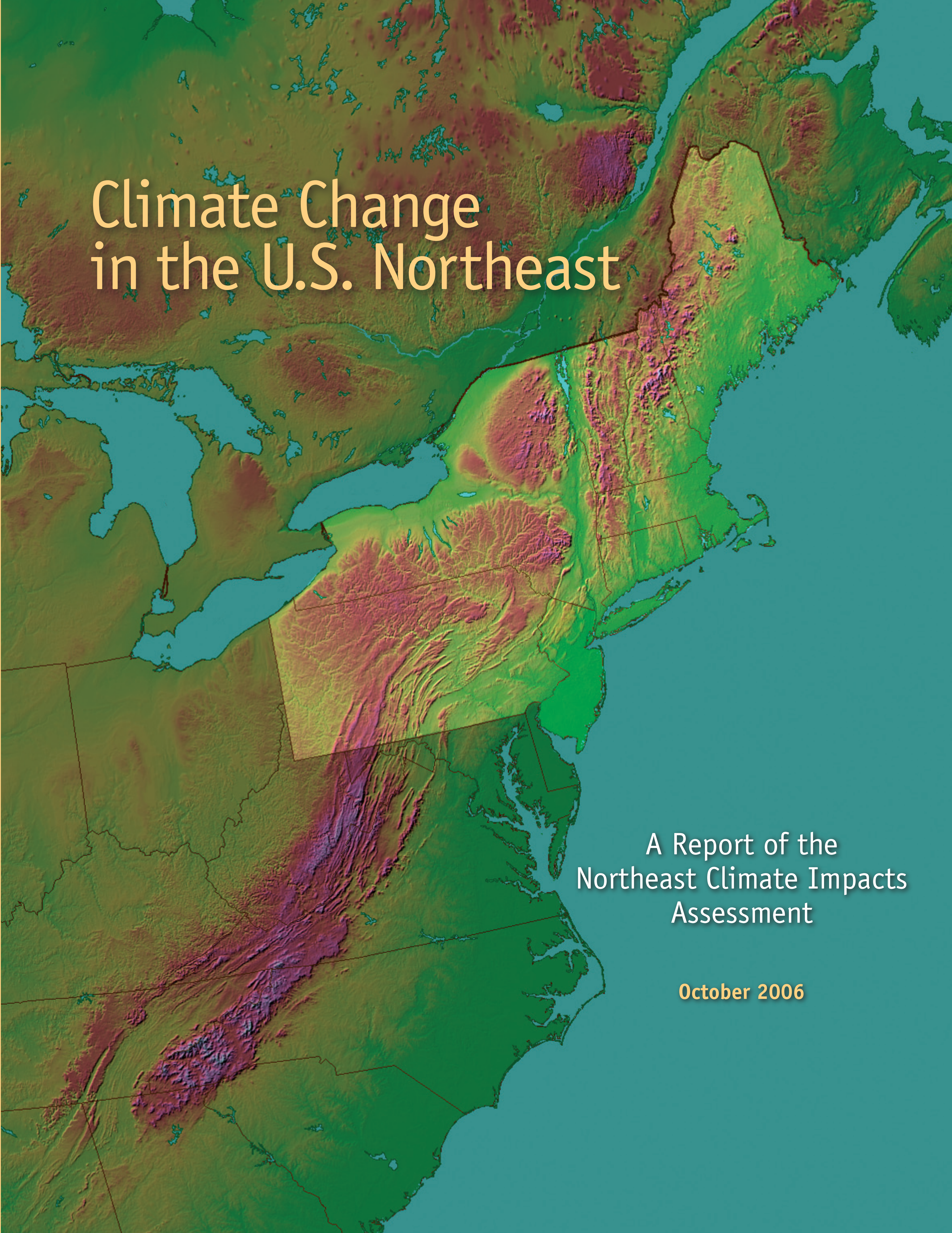
Climate Change in the U.S. Northeast



A Report of the
Northeast Climate Impacts
Assessment

October 2006

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About NECIA

The Northeast Climate Impacts Assessment (NECIA) is a collaboration between the Union of Concerned Scientists (UCS) and a team of independent experts to develop and communicate a new assessment of climate change and associated impacts on key climate-sensitive sectors in the northeastern United States. The goal of the assessment is to combine state-of-the-art analyses with effective outreach to provide opinion leaders, policy makers, and the public with the best available science upon which to base informed choices about climate change mitigation and adaptation.

NECIA oversight and guidance is provided by a multidisciplinary Synthesis Team of senior scientists:

NECIA Synthesis Team

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The material presented in this report is based on the research of the NECIA Climate Team, listed below. Most of the work discussed here is also presented in more technical detail in two scientific papers.[1,2]

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Additional analyses are currently under way to assess the impact of the climate changes described here on forests and agriculture, coastal and marine resources, human health, and urban centers across the Northeast, as well as options for mitigation and adaptation. A major synthesis report on these findings is expected in early 2007.

More information about the Northeast Climate Impacts Assessment is available at *http://www.northeastclimateimpacts.org* or from Erika Spanger-Siegfried, Northeast Climate Project Manager, at *esiegfried@ucsusa.org*.

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Executive Summary

The pulse of life and economic activity across the Northeast is marked by the region's dramatic seasonal cycle, changeable weather, and extreme events such as floods and nor'easters. This familiar climate is already changing in noticeable ways. Temperatures have been rising, particularly in winter, and the number of extremely hot days in summer has been increasing. Snow cover is decreasing and spring is arriving earlier in the year. Recent changes in our climate in the Northeast are consistent with those expected due to increasing levels of carbon dioxide and other heat-trapping gases in the atmosphere. These gases are released by the burning of fossil fuels and other human activities.

This study draws on recent advances in climate modeling to assess how global warming may further affect the Northeast's climate. Using projections from three state-of-the-art global climate models, we compare the types and magnitude of climate changes that will result from higher emissions of heat-trapping gases versus lower emissions. The first scenario is a future where people—individuals, communities, businesses, states, and nations—allow emissions to continue growing rapidly, and the second is one in which society transitions onto a pathway of economic development with substantially lower emissions.

Over the next few decades, similar changes in climate are expected under either emissions scenario. For example, temperatures across the region are likely to rise by 2.5 to 4 degrees Fahrenheit (°F) in winter and 1 to 3°F in summer, regardless of the emissions during that period. These changes have already been set in motion by our emissions over the past few decades, but it takes years or decades for the climate to respond in noticeable ways.

By mid-century and later, however, most changes projected to occur depend strongly on the emissions choices we make in the near future and carry through the rest of the century. Specifically, under the **higher-emissions scenario**, in which the world remains on a pathway of highly fossil fuel-intensive economic growth (with heat-trapping emissions from automobiles, power plants, and industries continuing to increase through the end of the century), new projections for the Northeast show that:

- By the end of this century, winters could warm by 8 to 12°F and summers by 6 to 14°F.
- Historically, major cities in the Northeast experience 10 to 15 days per year when temperatures exceed 90°F. By mid-century, cities such as Philadelphia, New York City, and Boston could experience 30 to 60 days of temperatures over 90°F each summer. By late in the century, most cities in the region are likely to experience more than 60 days with temperatures over 90°F, including 14 to 28 days with temperatures over 100°F (compared with one or two days per year historically).
- As winter temperatures rise, more precipitation will fall as rain and less as snow. By the end of the century, the length of the winter snow season could be cut in half.

- The frequency of late summer and fall droughts is projected to increase significantly, with short-term droughts (lasting one to three months) becoming as frequent as once per year over much of the Northeast by the end of the century.
- The character of the seasons will change significantly, with spring arriving three weeks earlier by the end of the century, summer lengthening by about three weeks at both its beginning and end, fall becoming warmer and drier, and winter becoming shorter and milder.
- Sea-level rise will continue, reaching anywhere from a few inches to more than one foot by mid-century. By the end of the century, global sea level could rise from eight inches up to nearly three feet, increasing the risk of coastal flooding and damage from storm surges.
- Higher global temperatures also imply a greater risk of destabilizing the Greenland and West Antarctic ice sheets. It is possible, particularly under the higher-emissions scenario, that warming could reach a level during this century beyond which it would no longer be possible to avoid rapid ice sheet melting and a sea-level rise of more than 20 feet over the next few centuries.

In contrast, under the **lower-emissions scenario**, in which the world follows a pathway of high economic growth but shifts toward less fossil fuel-intensive industries and introduces clean and resource-efficient technologies, heat-trapping emissions would peak by about mid-century and then decline. New projections for this region show that smaller climate-related changes can be expected if the world follows the lower-emissions pathway—typically, about half the change expected under the higher-emissions scenario. In this case, projected changes for the region include:

Some global warming is now unavoidable, but the extent of change in the Northeast largely depends on choices we make today.

- End-of-century temperature increases of 5 to 7.5°F in winter and 3 to 7°F in summer.
- An average of 30 rather than 60 days over 90°F for most cities in the region by the end of the century, and only a few days over 100°F.
- A 25 percent loss of the winter snow season.
- A likelihood of short-term drought only slightly higher than today.
- Arrival of spring one to two weeks earlier by century's end; summer would arrive only one week earlier and extend a week and a half longer into the fall.
- Sea-level rise of a few inches to less than two feet by century's end, reducing though not eliminating the risk of exceeding the warming threshold that would destabilize major ice sheets.

Under either emissions scenario, the Northeast of the future will be a tangibly different place. Additional future changes that do not show dramatic differences between scenarios include:

- Increases in the likelihood and severity of heavy rainfall events, including more than a 10 percent increase in the number of annual extreme rainfall events and a 20 percent increase in the maximum amount of rain that falls in a five-day period each year.
- Increases in winter precipitation on the order of 20 to 30 percent, with slightly greater increases under the higher-emissions scenario.
- A combination of higher temperatures, increased evaporation, expanded growing season, and other factors that will cause summer and fall to become drier, with extended periods of low streamflow. This will reduce the availability of water from northeastern rivers to natural ecosystems, agriculture, and other needs.

Although some changes are now unavoidable, the extent of change and the impact of these changes on the Northeast depend to a large degree on the emissions choices we in the Northeast and the world make today. The "higher" emissions scenario described here is not a ceiling on what our future emissions might be, but neither is the “lower” scenario a floor on the lowest emissions we can achieve. While actions to reduce emissions in the Northeast alone will not stabilize the climate, the region is a center of global leadership in technology, finance, and innovation. Ranked against the nations of the world, it is also the seventh largest source of carbon dioxide emissions from energy use. As such, the Northeast is well positioned to be a technology and policy leader in reducing emissions and driving the national and international progress essential to providing our children and grandchildren with a safe and stable future climate.

CHAPTER 1

CLIMATE CHANGE IN THE NORTHEAST: AN INTRODUCTION

From the sandy beaches of New Jersey to the rocky shores of Maine, and inland from the cornfields of Pennsylvania to the mountains of New Hampshire, Vermont, and New York, the northeastern United States boasts enormous geographical diversity. While relatively small in extent, the Northeast has one of the steepest climate gradients[3,4] and hence one of the most varied regional climates in the nation.

The character and economy of the Northeast are defined in no small part by its climate: the strong seasonal cycle that produces snowy winters, verdant springs, humid summers, and colorful autumns; the year-to-year and day-to-day variability that brings extreme events such as nor'easters and ice storms; and the moderating influence of offshore currents such as the Gulf Stream.

The Northeast has been dramatically shaped by past changes in climate. Eighteen thousand years ago, for example, when global average temperatures were an estimated 6 to 9°F cooler than they are today,[5] the region was covered by a thick ice sheet. By 10,000 years ago, the climate had warmed and the glaciers retreated, scouring out many of the lakes and rocky shores that now cover the northern part of the region.

Such previous cyclical changes in climate were driven by changes in Earth's orbit around the sun and enhanced by natural variability in the climate system. In contrast, there is strong evidence that global climate change[6] is now being driven by human activities worldwide, primarily the burning of fossil fuels and tropical deforestation. These activities release carbon dioxide and other heat-trapping gases into the atmosphere.

Carbon dioxide concentrations are now higher than at any time in more than 700,000 years,[7] and average global temperatures in the Northern Hemisphere have risen more than 1°F over the past 150 years due to increases in carbon dioxide and other gases. The human contribution to these changes has been confirmed by international bodies such as the Intergovernmental Panel on Climate Change (IPCC) and 11 national science academies, including that of the United States.

BOX 1: CHARACTERISTICS OF THE NORTHEAST REGION

- The Northeast region defined here includes the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Pennsylvania.
- Collectively, Northeast states are the world's seventh largest source of carbon dioxide emissions (the most important heat-trapping gas), compared with the major carbon-emitting nations (Figure 1).
- Carbon dioxide emissions in the Northeast come from transportation (35 percent), electric power (30 percent), and residential, industrial, and commercial energy use (35 percent).
- One in five Americans—57,000,000 people—live in the Northeast.
- Several major metropolitan areas are located in the Northeast, including New York, Boston, and Philadelphia.
- Climate-sensitive sectors of the Northeast's economy include forestry, fisheries, recreation, tourism, and agriculture.

Changes consistent with global warming are already under way across the Northeast. Since 1970, the region has been warming at a rate of nearly 0.5°F per decade. Winter temperatures have risen even faster, at a rate of 1.3°F per decade from 1970 to 2000. This warming has been correlated with many noticeable changes across the Northeast, including:

Changes consistent with global warming are already underway across the Northeast.

- More frequent extreme-heat days (maximum temperatures greater than 90°F)[8]
- A longer growing season[9]
- Earlier leaf and bloom dates for plants[10,11]
- Shifts in the mating cycles of frogs to earlier in the year[12]
- Earlier migration of Atlantic salmon in northeastern rivers[13,14]
- An increase in heavy rainfall events[10,15]
- Earlier breakup of winter ice on lakes and rivers[16,57]
- Earlier spring snowmelt resulting in earlier high spring river flows[17]
- Less precipitation falling as snow and more as rain[18]
- Rising sea surface temperatures and sea level[19]
- Reduced snowpack and increased snow density[20]

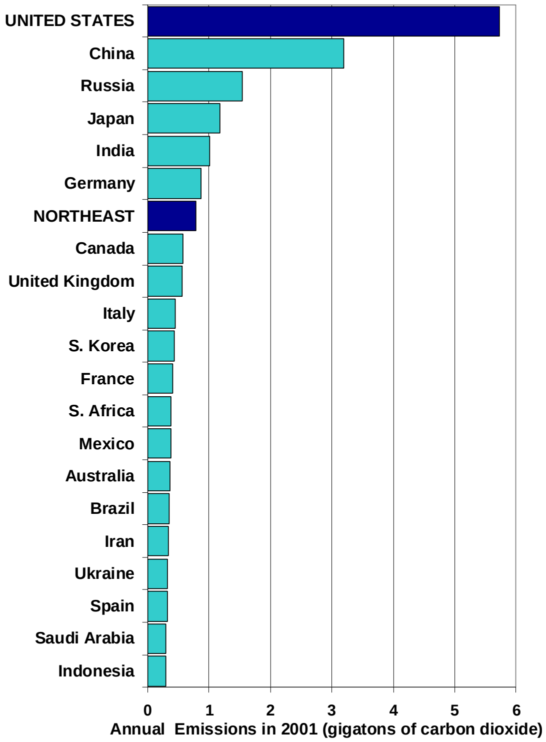


Figure 1. Energy-related carbon dioxide emissions in the Northeast, ranked against the major emitting nations of the world. U.S. emissions include the Northeast states.[84]

As the Northeast continues to warm in the coming decades, even more dramatic changes are projected—changes that have the potential to dramatically alter many aspects of the region's climate that are vital to its economy, ecosystems, character, and quality of life. However, the amount of climate change will be determined by actions taken in the Northeast and globally, and by the effects of these actions on further emissions of heat-trapping gases.

The collaborative research results presented here describe the changes that might be expected over the coming decades and the rest of this century based on two different emissions scenarios—pictures of two plausible alternative futures. Using state-of-the-art climate models and techniques, our work builds on previous studies and assessments of observed and projected climate change[21] to provide the latest, most robust climate projections for the Northeast.

In Chapter 2, we describe the observational data, models, and methods used to derive these projections of future climate change across the Northeast. In Chapter 3, we focus on specific types of changes (seasonal temperature, extreme heat, rainfall and snow, drought, surface water, growing season, sea-level rise, and changes in storms and extreme events) to examine how these have changed in the recent past and how they are likely to be affected by global warming in the coming decades. We conclude in Chapter 4 with a brief discussion of the importance of the choices we make today in determining the pathway we follow and the magnitude of the climate change we can expect during the rest of the century.

CHAPTER 2

DATA SOURCES AND MODEL PROJECTIONS

2.1 Historical Climate Data

To determine how climate in the Northeast has already changed, we use:

- **Weather station records of daily temperature and precipitation**
- **Climate "indicators" such as the bloom dates for specific plant species**
- **Measurements of snow depth and density**
- **Streamflow gauges that measure changes in the amount of water in rivers and streams**
- **A hydrological model that uses observed temperature and precipitation as inputs to determine likely historical evaporation rates, runoff, soil moisture, and other variables for which we do not have consistent, long-term observations**

To examine past changes in climate across the Northeast, we rely on the daily temperature and precipitation values recorded by the United States Historical Climatology Network (USHCN) weather stations.[22,23,24] These stations were selected based on the length of their records and the quality of their data.[25,26,27,28,29] Temperature and precipitation data from the USHCN stations can be used to estimate changes in seasonal and annual temperatures as well as day-to-day variations in extreme-heat days or heavy rainfall events.

Indirect evidence of warming is also obtained from climate indicators, or specific events that are known to respond to temperature changes. For example, we use the date of leaf-out and bloom events for specific tree and plant species as captured by the Spring Indices (SI) models.[30,31] These models are based on more than 2,000 station-years of weather data combined with first-leaf and first-bloom data for lilac and honeysuckle. The average date on which the first leaf and first bloom occurred for these plants is based on data collected from 1961 to 1994 at sites throughout the north-central and northeastern United States. This date was then statistically linked to the number of warm days that accumulated prior to the leaf and bloom events, as well as to the winter chilling requirements of different species. Changes in the leaf and bloom dates therefore represent changes in accumulated temperatures over the course of the preceding months.

A number of hydrological indicators were also used to assess changes in the availability and supply of water in the Northeast. These include observational records from stream gauges that measure streamflow and can detect the dates when ice breaks up on rivers, and snow observation sites where snow depth and density have been measured. We supplemented observational records with a well-tested hydrological model, the Variable Infiltration Capacity (VIC) model.[32,33,34] This model simulates the full water and energy balance at Earth's surface by modeling runoff, infiltration, soil water drainage, evapotranspiration (the loss of water through evaporation from soil and emission from plant leaves), and snowpack accumulation and melt. Meteorological observations, including daily precipitation and temperature, were used to drive the VIC model for the period 1950 to 1999. The output from the model provides a robust estimate of historical evapotranspiration, runoff, snow water equivalent, and soil moisture across the entire Northeast. These outputs were then compared with available records in certain locations,[2,35,36] confirming that the model is capable of reproducing seasonal soil moisture, streamflow, and other hydrological indicators.[37]

2.2 Future Climate Projections

To estimate future changes in the Northeast’s climate, we use:

- **Global emissions scenarios that project future emissions resulting from alternative pathways of population growth, energy use, economic development, and technology.**
- **Global climate models that calculate changes in temperature, precipitation, and other climate variables that would occur under different emissions scenarios.**
- **Downscaling methods that take the coarse-resolution global climate model outputs and translate them into high-resolution regional temperature and precipitation projections.**

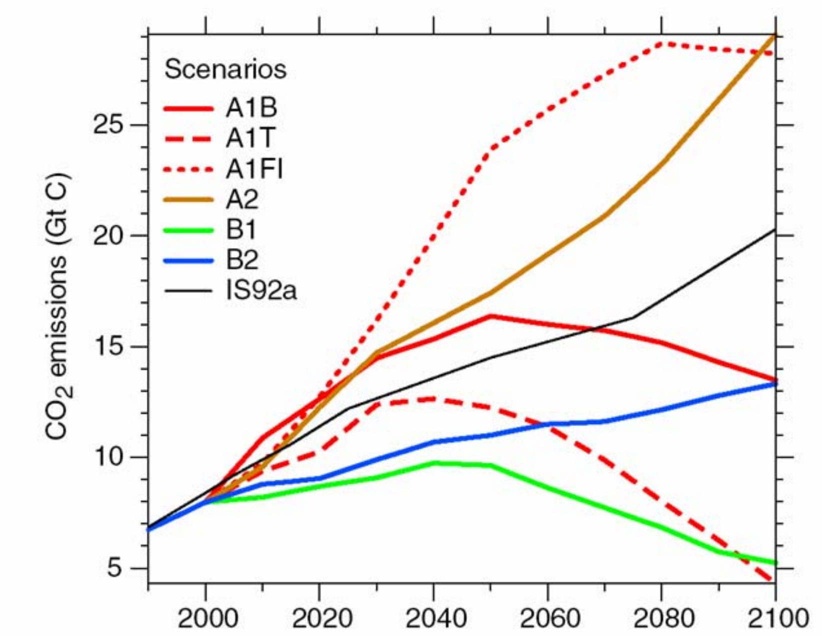


Figure 2. Projected future carbon emissions for the SRES emissions scenarios.[38] Emissions for the higher scenario (A1fi) correspond to the red dotted line, while emissions for the lower (B1) scenario are indicated by the solid green line.

BOX 2: INTER-SCENARIO DIFFERENCES

Over the next few decades, changes in temperature and other related climate variables are not expected to be significantly affected by changes in emissions during that time period. That is because near-term climate change (over the next few decades) is primarily determined by emissions that have already occurred. Two factors account for this: the time it takes for the oceans to respond to increasing atmospheric levels of heat-trapping gases, and the long lifetime of the gases we have already produced, which can remain from tens to hundreds of years in the atmosphere.

By mid-century, however, significant differences begin to emerge in the climate changes expected under the higher- versus the lower- emissions scenario. By the end of the century, temperature changes in the Northeast under the higher-emissions scenario are nearly double those under the lower scenario. This highlights the fact that decisions made now and over the next few decades will be critical to determining what climate our children and grandchildren will inherit.

Emissions Scenarios

Before estimating potential changes in climate during the rest of the century, we first need to ask: how might human societies and economies develop over the coming decades? What technological advances might we expect? On what energy sources might we rely? The answers to these questions will affect future emissions of greenhouse gases from human activities. And these emissions will in turn determine future climate change at both the global level and in the Northeast.

To address these questions, the Intergovernmental Panel on Climate Change (IPCC) has developed a set of future emissions scenarios known as SRES (Special Report on Emissions Scenarios).[38] These scenarios use a wide range 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 cover a wide range of plausible futures we can use to assess the differences in the extent and severity of the global warming that would result from alternative emissions choices that societies may make. Depending on these choices, emissions could end up being either higher or lower than the estimated range; however, there is already a substantial difference between the higher- and lower-emissions scenarios used here—sufficient to illustrate the potential range of changes that could be expected and how these depend on future emissions.

In this study, we use the SRES A1fi (fossil fuel-intensive) and B1 scenarios to represent possible higher- and lower-emissions choices, respectively, over the rest of the century (Figure 2). The higher-emissions scenario (A1fi) 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 lower-emissions scenario (B1) 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 heat-trapping gases peak around mid-century and then decline. Atmospheric carbon dioxide concentrations reach 550 ppm by 2100—about double pre-industrial levels.

Global Climate Models

Emissions scenarios are used as input to global climate models, also known as atmosphere-ocean general circulation models (AOGCMs). These are large, three-dimensional coupled models that incorporate the latest understanding of the physical processes at work in the atmosphere, oceans, and Earth's surface. Models are constantly being enhanced as our understanding of climate improves and as computational power increases. As output, they 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.

In this study, we rely on three global climate models: 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 Parallel Climate Model (PCM).

The three models used in this analysis represent different climate sensitivities. Climate sensitivity is defined as the temperature change resulting from a doubling of atmospheric carbon dioxide concentrations relative to pre-industrial times, and determines the extent to which temperatures will rise under a given increase in atmospheric concentrations of greenhouse gases. Because many of the processes at work in the earth-atmosphere system and their feedbacks are not yet fully understood, these are represented somewhat differently in different global climate models. GFDL and HadCM3 have medium to medium-high climate sensitivities, while PCM has low climate sensitivity.[39] The ranges in projected temperature change and other climate variables presented in this report arise from the different climate sensitivity of these models.

Confidence in applying these global models to assess future Northeast climate derives from evidence that they are able

BOX 3: COMPARING MODELED TEMPERATURE TRENDS WITH OBSERVATIONS

Global climate models reproduce annual observed warming across the Northeast, including long-term trends seen over the past century (1900 to 1999) as well as the accelerated warming observed since 1970. However, these models have a tendency to underestimate the degree of change that has been observed to date. Most importantly, the models consistently underestimate the rapid winter warming the Northeast has experienced over the past 30 years.

This may be partly due to the fact that the models are not designed to reproduce the timing of observed natural variability in the climate system. Neither are they designed to incorporate "fine-scale" changes in surface snowpack, which has been decreasing over the past 30 years.[20] Diminished snowpack can play an important role in enhancing winter warming via a snow-albedo feedback loop: exposed ground absorbs more solar radiation than snow-covered ground, warms accordingly, and can cause additional melting and warming.

to reproduce key features of climate and regional change already observed across the Northeast.[1,2]

Downscaling

Global models provide a "coarse-scale" resolution, with geographic grid cells ranging in size from 50 to 250 miles per side. In general, this type of resolution is too coarse to capture the kinds of "fine-scale" changes we are already experiencing and are likely to continue experiencing across the Northeast. For that reason, we use several robust downscaling techniques to transform global climate model output into higher-resolution projections on the order of tens rather than hundreds of miles.

There are two main types of downscaling approaches: dynamical and statistical. **Dynamical downscaling** uses high-resolution regional-scale models (with grids on the order of 20 miles). These incorporate many more of the small-scale processes and high-resolution topography needed to model climate over a relatively small area such as the Northeast. For that reason, the output they produce is usually closer to what is actually observed across the Northeast than output from global models[1,40,41,42]—particularly since observations are extremely "local" in that they were taken at specific weather stations. Furthermore, dynamical downscaling is able to account for important changes in smaller-scale processes that can affect regional climate.

Statistical downscaling relies on historical instrumental data for calibration at the local scale.[43] A statistical relationship is first established between AOGCM output for a past time period and observed temperatures and precipitation. This relationship is averaged over a relatively long period of time, such as 30 or 40 years, to remove year-to-year fluctuations. The historical relationship between AOGCM output and monthly or daily climate variables at the regional scale is then used to downscale future AOGCM simulations to that same regional scale. Unlike regional climate modeling, statistical downscaling assumes that the relationships between large- and small-scale processes remain fixed over time—an assumption that may not always be justified for precipitation. However, 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.

In this study, we rely primarily on statistical downscaling. However, these projections have been evaluated against observations and regional-model simulations[1,44,45] driven by SRES A1fi (higher emissions) and B1 (lower emissions) output from the PCM model. Two statistical methods were used to downscale HadCM3, PCM, and GFDL monthly temperature and precipitation fields for the A1fi and B1 emissions scenarios. The first method[46] produced monthly and daily temperature and precipitation projections on a regular one-eighth-degree grid covering the entire Northeast, while the second method[47] produced daily temperature projections for each of seven northeastern cities: Boston; Buffalo; Concord, NH; Hartford; New York; Philadelphia; and Pittsburgh.

BOX 4: THE POTENTIAL FOR SURPRISE

There are a number of important features of Earth's climate system that climate models may not capture fully. An important example is the potential slowing or even complete shutdown of the ocean's thermohaline circulation. This system, driven by sinking water in the North Atlantic, distributes heat around the globe. In the past, sudden changes in thermohaline circulation are believed to have triggered abrupt climate changes in the Northern Hemisphere. Slowing or collapse of this "conveyor belt" of heat reduces the northward transport of heat from equatorial areas and the southward movement of cold polar waters.

Current state-of-the-art models project a weakening rather than a total collapse of thermohaline circulation in future centuries.[85] However, our current understanding of the dynamics governing the conveyor belt, and the potential impact its weakening or collapse would have on the Northeast, is limited.

CHAPTER 3

THE CHANGING NORTHEAST CLIMATE: CURRENT AND FUTURE

We are already experiencing an increase in the rate of climate change in the Northeast. Annual average temperatures are rising, with the greatest increases occurring in winter temperatures. These changes have been accompanied by a reduction in snow cover, earlier snowmelt, earlier arrival of spring, an extension of the summer season, and an increased risk of extreme heat. These changes are expected to grow in the future, with the amount of change depending on whether we follow a pathway of lower or higher greenhouse gas emissions.

Here, we focus on each of these changes by category, examining both past observed and future expected changes in key features of Northeast climate.

3.1 Seasonal and Annual Temperatures

- **Annual temperatures across the Northeast have risen more than 1.5°F since 1970.**
- **Winters have been warming fastest, at 1.3°F per decade since 1970.**
- **Under the lower-emissions scenario, annual temperatures are projected to increase 3.5 to 6.5°F by 2100, and 6.5 to 12.5°F under the higher-emissions scenario.**

The Northeast is a temperate region, with highly distinct seasons and a wide range in annual temperatures. Currently, annual average temperatures range from 40°F in the northern part of the region up to 50°F in the southern part. Across a single year, temperatures can range from well below freezing in winter to over 100°F in summer.

Given the day-to-day and year-to-year variability experienced in the Northeast, one year might be relatively warm and the following year could be colder than average. However, analysis of average annual and seasonal temperatures over longer periods of time shows a distinct upward trend. This is particularly true over the last few decades.

Since 1900, annual temperatures across the Northeast have risen an average of 0.14°F per decade.[48] From 1970 to 2002, however, the region has been warming at an average rate of 0.5°F per decade. This corresponds to an overall warming for the entire region during that time of 1.75°F on average—although of course any given year can still be warmer or cooler than average. The upward trend in winter

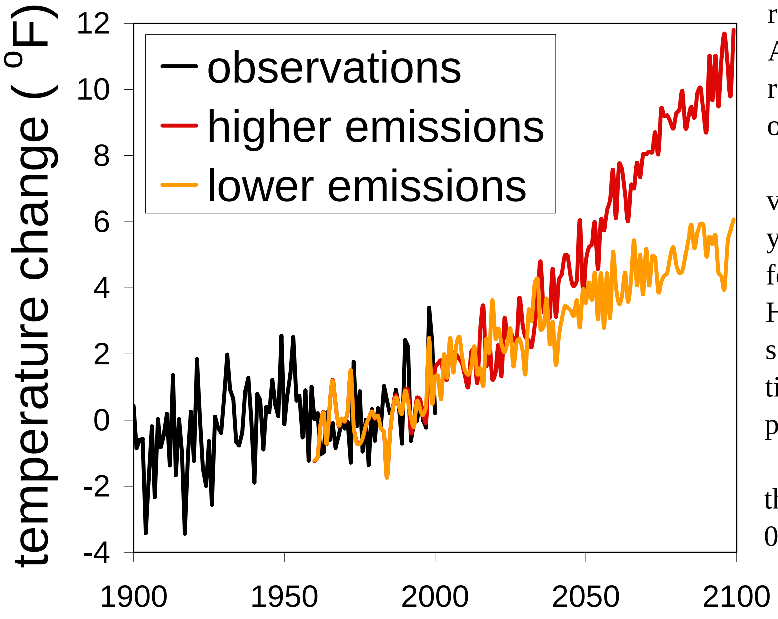


Figure 3. Observed and model-based changes in annual average temperature for the Northeast (in °F) relative to 1961-1990 average temperature. Modeled historic and future temperatures represent the average of the GFDL, HadCM3, and PCM models.

temperatures is even greater, rising an average 1.3°F per decade since 1970.

Over the next century, temperatures across the Northeast are projected to continue rising (Figure 3). In the next few decades (2010 to 2039), changes are similar under the lower- and higher-emissions scenarios, but by mid-century, temperature differences between the scenarios begin to appear. By the latter part of the century (2070 to 2099), the difference between the higher- and lower-emissions scenarios is a dramatic 4.5°F.

	ANNUAL		WINTER (DJF)		SUMMER (JJA)	
	Lower emissions	Higher emissions	Lower emissions	Higher emissions	Lower emissions	Higher emissions
2010–2039	2.4	2.6	3.3	3.4	2.2	2.6
2040–2069	3.7	5.8	4.3	6.1	3.8	6.4
2070–2099	5.0	9.5	5.8	9.8	5.1	10.6

Table 1. Averaged model-projected changes in average annual, winter, and summer temperatures (°F) as projected under the lower- (B1) and higher- (A1fi) emissions scenarios over the next few decades (2010–2039), by mid-century (2040–2069), and by the latter part of the century (2070–2099) compared with the 1961–1990 modeled average. Projected increases in both winter and summer temperatures are above the annual average, while increases in spring and fall temperatures are projected to be lower than the annual average.

Over the next few decades, temperatures are projected to increase more in winter than in summer, with little difference between emissions scenarios (Table 1). This is the same seasonal trend that has been observed over the past few decades. By the end of the century, however, temperature changes of a similar size are projected for both summer and winter, with substantially higher changes under the higher-emissions scenario compared with the lower-emissions scenario. Under the lower-emissions scenario, end-of-century temperatures are projected to rise on average by 5.8°F in winter and 5.1°F in summer compared with the 1961 to 1990 average. Under the higher-emissions scenario, end-of-century temperatures are projected to average 9.8°F warmer in winter (ranging from 8 to 12°F warmer) and 10.6°F warmer in summer (ranging from 6 to 14°F warmer).

3.2 Heat Index and “Migrating” States

- **The “heat index” provides a measure of how hot it *feels.***
- **Taking into account humidity, future temperature increases are likely to feel nearly twice what they actually are.**
- **By the end of the century, summers in upstate New York may feel like Virginia under the lower-emissions scenario, and South Carolina or Georgia under the higher scenario.**

How cold or hot it feels does not depend only on temperature; it is also a function of wind and humidity. As Northeasterners know all too well, a sunny winter day with no wind might feel warmer than a damp, windy spring day, while summer days in the Northeast can be stifling, with hot temperatures aggravated by high humidity. For that reason, heat index (HI), which combines temperature and humidity, can be a better measure of how hot it actually “feels” in the summer—and how hot it will feel in the future.

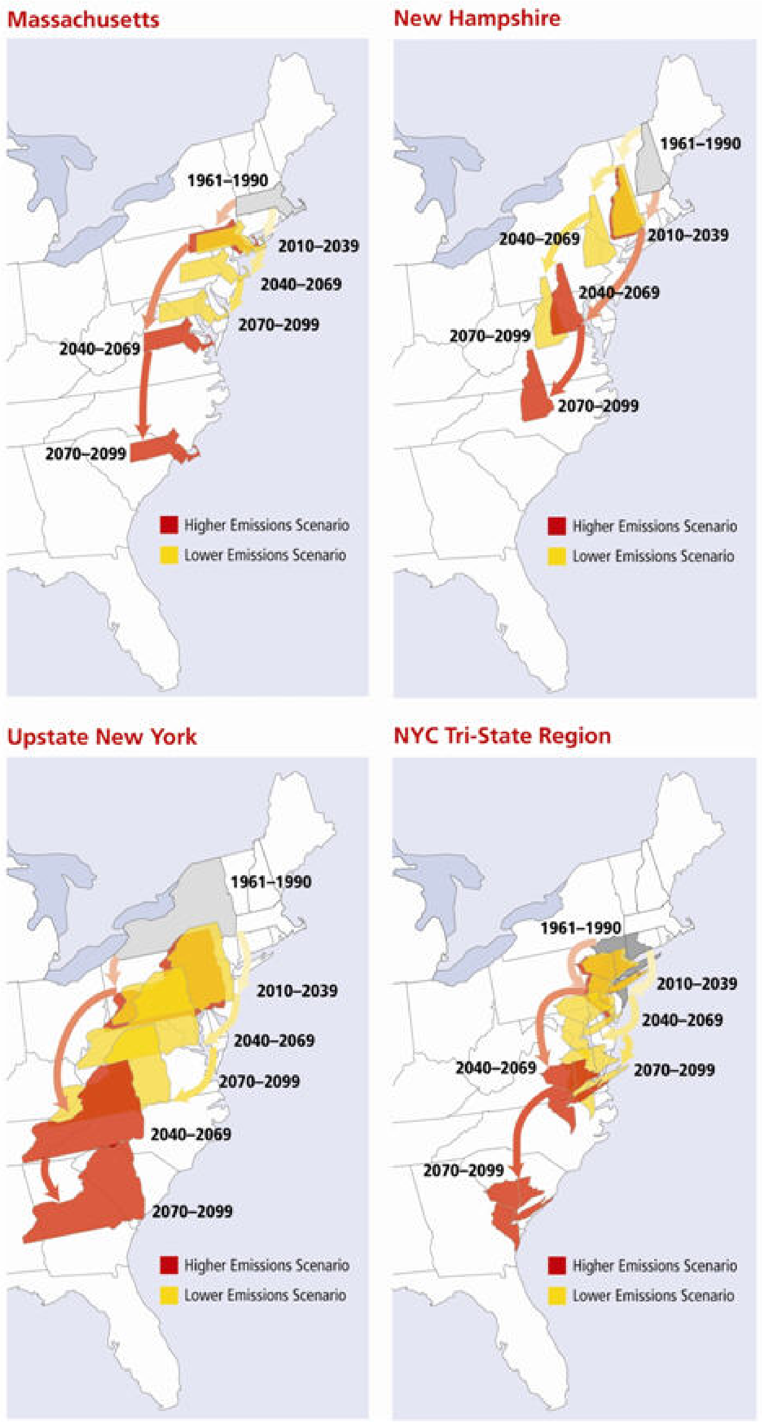


Figure 4: Projected climate "migrations" for several states and regions in the Northeast, based on average summer heat index, under the lower- and higher-emissions scenarios. Based on the average of the GFDL, HadCM3 and PCM model projections.

BOX 5: HEAT INDEX

Heat index is defined as the temperature perceived by the human body based on both air temperature and the amount of moisture or humidity present in the air.

The impact of changes in summer heat and humidity can best be illustrated by comparing the types of future conditions expected in northeastern states with states along the southeastern U.S. coast (Figure 4). For example, based on present-day average heat index values, the state of Massachusetts is projected to resemble New Jersey under the lower-emissions scenario by mid-century, and Maryland under the higher-emissions scenario.

With higher emissions, a typical summer day may feel 12 to 16°F warmer late in this century.

Even greater changes are expected by the end of the century. Under higher emissions, the typical northeastern summer day is projected to feel 12 to 16°F warmer than it did on average between 1961 and 1990 (the historical reference period used in this study). Thus, an average summer in the NYC Tri-State region could resemble those of South Carolina today under the higher-emissions scenario, and Virginia under the lower-emissions scenario. Summers in New Hampshire and upstate New York are projected to feel more like current summers in North Carolina and Georgia, respectively, under the higher-emissions scenario, and like Virginia under the lower-emissions scenario.

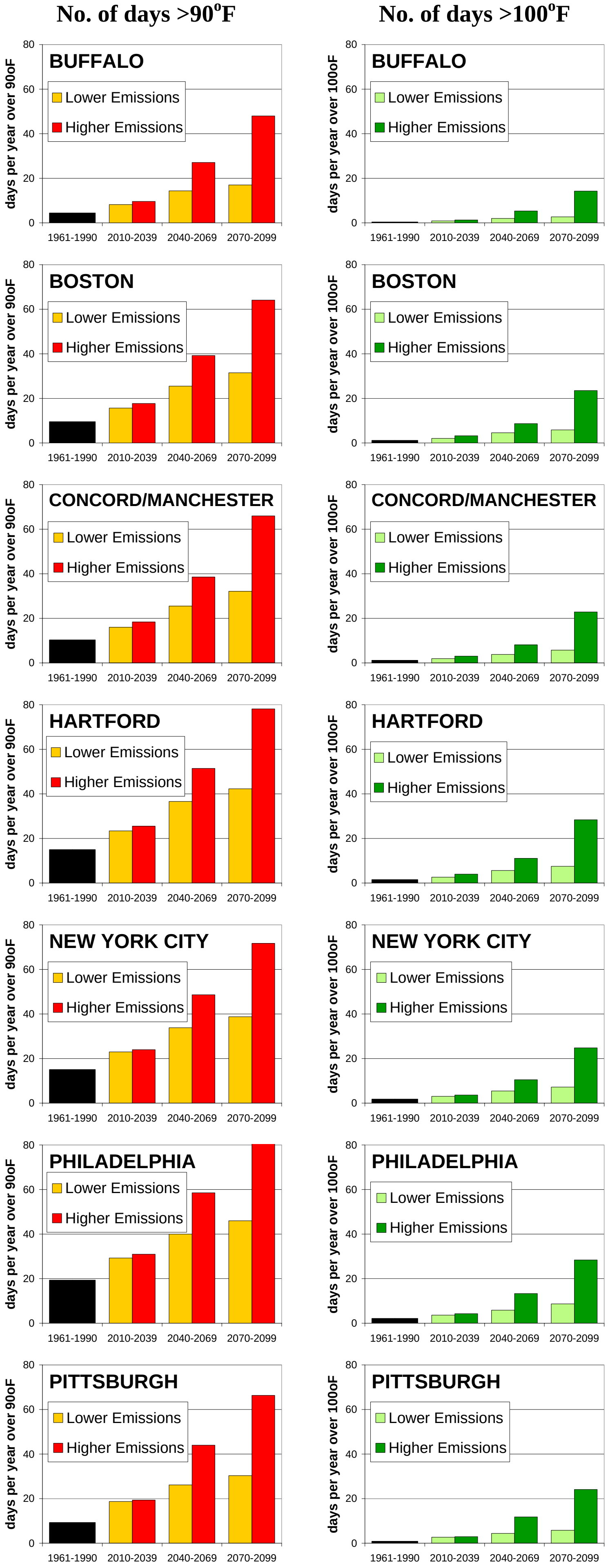
3.3 Heat Waves and Temperature Extremes

- **The number of very hot days is increasing across the Northeast.**
- **By the end of the century, many northeastern cities can expect 30 or more days over 90°F under the lower-emissions scenario, and 60 or more days per year under the higher-emissions scenario.**
- **Currently, northeastern cities experience one or two days per summer over 100°F. This number could increase by late century to between three and nine days under lower emissions and between 14 and 28 days under higher emissions.**

Extreme heat can be particularly problematic in urban areas. Hot temperatures, amplified by the urban heat island effect, can create dangerous conditions, especially for children, the elderly, and other vulnerable populations. Heat waves with multiple consecutive days over 90°F descend on parts of the Northeast each summer, sometimes more than once, increasing public health risks and challenging health and emergency response systems.

However, heat waves generally last no more than a week and scorching days over 100°F are rare. Today, most of the Northeast copes with extreme heat as a trying but infrequent summer challenge. For example, as of 2001, only 14 percent of New England homes had central air conditioning, while an additional 44 percent utilized single-room units; in all, 58 percent of homes in New England have some form of air conditioning, compared with 77 percent of homes nationwide.[49]

In the Northeast, the average number of very hot days (temperatures exceeding 90°F) per year has already increased by roughly two over the last 45 years.[8,50] Currently, cities across the Northeast experience an average of five summer days over 90°F in the northern part of the region and up to 20 such days in the more southern and inland areas. The number of days over 100°F ranges from one day every two years in more northern cities such as Buffalo up to as many as two days per year for more southern cities such as Philadelphia and New York City.



Global warming is projected to increase these numbers dramatically (Figure 5). By mid-century, models project an additional 30 to 60 days per year (one to two months) over 90°F under the higher-emissions scenario and 20 to 30 days per year (almost a full month) over 90°F under the lower-emissions scenario.

By the end of the century, most northeastern cities are projected to experience more than 60 days each year with temperatures over 90°F under the higher-emissions scenario. The smallest changes are expected for more northern cities such as Buffalo, with just over 40 days per year, while Philadelphia is projected to experience an average of 82 days over 90°F per year. The number of days per year over 100°F is likely to be at least 20 and closer to 30 in more southern cities such as Philadelphia and New York.

It should be noted that increases in extreme heat under the lower-emissions scenario are less than those projected under the higher-emissions scenario, but are still much greater than today. By the end of the century, most northeastern cities are projected to have at least 30 days per year over 90°F. Projected increases in the number of days per year over 100°F range from three in more northern cities up to nine in more southern cities.

Figure 5. Number of summer days that exceed 90°F and 100°F for seven cities in the Northeast under a lower- and higher-emissions scenario. Modeled future extreme-heat days represent the average of the GFDL, HadCM3 and PCM projections.

3.4 Precipitation

- **Winter precipitation (in the form of both snow and rain falling in winter months) has been increasing over the past few decades, and is projected to continue increasing, with slightly larger changes under the higher-emissions scenario than the lower-emissions scenario.**
- **Little change is expected in summer rainfall, although projections are highly variable.**

On average, precipitation in the Northeast is relatively consistent throughout the year, although it can vary greatly from year to year and month to month. The recent historical precipitation pattern in the Northeast was dominated by an extended drought in the early 1960s, which lasted for several years (Figure 6). This drought was the worst to occur in the Northeast region since the beginning of record keeping in the late nineteenth century, and possibly since European settlement.[51,52]

Excluding this event, there has been a gradual increase of about 5 to 10 percent in annual average precipitation across the Northeast since 1900.[2,53] Most of that increase is evenly split between spring, summer, and fall, with little change in winter precipitation. Over the past few decades, however, this trend has reversed. Average annual precipitation shows a slight decrease, but winter precipitation has begun to increase at a rate of up to 0.15 inch per decade.

The most significant trend has been in the type of precipitation that falls. As winter temperatures rise, more precipitation is falling as rain and less as snow.

In the future, most model simulations suggest a steady increase in annual precipitation, with a total increase of 10 percent (or about four inches per year) by the end of the century. Unlike temperature, the magnitude of annual precipitation changes is not projected to differ significantly under the higher- and lower-emissions scenarios.

Winter precipitation, however, is projected to increase more under the higher-emissions scenario than the lower-emissions scenario (Figure 6). By mid-century, winter precipitation could increase between 11 percent (lower emissions) and 16 percent (higher emissions) on average. By the end of the century, winter precipitation could increase an average of 20 to 30 percent, with greater increases under the higher-emissions scenario. And compared with the past few decades, a greater proportion would be expected to fall as rain rather than as snow. Overall, little change in precipitation is projected in summer months, although individual models project both increases and decreases, in part due to the high variability in year-to-year rainfall.

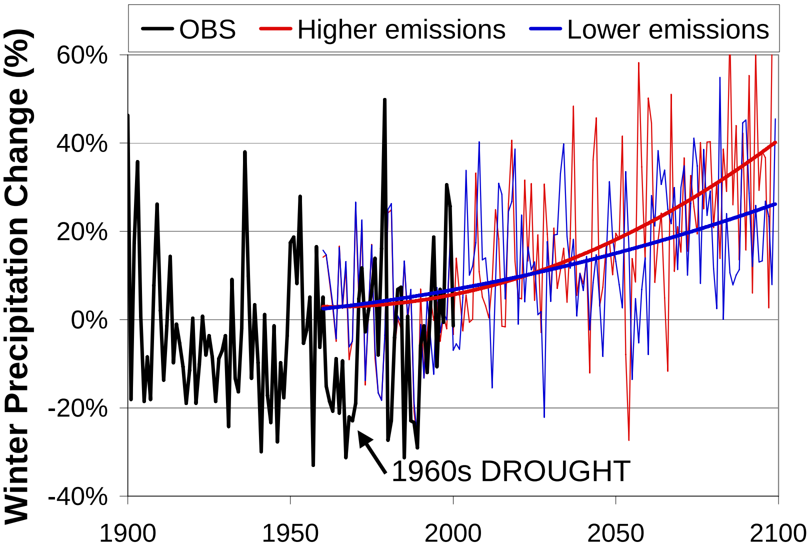


Figure 6. Observed and model-based winter precipitation for the Northeast, in units of percentage change relative to the 1961-1990 average. Model-simulated precipitation represents the average of the GFDL, HadCM3, and PCM projections.

3.5 Extreme Precipitation and Storms

- **The frequency of heavy rainfall events is increasing across the Northeast.**
- **Under both emissions scenarios, rainfall is expected to become more intense. In addition, periods of heavy rainfall are expected to become more frequent.**
- **Some East Coast winter storms are projected to shift from earlier to later in the winter season as temperatures rise, and more storms are expected to travel further up the coast and affect the Northeast.**

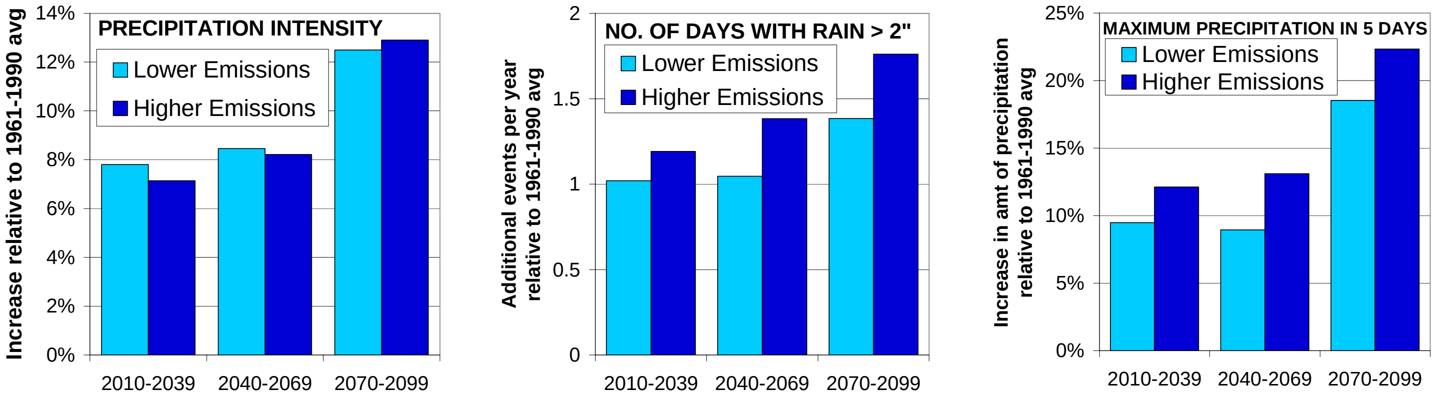
Extreme precipitation can inflict tremendous damage on homes, businesses, public infrastructure, and ecosystems, as well as disrupting our economic activity and daily lives. Several such events that hit the Northeast hard in fall 2005 and spring 2006 resulted in loss of life and an estimated $130 million in property damage.

During the 1980s and 1990s, the Northeast experienced a rise in heavy precipitation events (defined as more than two inches of rain falling in less than 48 hours).[9] To assess possible future changes in extreme events, we used the following three measures:

- The average intensity of precipitation, calculated as the number of rainy days each year divided by total annual rainfall
- The number of heavy precipitation events
- The intensity of once-a-year extreme precipitation events, calculated as the amount of precipitation that falls over five consecutive days in a given year

All three measures of extreme precipitation are expected to increase over the rest of the century. For precipitation intensity, or the average amount of rain that falls on any given rainy day in the Northeast, increases of eight or nine percent are projected by mid-century, and increases of 10 to 15 percent by the end of the century. In other words, wet days will become wetter.

Figure 7. Projected increases in three indices of extreme precipitation: (1) precipitation intensity, (2) number of days per year with more than two inches of rain, and (3) maximum amount of precipitation to fall during a five-day period each year. Changes are shown for the lower- and higher-emissions scenarios. Model-simulated precipitation represents the average of the GFDL and PCM models (daily precipitation projections for the HadCM3 model were not available).



Under both lower and higher emissions, periods of heavy rainfall may become more common, increasing the risk of flooding.

The number of heavy precipitation events is also projected to increase by eight percent by mid-century, and 12 to 13 percent by the end of the century. This means that, in addition to having more rain when it does rain, there will also be more two-day periods with heavy downpours. Finally, increases are also projected for the wettest five-day period of each year. By mid-century, 10 percent more rain is projected to fall during these events. By the end of the century, 20 percent more rain is projected relative to the average event during the years 1961 to 1990. Overall, these changes indicate that the types of heavy rainfall events that have occurred in the Northeast in recent years will become increasingly common (Figure 7), raising the risk of floods.

Changes in precipitation—particularly winter precipitation—are likely connected to changes in atmospheric circulation patterns and storm frequency. One of the most important types of storms in the region is the nor'easter, named for its fierce winds that typically blow from the northeast and drive the storm toward the coast. In past winters, these storms have rapidly blanketed the region in several feet of snow.

Historically, nor'easters have inflicted significant damage on the Northeast. The so-called Blizzard of '78 and the 1991 Halloween Nor'easter are just a few examples of the many storms that have swept the region. We assessed the potential impact of climate change on the frequency and timing of these storms. Changes in storm intensity were not examined here, although there is evidence that the intensity of larger tropical storms and hurricanes may be increasing (Box 6).

Currently, an average of 10 to 11 serious storms hit the East Coast each winter. Approximately 70 to 80 percent of these storms move far enough north to affect the Northeast during November and December, but only 50 to 70 percent during the months of January, February, and March. Climate models suggest little change in storm frequency this century, but under the higher-emissions scenario, between 5 and 15 percent more of the storms that occur during late winter (January, February, and March) will move far enough northward by century's end to affect the Northeast. Hence, there is some indication that global warming may increase the number of late winter storms experienced in the Northeast by about one additional storm per year under the higher-emissions scenario. Little change is projected under the lower-emissions scenario; however, even with no change in the number of storms, higher sea levels will increase the likelihood of damage to coastal infrastructure.

BOX 6: GLOBAL WARMING AND HURRICANES

In the wake of the 2005 hurricane season, much attention has been directed toward the question of whether tropical storms in the Atlantic are increasing in strength and number. While debate continues over a definitive link between climate change and increased **hurricane frequency**,[86] it is clear that observed ocean warming—a key condition for the formation and strengthening of these storms—cannot be explained by natural cycles alone. Recent studies suggest that increased **hurricane intensity** (exemplified by the rising number of hurricanes that achieve category 4 and 5 status) is driven at least in part by global warming.[87,88]

The devastation wrought by successive 2005 hurricanes indicates the potential for future increases in the duration and strength of tropical storms and suggests significant risk for coastal communities and ecosystems.

The path of Atlantic hurricanes frequently brings them toward the Northeast, yet landfall of the most severe storms is historically rare—the strongest recorded storm to hit New England was the Great Hurricane of 1938. Since that time, the Northeast's coastline has experienced extensive residential, industrial, infrastructure, and tourism-related development, significantly increasing the potential for economic and property damage as well as loss of life due to storms, floods, and coastal erosion. Even if the intensity of hurricanes and nor'easters does not increase, the combination of expanded infrastructure and global warming-related sea-level rise will substantially increase the risk of major storm damage to the Northeast's coast (see section 3.10).

3.6 Evaporation, Soil Moisture, Runoff, and Drought

- **Rising temperatures will increase evaporation rates and reduce soil moisture in summer.**
- **By mid-century, these changes are projected to lead to more frequent short-term droughts (an average of two every three years) under both scenarios, with a slightly higher frequency under the higher-emissions scenario.**
- **By the end of the century, short-term droughts under the higher-emissions scenario may be as frequent as once per year in parts of the Northeast. Only a slight increase in drought risk is expected under the lower-emissions scenario.**

Lush green hills, clear forest streams, and jewel-like lakes lying at the feet of mountains—all iconic images of the Northeast—suggest a landscape rich in water resources. While human demand for water continues to rise, the image of the Northeast as a water-rich region remains largely true. In the future, however, changes in the timing and amount of water availability and increased frequency of drought may fundamentally alter this image.

Changes in surface water balance are reflected in evaporation, soil moisture, and runoff. How much water is entering the system (through precipitation)? How much is leaving (through evaporation and runoff)? How much remains (as measured by soil moisture)? To examine the potential impact of climate change on surface or terrestrial hydrology in the Northeast, we rely on simulations from the VIC hydrological model. These simulations are driven by historical (observed) temperatures and precipitation and by projected changes in temperature and precipitation that would likely occur under the higher- and lower-emissions scenarios.

Climate change is projected to increase temperatures and winter precipitation, with little change in summer rainfall. Increasing winter precipitation would mean more water available for runoff and evaporation. Rising temperatures would melt snow faster and earlier, likely increasing runoff and soil moisture in winter and early spring. These increases could be followed by reductions in soil moisture in the late summer and early fall, since warmer temperatures drive higher evaporation rates, which would not be compensated by additional rainfall. Water shortages could result. Projected winter and spring increases in soil moisture, and summer and fall decreases, are generally greater under the higher-emissions scenario than the lower-emissions scenario, highlighting the important influence of temperature on hydrology and surface water in the Northeast.

These trends will have important implications for the availability of water for agriculture and other uses in the Northeast. Moreover, extreme events such as droughts that can occur on top of these long-term trends have even greater potential for economic and ecosystem damage. A drought is defined here as occurring when monthly soil moisture is more than 10 percent below the long-term mean (relative to historical simulations). This definition relates directly to the availability of water for agriculture and water supply. Drought events are classified as being short-term (one to three months), medium-term (three to six months), or long-term (more than six months).

Historically, short-term droughts occur once every two years across most of the Northeast and once every three years over upstate New York, western Pennsylvania, and northern Maine. Medium-term droughts are far less common; historically, they have occurred once every 15 years for the inland regions listed above, but not at all for some coastal areas. Long-term droughts occurred on average less than once every 30 years.[54]

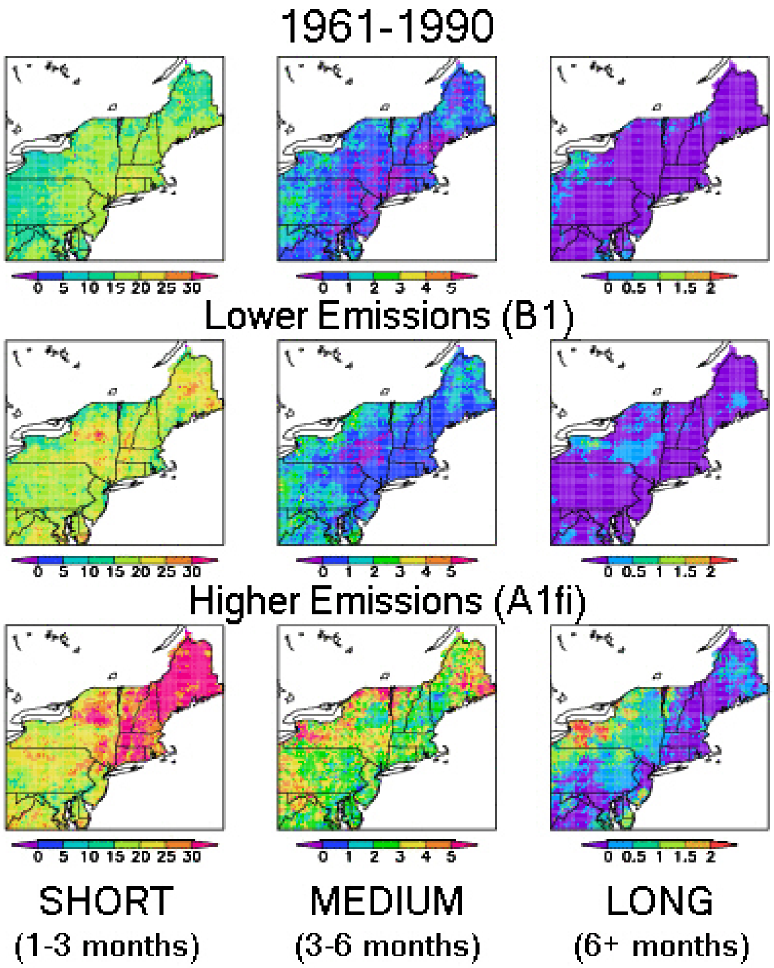


Figure 8. Each map shows the total number of short-term (1-3 month), medium-term (3-6 month) and long-term (6+ month) droughts occurring during the historic 30-year reference period (1961–1990) and the 30-year period at the end of the century (2070–2099) under a higher- and lower-emissions scenario. Projected values are the average of the HadCM3 and PCM-based VIC simulations.

By the end of the century, short- and medium-term droughts in the Northeast are projected to increase dramatically under the higher-emissions scenario, with only slight increases under the lower-emissions scenario (Figure 8). Under the higher-emissions scenario, short-term droughts are projected to occur as frequently as once per year in the north and eastern parts of the region. The frequency of medium-term droughts also increases substantially under this scenario. These changes result primarily from reductions in soil moisture during late summer and autumn, which in turn are caused by both increased evapotranspiration and stable or even reduced precipitation. Droughts longer than six months are still projected to be infrequent due to the high variability in the Northeast's climate.

Drier, hotter summers, coupled with wetter periods early in the year, have the potential to affect water supply and agriculture. Even very short (e.g., one- to four-week) water deficits during critical growth stages can have profound effects on plant productivity and reproductive success. With climate change, additional possible stresses on water availability may occur through changes in the amount of groundwater available in wells.

During a drought, evapotranspiration continues to draw down surface water resources, further depleting supply. As water deficits deepen, productivity of natural vegetation and agricultural crops declines. Drought also affects natural systems as well as households and communities. Extended periods of low flows in rivers and streams eventually affect vulnerable aquatic wildlife. As soil moisture is further depleted and vegetation becomes increasingly water stressed, the risk of wildfires also rises.[55,56]

3.7 Streamflow and Water Supply

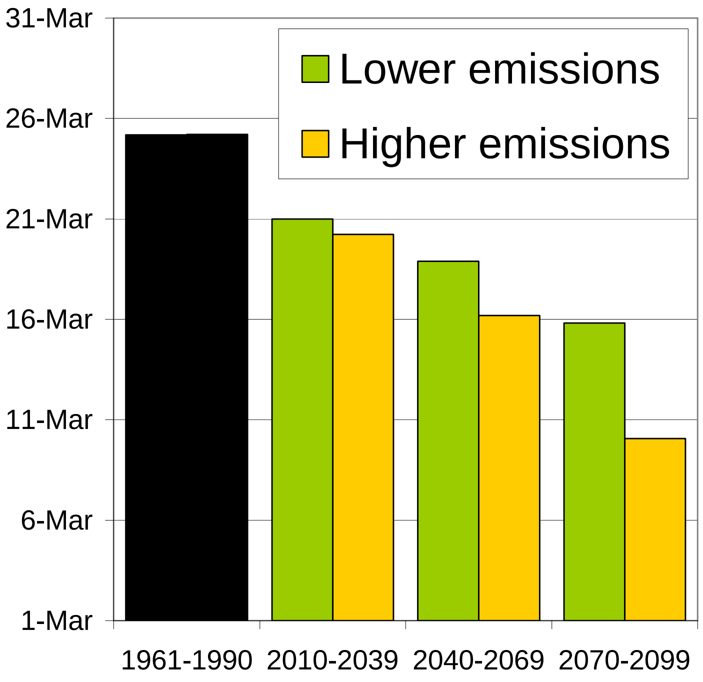
- **Warmer winter and spring temperatures in the Northeast are melting the snow earlier and causing earlier high spring flows.**
- **As temperatures continue to rise, snow and ice will melt even earlier, advancing spring streamflow 10 days earlier under the lower emissions scenario and more than two weeks earlier under the higher emissions scenario.**
- **Warming temperatures will also cause more water to evaporate in the summer months, extending the summer low-flow period by nearly a month under the higher-emissions scenario and increasing the risk of water shortages and drought.**
- **Global warming is also expected to increase the likelihood of high flow events in the winter, particularly under the higher-emissions scenario, which implies a greater risk of flooding.**

Rising temperatures in the Northeast are already changing the timing of important components of the region’s water cycle. One critical time of year is late winter/early spring, when snow melts, ice breaks up on lakes and rivers, and the amount of water in rivers (called streamflow) reaches a maximum. Another critical period comes in mid- to late summer, when high temperatures, evaporation, and increased demand from urban users, ecosystems, and agriculture produce extended low-flow periods.

Winters in the Northeast have warmed by 1.3°F per decade since 1970. This has produced a number of visible changes in winter and spring streamflow and ice cover. Since 1850, for example, the date of spring ice-out on lakes in the Northeast has shifted earlier in the year by nine days in the northern states and 16 days in the southern part of the region.[16] Similarly, the highest spring streamflow over the northern part of the region now arrives 7 to 14 days earlier than in the past.[17] These changes are directly related to air temperature, which determines ice-out dates and the timing of snowmelt. Measurements of the effects of ice cover on streamflow in nine of the northeastern rivers with the longest records have shown that the length of ice cover on those rivers has decreased by 20 days, with most of the change occurring from the 1960s to 2000.[57]

How might global warming affect future streamflow in the Northeast?[58] Under both emissions scenarios, the date of peak spring flow is projected to move earlier in the year as temperatures rise (Figure 9). Advances of four to five days are expected over the next few decades (2010–2039), reaching seven to nine days by mid-century. By the end of the century, peak streamflow could occur 10 days earlier under the lower-emissions scenario and more than two weeks earlier under the higher-emissions scenario relative to the historical reference period (1961–1990).

As winter precipitation increases and warmer temperatures begin to melt the snow faster, high-flow events are also projected to occur more frequently, especially under the higher-emissions scenario and toward the northern part of the Northeast.[2] In New Hampshire, Vermont, and Maine, the probability of high-flow events may increase as much as 80 percent, accompanied by a likely increase in flood risk.



Important indicators of streamflow and water supply in summer are the timing and number of low-flow events that typically occur toward the end of summer. These have remained largely unchanged over the past century in the Northeast.[89] Even though evapotranspiration may have been increasing during that time due to rising temperatures, increases in precipitation may have compensated, masking any underlying trend. In the future, little change is expected under the lower-emissions scenario. Under the higher-emissions scenario, however, the amount of streamflow during the lowest week of the year is projected to drop 10 percent or more by the end of the century (relative to the 1961 to 1990 average).

Figure 9. Projected changes in the date at which 50 percent of winter and spring streamflow has passed, driven by snow melt, under the lower- and higher-emissions scenarios.[17] Projections represent the average of the GFDL, HadCM3 and PCM models.

The U.S. Fish and Wildlife Service (USFWS) defines a low-flow threshold as 0.5 cubic foot per second per square mile, approximately equal to the average flow during the month of August. This is the minimum streamflow required to maintain habitats for aquatic ecosystems in the Northeast.[59] From 1961 to 1990, most streams in the region dropped below the USFWS low-flow threshold sometime in the middle of July and remained below that level through the first week of September (Figure 10).

Rivers and streams could have greater winter flows, increasing the risk of flooding, and lower summer flows, exacerbating drought.

In the future, the duration of low-flow periods is not projected to change much under the lower-emissions scenario. However, streamflow in September and October will still remain significantly below the 1961 to 1990 average by the end of the century. Under the higher-emissions scenario, changes are projected in both the duration of the low-flow period and the level of September-October streamflow. The low-flow period is projected to arrive more than a week earlier in the year and extend several weeks longer into the fall. Even with the projected increases in precipitation over the winter months, drying in summer and fall should be expected due to increased evapotranspiration, particularly under the higher-emissions scenario. Furthermore, lower streamflow in late summer and fall is consistent with increased drought risk during that time, as discussed in section 3.6.

To summarize, streamflow is projected to become more extreme—higher in winter, likely increasing flood risk, and lower in summer, exacerbating drought. Higher winter flows increase the frequency of ice jams, resulting in major flooding and infrastructure damage.[60] The impact is also likely to be significant on aquatic plants and wildlife sensitive to the timing of high spring flow (such as spring-spawning fish) and on river systems where even moderate reductions in low summer flows could put pressure on surface water resources used for agriculture and human consumption. Even in the Northeast where water is considered relatively abundant, the current competition for water among agricultural, industrial (hydropower generation), municipal, and ecological/habitat concerns could be intensified by additional variability and shifts in streamflow timing due to global warming.

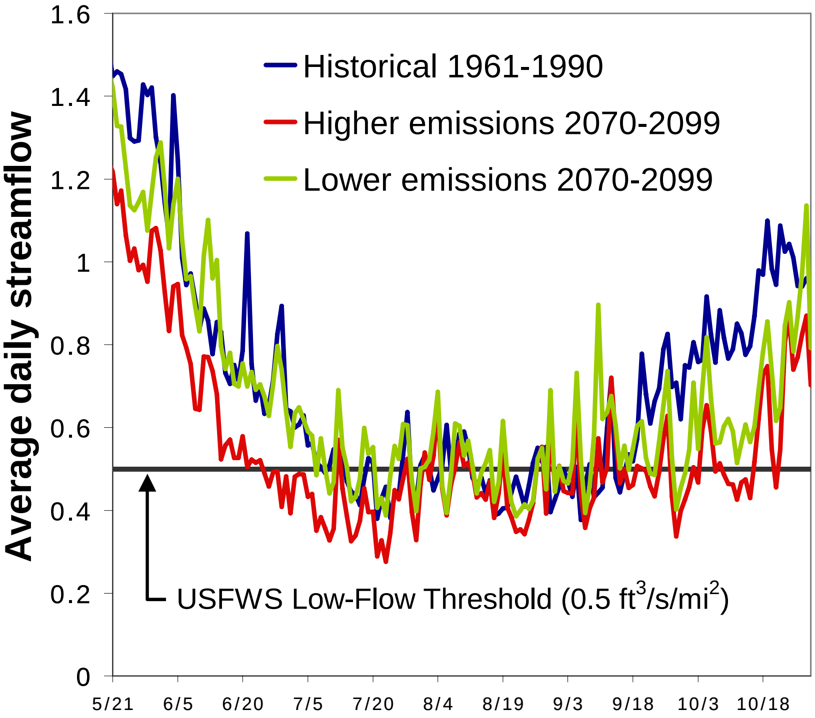


Figure 10. Projected changes in average daily streamflow from May through October (in units of cubic feet per second per square mile of drainage area).[59] The U.S. Fish and Wildlife Service (USFWS) low-flow threshold is shown for reference. Projections represent the average of the GFDL, HadCM3 and PCM models.

3.8 Winter Snow

- **The number of snow-covered days across the Northeast has already decreased, as less precipitation falls as snow and more as rain, and as warmer temperatures melt the snow more quickly.**
- **Snow density has increased as the snow has become wetter and heavier (i.e., more “slushy”).**
- **By the end of the century, the northern part of the Northeast, currently snow-covered for almost the entire winter season, could lose up to one-quarter of its snow-covered days under the lower-emissions scenario and more than half of its snow-covered days under the higher-emissions scenario.**
- **By the end of the century, the southern and western parts of the Northeast could experience as few as 5 to 10 snow-covered days in winter, compared with 10 to 45 days historically.**

Snow—welcome to some, dismaying to others—is an iconic characteristic of winter in the Northeast and forms the basis for much of our winter activity.

As with streamflow and river/lake ice, rising temperatures over the past few decades have already produced some noticeable changes in the region’s snow. For example, both observation-driven simulations for the period 1950 to 1999 and observed historical trends show that the wetness, or density, of snow has been increasing.[61] At the same time, the number of snow-covered days has decreased.[62] Four sites with the longest (1926–2004) and most complete records have seen an average decrease in snowpack depth of 16 percent and an 11 percent increase in snow density in March and April.[20]

The current number of snow-covered days per month in the Northeast[63] ranges, on average, from close to zero in southern Pennsylvania to as many as 30 in parts of northern New York, Vermont, New Hampshire, and Maine (Figure 11).

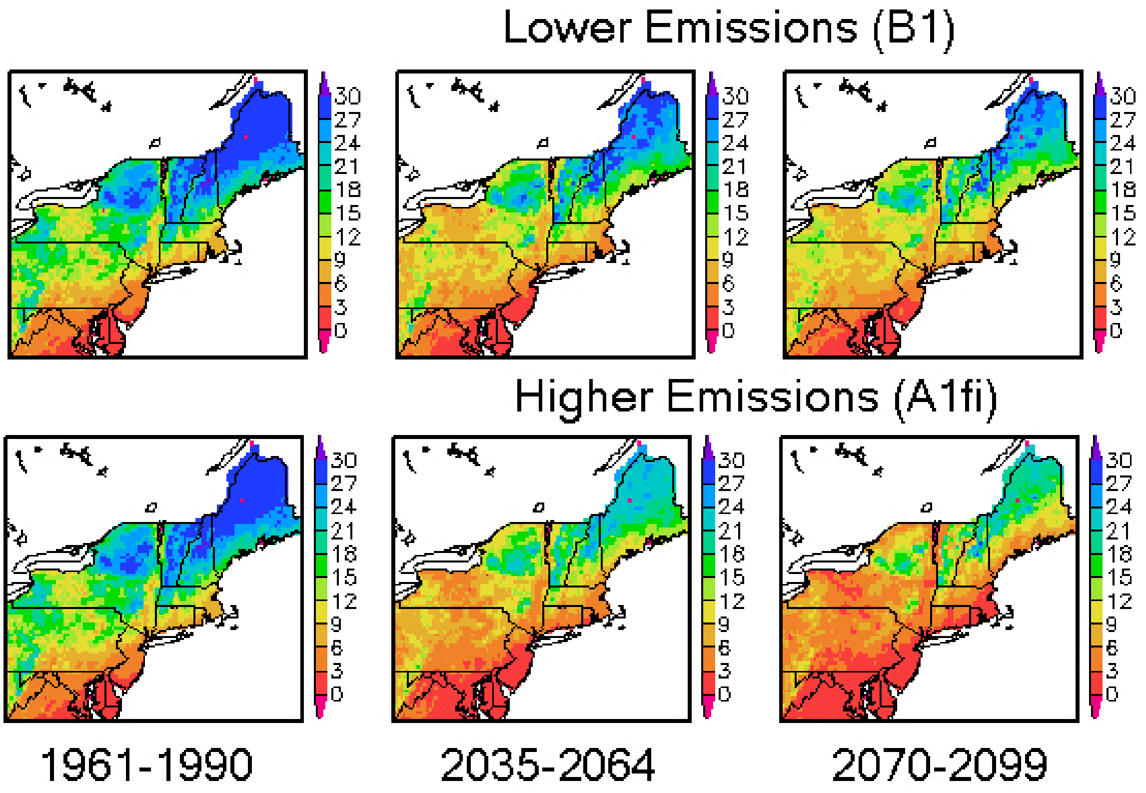


Figure 11. The number of snow-covered days per month (December–February) in the Northeast, averaged over 30-year periods. Values are the averages of the HadCM3 and PCM simulations from the VIC model.

By the end of the century, most of the Northeast could lose four to eight snow-covered days per month under the lower-emissions scenario and 10 to 15 snow-covered days per month under the higher-emissions scenario. The largest decreases may occur across the central part of the region and southern Maine, where the threshold between snow and no snow is most sensitive. The projected decrease in the number of snow-covered days in both scenarios is primarily driven by increasing temperatures, especially in February and March, which reduce the number of freezing days and thus the ratio of snow to rain. Warmer temperatures also increase the likelihood of rain falling on existing snowpack and accelerating snowmelt.

Increasing winter temperatures mean less snowfall, more winter rain, and accelerated melting of snowpack.

A reduced number of snow-covered days also means that the overall snow season is shortened. As temperatures rise, snow is projected to appear later in the winter and disappear earlier in the spring. This will likely be most evident in northern regions where snow is more prevalent. By the end of the century, both emissions scenarios show large reductions in the length of the snow season in winter/early spring: more than 25 percent (lower emissions) and 50 percent (higher emissions). These changes will affect the tourism and ski industries that depend on snow cover for recreational opportunities and related revenue,[64] as well as forests and ecosystems that rely on snow cover for protection during frosts and for soil moisture during the spring.[65]

3.9 Timing of Seasons

- **Many species of flowers and trees in the Northeast are currently blooming about four to eight days earlier than the historical average.**
- **By the end of the century, key harbingers of spring are expected to arrive one to two weeks earlier under a lower-emissions scenario and almost three weeks earlier under a higher-emissions scenario.**
- **The growing season in the Northeast has been getting longer by 2.5 days per decade since 1970.**
- **By the end of the century, the growing season is projected to be four weeks longer (under lower emissions) to six weeks longer (under higher emissions) compared with the 1961 to 1990 average.**
- **Summer is expected to arrive three weeks earlier in the spring and stay three weeks later in the fall under a higher-emissions scenario; under a lower-emissions scenario, it could arrive 1 to 1.5 weeks earlier in the spring and stay almost two weeks longer in the fall.**

The blooming of certain flowers and the budding of leaves on trees are both popular harbingers of spring, as well as important indicators of our changing climate. The dates at which these occur are often directly related to the accumulated cold and warm temperatures over the winter and spring seasons. The biosphere tends to respond to a buildup of temperature change, creating unique cumulative (rather than instantaneous) indicators. Thus, another method of documenting existing and future response of ecosystems to climate change is by tracking the dates at which certain species bloom or produce leaves.

Observations show that the first-flower (or first-bloom) dates for lilacs have advanced four days since the 1960s.[9] Even greater advances of six to eight days have been seen for grape vines and apple trees over the same time. Plants at Harvard University’s Arnold Arboretum flowered on average eight days earlier from 1980 to 2002 compared with 1900 to 1920.[66] In general, most documented dates related to flora and fauna appearances in the Northeast are occurring earlier.

We used additional models to study historical and projected changes in two key dates: (1) **first-leaf date**, an early spring date related to the general onset of growth in grasses and shrubs, and (2) **first-bloom date**, a late spring date when flowers in three indicator species start to open, which is related to the general onset of growth in dominant forest vegetation.[67] The first-leaf date is particularly important since it often displays the strongest response to temperature change, and is crucial for assessing processes related to the start and duration of the growing season.[10]

First-leaf dates have advanced two days per decade from 1960 to 2001, while first-bloom dates have moved more than a day earlier each decade. Comprehensive analysis of European phenological data finds that similar trends in a far broader set of species are attributable to increasing temperatures.[68] Model simulations show a consistent trend toward earlier spring dates in the future, with changes of more than two days per decade for first-leaf and first-bloom dates under a higher-emissions scenario—or almost three weeks earlier by the end of the century. Changes under a lower-emissions scenario are smaller: roughly one day per decade, or one to two weeks earlier by the end of the century (Table 2).

Earlier spring emergence of plant species throughout the Northeast will change the character of the region. This trend also has the potential to disturb phenological relationships (i.e., periodic biological phenomena linked to climatic conditions) and migratory cycles. For example, if bird species whose seasonal migration is triggered by length of day arrive at their destination out of synch with tree and insect species that respond to regional temperature changes, the birds may not find sufficient food.

Another indicator of seasonality is the arrival and departure of summer. Here, we define the beginning and end of summer by the average number of **growing degree days** (defined as the number of days on which temperatures exceed 65°F, multiplied by how many degrees over 65°F the daily maximum temperature is for that day) that accumulate by June 1 (marking the beginning of summer) and September 1 (marking the end of summer) during the years 1961 to 1990.

By mid-century, summer is projected to arrive in the Northeast an average of six days earlier under a lower-emissions scenario and 11 days earlier under a higher-emissions scenario. It is also projected to extend longer into the fall—10 days under a lower-emissions scenario and 16 days under a higher-emissions scenario. By the end of the century, even greater changes are projected, with summers beginning nine days earlier under a lower-emissions scenario and 21 days earlier under a higher-emissions scenario. Similarly, summer is projected to last even longer into fall—12 days under a lower-emissions scenario and more than three weeks under a higher-emissions scenario.

A third important indicator of seasonality in the Northeast is the length of the growing season. Here, we define the growing season as the length of time between the last spring freeze of the year and the first freeze of the next autumn (when daily minimum temperatures drop to or below 28°F). Sustained temperatures of 28°F, or 4°F below freezing, define a "hard frost" in which plants are likely to be killed.

In the Northeast, the growing (or frost-free) season typically lasts about half the year, or 185 days. From 1915 to 2003, the length of the growing season has been increasing an average of 0.7 day per decade. From 1970 to 2000, the trend has accelerated to an increase of 2.4 days per decade. While first-freeze dates in fall are getting somewhat later, the observed increase in growing season length is being driven primarily by last-freeze dates occurring earlier in the spring.[11]

	2035-2064		**2070-2099**	
	Lower emissions	**Higher emissions**	**Lower emissions**	**Higher emissions**
Onset of summer	-6	-11	-9	-21
End of summer	+10	+16	+12	+23
First frost (fall)	+1	+16	+6	+20
Last frost (spring)	-8	-14	-16	-23
Length of growing season	+12	+27	+29	+43
First leaf (spring)	-3	-5	-7	-15
First bloom (spring)	-4	-6	-6	-15

Table 2. Projected changes (in days) in key indicators related to plant growth in the Northeast, as simulated for a lower- and higher-emissions scenario.

By mid-century, the growing season is projected to be two to four weeks longer. By the end of the century (2080–2099), the growing season may be an average of four weeks longer under a lower-emissions scenario and six weeks longer under a higher-emissions scenario.

An extended growing season would seem to favor the farmer, but farming in the Northeast is also limited by water availability. As noted in sections 3.6 and 3.7, reduced summer streamflow and increased risk of drought may limit water supply in summer months.

3.10 Ocean Temperatures and Sea-Level Rise

- **Sea surface temperatures off the Northeast's coast increased by 1°F over the last century.**
- **By the end of the century, these temperatures are projected to increase 5°F under the lower-emissions scenario and up to 8°F under the higher-emissions scenario.**
- **As global ocean temperatures rise and ice sheets and glaciers melt, sea levels will continue to rise.**
- **By the end of the century, sea levels are conservatively expected to rise 4 to 21 inches under the lower-emissions scenario and 8 to 33 inches under the higher-emissions scenario, with the potential for additional increases due to more rapid melting of major polar ice sheets.**

The oceans are an important factor in the Northeast's climate, strongly influencing the region's north-to-south and east-to-west gradients in air temperature. Sea surface temperatures (SSTs) have already increased, as evidenced by the 100-year record for Boothbay Harbor, ME (Figure 12). Regional SSTs have increased almost 2°F since 1970 and are projected to continue increasing, though at a slightly slower rate than regional air temperatures because of the oceans' moderating influence—by the end of the century, SSTs could rise 6 to 8°F under the higher-emissions scenario and 4 to 5°F under the lower-emissions scenario. These increases may adversely affect native marine species in the Northeast, including commercially important species whose southernmost range is limited by warm temperatures. Warmer SSTs may also increase opportunities for invasive species whose populations are currently limited by the colder water temperatures off the Northeast's coast.

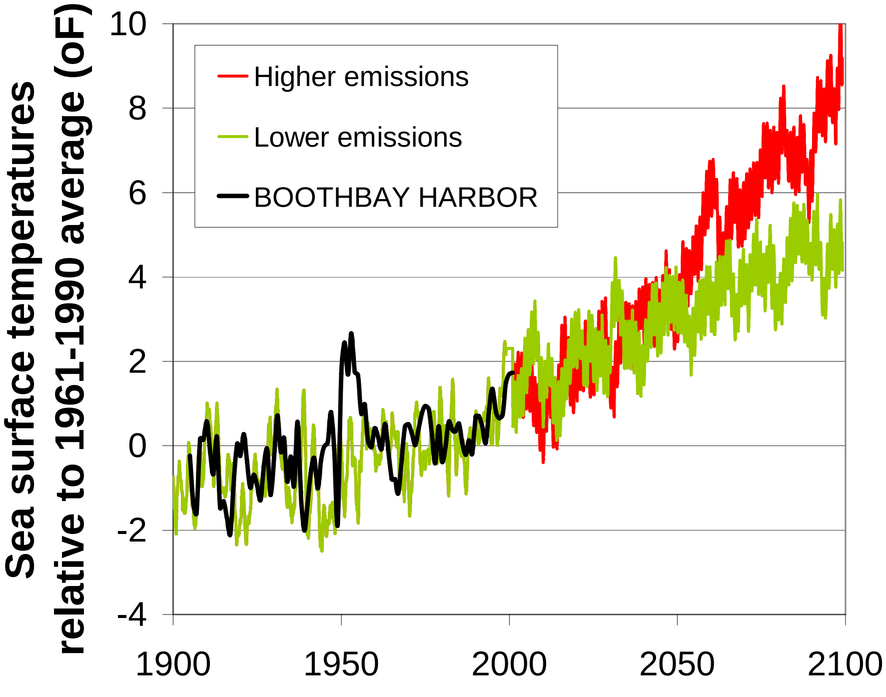


Figure 12. Observed and model-based changes in sea surface temperatures (in °F) relative to the 1961-1990 average. Observations were taken at Boothbay Harbor, ME. Climate model averages based on GFDL, HadCM3 and PCM are for the Northeast coast under the higher- and lower-emissions scenarios.

Globally, sea level is already rising. This global sea-level rise (SLR) has two components, both related to temperature increases. The first is thermal expansion of sea water as it warms; and the second is an increase in the amount of water in the ocean basins resulting from the addition of fresh water as continental ice sheets and glaciers melt. While SLR is one of the most certain impacts of global warming, there is still considerable uncertainty in the estimates of the relative contributions of these two components to observed and projected global mean changes in sea level.

By mid-century, projected global SLR ranges from 2.5 to 13 inches, with no discernible differences between emissions scenarios. By the end of the century, however, sea levels are projected to rise 4 to 21 inches under the lower-emissions scenario and 8 to 33 inches under the higher-emissions scenario (Figure 13), putting low-lying coastal areas of the Northeast at increasing risk of erosion as well as flooding during storms.

Rising sea level and warming ocean temperatures may adversely affect coastal and marine resources in the Northeast.

These model projections of SLR may be quite conservative, particularly for the lower-emissions scenarios. Recently observed rates of continental ice melt[19,69,70] (particularly for Greenland[71,72,73,74] and West Antarctica[75,76,77,78,79]) and sea level rise are greater than those used to generate these estimates of sea level rise over the coming century. Of even greater long-term concern is the risk that major Greenland and West Antarctic ice sheets could become destabilized at temperatures projected for this century, leading to long-term average increases in global sea-level rise of more than 20 feet over the next few centuries. Such changes would have catastrophic consequences for low-lying coastal regions, including those in the Northeast.[80]

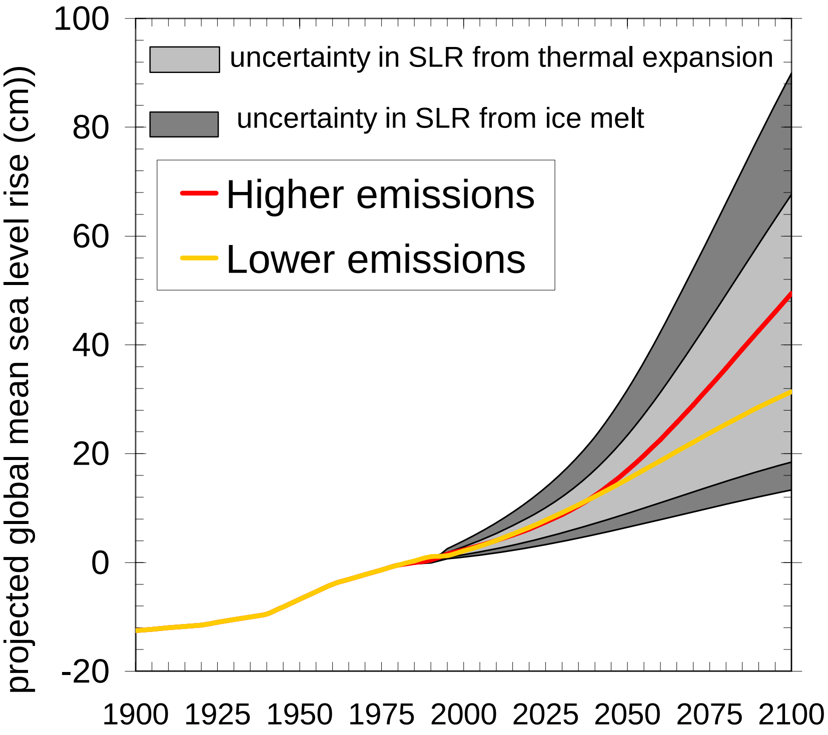


Figure 13. Model-simulated sea-level rise (SLR) under the higher- and lower-emissions scenarios.[90]

CHAPTER 4

CONFRONTING CLIMATE CHANGE IN THE NORTHEAST

It is clear from observational temperature records as well as a host of indirect indicators such as the length of the growing season, flowering and leaf-out dates, snow melt and streamflow timing, that the Northeast climate is already changing in ways consistent with global warming. It is also clear from the projections presented in this analysis that a much greater degree of change can be expected over the coming century, particularly under a scenario of continued high emissions of heat-trapping gases.

Changes in air and sea surface temperature, sea levels, periods of extreme heat, extreme precipitation, drought, and other features of the Northeast's climate will have a considerable impact on the region's character, its major ecosystems, and climate-sensitive sectors of its economy. A subsequent report by the Northeast Climate Impacts Assessment will explore the implications of these changes for agriculture, marine fisheries, human health, coastal areas, winter recreation, and natural ecosystems across the region.

Although some uncertainties in climate projections still remain to be resolved, particularly those related to the fine-scale spatial distribution of changes over a climatically diverse region such as the northeastern United States, the greatest uncertainty in future climate is the extent to which society resolves to reduce further emissions of heat-trapping gases. Model-simulated trends in temperature and precipitation-related indicators presented here are consistent with both observed historical trends as well as a broad range of model simulations of the future. These provide confidence in the direction and range of our regional projections.

BOX 7: ACHIEVING LONG-TERM EMISSIONS REDUCTION TARGETS IN THE NORTHEAST

In August 2001, in the first action of its kind in North America, the New England Governors and Eastern Canadian Premiers (NEG/ECP) signed an agreement committing themselves to a comprehensive regional Climate Change Action Plan. The plan includes a long-term goal of reducing regional emissions of heat-trapping gases 75 to 85 percent below 2001 levels. California has since adopted a similar goal of reducing its heat-trapping emissions 80 percent below 1990 levels by 2050.

Suppose that the Northeast and the rest of the industrialized world agreed to reduce emissions 80 percent below 2000 levels by 2050—equivalent to an average annual reduction of roughly three percent. Suppose further that emissions from developing nations were consistent with the lower-emissions scenario used in this analysis. The world would be on track to keep temperatures from rising above those projected in our lower-emissions scenario[90,91] Reduction goals such as the one set by the NEG/ECP could help spur the innovation necessary to lead the world to this low-emissions future.

Because global warming is already upon us, and some additional warming is inevitable, it is essential to prepare to adapt to the changes that cannot be avoided.[81] However, serious actions to reduce emissions have the potential to keep temperatures from rising to levels at or even below those presented for the lower-emissions scenario (B1) used in this study (Box 7). The greater the extent of the emissions reductions we are able to achieve, the greater the ability of ecosystems, human communities, and economic sectors to adapt to the coming climate. Our findings make clear that the emissions choices we make here in the Northeast and globally, now and over the next several years, will have dramatic implications for the climate our children and grandchildren will inherit.

The greatest uncertainty in the future climate is the extent to which society resolves to reduce further emissions of heat-trapping gases. The choices we make now will dramatically affect the climate that our children and grandchildren inherit.

Of course, actions to reduce emissions in the Northeast alone will not be sufficient to avoid dangerous climate change. But as both a global leader in technology, finance, and innovation and a major source of heat-trapping emissions, the Northeast is well positioned to help drive national and international progress in reducing emissions. Indeed, many individuals, communities, businesses, policy makers, and state governments across the region are already taking innovative steps to do just that.[82,83] By reducing emissions today, we have an opportunity to avoid the most severe consequences of global warming and provide a safe climate for future generations.

References

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1 Hayhoe, K., C.P. Wake, B. Anderson, J. Bradbury, A. DeGaetano, A. Hertel, X-Z Liang, E. Maurer, D. Wuebbles and J. Zhu. Quantifying the regional impacts of global climate change: Evaluating AOGCM simulations of past and future trends in temperature, precipitation, and atmospheric circulation in the Northeast U.S. In review at the *Bulletin of the American Meteorological Society*.

2 Hayhoe, K., C.P. Wake, T.G. Huntington, L. Luo, M.D. Schwartz, J. Sheffield, E.F. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe. 2006. Past and future changes in climate and hydrological indicators in the U.S. Northeast. *Climate Dynamic*s. DOI 10.1007/s00382-006-0187-8

3 Ludlum, D.M. 1976. *The country journal: Northeast weather book*. Houghton Mifflin: Boston, MA.

4 Zielinski, G.A., and B.D. Keim. 2003. *New England weather, New England climate*. University Press of New England: Hanover, NH.

5 Taylor, K.E., et al. 2000. Analysis of forcing, response, and feedbacks in a paleoclimate modeling experiment. Paleoclimate Modelling Intercomparison Project (PMIP), edited by P. Braconnot. 1007:43–49.

6 This report focuses on climate change associated with global warming. We use the UN Framework Convention on Climate Change definition of climate change: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.”

7 Augustin, L., et al. 2004. Eight glacial cycles from an Antarctic ice core. *Nature* 429:623–628.

8 DeGaetano, A.T., and R.J. Allen. 2002. Trends in twentieth-century temperature extremes across the United States. *Journal of Climate* 15:3188–3205.

9 Wake, C.P., and A. Markham. 2005. Indicators of climate change in the Northeast 2005. Clean Air—Cool Planet: Portsmouth, NH.

10 Wolfe, D.W., et al. 2005. Climate change and shifts in spring phenology of three horticultural woody perennials in the northeastern United States. *International Journal of Biometeorology* 49:303–309.

11 Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Global Change Biology* 12:343–351.

12 Gibbs, J.P., and A.R. Breisch. 2001. Climate warming and calling phenology of frogs near Ithaca, NY, 1900–1999. *Conservation Biology* 15:1175–1178.

13 Huntington, T.G., G.A. Hodgkins, and R.W. Dudley. 2003. Historical trend in river ice thickness and coherence in hydroclimatological trends in Maine. *Climatic Change* 61:217–236.

14 Juanes, F., S. Gephard, and K.F. Beland. 2004. Long-term changes in migration timing of adult Atlantic salmon (*Salmo salar*) at the southern edge of the species distribution. *Canadian Journal of Fisheries and Aquatic Sciences* 61:2392–2400.

15 As measured by the number of 48-hour periods with more than two inches of rain.

16 Hodgkins, G.A., I.C. James II, and T.G. Huntington. 2002. Historical changes in lake ice-out dates as indicators of climate change in New England, 1850–2000. *International Journal of Climatology* 22:1819–1827.

17 Hodgkins, G.A., R.W. Dudley, and T.G. Huntington. 2003. Changes in the timing of high river flows in New England over the 20th century. *Journal of Hydrology* 278:244–252.

18 Huntington, T.G., G.A. Hodgkins, B.D. Keim, and R.W. Dudley. 2004. Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000). *Journal of Climate* 17:2626–2636.

---

19 Huybrechts, P., et al. 2001. Changes in sea level rise. In *Climate change 2001: The scientific basis.* Intergovernmental Panel on Climate Change (IPCC) Working Group I.

20 Hodgkins, G.A. and R.W. Dudley. 2006. Changes in late-winter snowpack depth, water equivalent, and density in Maine, 1926–2004. *Hydrological Processes* 20:741–751.

21 New England Regional Assessment Group. 2001. *Preparing for a changing climate: The potential consequences of climate variability and change*. *New England regional overview*. U.S. Global Change Research Program, University of New Hampshire.

22 Karl, T.R., C.N. Williams, Jr., F.T. Quinlan, and T.A. Boden. 1990. United States Historical Climatology Network (HCN) serial temperature and precipitation data. Oak Ridge, TN: Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

23 Easterling, D.R., et al. 1999. United States Historical Climatology Network (HCN) daily temperature, precipitation, and snow data for 1871–1997. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

24 Williams, Jr., C.N., et al. 2005. United States Historical Climatology Network (HCN) monthly temperature and precipitation data. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

25 Selection of weather stations is based on criteria such as limited number of station changes and numerous quality assurances and adjustments to monthly data) to remove various biases. These adjustments take into consideration extreme outliers in the records and potential biases that may be caused by changes in the time of observation, in the instruments used, in the location of the stations, and by the urban heat island effect.

26 Karl, T.R., H.F. Diaz, and G. Kukla. 1988. Urbanization: Its detection and effect in the United States climate record. *Journal of Climate* 1:1099–1123.

27 Karl, T.R., and C.N. Williams, Jr. 1987. An approach to adjusting climatological time series for discontinuous inhomogeneities. *Journal of Applied Climate and Meteorology* 26:1744–1763.

28 Quayle, R.G., et al. 1991. Effects of recent thermometer changes in the cooperative station network. *Bulletin of the American Meteorological Society* 72:1718–1724.

29 Karl, T.R., et al. 1986. A model to estimate the time of observation bias with monthly mean maximum, minimum, and mean temperatures for the United States. *Journal of Applied Climate and Meteorology* 25:145–160.

30 Schwartz, M.D. 1997. Spring index models: An approach to connecting satellite and surface phenology. In *Phenology in Seasonal Climates I*, edited by H. Lieth and M.D. Schwartz. The Netherlands: Backhuys Publishers, 23–38.

31 Schwartz, M.D., R. Ahas, and A. Aasa. 2006. Onset of spring starting earlier across the Northern Hemisphere. *Global Change Biology* 12:343–351.

32 Liang, X., et al. 1994. A simple hydrologically based model of land surface water and energy fluxes for GSMs. *Journal of Geophysical Research* 14:415–14,428.

33 Liang, X., E.F. Wood, and D.P. Lettenmaier. 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications. *Global and Planetary Change* 13:195–206.

34 Cherkauer, K.A., L.C. Bowling, and D.P. Lettenmaier. 2002. Variable Infiltration Capacity (VIC) cold land process model updates. *Global and Planetary Change* 38:151–159.

35 Maurer, E.P., G.M. O'Donnell, D.P. Lettenmaier, and J.O. Roads. 2001. Evaluation of the land surface water budget in NCEP/NCAR and NCEP/DOE reanalyses using an off-line hydrologic model. *Journal of Geophysical Research* 106:17841–17862.

36 Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *Journal of Climate* 15:3237–3251.

---

37 The VIC model does not include groundwater, so it is unable to estimate climate change effects on the water table component of water resources.

38 Nakićenović, N., et al. 2000. *IPCC special report on emissions scenarios*. Cambridge, UK, and New York, NY: Cambridge University Press.

39 Hayhoe et al. (see references 1 and 2) examined a total of 35 simulations from five additional models with climate sensitivities covering the full IPCC range of climate sensitivity, including CCSM3, CGCM3, GISS A-O, ECHAM5, and MIROC-med.

40 Liang, X.-Z., L. Li, A. Dai, and K.E. Kunkel. 2004. Regional climate model simulation of summer precipitation diurnal cycle over the United States. *Geophysical Research Letters* 31:L24208, 10.1029/2004GL021054.

41 Liang, X.Z., L. Li, K.E. Kunkel, M.F. Ting, and J.X.L. Wang. 2004. Regional climate model simulation of U.S. precipitation during 1982–2002. Part 1: Annual cycle. *Journal of Climate* 17:3510–3528.

42 Zhu, J., and X.Z. Liang. 2005. Regional climate model simulation of U.S. soil temperature and moisture during 1982–2002. *Journal of Geophysical Research* 110:D24110, doi:10.1029/2005JD006472.

43 This method of statistical downscaling involves interpolation onto a regular grid or for individual weather stations.

44 Dudhia, J.D., et al. 2000. PSU/NCAR Mesoscale modeling system tutorial class notes and users guide: MM5 modeling system version 3.

45 Liang, X.Z., K.E. Kunkel, and A.N. Samel. 2001. Development of a regional climate model for U.S. Midwest applications. Part I: Sensitivity to buffer zone treatment. *Journal of Climate* 14:4363–4378.

46 Wood, A.W., E.P. Maurer, A. Kumar, and D.P. Lettenmaier. 2002. Long-range experimental hydrologic forecasting for the eastern United States. *Journal of Geophysical Research* 107:4429.

47 Dettinger, M.D. 2005. From climate change spaghetti to climate change distributions. *Proceedings of the National Academy of Sciences* 101:12422–12427.

48 The average rate of temperature increase from 1900 to 1999 is estimated at +0.08±0.01oC (see references 1 and 2) taking into account the uncertainty in estimating a linear trend from data with significant inter-annual variability.

49 Energy Information Administration. 2001. *New England appliance report 2001*. Washington, DC: U.S. Department of Energy.

50 “Very hot days” are defined as the number of days per year in which temperature is equal to or greater than temperatures during the hottest five percent (or 18 hottest days) of the year as determined from the long-term record (see reference 8).

51 Leathers, D. J., A. J. Grundstein, A. W. Ellis, 2000. Growing season moisture deficits across the northeastern United States. *Climate Research*, 14, 43-55.

52 Ludlum DM (1976) *The Country Journal: Northeast Weather Book*. Houghton Mifflin, Boston.

53 Keim, B.D., M.R. Fischer, and A.M. Wilson. 2005. Are there spurious precipitation trends in the United States Climate Division database? *Geophysical Research Letters* 32:L04702, DOI 10.1029/2004GL021985.

54 Note that these simulations do not include the 1960s drought, since they are not based on observed temperature and precipitation. Historical drought estimates were generated using the Variable Infiltration Capacity (VIC) model, driven by historical climate model simulations, as discussed in Chapter 2.

55 Brown, T.J., B.L. Hall, and A.L. Westerling. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: An applications perspective. *Climatic Change* 62:365–388.

56 Amiro, B.D., B.J. Stocks, M.E. Alexander, M.D. Flannigan, and B.M. Wotton. 2001. Fire, climate change, carbon and fuel management in the Canadian boreal forest. *International Journal of Wildland Fire* 10:405–413.

---

[57] Hodgkins, G.A., R.W. Dudley, and T.G. Huntington. 2005. Changes in the number and timing of ice-affected flow days on New England rivers, 1930–2000. *Climatic Change* 71:319–340.

[58] Projections of future changes in streamflow rely on VIC hydrological modeling of streamflow in 51 unmanaged streams throughout the Northeast (i.e., where the streams are not affected by human intervention), driven by climate model simulations of changes in temperature and precipitation under the higher- and lower-emissions scenarios.

[59] U.S. Fish and Wildlife Service. 1981. Interim regional policy for New England stream flow recommendations: Region I. Concord, NH: U.S. Fish and Wildlife Service: Concord.

[60] Beltaos, S., and T.D. Prowse. 2002. Effects of climate on mid-winter ice jams. *Hydrologic Processes* 16:789–804.

[61] Observation-driven VIC simulations for 1950 to 1999 show that snow water equivalence (SWE)—essentially the amount of water that would be left if the snow in a given location were melted—has increased by 0.05 mm per decade.

[62] Observation-driven VIC simulations for 1950 to 1999 show that the number of snow days has actually decreased by 0.07 day/month decade-1.

[63] A snow-covered day is defined as one with mean snow water equivalent (SWE) greater than 0.2 inch. In actual snow depth, this is equivalent to 0.6 inch or more. The analysis of winter snow-covered days was done using the VIC simulations driven by AOGCM-based temperature and precipitation.

[64] Hamilton, L.C., D. Rohall, B. Brown, G. Hayward, and B. Keim. 2003. Warming winters and New Hampshire’s lost ski areas: An integrated case study. *International Journal of Society and Social Policy* 23:52–73.

[65] Perfect, E., R.D. Miller, and B. Burton. 1987. Root morphology and vigor effects on winter heaving of established alfalfa. *Agronomy Journal* 79:1061–1067.

[66] Primack, D., C. Imbres, R.B. Primack, A. Miller-Rushing, and P. del Tredici. 2004. Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. *American Journal of Botany* 91:1260–1264.

[67] To study observed and model-based changes in first leaf and bloom dates, the Spring Indices (SI) models were used.

[68] Sparks, T.H., et al. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology* 12:1–8.

[69] Holgate, S.J., and P.L. Woodworth. 2004. Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters* 31:L07305, doi:10.1029/2004GL019626.

[70] Warrick, R.A., E.M. Barrow, and T.M.L. Wigley (editors). 1993. *Climate and sea-level change: Observations, projections and implications*. Cambridge, UK: Cambridge University Press.

[71] Rignot, E., and P. Kanagaratnam. 2006. Changes in the velocity structure of the Greenland Ice Sheet. *Science* 311:986–990.

[72] Zwally, H.J., et al. 2005. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002. *Journal of Glaciology* 51:509–527.

[73] Dowdesdell, J.A. 2006. Greenland ice sheet and global sea level rise. *Science* 311:963–964.

[74] Krabill, W., et al. 2004. Greenland ice sheet: Increased coastal thinning. *Geophysical Research Letters* 31:L24402; 10.1029/2004GL02153.

[75] Chen, J.L., C.R. Wilson, D.D. Blankenship, and B.D. Tapley. 2006. Antarctic mass rates from GRACE. *Geophysical Research Letters* 33:L11502, doi:10.1029/2006GL026369.

[76] Thomas, R., et al. 2004. Accelerated sea-level rise from West Antarctica. *Science* 306:255–258.

---

77 Rignot, E., and R.H. Thomas. 2002. Mass balance of polar ice sheets. *Science* 297:1502–1506.

78 Payne, A.J., et al. 2004. Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. *Geophysical Research Letters* 31:L23401; 10.1029/2004GL021284.

79 Shepherd, A., D. Wingham, and E. Rignot. 2004. Warm ocean is eroding West Antarctic ice sheet. *Geophysical Research Letters* 31:L23402; 10.1029/2004GL021106.

80 Schellnhuber, H.J., et al. (editors). 2006. *Avoiding dangerous climate change*. Cambridge, UK: Cambridge University Press.

81 Moser, S.C., R.E. Kasperson, G. Yohe, and J. Agyeman. 2006. *Adaptation to climate change in the Northeast: Opportunities, processes, constraints*. Forthcoming report of the Northeast Climate Impacts Assessment.

82 Website: *http://www.climatechoices.org/ne*

83 Moomaw, W., and L. Johnston. 2006. *Climate Change Mitigation Strategies and Policies for the Northeast United States.* Forthcoming report of the Northeast Climate Impacts Assessment.

84 International data from EIA Table H.1 in CO_2*,World carbon dioxide emissions from the consumption and flaring of fossil fuels (1990–2003)*, July 11, 2005. U.S. data from EIA *Emissions of greenhouse gases in the United States*, 2004. DOE/EIA-0573(2004). Washington, DC: U.S. Department of Energy.

85 Wood, R.A., et al. 2006. Towards a risk assessment for shutdown of the Atlantic thermohaline circulation. In *Avoiding dangerous climate change*, edited by H.J. Schellnhuber et al. Cambridge, UK: Cambridge University Press.

86 Trenberth, K.E. 2005. Uncertainty in hurricanes and global warming. *Science* 308:1753–1754.

87 Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686–688.

88 Webster, P.J., et al. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846.

89 Hodgkins, G.A., R.W. Dudley, and T.G. Huntington. 2005. Summer low flows in New England over the 20th century. *American Water Resources Association Journal* 41:403-412.

90 Cayan, D. et al. 2006. *Scenarios of climate change in California: An overview.* Sacramento, CA: California Climate Change Center.

91 Emissions corresponding to the B1 scenario or below were calculated as follows: (1) Organisation for Economic Co-operation and Development (OECD) population and total emissions were based on SRES B1 IMAGE runs38; OECD total emissions in 2000 were 3.2 GtC. (2) Eighty percent below this value is 640 MtC. (3) Total global emissions was calculated by adding 640 MtC to the total emissions for non-OECD countries as projected by SRES B1. This value is approximately 10 GtC. (4) This 10 GtC/yr was compared to the global emissions projected in the B1 scenario (approximately 11 GtC/yr). Beyond 2050, global emissions will need to decrease substantially below 10 GtC/yr to stay on or below the B1 pathway. The SRES B1 pathway assumes global emissions decrease to 4.23 GtC/yr by 2100.

About NECIA

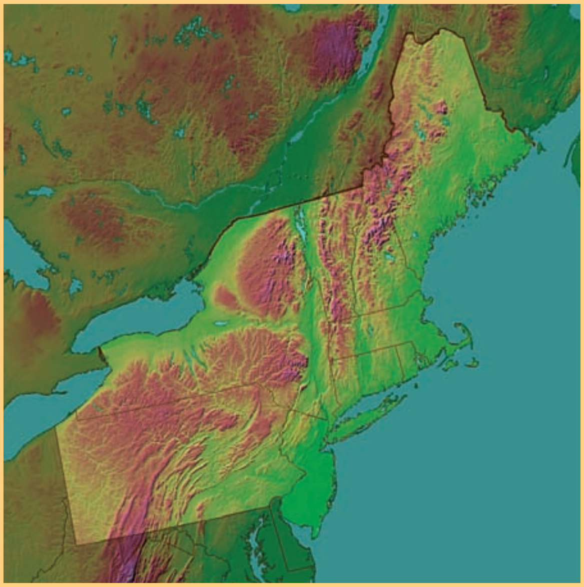
The Northeast Climate Impacts Assessment (NECIA) is a collaboration between the Union of Concerned Scientists (UCS) and a team of independent experts to develop and communicate a new assessment of climate change and associated impacts on key climate-sensitive sectors in the northeastern United States. The goal of the assessment is to combine state-of-the-art analyses with effective outreach to provide opinion leaders, policy makers, and the public with the best available science upon which to base informed choices about climate change mitigation and adaptation.

For more information visit the NECIA website at *http://www.northeastclimateimpacts.org*.

About UCS

The Union of Concerned Scientists (UCS) is the leading science-based nonprofit working for a healthy environment and a safer world. For more information visit the UCS website at *http://www.ucsusa.org*.

Climate Change in the U.S. Northeast



A Report of the Northeast Climate Impacts Assessment

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