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### Climate Change In The Casco Bay Watershed: Past, Present, And Future

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# CLIMATE CHANGE

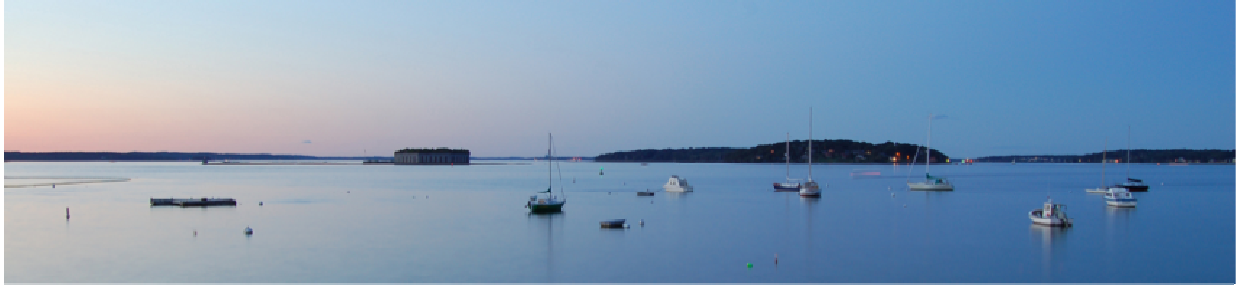
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Casco Bay Watershed



CLIMATE CHANGE IN THE CASCO BAY WATERSHED: PAST, PRESENT, AND FUTURE  
DECEMBER 2009



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# **Climate Change in the Casco Bay Watershed: Past, Present, and Future**

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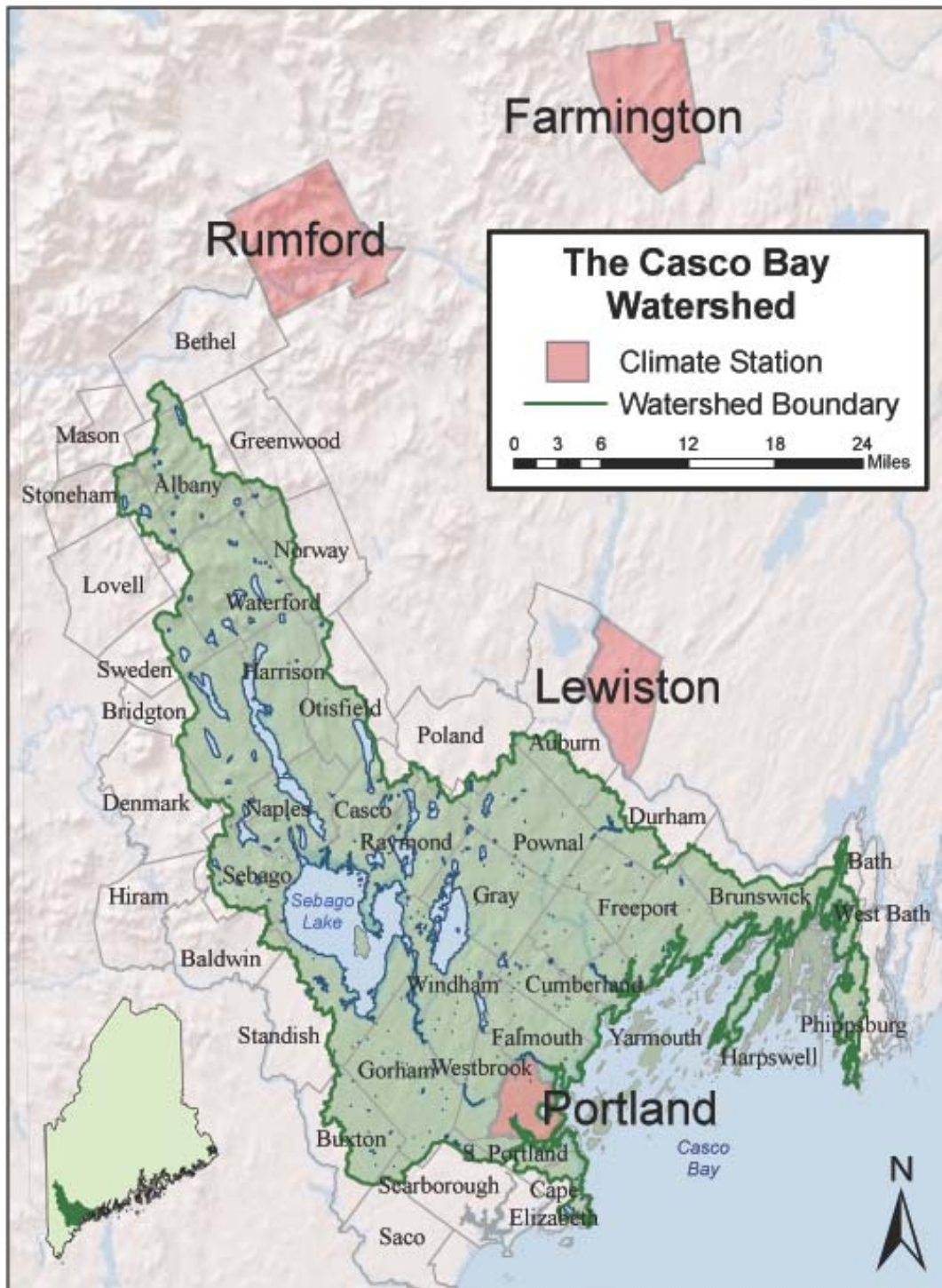
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**Figure 1.** The Casco Bay Watershed region, showing the watershed boundary and the four climate stations used in this report.

## **EXECUTIVE SUMMARY**

This report describes how the climate of Casco Bay watershed in Maine, has changed over the past century and how the future climate of the region is likely to be affected by human emissions of heat-trapping greenhouse gases that are warming the planet.

Overall, the region has been getting warmer and wetter over the last century, and these trends have increased over the last four decades. Detailed analysis of data collected at four meteorological stations in the region (Farmington, Lewiston, Portland, and Rumford) show that since 1965 the region has warmed 1.5 to 3.0°F, with the greatest warming occurring in winter (1.6 – 4.9° F). Overall annual precipitation and extreme precipitation events (both 1” in 24 hours and 2” in 48 hours) have increased in Portland. The number of snow covered days is decreasing (especially on the coast), and winter snowfall is decreasing. Data collected from ships, buoys, and other observational platforms shows that sea surface temperatures in the Gulf of Maine are warming. Tidal gauge data indicates relative sea level at Portland is continuing to rise. Finally, analysis of phenological data indicates that ice-out dates on Sebago Lake are occurring earlier.

To generate future projections for Portland, Farmington, and Lewiston, simulated temperature and precipitation from four climate models were fitted to local, long-term weather observations. Unknowns regarding fossil fuel consumption were accounted for by using two future scenarios. These scenarios paint very different pictures of the future. In the lower emissions scenario, conservation practices and 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 four 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 Casco Bay watershed. Depending on the scenario, mid-century temperatures may increase as much as 2° F to 6° F, and end-of-century temperatures may increase as much as 3° F to 8° F. Summer temperatures may experience the most dramatic change, up to 10° 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 may increase to 14 days per year from their current average of 4 days per year. Under a higher emissions scenario, these days increase to as many as 60 days each year, 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 35 days per

year from their current average of just 1 day each year. The hottest day under this scenario for both Portland and Farmington soars to 114°F, 19 degrees above the average hottest day now.

Extreme cold temperatures are projected to occur less often, and cold days will be warmer than in the past. By end-of-century, under lower emissions, 15 fewer days with minimum temperatures below 32°F are projected for Portland, which currently experiences 150 days minimum temperatures below 32°F, and for Farmington, which usually expects 200 days. Under higher emissions, 30 fewer days with minimum temperatures below 32°F are projected.

Very cold days, where minimum temperature falls below 0°F, are projected to drop from their current average of 40 days per year, to 24 days per year under lower emissions and 12 days under higher emissions before the end of the century at inland sites. On the coast, the number of days below 0°F may drop from the current 10 days per year to 4 days under lower emissions and just 1 day per year under higher emissions.

Coldest temperatures of the year are also expected to warm. As just one example, the coldest day of the year in Farmington, today a chilly -25°F, is projected to rise to -12°F. 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, but 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 5% by mid-century and 10% by end-of-century. Larger increases are expected for winter and spring, exacerbating concerns regarding rapid snow melt, high peak stream flows, and flood risk.

The frequency and intensity of “heavy precipitation events,” the days per year with more than 2 inches of rain, is likely to continue to increase. By end-of-century, under lower emissions, the number of days each year with more than 2 inches of rain is projected to increase to an average 2.0 - 2.5 days from the current 1.5 days each year. Under higher emissions, heavy rain days increase to 3.0 days per year, increasing possible flood risk.

Frequency of drought, a precipitation deficit more than 20% below long-term historical averages for a month, is projected to increase under higher emissions, from a current average of 1 in every 10 years to one month of drought every 3 years. Little to no change in drought frequency is expected under lower emissions.

To generate future projections of coastal flooding in Portland, simulated increases in global and regional sea level were combined with current 100-year flood (stillwater) elevations, also using two future emissions scenarios. Coastal flooding projections, not including wave effects, were generated for 2050 and 2100, relative to 1990. Increases in the frequency of future coastal flooding events and estimates of future coastal flood heights were not determined in this study due to data quality issues with the long-term hourly sea level observations at the Portland tide gauge. Therefore, preliminary estimates of future coastal flooding elevations for Portland were generated based on published stillwater elevations. Flood maps showing the spatial extent of these preliminary estimates of future coastal flooding elevations for Portland were developed using a best-available digital elevation model.

Preliminary estimates of the 100-year coastal flooding elevations in 2050 under both higher and lower emissions scenarios suggest only limited increases (~1 foot) over current flood elevations, not including wave effects. This is consistent with a delayed response in global sea level rise in response to global surface air temperature increases due to climate change.

Preliminary estimates of coastal flooding elevations in 2100 suggest that large areas of coastal Portland could be flooded, including areas along the southern coast of Back Cove, as well as areas of both Portland and South Portland adjacent to the Fore River. The preliminary estimates of the future 100-year



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coastal flooding elevation in 2100 under the lower emissions scenario suggest increases of approximately 2 feet over current flood elevations, and 5 feet over current flood elevations under the higher emissions scenario. Those estimated stillwater elevations do not include wave effects, which can be significant. Some future changes are inevitable, so smart choices must be made to ensure our society and our environment will be able to adapt to coming change. But with prompt action, many of the most extreme consequences of climate change could be avoided or their worst impacts reduced.

## **I. 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<sup>i</sup>.

Today, however, the story is noticeably different. Since the Industrial Revolution, atmospheric concentrations of greenhouse gases such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) have been rising because of increasing emissions from human activities<sup>ii</sup>. The primary source of CO<sub>2</sub> comes from the burning of fossil fuels such as coal, oil, and natural gas. Carbon dioxide is also produced by land use changes, including tropical deforestation. Agricultural activity and waste treatment are critical sources of CH<sub>4</sub> and N<sub>2</sub>O 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.<sup>iii</sup> Average surface temperatures in the Northern Hemisphere have risen by 1.3°F over the past 150 years. Based on these and many other lines of evidence, the Intergovernmental Panel on Climate Change (IPCC), which summarizes the published work of thousands of climate scientists around the world, has concluded that an overwhelming body of scientific evidence 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.<sup>ii</sup>

The northeast United States (US) has already experienced an overall warming over the past century, with an increase in the rate of warming over the past four decades.<sup>iv</sup> This change in our regional climate 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 number of extreme precipitation events, an increase in the rain-to-snow precipitation ratio, a decrease in snow cover days, earlier ice-out dates, earlier spring runoff, earlier spring bloom dates for lilacs, longer growing seasons, and rising sea levels.<sup>iv</sup>

Over the coming century, Maine's climate – together with that of the rest of the planet – 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: (1) predicting our future emissions of greenhouse gases; and (2) predicting 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 global climate 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 the Casco Bay watershed. For that reason, state-of-the-art statistical techniques were used to “downscale” or match the regional temperature and precipitation simulations generated by the global climate models<sup>v</sup> to observed conditions at three individual long-term weather stations in the Casco Bay region: Portland, Farmington, and Lewiston (Figure 1).

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 Casco 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, sea surface temperatures, and sea level rise. 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 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; (3) describes projected changes in annual and seasonal rain and snow, as well as heavy rainfall events, for those same future time periods; and (4) describes the potential impacts of increased coastal flooding as sea levels continue to rise. Finally, Section IV 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 Casco Bay area are pervasive. For example, warmer temperatures affect the types of trees, plants, and even crops – such as blueberries – 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 will also have an impact on winter recreation opportunities. Although little change in snowy days is expected until later in the century, rising winter and spring precipitation could increase the risk of spring riverine flooding. Under the higher emissions future, drought may also become more frequent. 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 21<sup>st</sup> century.

## **II. INDICATORS OF PAST CLIMATE CHANGE**

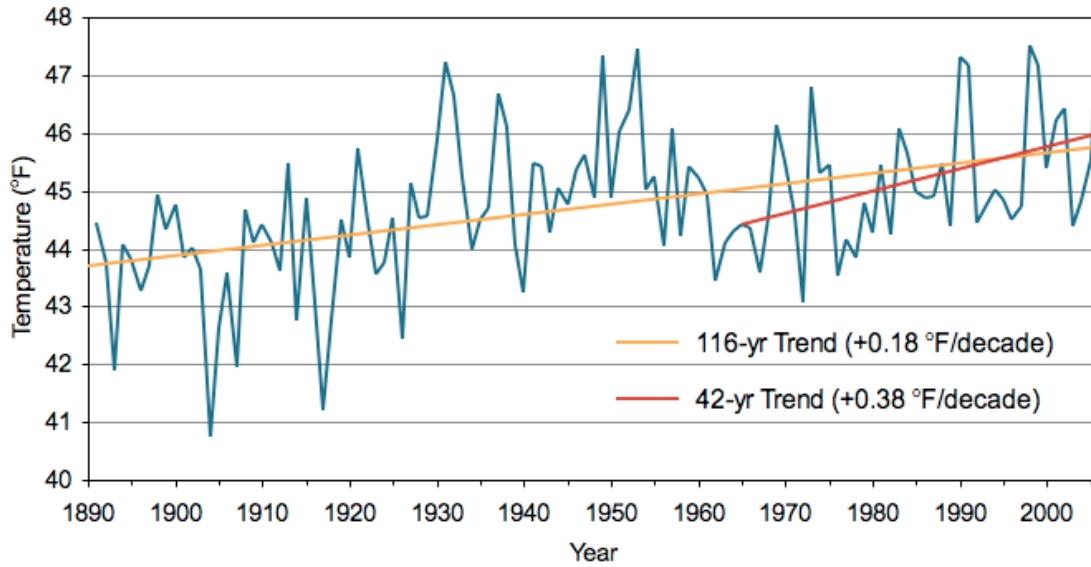
### **TEMPERATURE**

The temperature record from Portland, Maine, provides the best available long-term temperature record within the Casco Bay watershed. High quality temperature records from Lewiston and Farmington are also included in the analysis to provide estimates of temperature trends at northerly inland and mountainous regions in Maine (Figure 1). The three temperature records come from the United States Historical Climate Network (USHCN) monthly dataset<sup>vi</sup> and have been subjected to extensive quality assurance and quality control measures including corrections for time of observation biases, instrument changes, station relocations, and urban-heat adjustments<sup>vii</sup>. The records provide evidence of a ubiquitous warming trend present in all four seasons in the Casco Bay region over the period 1891-2006. This warming has intensified during recent decades (1965-2006). The period 1965-2006 coincides with the time during which global temperature increases are being driven primarily by increased concentrations of anthropogenic greenhouse gases.<sup>ii</sup>

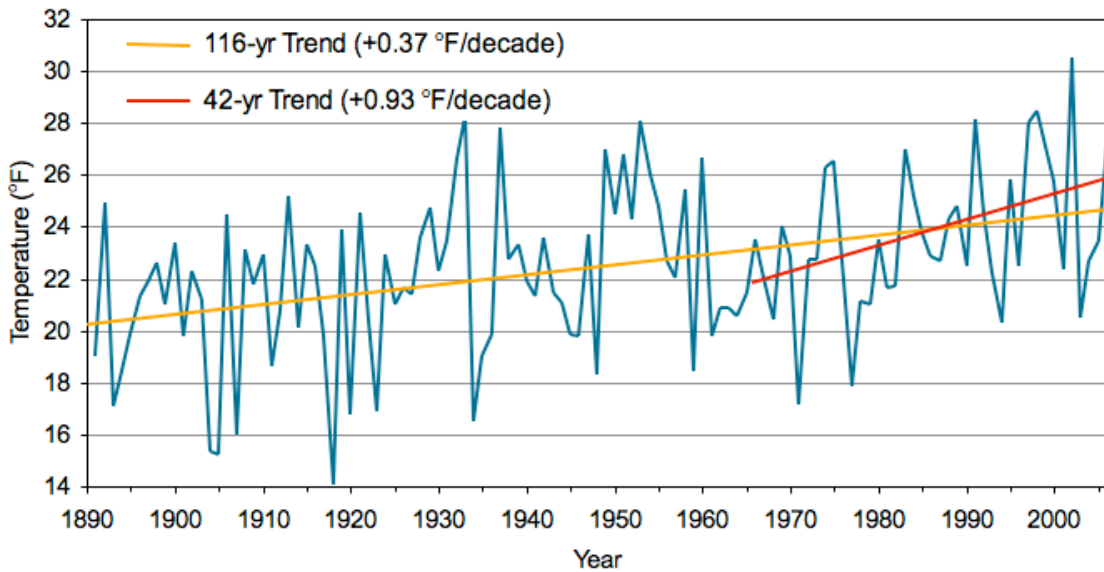
The three stations show statistically significant annual warming trends ranging from +0.15°F/decade to +0.41°F/decade in minimum, mean, and maximum temperature records over the period 1891-2006 (Figure 2; Table 1). Warming trends in annual maximum and minimum temperature trends are generally the same for Portland and Lewiston. In Farmington, however, the rate of warming in annual minimum (+0.41°F/decade) temperatures is more than double the warming rate in annual maximum (+0.15°F/decade) temperatures.

Seasonal rates of warming are greatest in winter (Figure 3) and weakest in summer for all three stations (Table 1 and Table 2), consistent with trends across the entire northeast US<sup>viii</sup>. The greatest rate of seasonal warming was identified in Farmington minimum winter temperatures, which increased by +0.41°F/decade over the period 1891-2006.

Warming trends intensify over the period 1965-2005 relative to the 1891-2006 trends (Table 2). In Portland, the rate of warming in mean annual temperature during recent decades (+0.38°F/decade) is more than double the rate of warming observed in the long term record (+0.18°F/decade). Winter warming trends in Portland increased by nearly three-fold from 0.37°F/decade over the period 1891-2006 to +0.93°F/decade over the period 1965-2006 (Figure 3). Sensitivity analyses over 1965-2006 indicate that temperature trends observed during this period are robust, especially for annual and winter trends (See Appendix A).



**Figure 2.** Time series of annual mean temperature recorded in Portland, Maine over the period 1891-2006. The orange line is the linear regression applied to the entire 116-yr time series, and the red line is the linear regression applied 42-yr time series 1965-2006.



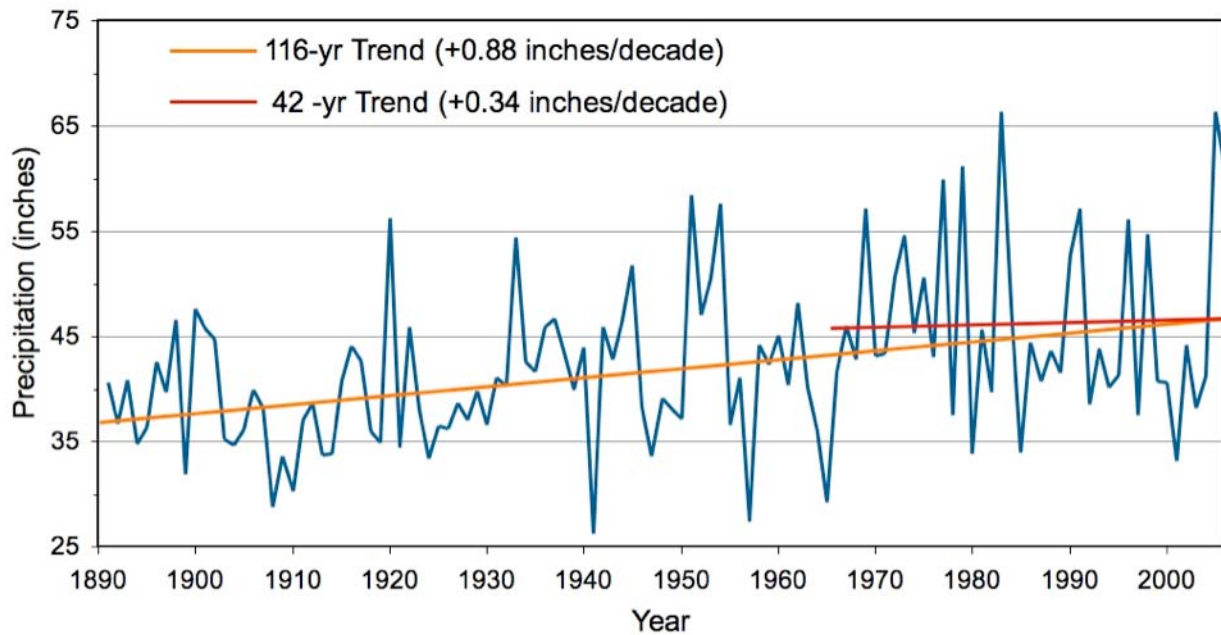
**Figure 3.** Time series of winter mean temperature recorded in Portland, Maine over the period 1891-2006. The orange line is the linear regression applied to the entire 116-yr time series, and the red line is the linear regression applied 42-yr time series 1965-2006.

## PRECIPITATION

Precipitation trends are obtained from the highly quality controlled monthly USHCN records for Portland, Lewiston, and Farmington. Portland, located at the mouth of the Casco Bay Watershed, provides a representative record of coastal precipitation trends. Lewiston and Farmington provide estimates of inland and mountain precipitation trends (Figure 1). Previous research has indicated strong increasing precipitation trends along New England coasts, with weaker increasing trends inland and in the mountains.<sup>ix</sup> The same spatial pattern is also observed in the Casco Bay region.

Portland annual precipitation increased by +0.88 inches/decade over the period 1891-2006, while Lewiston and Farmington showed increases of +0.27 and +0.33 inches/decade over the same time period (Figure 4; Table 1). For all three stations, the increase in annual precipitation is driven primarily by strong increases in fall (September-November) and spring (March-May) precipitation (Table 1). Winter precipitation remained essentially unchanged in Portland, Lewiston, and Farmington.

Over the period 1965-2006, annual precipitation trends increase at Portland (+0.34 inches/decade) and Farmington (+0.77 inches/decade), but decrease at Lewiston (-0.87 inches/decade). Decreasing trends at all three stations in winter precipitation over the last four decades are likely a result of decreases in snowfall<sup>x</sup>. A more detailed analysis of seasonal precipitation trends over this time period indicates that recent decades are characterized by strong decreases in winter precipitation at all three stations (See Appendix A).



**Figure 4.** Time series of annual total precipitation recorded in Portland, Maine, 1891-2006. The orange line represents the long-term trend of the entire time series, and the red line is the short-term trend, 1965-2006.

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**Table 1.** Summary of precipitation and temperature trends for Portland, Lewiston, and Farmington, Maine over the period **1891-2006**. Bold trends are statistically significant at  $p < 0.01$ ; underlined trends significant at  $p < 0.05$ .

PORTLAND, ME	Winter	Spring	Summer	Fall	Annual
Precipitation (inches/decade)	0.00	<u>+0.23</u>	+0.12	<b>+0.52</b>	<b>+0.88</b>
Maximum Temp (°F/decade)	<b>+0.29</b>	<b>+0.17</b>	<b>+0.13</b>	<b>+0.23</b>	<b>+0.20</b>
Mean Temp (°F/decade)	<b>+0.37</b>	<b>+0.18</b>	<u>+0.09</u>	<u>+0.09</u>	<b>+0.18</b>
Minimum Temp (°F/decade)	<b>+0.46</b>	<b>+0.20</b>	+0.02	+0.02	<b>+0.17</b>
LEWISTON, ME					
Precipitation (inches/decade)	-0.06	+0.10	0.00	<b>+0.26</b>	+0.27
Maximum Temp (°F/decade)	<b>+0.29</b>	<b>+0.32</b>	<b>+0.26</b>	<b>+0.16</b>	<b>+0.26</b>
Mean Temp (°F/decade)	<b>+0.34</b>	<b>+0.27</b>	<b>+0.22</b>	<b>+0.15</b>	<b>+0.24</b>
Minimum Temp (°F/decade)	<b>+0.38</b>	<b>+0.24</b>	<b>+0.18</b>	<b>+0.15</b>	<b>+0.24</b>
FARMINGTON, ME					
Precipitation (inches/decade)	-0.09	+0.13	+0.04	<b>+0.26</b>	+0.33
Maximum Temp (°F/decade)	<b>+0.35</b>	+0.11	-0.02	<u>+0.14</u>	+0.15
Mean Temp (°F/decade)	<b>+0.49</b>	<b>+0.24</b>	<b>+0.14</b>	<b>+0.25</b>	+0.28
Minimum Temp (°F/decade)	<b>+0.64</b>	<b>+0.36</b>	<b>+0.29</b>	<b>+0.36</b>	+0.41

**Table 2.** Summary of precipitation and temperature trends for Portland, Lewiston, and Farmington, Maine over the period **1965-2006**. Bold trends are statistically significant at  $p < 0.01$ ; underlined trends significant at  $p < 0.05$ .

PORTLAND, ME	Winter	Spring	Summer	Fall	Annual
Precipitation (in/decade)	<u>-0.95</u>	+0.56	+0.13	+0.66	+0.34
Maximum Temp (°F/decade)	<u>+0.71</u>	+0.24	-0.05	+0.32	<u>+0.31</u>
Mean Temp (°F/decade)	<b>+0.93</b>	+0.33	-0.07	+0.26	<b>+0.38</b>
Minimum Temp (°F/decade)	<b>+1.16</b>	+0.43	-0.10	+0.02	<u>+0.39</u>
LEWISTON, ME					
Precipitation (in/decade)	<u>-1.03</u>	+0.26	-0.25	+0.50	-0.87
Maximum Temp (°F/decade)	+0.46	+0.24	+0.17	+0.24	<u>+0.29</u>
Mean Temp (°F/decade)	+0.54	+0.29	<u>+0.34</u>	+0.30	<b>+0.39</b>
Minimum Temp (°F/decade)	+0.65	+0.34	<b>+0.52</b>	<u>+0.35</u>	<b>+0.48</b>
FARMINGTON, ME					
Precipitation (in/decade)	-0.65	+0.74	0.0	+0.72	+0.77
Maximum Temp (°F/decade)	<b>+0.81</b>	<u>+0.60</u>	+0.15	+0.40	<b>+0.51</b>
Mean Temp (°F/decade)	<b>+1.23</b>	<b>+0.74</b>	<u>+0.42</u>	<b>+0.56</b>	<b>+0.76</b>
Minimum Temp (°F/decade)	<b>+1.65</b>	<b>+0.88</b>	<b>+0.70</b>	<b>+0.70</b>	<b>+1.00</b>

## EXTREME PRECIPITATION

National studies show that more than half of annual precipitation increases observed over the twentieth century is reflected in the upper 10<sup>th</sup> percentile of precipitation events.<sup>xi</sup> The increase in extreme precipitation events has potentially important impacts on runoff, flooding, and water quality. It is likely that greenhouse gas warming will cause global increases in extreme precipitation, especially at mid-latitudes, because of increases in atmospheric water vapor and destabilization of the atmosphere.<sup>xii</sup>

Extreme precipitation events potentially threaten Casco Bay’s \$35-million dollar shellfish industry. When relatively acidic river plumes associated with extreme precipitation events mix with ocean water during shellfish spawning periods they create suboptimal conditions for shellfish growth.<sup>xiii</sup> In addition, rainfall events over one to two inches also often overwhelm sewer systems and transport sewage and other pollutants into coastal waters and inland lakes.



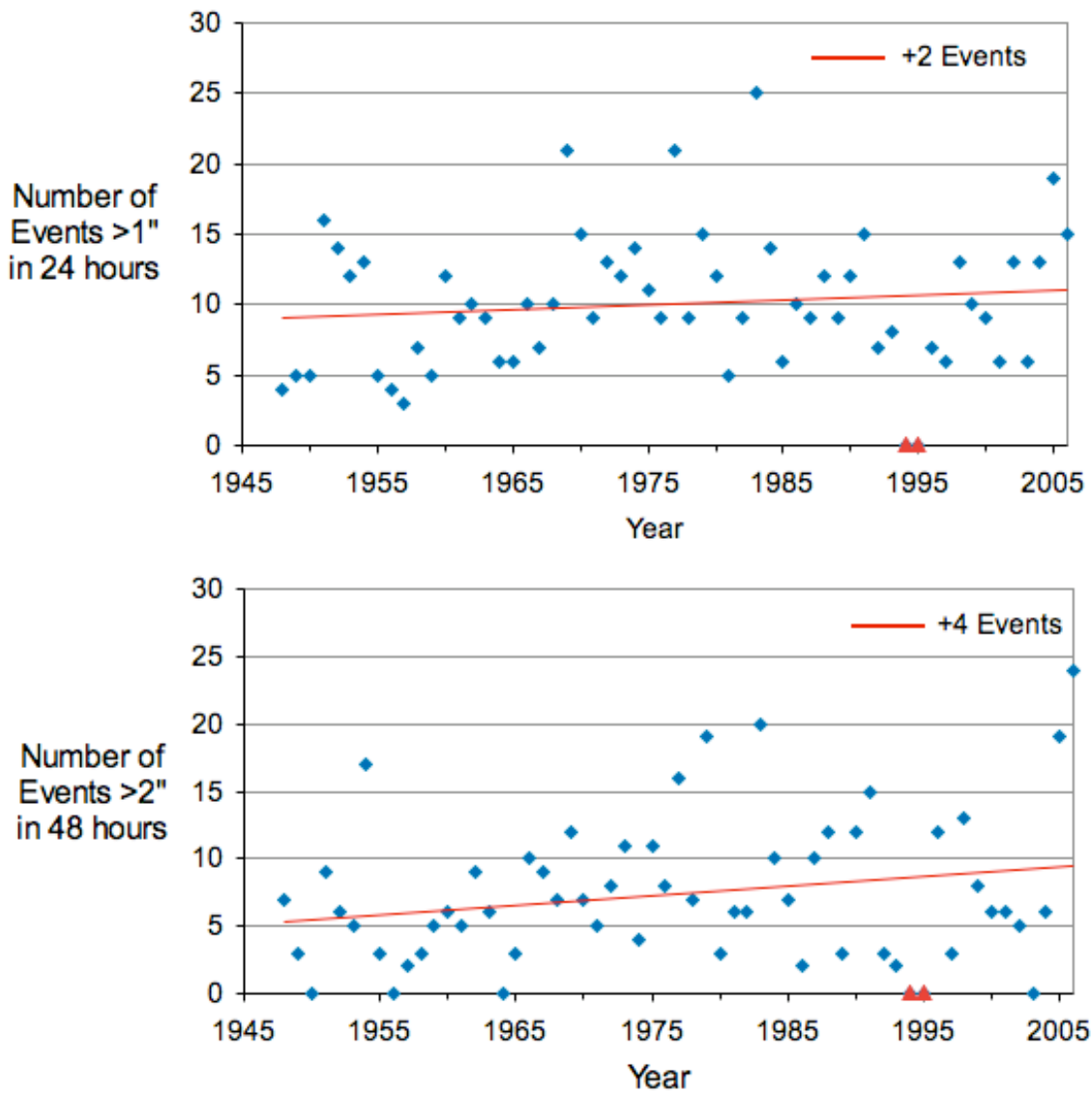
The increase in extreme precipitation events affects not only ecosystems, but also important infrastructure. Rapid rainfall events inundate culverts and can lead to culvert failure and subsequent road collapse. In April 2007, two major extreme precipitation events caused over \$22 million dollars in storm and flood damage in southern New Hampshire.<sup>xiv</sup> Advance planning and investment in measures to adapt to climate change will typically result in less damage and lower overall costs to municipal and state governments.<sup>xv</sup>

Daily precipitation records from the USHCN were utilized to construct records of two extreme precipitation definitions: (1) greater than one inch in 24 hours and (2) greater than two inches in 48 hours.<sup>xvi</sup>

Extreme precipitation events greater than one inch in 24 hours increased in Portland by +2.0 events, over the period 1949-2006 (Figure 5; Table 3); but the trend is significant only at the  $p < 0.10$  level. The increase in extreme events greater than two inches in 48 hours in Portland is +4.1 events over the period 1949-2006, and is significant at the  $p < 0.05$  level. Farmington experienced an overall increase in extreme precipitation events, and Lewiston experienced a slight decrease in extreme precipitation events over the period of record; neither trend is significant, however.

**Table 3.** Summary of extreme precipitation event trends over the period **1948-2005**. Underlined trends significant at  $p < 0.05$ .

Location	>1" in 24 hours	>2" in 48 hours
Portland	+2.0	<u>+4.1</u>
Lewiston	-0.5	-1.3
Farmington	+2.5	+2.5



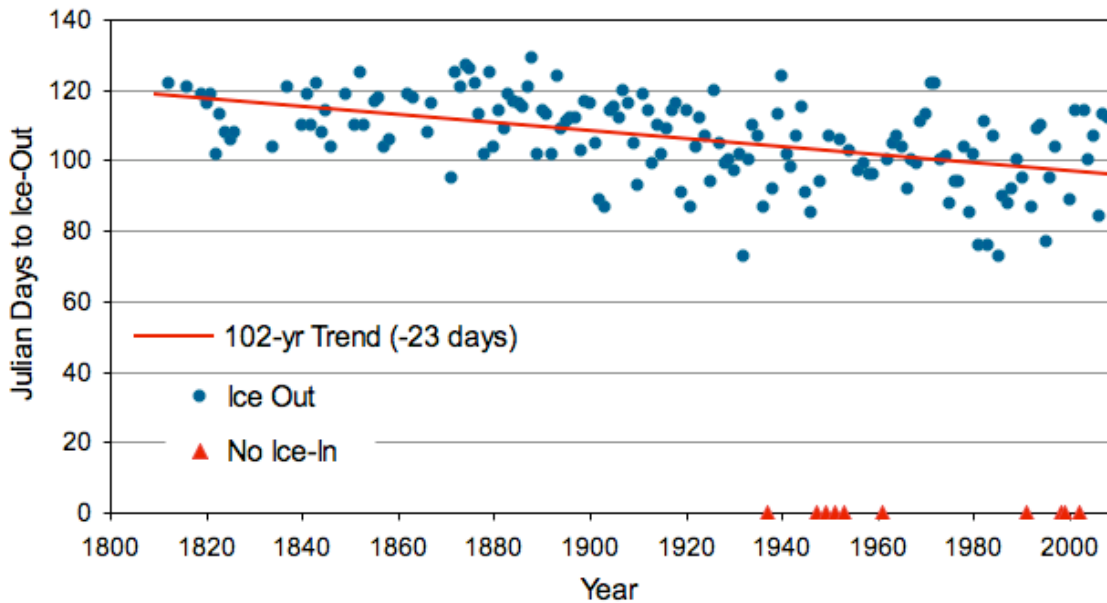
**Figure 5.** Time series of extreme precipitation events greater than one inch in 24 hours (top) and greater than two inches in 48 hours (bottom) for Portland, over the period 1948-2006. The red line is the linear regression applied to the time series, and is used to estimate the trends in extreme events in the 59-year record. Red triangles indicate years with missing data.

## LAKE ICE OUT

In New England, the timing of lake ice-out can be a useful indicator of climate change because the ice-out dates correlate strongly with temperatures in the month or two prior to ice-out.<sup>xvii</sup> Sebago Lake is the largest body of freshwater located in the Casco Bay Watershed and in the state of Maine. The lake also serves as the primary water supply to the Greater Portland area, home to nearly a quarter of the state's population. The length of the ice-free period impacts a lake's primary productivity rates. The duration of ice-cover is also important to popular winter recreational activities like ice fishing, snowmobiling, and Nordic skiing.

Ice-out records have been kept at Sebago Lake from 1807 to the present and provide one of the longest records of lake ice-out in New England. Sebago Lake is considered ice-free when the Great Basin (or Big Bay) is free of ice. Over the period from 1935 to 2008, there were 10 years when the lake did not ice over completely.

Based on the long-term record, Sebago Lake ice-out occurs 23 days earlier today than it did in 1807 (Figure 6). This statistically significant ( $p < 0.001$ ) trend toward earlier lake ice-out is consistent with other southern Maine and New Hampshire lake ice-out records, which on average ice-out 16 days earlier over the period 1850-2000.



**Figure 6.** Day of ice-out at Sebago Lake, Maine, from 1807-2008. The day of ice-out is defined as the number of days past January 1<sup>st</sup> until the lake is considered ice-free. Red triangles indicate years in which the lake did not freeze over.

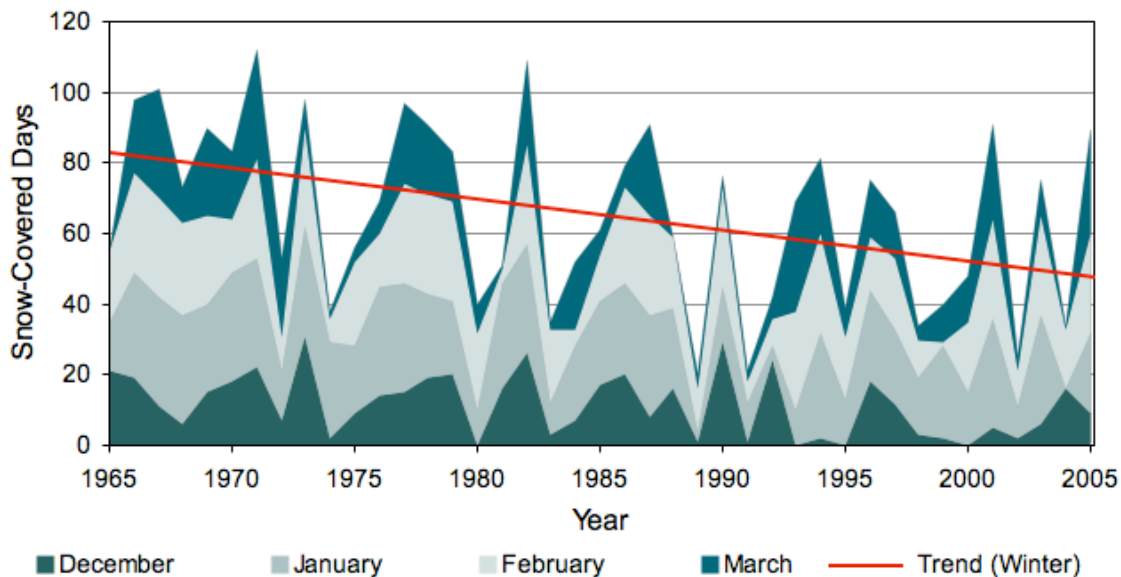
## SNOW-COVERED DAYS

Snow cover plays a major role in the climate system through strong feedbacks related to its reflectivity, or albedo. In a warmer climate, snow cover retreat exposes land surfaces that absorb more of the sun's solar radiation and result in enhanced warming in the region of reduced snow cover.

In Maine, natural snow cover is vital to the state's thriving multi-million dollar winter recreation industry. While the alpine skiing sector has adapted to decreased snow cover by investing heavily in snow making technology, snowmobiling, Nordic skiing, and snowshoeing lack this adaptive capacity and will likely continue to experience negative economic impacts resulting from diminished snow cover.<sup>xviii</sup> Neighboring states like New Hampshire have already seen negative impacts in the skiing and snowmobile industry, including millions of dollars of lost revenue and closure of smaller resorts following consecutive warm winters.<sup>xix</sup>

Daily snow depth data from the USHCN and National Weather Service Cooperative Network have been extensively quality controlled<sup>xx</sup> for Portland, Farmington, and Rumford (Figure 7). At any given meteorological station, a day is considered snow-covered if the daily snow depth is greater than one inch. The month of March is included in the winter season because March typically has more snow-covered days than December.

Over the period 1965-2005, the number of snow-covered days in Portland has decreased significantly at a rate of -7.9 days/decade, with all months showing decreasing trends (Figure 7, Table 4). The most significant decreases in Portland snow cover over the past 41 years have occurred during the months of December (-2.7 days/decade) and January (-2.7 days/decade). The snow cover decreases observed in the Portland are consistent with trends observed in neighboring New England States. Farmington and Rumford have experienced relatively small changes in the number of snow covered days.



**Figure 7.** Change in total number of winter (Dec-Mar) snow-covered days in Portland, Maine over the period 1965-2005.

**Table 4.** Summary of snow-covered day trends (days/decade) over the period 1965-2005. Underlined trends significant at  $p < 0.05$ .

	Portland	Farmington	Rumford
December	<u>-2.7</u>	-1.3	0.0
January	<u>-2.7</u>	-0.4	-0.3
February	-1.2	+1.0	+0.2
March	-1.1	-0.2	-0.4
Winter (DJFM)	<u>-7.9</u>	-0.8	-0.6

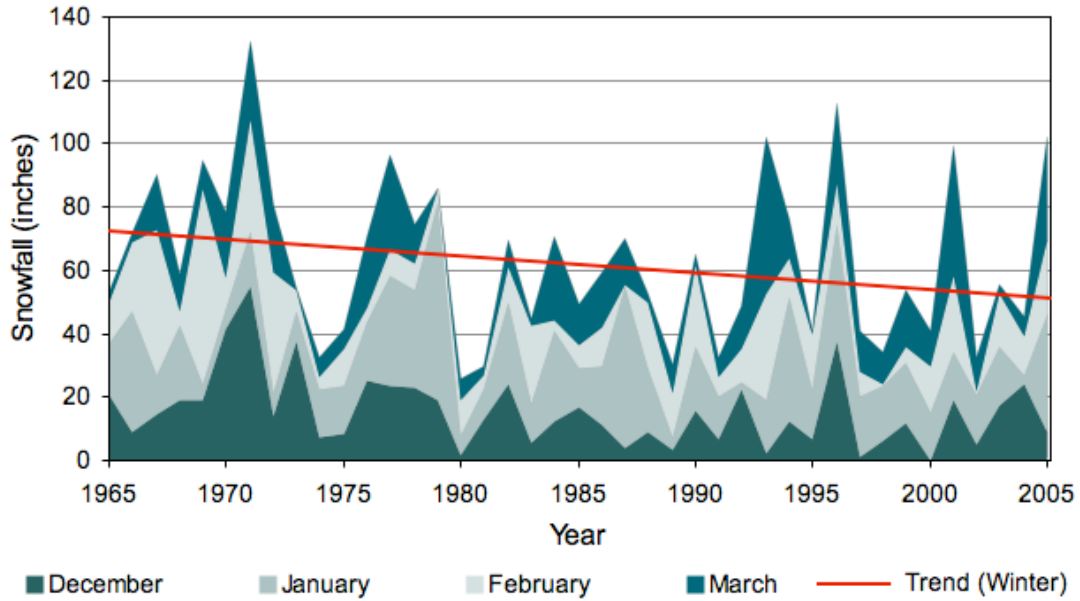
## SNOWFALL

Snowfall is a complex indicator of climate change because it is influenced by the availability of moisture in the atmosphere, air mass temperature, and surface air temperature. In some regions snowfall will increase in a world warmed by greenhouse gases because warmer air masses hold more moisture than cold air masses. As long as the temperature in the atmosphere remains below freezing, the precipitation will likely fall as snow.

The arrival of the first snow heralds the start of the state’s multi-million dollar winter recreation season. Ski resorts that have in the past relied on natural snowfall have had to invest heavily in snowmaking capabilities to accommodate for low snowfall years.<sup>xxi</sup> Shawnee Peak in Bridgton, the oldest continually running ski mountain in Maine, today provides snowmaking for 98% of its terrain. Snowmobiling, an industry that relies almost entirely on natural snowfall, generates over \$100 million dollars in expenditures within the state of Maine.<sup>xxii</sup>

Natural snowfall is also important component of annual runoff, recharge, and water supplies. In Portland, the ratio of snow to total precipitation has decreased significantly, largely due to decreases in snowfall, and to a lesser extent increases in rainfall.<sup>xxiii</sup>

The time series of winter snowfall for Portland over the period 1965-2005 points to significant year-to-year variability (Figure 8). Record high snowfall totals occurred around 1970, and have trended toward lower values up to present. All three stations have seen decreases in total winter snowfall, with the strongest decreases occurring in December (Table 5). Portland snowfall has decreased by -4.0 inches/decade over the period 1965-2005 (Figure 8, Table 5). The strongest decreases in Portland have occurred during the months of December (-3.5 inches/decade) and February (-2.5 inches/decade). However, March snowfall has increased at all three stations: Portland (+1.5 inches/decade), Farmington (+3.1 inches/decade), and Rumford (+2.0 inches/decade).



**Figure 8.** Change in total winter (Dec-Mar) snowfall (inches) in Portland, Maine over the period 1965-2005.

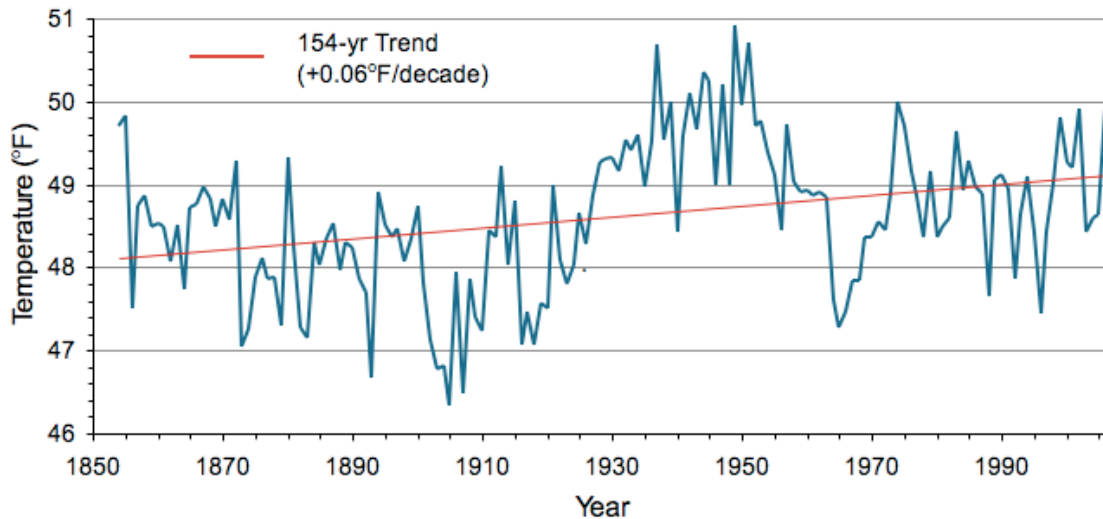
**Table 5.** Summary of snowfall trends (inches/decade) over the period 1965-2005. Underlined trends significant at  $p < 0.05$ .

	Portland	Farmington	Rumford
December	<u>-3.5</u>	-2.5	<u>-3.4</u>
January	+0.3	-0.4	+0.1
February	-2.5	-0.6	-1.4
March	+1.5	+3.1	+2.0
Winter (DJFM)	-4.0	-0.4	-2.7

## SEA SURFACE TEMPERATURE

The vast heat capacity of the Gulf of Maine waters moderate climate by keeping coastal areas warmer in winter and cooler in summer. Sea surface temperatures have been linked to winter storm tracks and storm intensity in the northeastern US.<sup>xxiv</sup> Warmer sea surface temperatures also threaten the Gulf of Maine's \$450 million dollar shellfish industry because they can favor the growth of red tide organisms.<sup>xxv</sup>

Sea surface temperatures in the Gulf of Maine have been collected from ships, buoys, and other observational platforms since 1854.<sup>xxvi</sup> The 154-year record shows multi-decadal swings in sea surface temperatures, with the warmest period spanning the mid-1930s to 1950 (Figure 9). Since 1854, the average annual sea surface temperature in the Gulf of Maine has increased significantly by 1.0°F at a rate of about 0.06 °F/decade.



**Figure 9.** Annual sea surface temperature (°F) in the Gulf of Maine, 1854-2007. The red line is the linear regression applied to the entire 154-year record. Trend is statistically significant at  $p < 0.001$ .

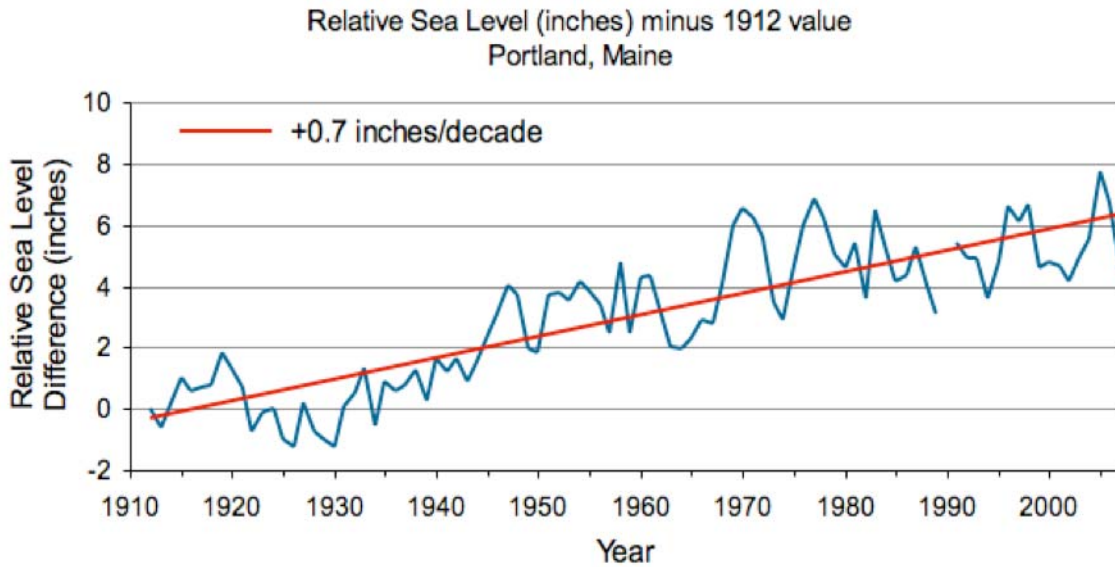
## SEA LEVEL RISE

Globally, mean sea level may be influenced by climate in two ways: by the direct transfer of heat to the oceans, resulting in thermal expansion of sea water, and by indirectly accelerating the rate of fresh water input from melting glaciers and ice caps. As the climate warms, both processes will contribute to increasing the volume of water in the oceans and the continuing rise of sea level relative to the coast. Regionally, mean sea level may be influenced by climate-induced oceanographic factors. Some of these factors, such as changes in ocean circulation due to the North Atlantic Oscillation, are known to cause both sea level rise as well as sea level fall over periods of years or decades. In the northeast US, climate induced changes in the Atlantic Meridional Overturning Circulation may affect the mean sea level of the western edge of the Gulf Stream, including the Maine coast.<sup>xxvii</sup>

Coastal Maine faces an additional regional non-climate influence on mean sea level known as subsidence. This relative sea level change is the result of crustal motions up or down following the retreat of glaciers. In the Gulf of Maine region, the crust has concluded its post-glacial rebound and is now subsiding,<sup>xxviii</sup> or sinking at the rate of about 0.1 millimeters per year (0.04 inches per decade). (See

discussion on changes in sea level and coastal flooding in Section III below for more information). The combined effects of thermal expansion, meltwater, crustal movements, and ocean circulation make coastal Maine particularly vulnerable to rising sea level. Changes in sea level contribute to increased erosion, saltwater contamination of freshwater ecosystems and loss of salt marshes and cordgrass. Low-lying shorelines such as sandy beaches and marshes are likely to be the most vulnerable to rising seas.

Relative sea level has been recorded at the Portland Harbor tidal gauge continuously since 1912.<sup>xxix</sup> In Figure 10, the 1912 value has been subtracted from the annual values to illustrate the change in sea level at Portland relative to the start of data collection. Over the past 96 years, sea level rose by over a half of a foot, at a rate of about 0.7 inches per decade.



**Figure 10.** Relative sea level (inches) measured at the Portland Harbor tidal gauge, 1912-2007. The 1912 value has been subtracted from annual values to illustrate the change in sea level relative to the start of the record. The red line is the linear regression applied to the time series and is used to calculate the rate of change, 0.7 inches/decade.



### **III. CLIMATE PROJECTIONS: DATA AND METHODS**

To evaluate possible future changes in climate, we use global climate model simulations driven by future emission scenarios. These scenarios incorporate assumptions about population, energy use, and technology to build pictures of how the future might look. Each of these pictures is associated with a unique “signature” of greenhouse gases emissions. As the spatial resolution of these global climate models limits them from providing valuable information on climate change on scales smaller than a few hundred kilometers, we then apply 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 three nearest reliable long-term weather stations to Casco Bay: Portland, Farmington, and Lewiston (Figure 1). The spatial resolution of the global climate models is, however, sufficient for local-scale sea level rise (SLR) projections. Relative SLR projections are generated for the Portland Harbor tide gauge. Each of these datasets and methods is described in more detail below.

#### **Historical Climate Simulations**

Historical simulations by the global climate models used here were driven by the Coupled Model Intercomparison Project’s “20th Century Climate in Coupled Models” scenario.<sup>xxx</sup> 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.

#### **Future Emissions Scenarios**

To estimate future changes in climate, we need to project how human societies and economies may develop over the coming decades; what technological advances are expected; which energy sources maybe used in the future to generate electricity, power transportation, and serve industry; and how all these choices will affect future emissions of greenhouse gases and other species that interact with the energy emitted by the earth or the sun. These emissions will in turn determine future climate change at both the global level and across the United States.

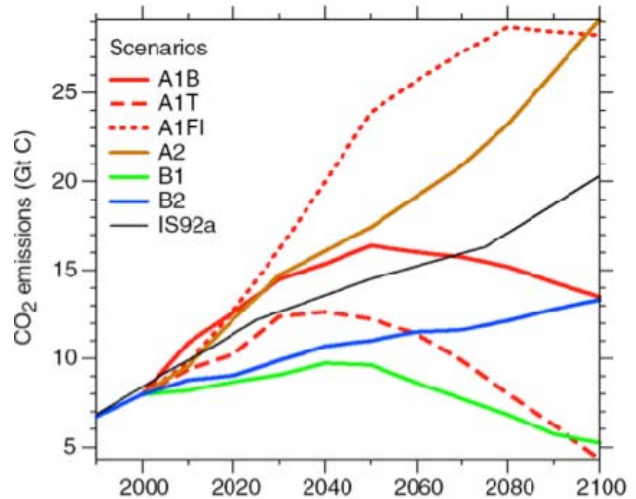
To address these questions, the IPCC has developed a set of future emissions scenarios known as SRES (Special Report on Emissions Scenarios<sup>xxxi</sup>). These scenarios use a variety of projections for future population, demographics, technology, and energy use to estimate the greenhouse gas emissions that would result from a variety of possible futures. In doing so, they encompass a range of plausible futures that illustrate differences in the extent and severity of the global warming that results from alternative emissions choices (Figure 11).

In this analysis, we compared projected climate changes under the SRES higher A1fi or fossil-intensive scenario (red dashed line) to that expected under the lower B1 scenario (solid green line).

The A1fi higher emissions scenario represents 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 concentrations reach 940 parts per million (ppm) by 2100—more than triple pre-industrial levels.

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.

As diverse as they are, the SRES scenarios still do not cover the entire range of possible futures. Since 2000, CO<sub>2</sub> emissions have already been set on a pathway to far higher levels than even the higher A1fi emission scenario. On the other hand, significant reductions in emissions—on the order of 80% by 2050, as already mandated by the state of California—could reduce CO<sub>2</sub> levels below the lower B1 emission scenario within a few decades. Nonetheless, the substantial difference between the SRES higher- and lower-emissions scenarios used here is sufficient to illustrate the potential range of changes that could be expected, and how much these depend on future emissions and human choices.



**Figure 11.** Projected future carbon emissions for the SRES emission scenarios. Emissions for the higher scenario (A1fi) corresponds to the red dotted line, while emissions for the lower (B1) scenario are indicated by the solid green line.<sup>xxxi</sup>

## Global Climate Models

Future emission scenarios such as those described above are used as input to global climate models, also known as atmosphere-ocean general circulation models (AOGCMs). 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.

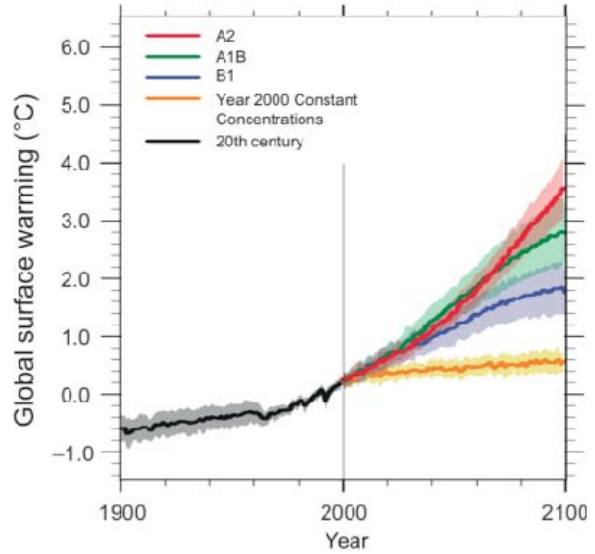
Because of the complexity of the models, AOGCMs are being enhanced as scientific understanding of climate improves, and as computational power increases. While some models are more successful than others at reproducing observed climate and trends over the past century, all future simulations agree that both global and regional temperatures will increase over the coming century in response to increasing emissions of greenhouse gases from human activities (Figure 12).

In this study, we relied on simulations from four different global climate models, as described in Table 6 below: 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, as follows.

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.

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.



**Figure 12.** Projected future global temperature change for the SRES emission scenarios (degrees C). The range for each individual emission scenario indicates model uncertainty in simulating the response of the Earth system to human emissions of greenhouse gases.<sup>ii</sup>

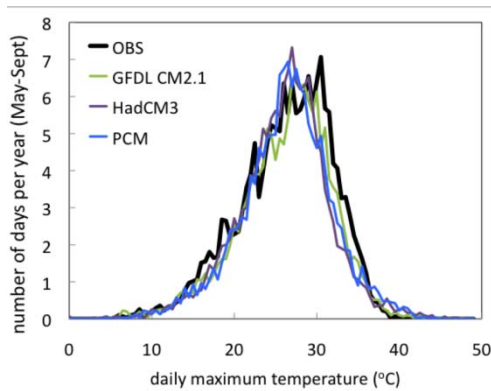
**Table 6.** Description of the four global climate models used in this analysis.

Model	Host Institution	Horizontal Resolution	Reference
CCSM3	National Center for Atmospheric Research (USA)	1.4 degrees	Collins, W. et al. 2006. The Community Climate System Model Version 3 (CCSM3). <i>Journal of Climate</i> , 19, 2122-2143.
GFDL CM2.1	National Ocean and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA)	1.8 degrees	Delworth, T. et al. 2006. GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. <i>Journal of Climate – Special Section</i> , 19, 643-674.
HadCM3	U.K. Meteorological Office, Hadley Centre (UK)	2.5 x 3.75 degrees	Pope, V. et al. 2000. The impact of new physical parameterizations in the Hadley Centre climate model HadAM3. <i>Climate Dynamics</i> , 16, 123-146.
PCM	National Center for Atmospheric Research (USA)	2.8 degrees	Washington, W. et al. 2000. Parallel Climate Model (PCM) Control and Transient Simulations. <i>Climate Dynamics</i> , 16, 755-774.

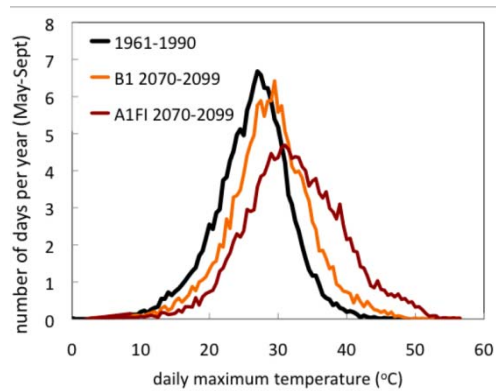
## Statistical Downscaling of Global Model Simulations

The geographic resolution of global climate models limits their ability to accurately capture the fine-scale changes experienced at the scale of Casco Bay. Hence, we used an advanced statistical downscaling technique to transform global climate model output into high-resolution projections capable of resolving the impacts of global climate change on local conditions. To develop a robust statistical downscaling method capable of translating region-wide changes into local conditions, we relied on the daily temperature and precipitation values recorded by the three USHCN weather stations closest to Casco Bay: Portland, Farmington, and Lewiston. Consistent daily maximum and minimum temperature and precipitation observations were available from the first two stations, and daily minimum temperature and precipitation observations from the last one.

For each of these three stations, we first took AOGCM output from a historical 20C3M simulation from the grid cell overlying that location. Output for a first “training” period, 1960-1979, was then regressed on observed daily temperature and precipitation for the same time period. The regression quantifies the statistical relationship between each individual quantile of that variable’s daily distribution. The validity of the relationship between daily AOGCM output and observed temperature and precipitation at each station was next evaluated using observations for a second “evaluation” period, 1980-1999 (Figure 13a). If the downscaled historical AOGCM simulations were able to reproduce the statistical properties of the observed temperature and precipitation during the evaluation period, the statistical relationship derived from the observations and historical AOGCM simulations were deemed robust. The final step was then to apply them to future AOGCM simulation output in order to downscale future temperature and precipitation conditions to the same locations used to derive the original regression relationships (Figure 13b).



**Figure 13a.** Observed (black) and historical simulated distribution of daily maximum summer temperatures by three AOGCMs for a weather station in Chicago for evaluation period 1980-1999.



**Figure 13b.** Observed historical (black) and future projected daily maximum summer temperature under the SRES higher (red) and lower (orange) emission scenarios.

Unlike regional climate modeling, statistical downscaling assumes that the relationships between large- and small-scale processes remain fixed over time. This assumption may not always hold true, particularly for precipitation. However, analyses for the northeast US indicate that, in areas of variable topography such as mountains and coastlines, statistical methods trained to match historical spatial patterns may perform better than regional climate models. In addition, statistical downscaling has a substantial time and cost advantage; hundreds of years of model simulations can be downscaled using the same computing resources required to run only a few years of regional-model downscaling.

## TEMPERATURE CHANGES

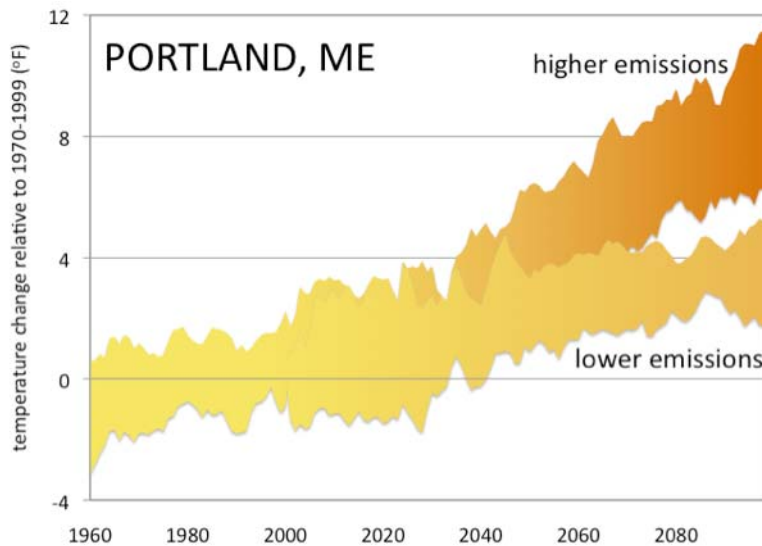
The northeast US and the state of Maine are already experiencing changes consistent with human-induced warming at the global scale. Annual average temperatures are rising, particularly in winter. The summer season is getting longer.

To the extent that present and future regional and local changes are driven by global-scale change, climate warming is expected to continue in the future. The amount of future change that can be expected depends on human emissions of heat-trapping greenhouse gases, as well as on the sensitivity of the Earth's climate system to those emissions.

### Seasonal and Annual Temperature

Increasing levels of heat-trapping gases in the atmosphere are projected to increase temperatures throughout the northeast US, including the Casco Bay region. Over the first part of this century, projected temperature changes are expected to be similar regardless of the emissions pathway followed over that time. This uniformity arises due to the lag time inherent in the climate system and represents a level of climate change that we are already committed to. It takes several decades for the Earth's temperature to respond to an initial change, and over 100 years for the Earth to reach equilibrium conditions. Thus, the majority of the changes that will happen over the next few decades are the result of greenhouse gas emissions that have already built up in the atmosphere.

By mid-century, however, the results of emission choices made today and over the next decade or two become evident (Figure 14). By the end of the century, a much greater increase in mean annual temperature is expected under higher as compared to lower emissions. Temperature changes were also projected to be significantly greater for daytime maxima as compared to nighttime minima; and by the end of the century as compared to earlier time periods. This is true even when factoring in the uncertainty



**Figure 14.** Projected changes in mean annual temperature for the city of Portland, Maine, under the IPCC SRES higher and lower emission scenarios. Temperature change is in degrees F relative to the 1970-1999 average as simulated by four AOGCMs. The range for each future scenario reflects AOGCM uncertainty in simulating the response of the Earth system to human emissions of greenhouse gases.

inherent in generating projections of future change, as quantified by the range of projections shown in Figure 14. For each individual scenario, the range in Figure 14 is the result of the difference in year-to-year projections generated by the four different global climate models used here.

In terms of seasonal changes, winter temperatures in the northeast US are currently rising at twice the rate of the annual average. Some have speculated this may be related to feedbacks between melting snow and temperature increase. In the future, however, this trend is projected to reverse, with greater increases in summer as compared to winter (Table 7). Slightly greater temperature increases are also

expected inland (e.g., Farmington) as compared to coastal areas (e.g., Portland), as the moderating effect of the ocean mitigates the effects of climate change on coastal temperatures.

Over the near term (2010-2039), average temperature increases on the order of 1.5 to 2°F are expected (Table 7), with greatest increases in summer and for inland locations. There is no significant difference between higher vs. lower emissions over this time period. By the middle of the century, temperatures are projected to increase by 2 to 3°F under lower emissions and 4 to 6°F under higher emissions. By the end of the century, temperature increases on the order of 3 to 4°F are expected under lower emissions, while under higher emissions temperatures could increase 6 to 8°F annually and in winter, and 10°F in summer.

**Table 7.** Projected increases in annual, winter (Dec-Jan-Feb), and summer (Jun-Jul-Aug) temperatures projected for the city of Portland, ME (*blue*), and Farmington, ME (*green italics*), relative to the 1970-1999 average. Average temperature data was not available for Lewiston, ME, because that station did not record historical maximum temperatures. Values shown are the average of four AOGCMs for the SRES lower (B1) and higher (A1fi) emissions scenario.

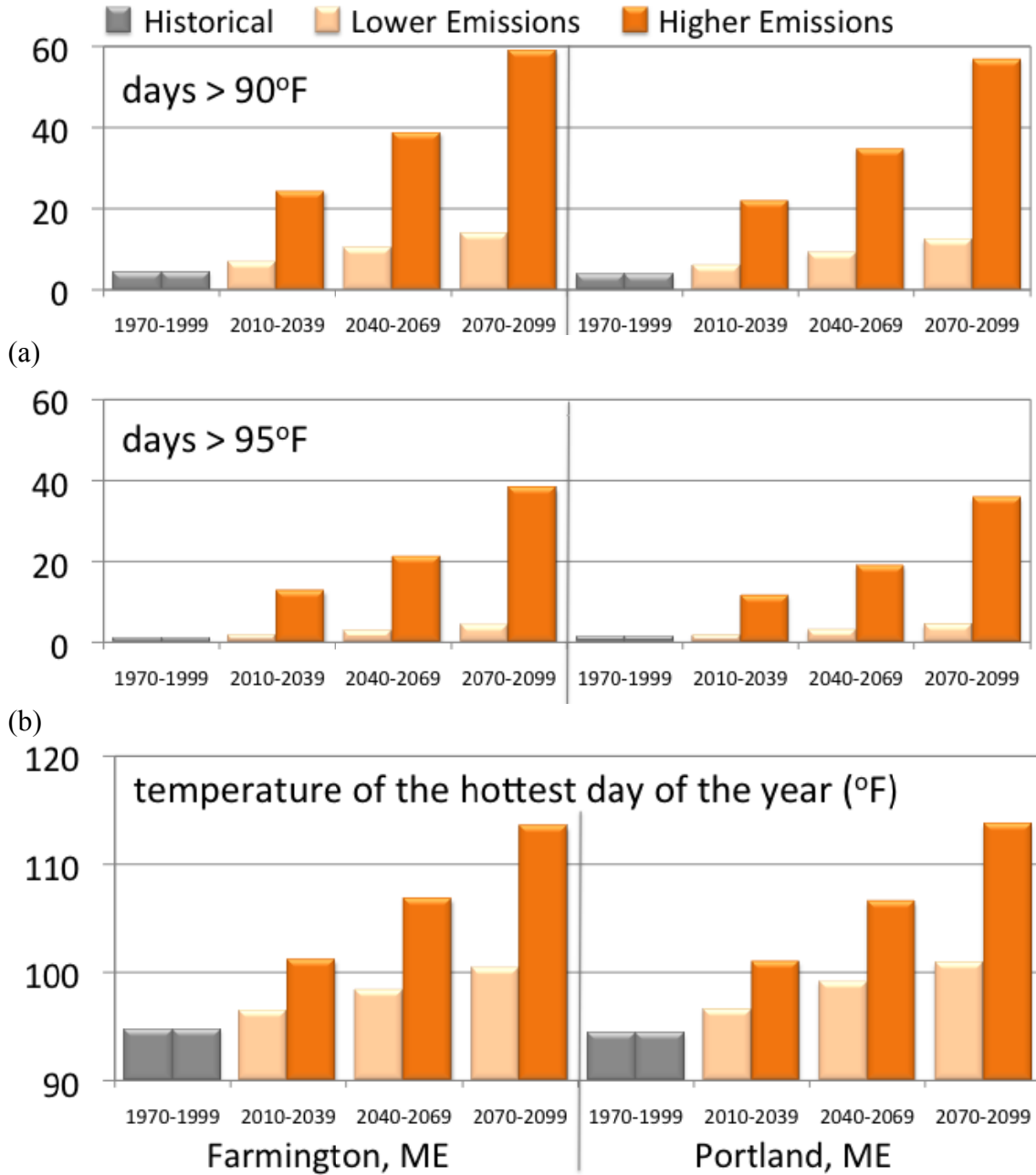
PROJECTED TEMPERATURE CHANGE: AVERAGE OF 4 GLOBAL CLIMATE MODELS												
	ANNUAL		WINTER (DJF)		SUMMER (JJA)							
	Lower emissions	Higher emissions	Lower emissions	Higher emissions	Lower emissions	Higher emissions						
2010–2039	1.5	1.6	1.5	1.8	1.8	1.7						
2040–2069	2.4	2.7	2.7	3.2	4.0	4.8	2.8	2.8	5.5	5.5		
2070–2099	3.3	3.6	7.8	8.6	3.3	3.8	6.2	8.6	3.9	4.0	9.8	9.9

### Extreme Heat

As average temperatures increase, extreme heat is also expected to become more frequent and more severe. Here, “hot days” are defined as days with maximum temperatures greater than 90°F; “very hot days” are days with maximum temperatures greater than 95°F. We estimated the occurrence of these days, and the average temperature on the hottest day of the year, for the two locations for which historical daily maximum temperature data are available: Portland and Farmington.

In terms of hot summer days, during the historical baseline period 1970-1999 both locations experienced an average of 4 days over 90°F each year, and an average of 1 day per year with daily maximum temperatures exceeding 95°F. In the future, the frequency of both type of days were projected to increase. Proportionally larger increases are expected under higher as compared to lower emission scenarios, by end-of-century as compared to earlier in the century, and for days over 95°F as compared to days over 90°F.





**Figure 15.** Historical simulated and projected future number of (a) average number of “hot days” over 90°F each year, (b) average number of “extremely hot days” over 95°F each year, and (c) average temperature on the hottest day of the year for Farmington and Portland. Values are the averages for each 30-year period as simulated by four AOGCMs under the IPCC SRES higher and lower emissions scenarios.

By 2070-2099, the number of days over 90°F was projected to increase by a factor of 3 relative to 1970-1999 values under lower emissions, and to be 15 times under higher emissions (Figure 15a). In other words, by the end of the century there are likely to be a total of approximately two weeks’ worth of days over 90°F each year in a lower emissions future and two months’ worth in a higher emissions future.

Under lower emissions, days over 95°F can be expected 3.5 to 4.5 more frequently than during 1970-1999, and 30 to 40 times more frequently under higher emissions (Figure 15b). This means that by the end of the century there are likely to be a still just a few days over 95°F each year under lower emissions, but more than five weeks' worth of such days under higher.

Climate change is also expected to alter the most extreme temperatures experienced in the Casco Bay area (Figure 15c). For the period 1970-1999, temperature on the average hottest day of the year was 95°F for Farmington and 94°F for Portland.

For the period 2010-2039, temperatures on the hottest day of the year are expected to increase by 2°F under lower emissions and 6°F under higher. By mid-century, the hottest day of the year is projected to be 4°F to 5°F hotter or 99°F under lower emissions and 12°F hotter or 107°F under higher. By the end of the century, the hottest day of the year is expected to increase by 6°F to just over 100°F under lower emissions and increase by 20°F to 114°F under higher emissions (Figure 15c). The hottest day of the year of 114°F would make it several degrees hotter than the current hottest day in Houston, Texas.

### **Cold Days**

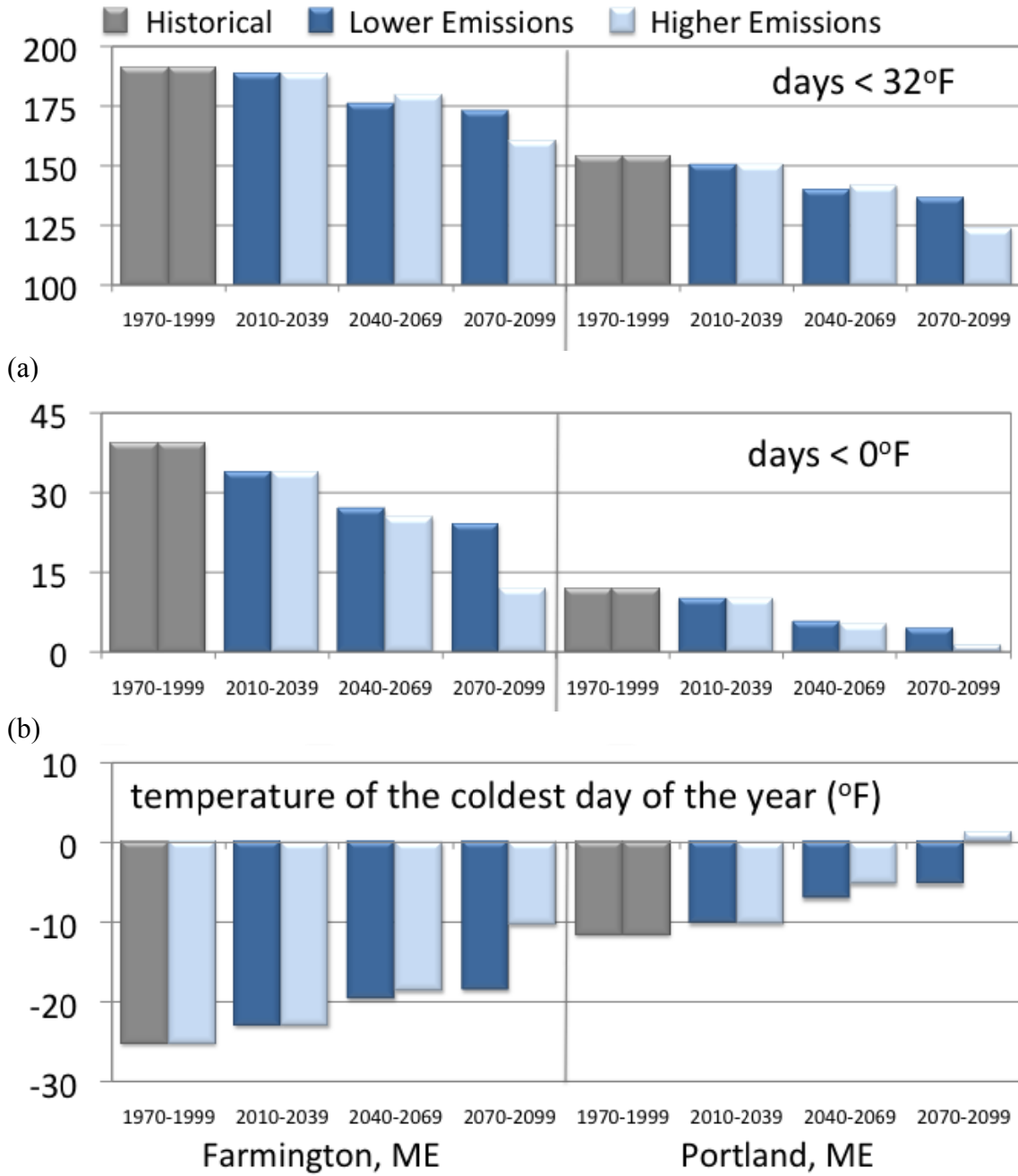
As average temperatures increase, extreme cold is also expected to become less frequent and severe. Here, “cold days” are defined as days with minimum temperatures below freezing or 32°F; similarly, “very cold days” are defined as days with minimum temperatures below 0°F. We estimate the occurrence of cold days, and the average temperature on the coldest day of the year, for the same two locations as used in the extreme heat analysis: Portland and Farmington.

In terms of cold days, inland Farmington currently experiences slightly colder winter conditions than coastal Portland, with nearly 200 days below freezing and nearly 40 days below 0°F. In comparison, a typical winter in coastal Portland sees approximately 150 days below freezing and just over 10 days below 0°F each year. As temperatures warm, these numbers are expected to drop slowly (Figure 16a, b). Little change is expected within a decade or two. By mid-century, however, each city could experience up to 14 fewer days below freezing; and by the end of the century, decreases of approximately 30 days are expected under higher emissions, and 17 to 18 under lower emissions.

Changes in projected days below 0°F are even larger. Again, little change is expected over the short term. By mid-century, however, decreases on the order of 12 to 14 days are expected in Farmington and 6 to 7 days in Portland. By the end of the century, in Farmington the number of days below 0°F is expected to shrink by 15 under lower emissions and 27 under higher. For Portland, the number of days could decrease by 7 under lower emissions and 10 under higher, leaving an average of only one day per year below 0°F before the end of the century.

For the period 1970-1999, the coldest temperatures of the year averaged -25°F for Farmington, -11°F for Lewiston, and -12°F for Portland. Little change is expected for the period 2010-2039. By mid-century, coldest temperatures of the year are projected to warm by 5 to 7°F. By the end of the century, temperatures are expected to warm by 6 to 7°F under lower emissions and 13 to 15°F under higher emissions. This would increase temperature on the average coldest day of the year to -10°F for Farmington, 2°F for Lewiston and 1°F for Portland (Figure 16c).





(c) **Figure 16.** Historical simulated and projected future number of (a) average number of “cold days” below 32°F each year, (b) average number of “extremely cold days” below 0°F each year, and (c) average temperature on the coldest day of the year for Farmington and Portland. Values are the averages for each 30-year period as simulated by 4 AOGCMs under the IPCC SRES higher and lower emission scenarios.

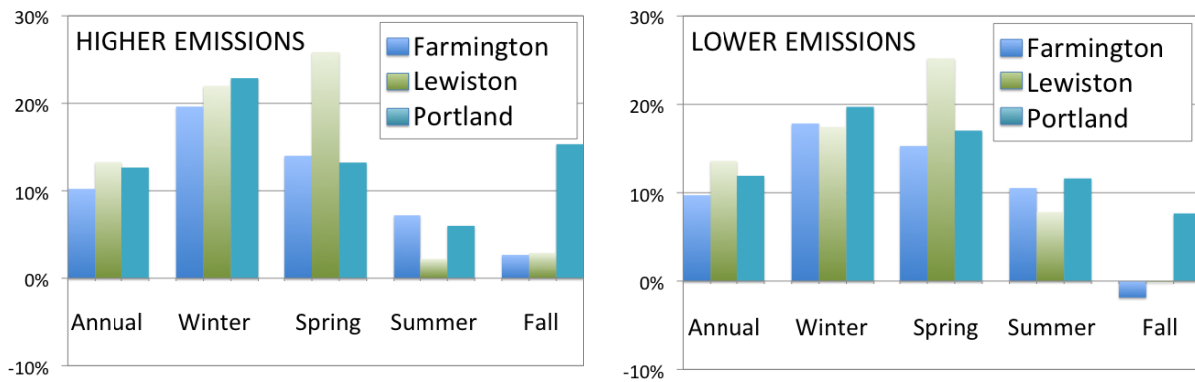
## CHANGES IN RAIN AND SNOW

As temperatures warm, the northeast United States and the state of Maine have begun experiencing reduced snow cover and earlier melting of snow. In the future, climate change is expected to continue to alter the amount and duration of snow in the region, as well as affecting the distribution of seasonal precipitation.

### Annual and Seasonal Precipitation

Climate change is expected to increase annual average precipitation in the Casco Bay area slightly, by about 5 percent in the near-term, 10 percent by mid-century, and slightly more than that by the end of the century. In addition, the projected increase in precipitation displays a strong seasonality (Figure 17). Mirroring projected precipitation patterns over the northeast US as a whole, the largest increase is expected during the winter and spring seasons—an average of 10 percent within a few decades, 15 percent by mid-century, and on the order of 20 percent by the end of the century.

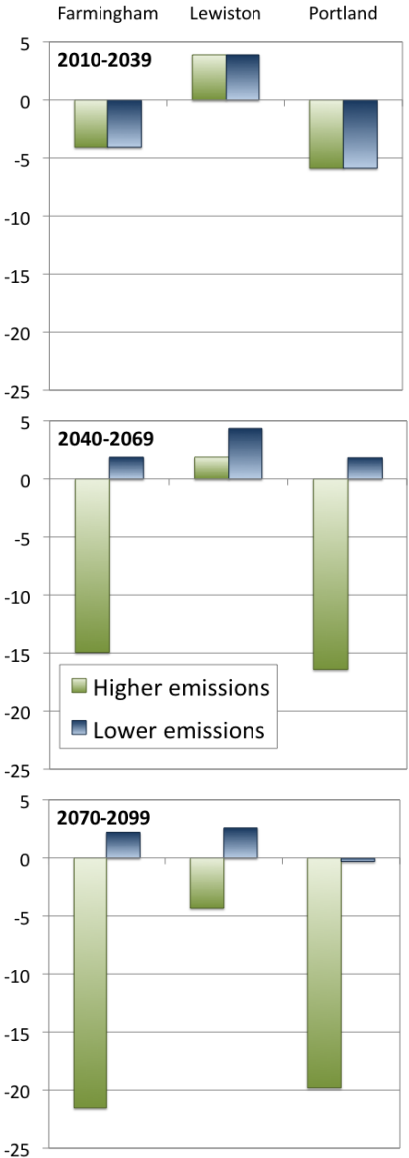
Fall precipitation does not change much for inland locations, but is projected to increase for coastal Portland, particularly under higher emissions. This may be an indication of the summer season extending into what were previously considered to be fall months. A large ocean-land temperature difference generally prevails during summer months along the coast. During the day, this temperature difference powers strong onshore winds that create convective precipitation events during hot summer afternoons. If future autumn days continue to be as warm as today’s summer days, strong sea breezes and the convective precipitation that results could continue well into September and even October.



**Figure 17.** Projected changes in end-of-century average annual, winter (DJF), spring (MAM), summer (JJA) and fall (SON) precipitation, by city. Values shown are the average of simulations by four AOGCMs under higher and lower emissions for 2070-2099 relative to 1961-1990.

### Snow versus Rain

As temperatures warm, we would generally expect more precipitation to fall as rain, and less as snow. However, climate change is also projected to increase the likelihood of precipitation during winter and spring months, when below-freezing temperatures are common. Thus, even though winter and spring temperatures might be warming, more frequent precipitation days could mean that the Casco Bay region could still experience little change or even a temporary increase in snow days under a world warmed by greenhouse gases. Whether the region experiences more or less snow days, and how many of those occur, will depend on which is strongest: the influence of increasing winter and spring precipitation (which would lead to more snow days), or the influence of increasing temperature (which would lead to more



**Figure 18.** Projected change in the average number of snow days per year for 2010-2039, 2040-2069 and 2070-2099 projected under lower and higher emissions are compared to the 1961-1990 station average. Values shown are the average of four AOGCM simulations.

and second, the average amount of rain that falls on the wettest day of the year. We also examine the potential influence of climate change on drought through characterizing the number of months during each future 30-year period that experience rainfall deficits in excess of 20% relative to the average precipitation for that month during the period 1961-1990.

During the period 1970-1999, the three stations examined here experienced between one and two days per year with more than 2 inches of rain (note this is different that the metric used in Section II which was 2" of rain in a 48 hour period). Over the coming century, projections were consistent in showing gradual increases in the number of such days over time (Figure 19). These increases tended to be

rain days). As temperature increases more under higher emissions and towards the end of the century, we should expect snow days to decrease as this effect dominates. But could the number of snow days actually increase in the meantime?

Yes—according to these projections, this might very well happen (Figure 18). Over the near term, only a small change in the number of snow days per year was projected; on the order of 5 days more or less per year, regardless of the emission scenario used. By mid-century, under lower emissions, the precipitation effect dominates—all three locations experience more snow days under climate change. Under higher emissions, the effect of warmer temperatures outweighs the effect of increasing winter and spring precipitation for Farmington and Portland, but not Lewiston.

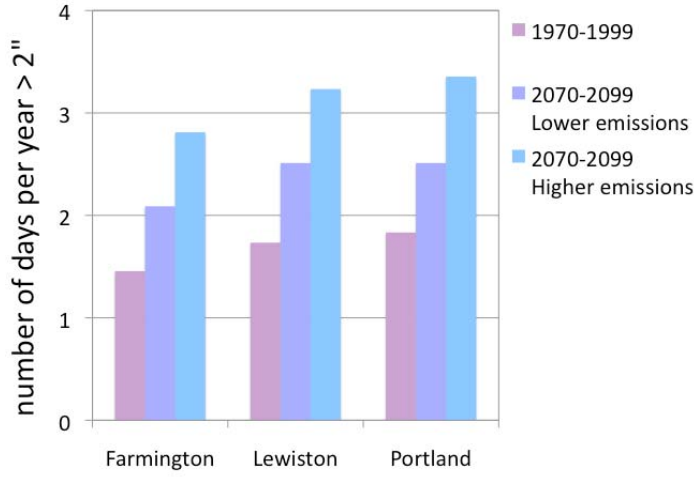
By the end of the century, under lower emissions it is nearly an even match between increasing temperature and increasing precipitation; little change is expected in the number of snow days relative to the historical baseline average. Under higher emissions, in contrast, the temperature effect wins out: a consistent decrease in snow days is projected, from 4 up to 22 less days per year, depending on where you live.

### Extreme Precipitation Events

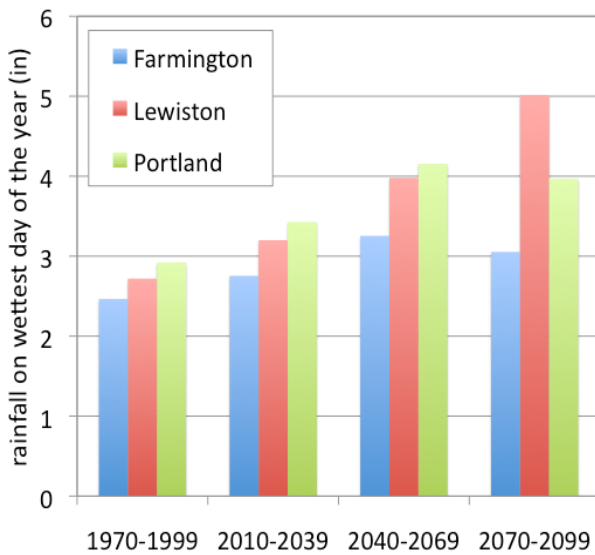
Climate change is likely to increase average and seasonal precipitation across the Casco Bay region; but what does this mean for precipitation extremes? More precipitation could just as well occur as more frequent rain days with little change in extreme rainfall conditions; or it could manifest itself in fewer rain days but more frequent and intense downpours. Similarly, it's still possible to have average and even seasonal average precipitation increase, on average, while still experiencing increased risk of extended dry periods or even drought.

Heavy rainfall events can damage homes, businesses, public infrastructure, and ecosystems. Periods of drought, particularly in summer, can be equally damaging. Here, two metrics are used to examine how climate change is likely to affect the frequency and intensity of heavy rainfall events: first, the number of days each year with more than 2 inches of rain;

greater under higher emissions relative to lower. By the end of the century, all locations are expected to



**Figure 19.** Projected change in the average number of days per year with more than 2 inches of rain in 24 hours. Values shown are the 1971-1999 station average, compared to future projections for 2070-2099 under lower and higher emissions. Values shown are the average of four AOGCM simulations



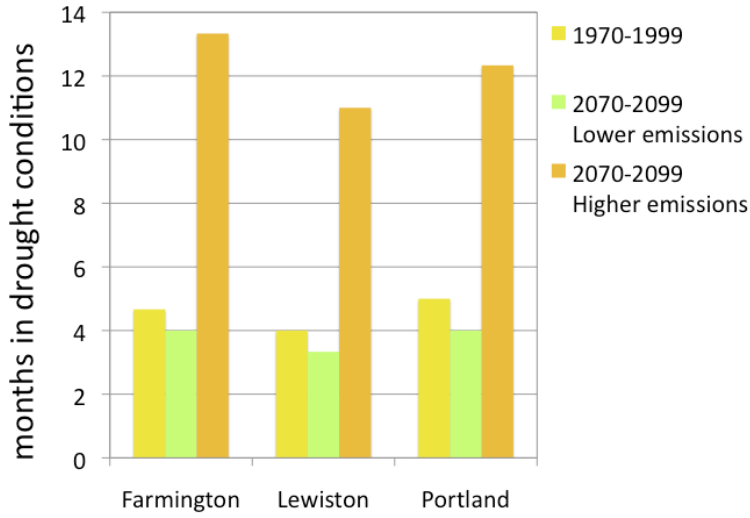
**Figure 20.** Projected change in the amount of rainfall that occurs on the wettest day of the year. Values shown are the average of four AOGCM simulations for the higher emissions scenario.

average between 2 and 3 such days under lower emissions, and closer to 3 such days each year under higher emissions. In other words, what would be considered the wettest day or two of the year currently will now occur on average two to three times per year.

Another way to look at the impact of climate change on extreme precipitation is to examine the amount of rain that typically falls on the wettest day of the year. For the period 1970-1999, the wettest day of the year averaged somewhere between 2 and 3 inches—more for Portland, on the coast, and less for inland locations. Over time, precipitation on the wet test day of the year is projected to increase gradually – to 3 inches within a few decades, to 3-4 inches by the middle of the century, and to 3-5 inches by the end of the century. No significant inter-scenario differences are evident, so only the projections for the higher emissions scenario are shown as they change over time (Figure 20).

Finally, under higher emissions, climate change is also expected to increase the number of months the region spends in short-term drought, here defined as months with precipitation deficits greater than 20% below the 1970-1999 historical baseline average for that month (Figure 21). Under lower emissions, little change to a decrease is expected.

It may seem paradoxical that both drought frequency and the frequency of extreme precipitation events can increase at the same time; but this is often the case. In the absence of significant increases in precipitation, intense and frequent downpours can occur interspersed with longer, dry periods in between.



**Figure 21.** Projected change in the number of months for each 30-year period with precipitation more than 20% below the 1970-1999 average for that month. Values shown are the average of four AOGCM simulations

## 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 Portland, simulated increases in global and regional sea level were combined with current 100-year flood (stillwater) elevations using two SRES emissions scenarios (B1 and A1fi). 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 the City of Portland, Maine, were based on methods developed by Kirshen and others<sup>xxxii</sup>, and updated to incorporate more recent sea-level rise (SLR) projections from the IPCC Fourth Assessment Report (AR4)<sup>xxxiii</sup>, as well as from current literature<sup>xxxiv</sup>. Historical hourly water-level data from the tide gauge in Portland were obtained from 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. Upon initial processing of the NOAA/NOS dataset, it was determined that the data quality was not sufficient to perform the flooding analysis at this time. Therefore, coastal flooding anomaly heights and the future change in recurrence intervals of today's 100-year coastal flooding event in Portland were not estimated. (Additional information related to the Kirshen –and other<sup>xxxii</sup> – methodology and discussion of those data quality issues is provided in Appendices B & C.)

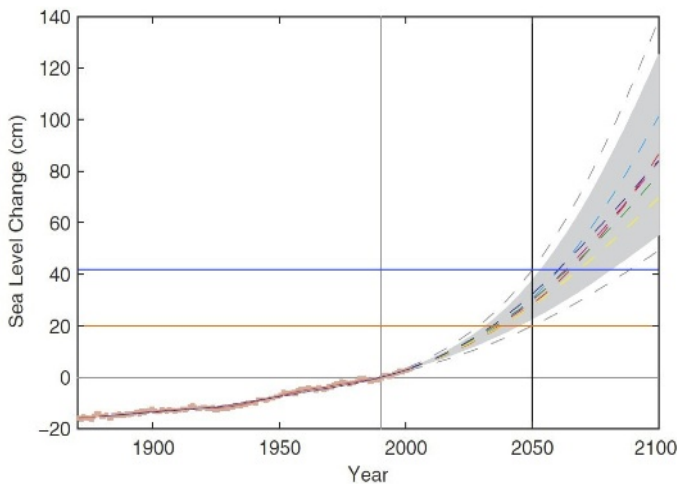
Preliminary estimates of stillwater elevations associated with future 100-year flood events were developed, therefore, exclusive of the local floodwater heights estimated from analysis of the historical record for Portland. The published stillwater elevation for the current 100-year flood event at State

Pier<sup>xxxv</sup> was used as a proxy for the estimated current 100-year flood stillwater elevation at the Portland tide gauge (located at State Pier).

### Future Estimates of SLR in Portland

Future estimates of relative SLR in Portland include three components: projected values of global (eustatic) and regional dynamic SLR from several recent publications, and estimates of future regional SLR due to subsidence. The IPCC AR4 projected a range of global SLR between approximately 8 and 24 inches (20 and 60 centimeters [cm]) by the end of the century excluding dynamical ice flow processes<sup>xxxvi</sup>. Based on a relationship between global mean SLR and global mean surface temperature during the past two centuries, Rahmstorf<sup>xxxiv</sup> projected a range of global SLR by 2100 of approximately 19.7 to 55.1 inches (50 to 140 cm) relative to 1990. Siddall and others<sup>xxxiv</sup> also reviewed this relationship based on 22,000 years of centennial-scale data and projected a range of global SLR by the end of the 21<sup>st</sup> century of approximately 3 to 32 inches (7 to 82 cm). Pfeffer and others<sup>xxxiv</sup> suggest that 31 inches (80 cm) of global SLR by 2100 is plausible based on their review of dynamically-forced discharge from marine-terminating glaciers, and further that global SLR by 2100 of more than 6 feet is possible but unlikely. Yin and others<sup>xxxiv</sup> found that, in response to possible weakening of the Atlantic Meridional Overturning Circulation, there may be an additional approximately 6.3 to 9.4 inches (16 to 24 cm) regional dynamic SLR by 2100 in Boston. The effects of future emissions of greenhouse gases (GHG) on New England are reinforced by Yin and others<sup>xxxiv</sup> who suggest that “dynamic sea level on the northeast coast of the United States is particularly sensitive to the [projected future] increase in GHG concentration.”

For this report, we use the range of global eustatic SLR by 2100 relative to 1990 developed by Rahmstorf<sup>xxxiv</sup>: 19.7 inches for the lower B1 SRES scenario, and 55.1 inches for the higher A1fi SRES



**Figure 22.** The orange and blue horizontal lines represent the range of estimated SLR for the year 2050 under a lower SRES emissions scenario (B1, 20 cm, orange line) and a higher emissions scenario (A1fi, 42 cm, blue line) from Rahmstorf<sup>xxxiv</sup>. The gray area represents the uncertainty range for the range of temperature rise and the dashed gray lines show the added uncertainty due to statistical error. Colored dashed lines represent the individual IPCC scenarios.

scenario. Also for 2100 we use the range of dynamic regional SLR projected by Yin<sup>xxxiv</sup>: 9.4 inches for the higher A2 SRES scenario, and 6.3 inches for the lower SRES B1 scenario. We assume that the dynamic oceanographic processes driving regional SLR along the northeast coast of the US are additive to any projections of eustatic SLR. Based on similarities in climate impacts, we also assume that the A1fi and A2 SRES emissions scenarios are equivalent to the extent that for 2100 the eustatic A1fi SLR value is additive to the dynamic A2 SLR value. Additionally, we assume that the dynamic SLR in Portland will be similar to dynamic SLR in Boston.

Projected values for eustatic SLR by the year 2050 under both lower and higher emissions scenarios were estimated using the SLR projection curve from Rahmstorf<sup>xxxiv</sup> as shown on Figure 22. Since Yin and others<sup>xxxiv</sup> did not provide

estimates for regional dynamic SLR in 2050, they are not included in our coastal flooding scenarios.

Future subsidence over the next century can be estimated by assuming that current rates will continue.<sup>xxxii</sup> Eustatic SLR rate for the 20<sup>th</sup> century was estimated by Bindoff and others to be 1.7 millimeters/year (mm/yr).<sup>xxxvi</sup> Relative SLR at the Portland gauge for the period 1912 to 2006 was calculated by NOAA to be 1.82 millimeters per year (mm/yr).<sup>xxxvii</sup> We presume that regional dynamic SLR over the past century has been negligible, due to the lack of evidence of changes in the MOC during that period.<sup>xxxvi</sup> Historical subsidence was, therefore, estimated by assuming both historical eustatic SLR and historical relative SLR are linear processes, and then subtracting historical eustatic SLR from the historical relative SLR. We estimated SLR due to subsidence at the Portland gauge to be 0.12 mm/yr, which results in 7.2 mm (0.28 inches) by 2050 and 13 mm (0.52 inches) by 2100, relative to 1990.

A summary of those components and their contribution to the preliminary estimates of future stillwater elevations is provided in Table 8.

<b>Table 8</b>				
<b>Preliminary Estimates of Future Stillwater Elevations at the Portland Tide Gauge Under Lower and Higher Emissions Scenarios (feet relative to NAVD<sup>1</sup>)</b>				
<b>Scenario</b>	<b>Lower</b>		<b>Higher</b>	
<b>Year</b>	<b>2050</b>	<b>2100</b>	<b>2050</b>	<b>2100</b>
FEMA 1998 Stillwater Elevation	8.9	8.9	8.9	8.9
Subsidence	0.024	0.043	0.024	0.043
Dynamic	NE	0.52	NE	0.79
Eustatic	0.66	1.6	1.4	4.6
<b>Total Stillwater Elevation<sup>2</sup> (ft)</b>	<b>9.5</b>	<b>11.1</b>	<b>10.3</b>	<b>14.3</b>
<small>1 - NAVD: North American Vertical Datum of 1988                  2 - Total Stillwater Elevation may not equal total of components due to rounding                  NE - not estimated</small>				

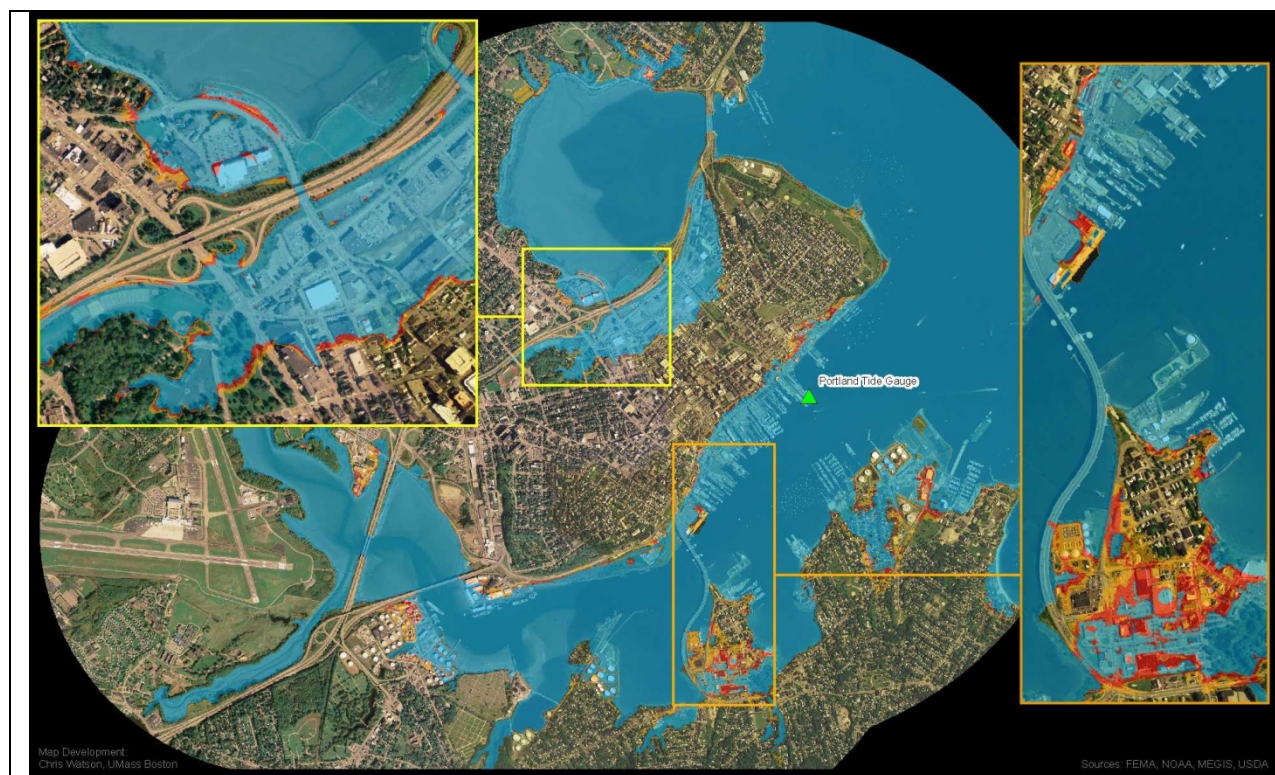
### Flood Mapping

Flood maps of the Portland area illustrate the areas likely to be flooded during a 100-year flood event in the year 2100 (Figure 23) and 2050 (Figure 24) based on the preliminary estimates of stillwater elevations listed in Table 8. Base flood elevations, which include wave effects where applicable, are not shown. Depending on the nature of the flooding event and the location along the coast, increased flooding due to wave effects can be significant.

The spatial extent of the flooded areas shown on Figures 23 and 24 were estimated using a five-foot by five-foot raster-based digital elevation model (DEM) developed at the University of Southern Maine (USM) GIS Lab from Light Detection and Ranging (LiDAR) data acquired by FEMA in 2006. This 2006 FEMA dataset is the only publicly-available LiDAR dataset that includes the City of Portland.<sup>xxxviii</sup> The 2006 FEMA LiDAR dataset includes bare-earth data generated by the FEMA contractor and provided in a point (XYZ) format. Based on a review of the limited metadata associated with this LiDAR dataset, discussions with staff at the Maine Geological Survey (MGS) and the Maine Geographic Information System (MGIS), as well as researchers at the USM GIS Lab, it is uncertain if the methodology used by

the FEMA contractor to generate the bare-earth dataset is applicable to the generation of DEMs<sup>xxxix</sup>. Although some quality assurance/quality control (QA/QC) activities were performed on the dataset by MGS staff in other areas of the state, QA/QC information for the Portland area was not available (Slovinski, personal communication). Because of those constraints, processing of the XYZ bare-earth dataset was not performed, and the five-foot by five-foot DEM, developed by the USM GIS Lab, was used for this project. Based on the FEMA contractor's specification for acquiring the LiDAR dataset, vertical accuracy of the DEM used for this project is assumed to be  $\pm 1.2$  feet (37 cm)<sup>xl</sup>.





**Figure 23.** Shading indicates estimated flood areas near Portland Harbor during a 100-year storm in the year 2100 under a higher coastal flooding scenario. This map was developed using a five-foot by five-foot raster-based digital elevation model (DEM) overlaid on recent aerial orthophotography. The future elevation of the 100-year flood is based on the current elevation of the 100-year flood added to projected SLR. The higher coastal flooding scenario includes regional SLR due to land subsidence, and the high end of the ranges of both regional dynamic SLR projected by Yin and others,<sup>xxxiv</sup> and eustatic (global) SLR projected by Rahmstorf.<sup>xxxiv</sup>

Under this higher coastal flooding scenario, the estimated elevation of the 100-year flood in 2100 is 14.3 feet relative to the North American Vertical Datum of 1988 (ft NAVD). The range of vertical error associated with the DEM ( $\pm 1.2$  ft at a 95% confidence level) is represented by the red shading (lower interval; 13.1 to 14.3 ft NAVD) and the orange shading (upper interval; 14.3 to 15.2 ft NAVD). Blue shading represents areas located at elevations below 13.1 ft NAVD, including both land and water bodies. Buildings, building shadows, other objects and open water bodies observed in the underlying orthophotography may cause the shading to appear darker in these areas. Horizontal error associated with the DEM is approximately  $\pm 3.3$  ft.



**Figure 24.** Shading indicates estimated flood areas near Portland Harbor during a 100-year storm in the year 2050 under a lower coastal flooding scenario. This map was developed using a five-foot by five-foot raster-based digital elevation model (DEM) overlaid on recent aerial orthophotography. The future elevation of the 100-year flood is based on the current elevation of the 100-year flood added to projected SLR. The lower coastal flooding scenario includes regional SLR due to land subsidence, and the low end of the range of eustatic (global) SLR projected by Rahmstorf<sup>xxxiv</sup>.

Under this lower coastal flooding scenario, the estimated elevation of the 100-year flood in 2050 is 9.5 feet relative to the North American Vertical Datum of 1988 (ft NAVD). The range of vertical error associated with the DEM ( $\pm 1.2$  ft at a 95% confidence level) is represented by the red shading (lower interval; 8.3 to 9.5 ft NAVD) and the orange shading (upper interval; 9.5 to 10.7 ft NAVD). Blue shading represents areas located at elevations below 8.3 ft NAVD, including both land and water bodies. Buildings, building shadows, other objects and open water bodies observed in the underlying orthophotography may cause the shading to appear darker in these areas. Horizontal error associated with the DEM is approximately  $\pm 3.3$  ft.

## **IV. CONCLUSIONS**

Climate change is already affecting the northeast US and the state of Maine in many ways. Temperatures have already begun to rise, particularly in winter. Snow covered days and snowfall are both decreasing, and ice covers the region's lakes and rivers for shorter periods in winter. At the same time, the frequency of prolonged heavy rainfall events is increasing, exacerbating risk of riverine flooding. Sea levels continue 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 Casco Bay region are expected to increase between 4°F and 8°F 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.

Winter and spring precipitation is expected to rise, exacerbating the risk of flooding. Along the coast, fall precipitation may rise as well, perhaps due to an extension of summer convective precipitation patterns into fall months. Coastal flood elevations will continue to increase due to sea level rise, leading to increasingly larger areas of flooding during coastal storms.

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 temperatures 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.

## **V. ACKNOWLEDGEMENTS**

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Maria Little (NOAA/NOS) was more than helpful in researching the historical operational record of the Portland tide gauge. Patrick Caldwell (JASL) facilitated our understanding of the RQDS. Peter Slovinski (MGS) provided the FEMA 2006 LiDAR dataset and insights regarding the quality of the dataset. Vincent Valentine (USM) and Michael Smith (MGIS) provided additional details into the problems associated with the LiDAR dataset. Margaret Vose (USM) created the DEM. Paul Kirshen (Battelle Institute) helped refine the SLR section.



## ENDNOTES

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