Sea-level range, cm above 1990	Model average, cm above 1990
B1	1.4–2.9	2.0	81–131	104
A1T	1.9–3.8	2.6	97–158	124
B2	2.0–3.8	2.7	89–145	114
A1B	2.3–4.3	3.1	97–156	124
A2	2.9–5.3	3.9	98–155	124
A1FI	3.4–6.1	4.6	113–179	143

The temperatures used are taken from the simple model emulation of 19 climate models as shown in figure 10.26 of the IPCC AR4 (2); they represent the mean ± 1 SD across all models, including carbon cycle uncertainty. The sea-level estimates were produced by using Eq. 2 and 342 temperature scenarios and are given here excluding the uncertainty of the statistical fit, which is approximately ± 7% (1 SD).

Figure 28. Projection of sea-level rise (SLR) from 1990 to 2100 (from Vermeer and Rahmstorf 2009)[42], based on temperature projections for three different emission scenarios[3]. The sea-level range projected in the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4)[3] for these scenarios is also shown for comparison in the vertical bars on the bottom right. Also shown is the observations-based annual global sea-level data (red) including artificial reservoir correction.

Future Estimates of Sea Level Rise in Portsmouth

Projections of global eustatic SLR produced for the 2007 Intergovernmental Panel on Climate Change report[2] ranged from 7.1 to 23 inches by 2100, but were based only on thermal expansion because of a lack of reliable ice melt estimates at the time. Accounting for ice melt increased this range of projections to 31 inches (most plausible) - 79 inches (possible but unlikely)[53] and 12 to 20 inches (moderate temperature scenario) to 16 to 31 inches (warm temperature scenario)[54]. Recent model projections of eustatic SLR[51] suggest a range in average sea level increase of 39 to 55 inches by 2100, with the range of uncertainty increasing from 31 to 75 inches. The large uncertainty is mainly due to the range of CO_2 emissions scenarios used in making these model-based projections.

For this report, we use the maximum extents of the range of global eustatic SLR by 2100 relative to 1990: 31 inches for the lower B1 SRES scenario, and 75 inches for the higher A1fi SRES scenario[51]. These values were estimated using the SLR projection curve (Figure 28) and include a $\pm$7% uncertainty error. Projected values for eustatic SLR by the year 2050 under both lower and higher emissions scenarios were also estimated using the SLR projection curve shown in Figure 28.

Future subsidence over the next century was estimated by assuming that current rates will continue[50]. Eustatic SLR rate for the 20th century was estimated at 0.67 inches per decade[41]. Relative SLR at the Seavey Island gauge for the period 1926 to 2001 was calculated by NOAA to be 0.69 inches per decade[49]. Historical subsidence was estimated by assuming both historical eustatic SLR and historical RSLR are linear processes, and then subtracting historical eustatic SLR from the historical RSLR. We estimated local SLR due to subsidence at the Seavey Island gauge to be 0.02 $\pm$ 0.26 inches per decade, which results in average values of 0.14 inches by 2050 and 0.26 inches by 2100, relative to 1990. Although this calculated value for subsidence is lower than the range of values discussed above, we used this smaller value to be consistent with previous analyses[50]. Additionally, for the purposes of this report, we assume that future subsidence over the next century for Fort Point will be the same as that measured at the Seavey Island tide gauge.

A summary of those components and their contribution to the preliminary estimates of future stillwater elevations is provided in Table 13. (Stillwater elevation is the elevation of the water surface that does not account for waves and run-up.). The estimated flood height is the result of our statistical analysis of the historical Seavey Island and Fort Point tide gauge data. The 100-year food height at the Fort Point tide gauge was estimated to be 6.8 feet. Adding this estimated flood height to the elevation of mean higher high water (MHHW, 4.4 ft), results in an estimate of the current 100-year coastal flood stillwater elevation of 11.2 feet relative to the North American Vertical Datum (NAVD). (MHHW is the average of the higher high water height of each tidal day; values are provided by NOAA. The NAVD is

	2050		2100	
	Lower	Higher	Lower	Higher
Current Elevation of MHHW [a,b]	4.4	4.4	4.4	4.4
100-Year Flood Height	6.8	6.8	6.8	6.8
Subsidence	0.0	0.0	0.0	0.0
Eustatic SLR	1.0	1.7	2.5	6.3
Total Stillwater Elevation [a,c]	**12.2**	**12.9**	**13.7**	**17.5**

a - NAVD: North American Vertical Datum of 1988
b - MHHW: Mean Higher High Water at Fort Point, NH
c - Total Stillwater Elevation may not equal total of components due to rounding

Table 13. Estimates (in feet) of future 100-year flood Stillwater elevations at Fort Point under lower and higher emission scenarios (relative to NAVD88) **based on the statistical analysis presented in this report**.

the current engineering standard for vertical datum and is used by FEMA for all new Flood Insurance Risk Maps.) By adding the estimated 100-year flood height to MHHW, our estimate represents a coastal flooding scenario that occurs during the highest daily tide. This serves as a valuable benchmark for future planning efforts as our largest nor'easters often result in storm surge that lasts for at least one, and sometimes several days.

The FEMA 100-year coastal flood stillwater elevation for Newcastle Island (where Fort Point is located) is 8.4 feet NAVD[55] (Table 14). This elevation is 2.8 feet lower than our estimated 100-year coastal flood stillwater elevation of 11.2 feet NAVD. This difference is most likely due to several reasons: 1) our stillwater elevation estimate relies on a statistical analysis of observed tide gauge data, whereas the FEMA estimate is based on an analysis of a synthetic storm surge dataset generated by a computer model[55]; 2) our stillwater elevation does not account for the hydrodynamic effects as the tide and storm surge move from the coast into Portsmouth harbor (according to the FEMA analysis, the stillwater elevation at Portsmouth is at least 0.3 feet lower than at the coast); 3), our stillwater elevation assumes that the maximum impact from the coastal flood event occurs during the bi-monthly astronomical high tide (spring tide).

Our analysis is based on the historical water level data from the Seavey Island and Fort Point tide gauges. There was missing data in the Seavey Island and Fort Point tidal records (Figure 27). Thus, there were a number of missing years in the water level time series developed for Portsmouth; these data gaps were filled using a regression model developed from tide gage data at Boston, Massachusetts and Portland, Maine. The root mean squared error for this regression model was 0.82 feet, which is nearly identical to the standard deviations of the Portsmouth, Boston, and Portland tide gage data. Although the specific limitations of the Seavey Island data cited by FEMA are unknown, we presume that these limitations include the data gaps discussed above.

Flood Mapping

The results presented in Tables 13 and 14 show that we can expect the 100 year flood height to range from 9.4 to 12.9 feet by 2050, and to range from 10.9 to 17.5 feet by 2100. Therefore, even under the low emissions scenario, we can expect the 100 year flood height to increase several feet over the next 90 years. This increase in the 100 year flood height will result in more severe flooding in coastal New Hampshire in the future.

To illustrate the impact of the higher 100 year flood height, a series of maps will be produced to show the extent of flooding based on stillwater elevations presented in Tables 13 and 14. However, we are waiting for more accurate topographic data and digital elevation model that is currently being developed from a series of LiDAR (Light Detection and Ranging) data that was collected during the spring of 2011. We expect these maps to be made publicly available (and included in an updated version of this report) early in 2012.

	2050		2100	
	Lower	Higher	Lower	Higher
100-Year Flood Height	8.4	8.4	8.4	8.4
Subsidence	0.0	0.0	0.0	0.0
Eustatic SLR	1.0	1.7	2.5	6.3
Total Stillwater Elevation [a,c]	**9.4**	**10.1**	**10.9**	**14.7**

a - NAVD: North American Vertical Datum of 1988
b - MHHW: Mean Higher High Water at Fort Point, NH
c - Total Stillwater Elevation may not equal total of components due to rounding

Table 14. Estimates (in feet) of future 100-year flood Stillwater elevations at Fort Point under lower and higher emission scenarios (relative to NAVD88) **based on the FEMA base flood elevation** [55].

Conclusions

An overwhelming body of scientific evidence clearly shows that global climate is changing, and that human activities are the primary driver of that change over the past four decades.[2,6] Climate change is already affecting the northeast United States and coastal New Hampshire in many ways.[7,8,9] Temperatures have already begun to rise, particularly in winter. Overall precipitation is increasing, as is the frequency of extreme precipitation events. River discharge is increasing. Lake ice-out dates are occurring earlier. Sea surface temperatures in the Gulf of Maine are rising rapidly. And sea level continues to rise.

In the future, these trends are expected to continue. With few exceptions, much greater changes are anticipated under higher as compared to lower future emission futures. Depending on the future emissions of heat trapping gases, annual average temperatures in the Piscataqua/Great Bay region are expected to increase between 4ºF and 9ºF before the end of the century, with greater increases in summer. Warmer temperatures mean increased frequency of extreme heat events, and decreases in extreme cold and days below freezing.

Precipitation, especially in winter and spring, is expected to rise, as is the frequency of extreme precipitation events, exacerbating the risk of flooding. Snow-covered days are expected to decrease. Coastal flood elevations will continue to increase due to sea level rise, leading to increasingly larger areas of flooding during coastal storms.

While not included in this report, detailed analysis of the impact of these changes on a range of sectors, including marine resources, coastal infrastructure, forests, agriculture, winter recreation, and human health across the northeast United States have been summarized in papers and reports developed by the Northeast Climate Impacts Assessment.[9]

Because climate change is already affecting the northeast U.S., and some additional warming is inevitable, it is essential to prepare to adapt to the changes that cannot be avoided. However, immediate and committed action to reduce emissions is the most effective means to keep future climate changes at those projected under the lower emissions scenario. The more we can reduce our fossil fuel emissions, the more ecosystems, human communities, and economic sectors will be able to adapt to those coming changes we cannot avoid.

Appendix A: Durham Minimum Temperatures

The United States Historical Climatology Network (USHCN) is a high-quality data set of daily and monthly records of basic meteorological variables from 1218 observing stations across the 48 contiguous United States (Menne et al. 2009). Despite rigorous efforts to adjust station records for non-climatic biases (e.g., station relocation, changes in instrumentation and observer, urbanization) some stations still exhibit inconsistent temporal characteristics compared to neighboring stations.

For example, minimum and maximum temperature records for Lawrence, Durham, and Portland are show in Figure A1. From 1895-1930, the data for Durham consistently records average monthly minimum temperatures higher than Portland. Between 1930 and 1940, the Durham station shows minimum temperatures lower than Portland. The overall effect is a cooling trend in Durham minimum temperatures between 1895-1940 while stations to the north and south of Durham consistently record warming trends. Yet the Durham maximum temperature record remains temporally consistent with neighboring stations throughout the entire 114-year record.

Why the inconsistency? The Durham station history file provides a few plausible explanations (Table A1). The first explanation could be related to a station relocation that occurred on June 1, 1948. Prior to June 1st 1948, the elevation of the Durham station is listed as 95 ft located at 43°08'N/70°56'W. On June 1, 1948 the elevation changes to 69 ft but interestingly the latitude and longitude remain unchanged. Elevation changes do affect temperature, but in this case the temperature *decreases* measured the lower elevation relative to the higher elevation are exactly the opposite of what one would expect. In addition, the elevation change hypothetically would have also impacted the maximum temperature record, but that is not observed here. Numerous undocumented station relocations also mar the Durham climate record. A close look at the handwritten climate records in the New Hampshire State Climate Office reveals numerous changes in latitude, longitude, and elevation that are not documented in the digital NCDC station history. The present location of the climate station places it less than 20 feet from a building and less than 100 feet from a major road. As such, its Climate Reference Network rating is very poor due to the artificial heat sources from the building and adjacent roadway[56].

In addition to numerous undocumented station relocations, the time of observation for temperature changed when the station was relocated. Records from the 1930's list the time of observation for minimum temperature as having occurred daily between 5:00 pm and 7:30 pm. Between 1947 and 1948 the time of observation changes to 11:00 pm, but after 1948 the time of observation is consistently recorded as 5:00 pm every day. It is not clear whether the change in time of observation during the late 1940s can be held accountable for Durham's minimum temperature inconsistency with neighboring stations. Nevertheless, it is clear homogeneity testing by the United States Historical Climate Network was insufficient for resolving non-climatic issues in the Durham minimum temperature record pre-1950.

START	END	LAT (N)	LON (W)	ELEV (FT)
1995	present	43.15	70.95	80
1986	1995	43.15	70.95	74
1975	1986	43.15	70.95	69
1948	1975	43.13	70.93	69
1939	1948	43.13	70.93	95

Table A1. Durham, NH station history, 1939-present, as documented by the National Climatic Data Center (NCDC).

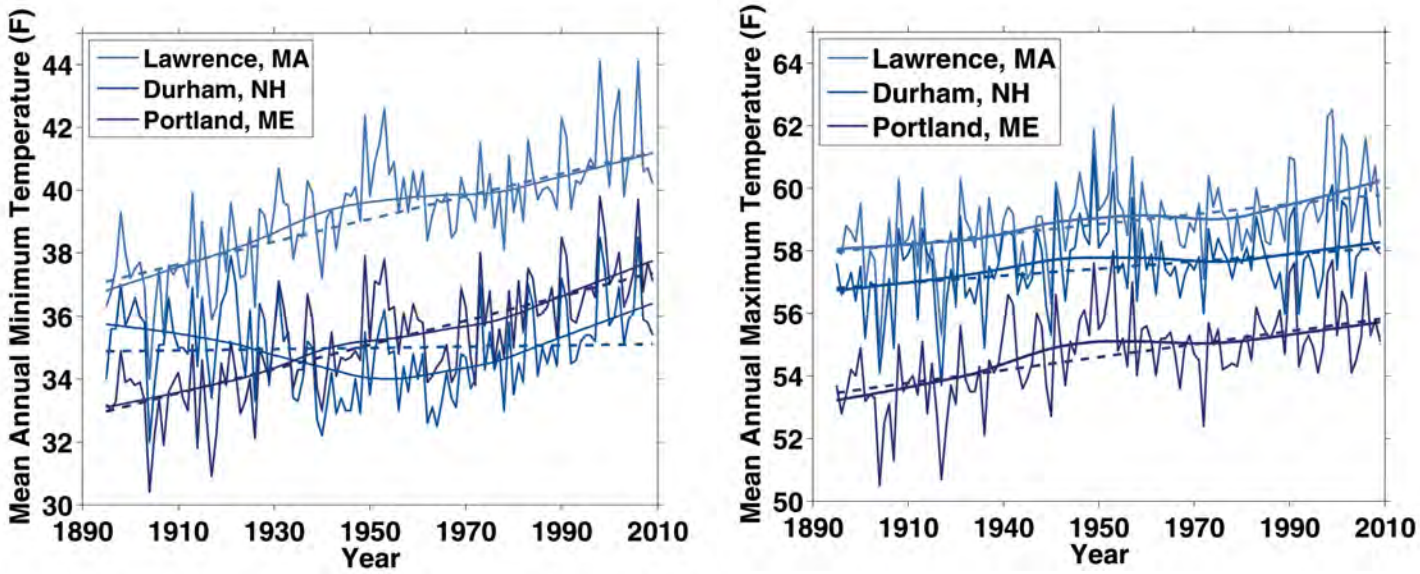


Figure A1. Mean annual minimum (left) and maximum (right) temperature records from Lawrence MA, Portland ME, and Durham NH, 1895-2009. LOWESS smooths (solid) and Sen's slope (dashed) included to illustrate long term variability and trend, respectively.

Appendix B:
A Modified Statistical Asynchronous Regression Downscaling Method

Anne Stoner, Katharine Hayhoe, and Xiaohui Yang

The modified statistical asynchronous regression (SAR) downscaling approach uses daily predictor fields from AOGCMs to statistically downscale maximum and minimum temperature and 24h cumulative precipitation. The AOGCM simulations are first re-gridded to the scale of the observations (whether for stations or grids) using bilinear interpolation. For training, the method requires a minimum of 20 years of observations with less than 5% missing data over that time period in order to produce robust results. Where data is available, at most the method uses the entire observational record from 1960 to present for training purposes.

The SAR downscaling approach is based on a highly generalizable statistical approach, quantile regression. This approach has two key advantages: first, it does not require temporal correspondence between AOGCM simulations and observations; and second, it is capable of incorporating AOGCM-simulated changes in the shape of the distribution (including shifts in the mean, skewness, and variance) into future projections.

Model predictor values and observed predict and values are ranked and a function (here, a piecewise linear regression) is fitted to the datasets by month, including two weeks of overlapping data on either side. This additional refinement was added to account for shifting seasons in future projections that may produce conditions outside the range of a typical historical month in the future, and allows the method to utilize each data point twice rather than once during the training process.

Optimal placements and number of break points (up to six) in the piecewise linear regressions are identified automatically as locations with higher curvature on a plot of ranked modeled vs. observed values. The slopes of the regression segments are checked to ensure no negative slopes are present, and if there is a negative slope a break point is removed to force a positive slope.

Temperature. Based on tests during the development stage of this method, it was determined that the most reliable predictor for daily maximum and minimum 2m temperature were those same fields as simulated by the AOGCMs. Improved performance on temperature downscaling is obtained by filtering the AOGCM fields using an EOF analysis and retaining only 97% of the original variance. As the linear regressions at the tails are based on a much lower number of data points than those in the center of the distribution, the low and high tail of the distributions undergo further scrutiny by performing bias correction at the tails, ensuring that values are within 30% of the observations.

Precipitation. The downscaling model for precipitation is similar to that for temperature in many aspects, but with some key differences. First, for practical reasons an AOGCM predictor had to be chosen that was commonly archived at the daily scale. Although upper-level humidity and geopotential height have shown promise in downscaling precipitation, few AOGCMs have preserved daily outputs. Thus, 24-hr cumulative precipitation was selected as the predictor for precipitation, with the additional refinement of incorporating convective and large-scale precipitation if both predictors were available. For models with these variables, the downscaling approach selects from three possible predictors the one best suited to each month: convective, large-scale, or total. This refinement significantly improved the method's ability to simulate precipitation over arid and semi-tropical regions. Second, EOF filtering of the GCM output is not performed since we found that to degrade the results along with introducing negative values for precipitation. Finally, the logarithm of precipitation values is used instead of raw precipitation amount. This was found to decrease the residuals of the regression.

The resulting outputs have been statistically estimated to be accurate to the 99.6th percentile of the distribution (i.e., to 1-2 days per year). This is likely a fairly conservative estimate, as it does not incorporate the effects of bias correction in the tails of the distribution. Analyses of biases in the quantiles of the distribution and in key thresholds such as wet days show good correspondence with historical observations (Figure B1).

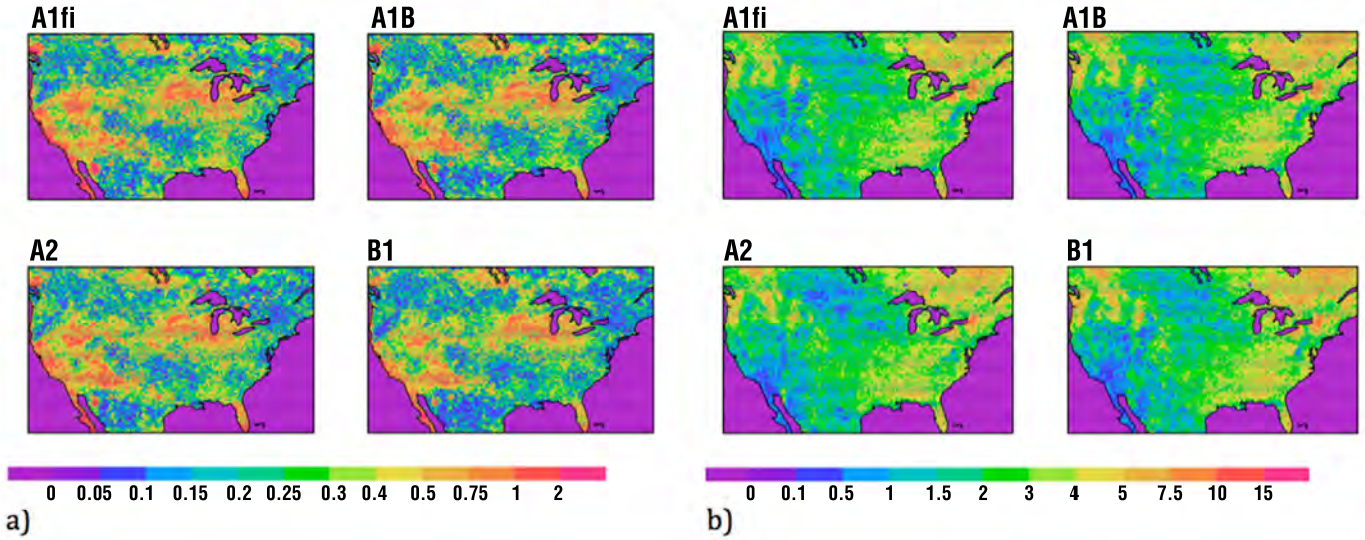


Figure B1. The bias in (a) the 99th quantile of the distribution of maximum temperature as simulated by downscaling GFDL CM2.1, and (b) the number of wet days per year (pr>0.1") in downscaled simulations compared to observations for the period 1960-2000, as simulated by downscaling HadCM3.

Endnotes

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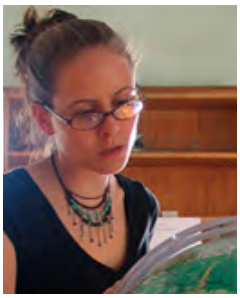

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The Japanese ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensor on board NASA's Terra satellite captured this spectacular view of the Coastal New Hampshire Watershed in 2008. ASTER provides high-resolution images of the Earth in 15 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. The resolution of images ranges between 15 to 90 meters. *Image provided by TerraPrints.com*

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