Indicators of Climate Change in the Northeast 2005

Clean Air - Cool Planet

and

Cameron P. Wake

The Climate Change Research Center, University of New Hampshire

Indicators of Climate Change in the Northeast 2005

Clean Air - Cool Planet

and

Cameron P. Wake

The Climate Change Research Center,
University of New Hampshire

Acknowledgements

J. Bloomfield, S. Droege, L. Goss, S. Hamburg, B. Harrington, J. Kelley, K. Kimball, S. Moser, B. Rock, C. Rogers, H. Walker, W. White and N. Willard all contributed significantly to the concept for this project through their participation in a Northeast climate indicators workshop convened by Clean Air-Cool Planet in Portsmouth, NH in January 2001. Dr. Tim Sparks of the Center for Ecology and Hydrology at Monks Wood, England, and a founder of the UK Phenology Network helped to plan that workshop and provided the inspiration for this report.

We would like to acknowledge the hard work of UNH graduate student Adam Wilson in assembling and analyzing the data for many of these indicators; the work of Professor David Wolfe in the Horticulture Department at Cornell University for authoring the section on phenology (bloom dates), along with his collaborators A. Lakso and Y. Otsuki at Cornell University and M. Schwartz at University of Wisconsin-Milwaukee; and UNH graduate student Gerry Hornok for data analysis and preparation of select graphics. T. Huntington and B. Keim also provided material incorporated into this report; we are indebted to K. Colburn at NESCAUM, N. Anderson at the Maine Lung Association, and others for their careful review. Most of the photographs are by Jerry and Marcy Monkman at EcoPhotography.

A downloadable Adobe Acrobat file is available at http://cleanair-coolplanet.org/information/pdf/indicators.pdf

Table of Contents

Introduction

Climate changes. It always has and always will. What is unique in modern times is that human activities are now a significant factor causing climate to change. This is evident in the recent rise in key greenhouse gases, such as carbon dioxide (CO_2), in the atmosphere, and in the recent increase in global temperatures in the lower atmosphere and in the surface ocean.

The evidence presented in this report clearly illustrates that climate in New England is also changing. Over the past 100 years, and especially the last 30 years, all of the climate change indicators for the region reveal a warming trend. While at this point we cannot prove conclusively that this regionl warming is due to human actions, the warming is fully consistent with what we would expect from global warming caused by increasing greenhouse gas concentrations.

There is no question that human induced climate change is a phenomenon that humans will have to deal with in the coming decades. The good news is that, because we are the primary source of pollution that is likely causing our atmosphere and oceans to warm, we can also do something about it by changing specific policies and behaviors.

It is our hope that by presenting this information in a succinct format, more people will understand the nature and scope of the problem and, therefore, be willing to make the changes necessary.

For more information about the science of global warming and the practicality of solutions, please visit the Clean Air – Cool Planet (www.cleanair-coolplanet.org) and the University of New Hampshire – Climate Education Initiative (www.sustainableunh.unh.edu/climate_ed/) web sites.

Adam Markham
Executive Director,
Clean Air - Cool Planet

Cameron Wake
Research Associate Professor,
University of New Hampshire
Climate Change Research Center

March, 2005

Average Annual Temperature 1899 through 2000

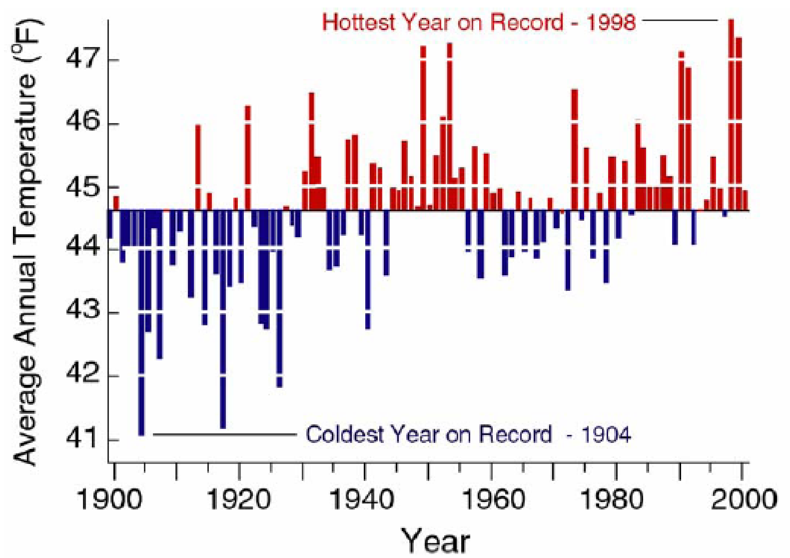


Figure 1: Average annual temperature for the Northeast from 1899 through 2000. This time-series is an areally weighted average of temperature records from 56 stations in the region.

Indicator Overview

Temperature is one of most frequently used indicators of climate change and has been recorded at numerous stations in the Northeast United States since 1899. It is possible to analyze the region's changing climate over the past century with this long-term instrumental record of average monthly temperature.[1]

Regional Importance

Weather in the Northeast is as diverse as it is variable. Mark Twain captured the essence of the region's climate when he stated "Yes, one of the brightest gems in the New England weather is the dazzling uncertainty of it." [2] Changes in temperature affect numerous aspects of our daily lives and our region's economy, including the ski industry, tourism, transportation, agriculture, emergency management, health, and fuel consumption for heating and cooling. Temperature is the determinant factor in the length of the growing season, it influences the amount of winter snowfall, and the comfort of a summer afternoon.

The National Oceanographic and Atmospheric Administration's National Climatic Data Center has maintained temperature records from various stations across the country. In the Northeast there are 56 stations that have been continuously operating since 1899, providing the best record of temperature variations for the region.

Sensitivity to Climate and Other Factors

Global surface temperatures reflect the interaction of several aspects of Earth's climate system, including the amount of incoming sunlight, volcanic activity, land use changes, the ability of the planet to reflect light, the exchange of energy between the ocean and the atmosphere, and the concentration of greenhouse gases and other pollutants. Since the 1860s, average global temperature has increased by about 1.1° F, likely due to increasing greenhouse gases from human activities.[3]

On a regional scale, the average temperature of the Northeast is sensitive to the same global influences, but also local aspects of the climatic system, including the locations of weather systems, storm tracks, fluctuations in the jet stream, topography, and changing ocean currents and sea surface temperatures.

Indicator Trend

Annual average temperature for the Northeast shows considerable variability on annual and longer time scales (Figure 1). For example, note the cooler years in 1904, 1917, and 1926 and the relatively warm years in 1949, 1953, 1990, and 1998. Extended warm periods are also evident, such as the early 1930s and the late

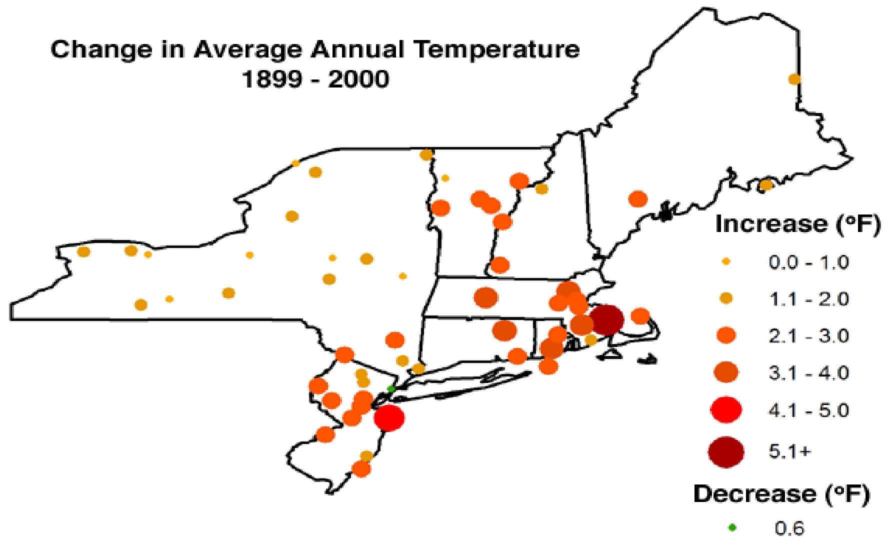


Figure 2: Map illustrating the linear trend in annual temperature (°F) from 1899-2000 for Northeast meteorological data. Cooling trends are shown with blue dots, while warming trends are shown with red dots. The change was estimated from a linear regression ofannual average temperature for each station.

The average annual Northeast temperature has increased 1.8° F since 1899.

1940s. Cool periods occurred at the beginning of the century and the late 1960s.

There is also a trend towards warmer temperatures over the period of record. Based on the linear trend, the Northeast's average annual temperature has increased by about 1.8° F since 1899. The 1990s were the warmest decade on record. Over the last 30 years, annual average temperatures have increased 1.4° F. The meteorological station data allows for an investigation of temperature change on a finer scale. As illustrated on the map of the Northeast, all of the stations but one showed an increase in temperature (Figure 2). Note that the coastal regions of Massachusetts, New Jersey, New York, Connecticut and Maine have all warmed more than the Northeast average. The monthly data also allows for the investigation of seasonal trends in temperature. Over the last 100 years, winter (December to February) temperatures show the greatest seasonal rate of warming (2.8° F). Even more striking is the 4.4°F increase in winter temperatures over the last 30 years (1970-2000) (Figure 3).

If emissions of greenhouse gases continue to increase, it is likely that the Northeast's temperature will also continue to rise. However, due to the uncertainties of future greenhouse gas emissions and the complexity of the climate system, it is impossible to predict what the exact consequences will be for the region. Despite the long-term temperature increase we are experiencing, Twain would assent that there will continue to be significant year-to-year variability.

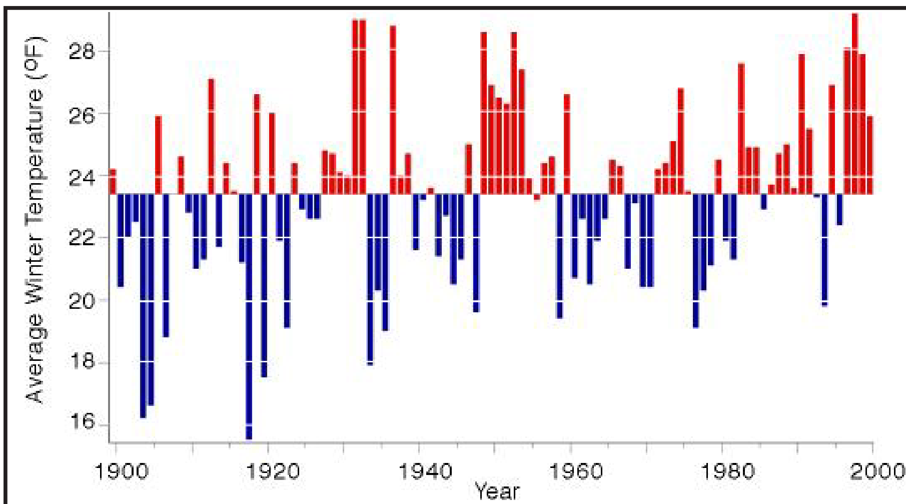


Figure 3. Average winter temperature for the Northeast, 1899 to 2000. This time-series is an areally weighted average of temperature records from 56 stations in the region.

Length of Growing Season
1874 - 2001

Indicator Overview

Length of the growing season is defined as the number of days between the last frost of spring and the first frost of winter. This period is called the growing season because it roughly marks the period during which plants, especially agricultural crops, grow most successfully.

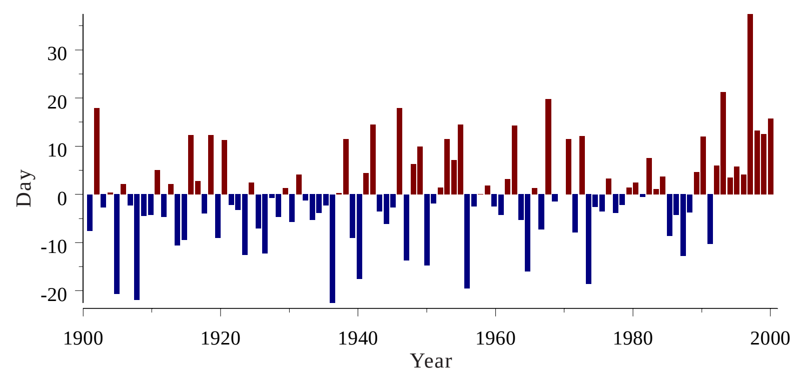


Figure 1: Average growing season anomaly at 7 stations in the Northeast, defined by the number of days between the last frost (minimum daily temperature below 32°F) and the first of the fall, 1900-2001. In the graph, zero represents 192 days, the average time between frosts. Years in blue experienced shorter than average seasons, while years in red experienced longer.

Regional Importance

The length of the growing season is important to any outdoor activity. While freezing temperatures affect all commercial, agricultural, industrial, recreational, and ecological systems, the human system most sensitive to changes in the length of the growing season is agriculture.[4]

An early fall frost may lead to crop failure and economic misfortune to the farmer. Earlier starts to the growing season may provide an opportunity to diversify crops, or to produce two or more harvests from the same plot. However, the majority of the Northeast's most competitive crops are "cool-season" crops. While it might seem that a successful response to a shorter growing season would be for farmers to switch to alternative warm-season crops, they would then have new competitors who might have advantages such as better soils and a longer growing season.[5] In either case, the length of the growing season is very important to successful agriculture in this region.

In addition, the length of the growing season is a defining characteristic of different ecosystems.[6] It is possible that a significant change in the length of the growing season could alter the ecology of the Northeast landscape.

Sensitivity to Climate and Other Factors

Growing season length is an event-driven phenomenon. An increase in the average temperature for a region does not necessarily imply an increase in the growing season, and vice versa. As the growing season is defined by the last frost of the spring and the first of the fall, it is solely dependent on specific cold weather events, rather than monthly or annual averages.

There are two types of frost events, radiation and advective frosts.[7] Energy absorbed from the sun by day radiates upward to space by night, causing the air near the surface to cool. On most nights there is enough wind to mix the warmer, upper air with the surface air and keep surface temperatures relatively warm. However, on calm, dry nights, the air near the surface radiates heat upward without mixing with it, creating very cold air at the surface — a radiation frost. This type of frost generally impacts relatively small geographic regions and occurs mostly in valleys.

Advective frosts are caused by a cold, polar airmass moving into the region. This type of frost is associated with strong winds and a well-mixed atmosphere and tends to affect large geographic areas. The most damaging frosts are combinations of these two types. First the polar airmass moves through and cools down a region, after which the winds slow down and can create ideal conditions for a radiative frost.

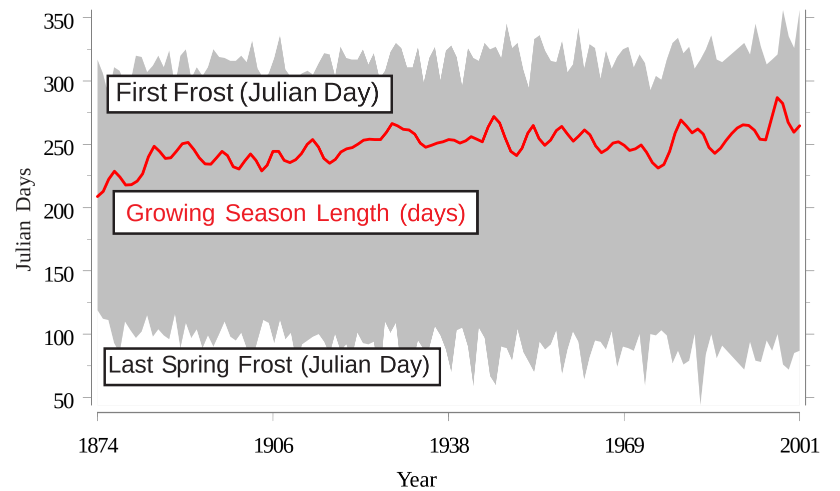


Figure 2: Growing season length and freeze dates at Atlantic City, NJ, defined by the number of days between the last frost (minimum daily temperature below 32 °F) and the first of the fall from 1874-2001. The red line represents the annual length of the growing season, while the gray area represents the date of the last spring (bottom) and first fall (top) frost, by Julian day. Over this time period, the growing season has lengthened by 38 days (19%).

Indicator Trend

There are seven stations in the Northeast that have been collecting daily temperature data since at least 1900.[7] These stations represent the best available instrumental record of growing season for this region going back a century. The length of the growing season in the Northeast has considerable variability on an annual timescale (Figure 1). However, despite this variability, a long-term trend is apparent. When the station data are averaged together, the overall increase (from linear regression) is 8 days. Some locations, such as Atlantic City (Figure 2), reveal a remarkable change in the length of the growing season. Since data collection began there (1874), the growing season has increased in Atlantic City by five weeks overall. The Northeast growing season has lengthened over the past 100 years, but there is also significant spatial variability, with some locations experiencing considerably longer growing seasons.

Bloom Dates for Lilacs, Apples, and Grapes

Indicator Overview

As evidence of climate change mounts, scientists have begun to search for signs of biological or ecological responses to this change. A shift in seasonal events in the life of plants and animals, such as flower bloom, spring arrival of migrating birds and insects, etc., are potential "bioindicators" of climate change.

Researchers[9] evaluated changes in spring bloom date from 1965 to 2001 utilizing a unique data set derived from genetically identical lilac plants (*Syringa chinensis*, clone 'Red Rothomagensis') monitored at 72 locations within the Northeastern U.S.

In addition, they examined bloom date records for apples and grapes collected at several sites in the region during approximately the same time period. Collectively, statistical analysis of the results indicated an average advance in spring bloom of about 4 to 8 days in the Northeast during the latter half of the 20th century. This trend is qualitatively consistent with a warming trend for the region, and is consistent with shifts in bloom date and migration patterns reported for various plant and animal species in other parts of the U.S. and Europe.

Regional Importance

The timing of flowering is not only a key event in the life cycle and reproduction of individual plants, it is indicative of a broad range of seasonal biological responses to climate that will have important consequences for ecological processes, forestry, agriculture, human health, and the regional economy. In general, species differences in sensitivity and adaptation to climate change will affect species distributions, the productivity of our farms, and "ecosystem services" (such as water and nutrient cycling) provided by our natural areas.

Figure 1. Monitoring sites for S. chinensis *throughout the Northeast*

There is already evidence in some regions that climate change can encourage invasive weeds, insects, or pathogens, while increasing extinction rates of native species that cannot migrate or disperse their seeds to new suitable habitats.[10]

Climate change is likely to upset the synchrony between the activity of pollinators (e.g., bees) and bloom of some plants, even if pollen production is increased due to the stimulatory effect of warmer temperatures and higher carbon dioxide (CO_2) on growth.[11] The pollen-allergy season is likely to arrive earlier in the spring and could be more severe in a warmer high-CO_2 world.[12] Finally, flowering time and fruit set are driving factors in the food web upon which humans all depend. Pollen, nectar, fruit, or seeds are important resources for many animals, including farmers, human consumers of farm products, and those involved in the agricultural economy of the region.

Sensitivity to Climate and Other Factors

Phenology is the study of seasonal biological events in the animal and plant world as influenced by the environment.[13] Plants are particularly useful to scientists as weather instruments and indicators of climate change because their phenological responses are based on a complex integration of temperature, sunshine, rainfall, and humidity that is difficult to match by simple analysis of weather records. Phenology data are usually quite variable because other factors influence the sensitivity of plants to weather and climate, such as genetics and age of the plant, day length (photoperiod response), soil conditions, pests, diseases, and competition from other plants.

Spring bloom date is just one example of a phenological event, but it can be a useful indicator of other biological responses to climate, such as the onset of spring leaf emergence or fall leaf color change, spring arrival date of migrating birds and insects, and animal hibernation.

The practice of monitoring spring bloom date is centuries old. Phenological calendars were used by the ancient Chinese and Romans to guide agricultural operations. Historical phenological records, going back centuries in some cases, have been discovered in Europe and Asia. Analysis of these data have revealed that flowering date of many plant species has been occurring earlier in many regions as winter and early spring temperatures have increased. Species range shifts to higher latitudes and altitudes have also been documented.[14]

Fewer good data sets are available in the U.S., but one study in Wisconsin, begun by the famous conservationist, Aldo Leopold, in the 1930s, monitored 55 species and found an average advance in spring earliness of about 6 days for the period 1936 to 1998.[15] A Smithsonian-sponsored study in the Washington D.C. area found that 89 of 100 plant species monitored from 1970 to 2000 showed a significant advance (4.5 day average) in first bloom date.[16]

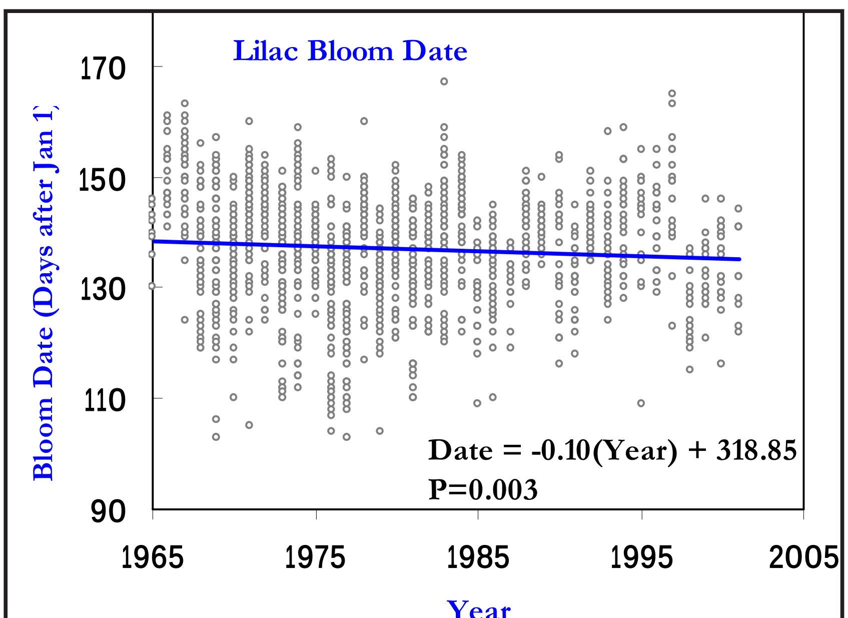


Figure 2. Trend of lilac bloom dates is indicated by the blue line.

The results presented here focus specifically on the northeastern U.S., where average annual temperatures increased 1.8° F, and winter temperatures (December through February) increased 2.8° F from 1899 to 2000. Records were evaluated from 72 locations in this region (see map, Fig. 1) where genetically identical lilac plants (*S. chinensis*, clone 'Red Rothomagensis') were planted and monitored for first flower (bloom) date during the period 1965 to 2001. Not all sites were established in the same year, and most sites were missing some years of record. On average, the sites used had 21 years of record. These plantings were originally established by a U.S. Department of Agriculture project[17] for the purpose of using phenological information to optimize farming practices (e.g., seeding date and pest control), and predict yield potential (crop "futures") for several economically important crops.

In addition to the unique, geographically dispersed lilac data set, an evaluation was done of trends in bloom date of apples ('Empire' and similar varieties) and grape (variety 'Concord') collected at a few sites in New York State during approximately the same time period.

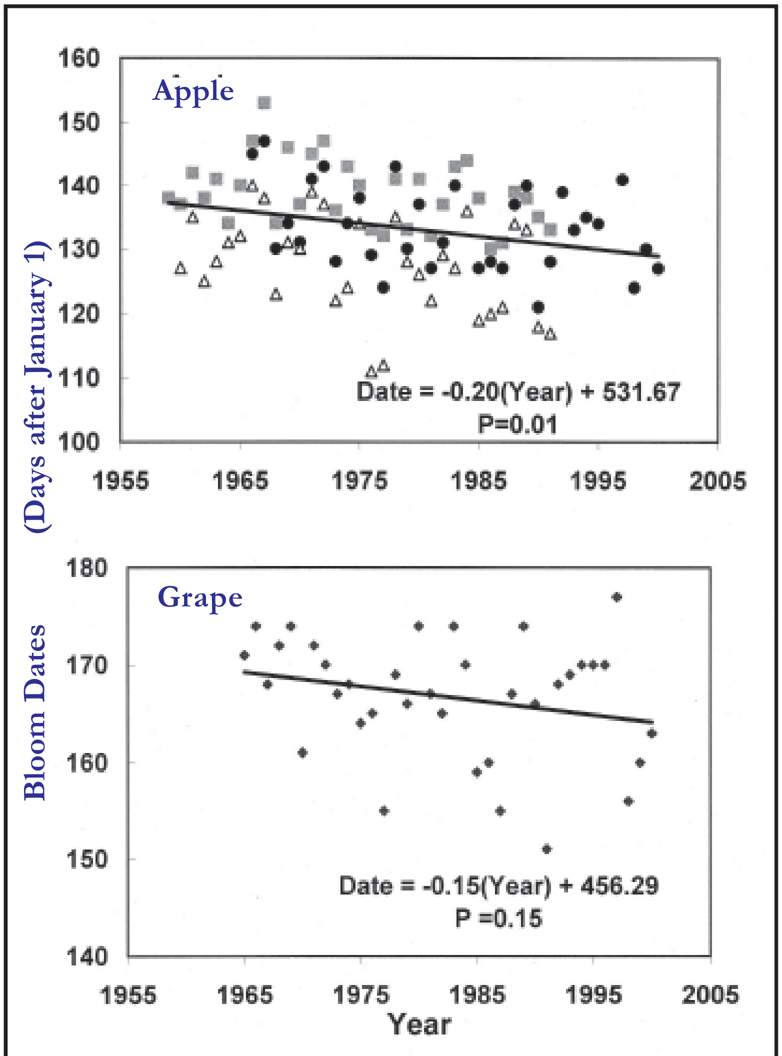


Figure 3. Apple and Grape bloom dates trends

Indicator Trend

During the period 1965 to 2001, lilac bloom dates advanced about 1 day per decade in the northeastern U.S. (Fig. 2). Although, as observed in all phenological studies of this type, there is substantial variability from site to site and from year to year, statistical analysis of the data indicated there is less than a 1 per cent probability ($P < 0.01$) that this trend could be due to chance alone. In other words, there is a high degree of confidence that the trend for earlier bloom is real. This is because of the large sample size. Also, the genetic similarity of the plants at all sites makes this a highly unique and powerful analysis compared to other similar studies.

In addition to the pooled analysis shown in Fig. 2, researchers evaluated the trend for each of the 72 sites individually. Of the 72 sites, 64 (89 %) had advanced spring bloom date, and at those few sites where spring bloom was later rather than earlier the trend was not statistically significant.

Analysis of the more geographically limited apple and grape data sets (Fig. 3) suggests a slightly more rapid advance in spring bloom (about 2 days per decade, or 8 days since the 1960s) for these species compared to lilac.

The implications of earlier bloom for agricultural crops will depend on many factors. In some cases, it may translate in a straightforward fashion to earlier yields. This will benefit farmers who receive higher prices for earlier production, but could have a negative effect if there is increased competition from farmers in other regions earlier in the season.

Earlier bloom could potentially reduce yields if spring temperatures become more variable as the climate changes and an early bloom increases the risk of frost damage to flowers and developing fruit. A recent analysis of historical apple yields in the New York State region[18] found that warmer temperatures during the January 1 to bud break period was correlated with lower, not higher yields.

Collectively, analyses for the northeastern U.S. indicate that, on average, lilacs are blooming about four days earlier, and apple and grapes are blooming about eight days earlier than they were half a century ago. The magnitude of this climate impact on woody perennials in the Northeast is similar to that reported for bloom of other plant species, and for bird and insect spring migration arrivals, by researchers in other parts of the U.S. and Europe (references: see footnotes 9-11). Results are also qualitatively in agreement with reports of earlier spring "green wave" advancement in the northern hemisphere based on satellite imagery of vegetative cover.[19]

This and other recent phenology studies have relied on historical records that were initially maintained for purposes other than examination of climate change. Given the importance of reliable data on ecological responses to climate change for policy-makers, strengthening the existing regional and global phenology monitoring networks[20] should be a high priority in the future.

Timing of High Spring Flow and River Ice-Out

Indicator Overview

Measurements associated with river discharge make it possible to rigorously and consistently record both the timing of high spring flow and the dates of ice-affected flow across the New England region. Both of these variables have been collected by the U.S. Geological Survey using consistent methods for many years on a substantial number of rivers that are free from any significant flow regulation by human activities.

The date marking the point where 50% of the water flow during the period January 1 to May 31 has occurred significantly earlier at most of the sites studied for periods ranging from 50 to 95 years through the year 2000. The date in the Spring when the ice on rivers broke up (ice-out date) has also occurred earlier and the total number of ice-affected flow days during the winter has decreased on most of the rivers studied.

Regional Importance

The timing of the delivery of freshwater to estuaries and near coastal marine waters could affect estuarine and marine ecology through changes in the timing of nutrient cycling and the inland migration of the salt water. In northwestern North America, earlier spring flow has resulted in a reduction in summer flows and a longer summer base flow period. These changes in summer flow regimes have not been observed in Northeastern North America because of a more even distribution of precipitation and possibly because of increasing summertime precipitation. Changes in seasonal flow regime may also influence the timing of migration of anadromous fish.

One potential effect of these trends in river ice involves more frequent formation of anchor ice. Anchor ice does not form when surface ice is present. With fewer ice-affected flow days in the winter, there may be less continuous surface-ice cover and more frequent opportunities for anchor ice to form. Anchor ice typically forms on very cold, clear winter nights. These conditions could still be present in winters that are generally warmer. Anchor ice **c**an restrict or even eliminate substrate flow. This has serious effects on stream biota sensitive to subfreezing conditions and (or) dissolved oxygen in the substrate water, particularly fish eggs and embryos developing within gravel beds.[21] The documented changes in the last dates of ice-affected flow in the spring could also have important effects on river ecology, including effects on primary producers, consumers, and trophic dynamics.

Sensitivity to Climate

The date on which half of the total volume of water for a given period flows by a river gauging station (center of volume date) is more sensitive to changes in the timing of bulk high-flows in a season than is the

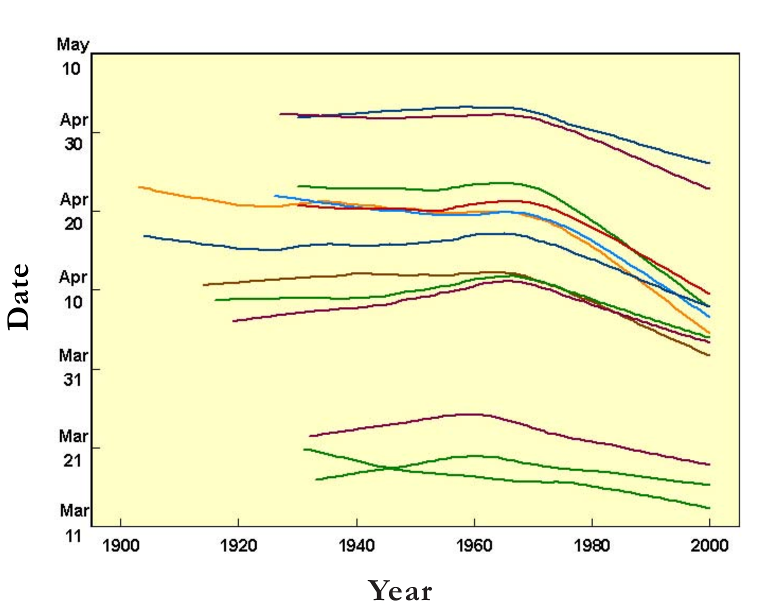


Figure 1. Smooths of winter/spring (January 1 to May 31) center-of-volume dates for the 13 longest-record, rural, unregulated rivers in New England.

date of peak flow. This center-of-volume date is a more robust indicator of seasonal flow timing, since the peak flow date can occur before or after the bulk of seasonal flows in response to a single storm. Climate warming results in earlier winter/spring seasonal center-of-volume dates because of an increased ratio of rainfall to snowfall and an earlier snowmelt.

The presence of ice in a river channel affects the relation between river height and flow; therefore, the presence of ice in rivers has been historically determined and recorded so that discharge records can be adjusted for the presence of ice. The formation of ice in river channels is a sensitive climate indicator that affects the river height/flow relation by causing backwater (a higher-than-normal river height for a given flow). This backwater varies with the quantity and nature of the ice, as well as with the flow. Backwater at a gauging station can be caused by anchor ice or by surface ice. The presence of river ice is readily detected because it results in signature anomalies in the temporal pattern of river stage.

Indicator Trend

There is substantial inter-annual variation in the timing of high spring flow, but most rivers studied indicate significantly earlier flows in recent decades. In one study of 27 rural, unregulated river gauging stations in New England with an average of 68 years of recording the center-of-volume date (January 1 to May 31), 14 sites had statistically significant earlier timing. All of the remaining stations were trending towards earlier dates but these trends were not statistically significant. In northern and mountainous areas, where snowfall is highest, the center-of-volume date became earlier by 1 to 2 weeks, with most of the change occurring since 1970 (Figure 1).[22] The center of volume date was correlated with March/April surface air temperature (r=-0.72) as expected. The center of volume date was not correlated with March/April precipitation, but was weakly correlated with January precipitation.

The total annual days of ice-affected flow decreased significantly over the 20th century at 12 of the 16 rivers studied. On average, for the nine longest-record rivers, the total annual days of ice-affected flow decreased by 20 days from 1936 to 2000, with most of the decrease occurring from the 1960s to 2000. Four of the 16 rivers had significantly later first dates of ice-affected flow in the fall. Twelve of the 16 rivers had

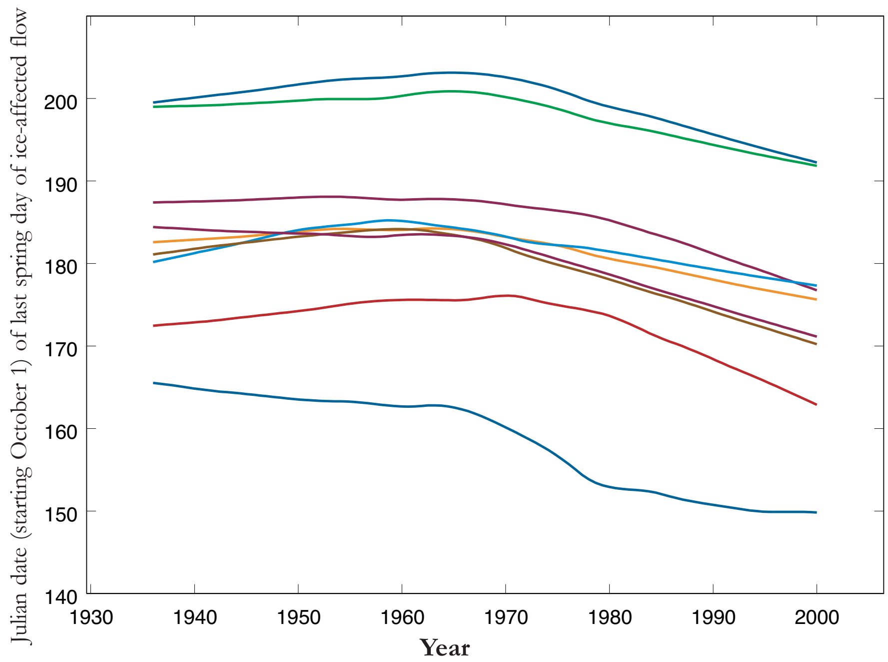


Figure 2. Smooths of last dates of ice-affected flow in the spring, over time, for the nine longest-record river gauges in northern New England.

significantly earlier last dates of ice-affected flow in the spring. On average, the last dates became earlier by 11 days from 1936 to 2000 with most of the change occurring from the 1960s to 2000 (Figure 2).[23] The total annual days of ice-affected flow were significantly correlated with November through April air temperatures (r = -0.70) and with November through April precipitation (r = -0.52). The last spring dates were significantly correlated with March through April air temperatures (r = -0.73) and with January through April precipitation (r = -0.37). March mean river flows increased significantly at 13 of the 16 rivers in this study.

Changes in the center of volume and river ice-out dates are consistent with changes in last-frost dates, lilac bloom dates, lake ice-out dates, river ice thickness and changes in the ratio of snow to total precipitation in New England.[24] This suggests that these New England spring geophysical and biological changes all were caused by a common mechanism, temperature increases.

Lake Ice-In and -Out Dates 1807 - 2000

Indicator Overview

Observations of lake ice are tangible, readily available and technically feasible indicators of local climate conditions in a geographic area. Ice-out (the day the majority of the lake ice is broken up in the spring) and ice-in (the day the majority of the lake first freezes over in the winter) have been recorded at several Northeastern lakes for many years. The day of ice-out has, on average, occurred earlier in recent years than it did decades ago, while the day of ice-in, recorded on Lake Champlain on the New York – Vermont border, has been occurring later or not at all.

Regional Importance

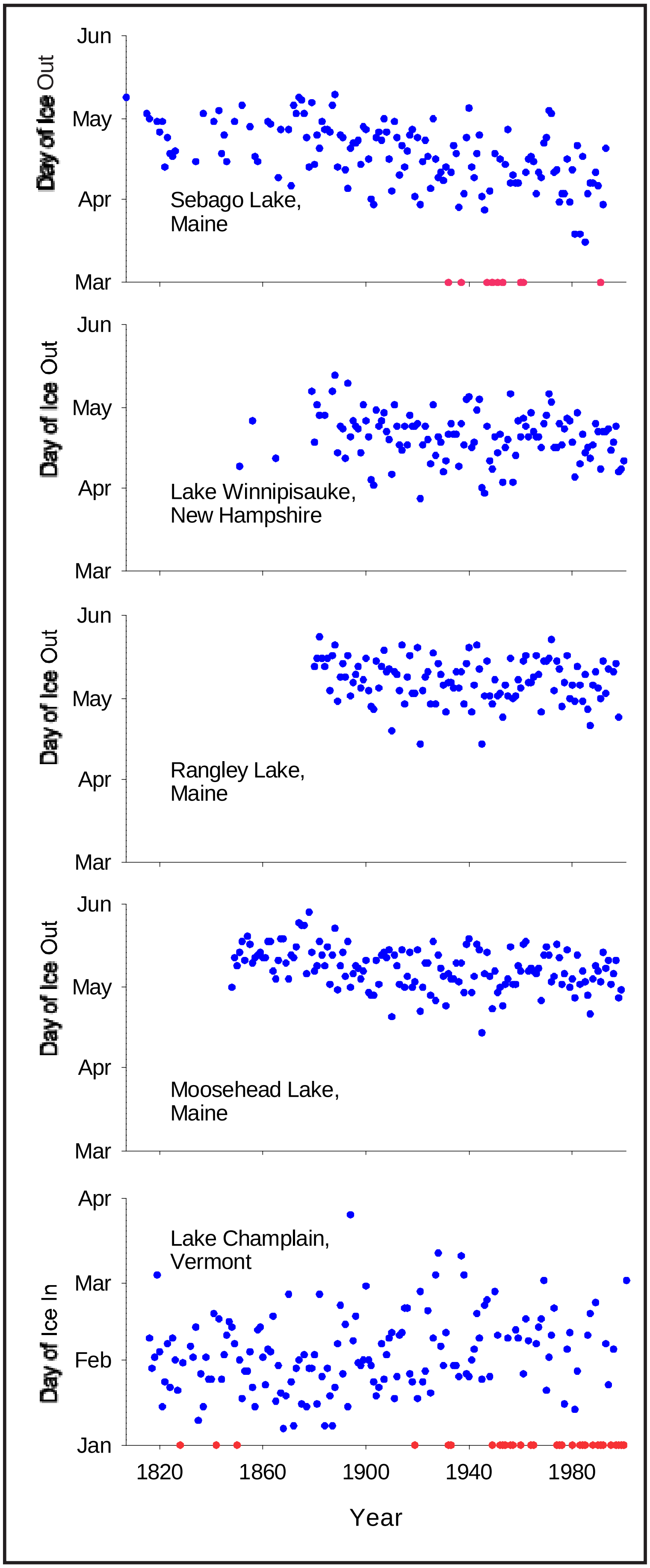
Many areas of the world, including the Northeast, are dependent on the freeze and thaw of lakes, reservoirs, and ponds. Used for local commerce and transportation, lakes have been important to people living in the region for centuries. When frozen, lakes are used for ice fishing, cross-country skiing, sled-dog racing, and snowmobiling, all of which are important for the Northeast's tourism economy. However, the spring break-up of the lakes is an important event, when boaters and ferry masters put their boats in the water to begin the warm season.

In addition to impacting human systems, changes in the average ice-out date may lead to changes in lake and river ecosystems. Ice cover is a factor in the oxygen concentration, pH, fish habitat, and seasonal succession of the lake.[25] It is uncertain what the long-term ecological effects of an earlier ice-out date will be.

Sensitivity to Climate and Other Factors

The methods used to determine the official ice-out day differ from lake to lake, but generally refer to the last day the lake has significant ice cover. The ice-in day is the first day the majority of the lake is frozen over. Methods have remained reasonably constant at each lake over the time period. For example, the official ice-out date on Lake Winnipesaukee occurs when the ferry boat, the MS Mount Washington, can safely leave port and motor, unobstructed by ice, to the ports in Center Harbor, Alton Bay, Wolfeboro, and Weirs Beach. The day of ice-out is primarily affected by the severity of the previous winter, lake temperatures, and the warmth of the spring months.

The official ice-out day is also slightly sensitive to somewhat unrelated factors, such as wind speed or direction on a certain day. For example, imagine there was a strong westerly wind one morning that blew all the remaining ice to one end of the lake; the MS Mount Washington may have been able to complete the route and the day labeled the ice-out day. However, if the wind had blown east that day and blown all the ice



into one of the ports, then that day would not have been recorded as the ice-out. While this phenomenon may happen occasionally, it would not affect the long term trends evident in the ice-out data.

Indicator Trend

In addition to considerable annual variation and some cyclical patterns, every lake with ice-out data shows a trend towards earlier ice-out dates over the length of their record.[26] Lake ice records from Sebago Lake in southern Maine and Lake Winnipesauke in central New Hampshire are relatively continuous since the early 1800s. Sebago Lake shows an ice-cover decrease of 14 days when comparing the period 1851-1900 to 1951-2000. The average ice-out date on Lake Winnipesauke occurs almost eight days earlier today than it did in the late 1800s. Both Moosehead Lake and Rangeley Lake, located at higher latitudes in Maine, have been breaking up an average of six days earlier.

Sebago Lake, located in the coastal Maine flood plain 15 miles from the Atlantic Ocean, has been breaking up earlier over the past 150 years, with the rate accelerating over the past 25 years. Sebago Lake has failed to completely freeze nine times since 1807. Seven of these ice-free years were in the last 55 years. All of the ice-free years have occurred since 1932. Lake Winnipesauke, located in the New Hampshire White Mountains,

Figure 1: Day of 'ice-out' at four New England Lakes: Sebago Lake, ME; Lake Winnipesauke, NH; Rangeley Lake, ME; Moosehead Lake, ME and day of 'ice-in' at Lake Champlain, VT. Ice-out date refers to the day of the year on which the lake was considered to be ice free, while the ice-in date is the first day the lake is considered totally frozen. The method of determining the official ice-out or ice-in day is different at each lake, but the methods have remained relatively similar for the period of the record. For example, the official "Ice-out" date on Lake Winnipesauke occurs when the ferry boat, the MS Mount Washington, can safely leave port and motor, unobstructed by ice, to the four ports on the lake. Red points denote years in which a lake did not freeze over.

has also broken up earlier. From 1951-2000, ice-out averaged April 20, a full week earlier than the 1851-1900 average of April 27.

The date Lake Champlain, VT, was first frozen over ('ice-in') has also changed over the past 150 years.[27] Today it freezes over 8 days later than it did in the second half of the 1800s. But the most remarkable part of the record is the occurrence of years in which the lake did not freeze over all winter. Over the 186 year record, the lake has not frozen over in 31 winters, 75% of which were since 1900, and almost half of them occurred since 1970 (years the lake did not freeze are denoted in the figure with red points).

In general, lakes farther from the ocean and at higher elevations show smaller decreases in the length of ice cover. Lakes at higher latitudes show smaller but equally significant warming trends over the past 150 years. Lakes with larger climate variability, those prone to inclement weather and large amounts of precipitation show ice-out dates more statistically dependent on local events. Overall, ice-out dates were 9 days and 16 days earlier between 1850 and 2000 in the northern/mountainous and southern regions of New England respectively.[28]

Ice-out and ice-in dates recorded in the Northeast are consistent with the warming trend evident in the annual and winter temperature records over the past 100 years.

Precipitation
1900 - 2000

Indicator Overview and Regional Importance

Here total annual precipitation in the Northeast is considered from 1900-2000.[29] This includes snowfall and ice as the amount of liquid equivalent. Precipitation can fall as rain, snow, sleet, hail, or freezing rain. In all of its forms it is very important to the Northeast. Ecological systems depend on precipitation for hydration and human communities depend on the replenishment of underground water sources and water for growing crops. In addition, precipitation is important for tourism.

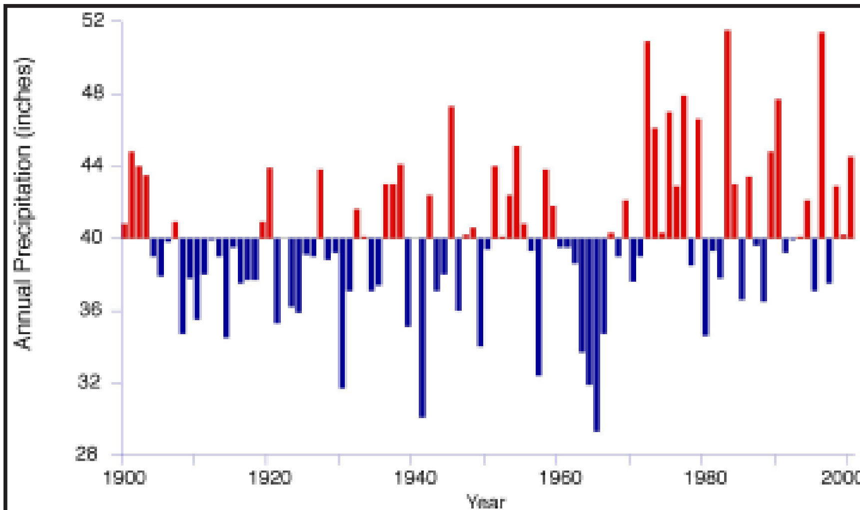


Figure 1: Average total annual precipitation of 79 stations in the Northeast (inches), 1900-2000. Years in red experienced more than average precipitation, while years in blue experienced less. Overall, precipitation in the Northeast has increased 3.3 inches during the past century, with the most remarkable increases since the 1970s.

Sensitivity to Climate and Other Factors

An increase in global surface temperatures will very likely lead to changes in precipitation and atmospheric moisture, due to changes in atmospheric circulation, a more active hydrological cycle, and increases in the water holding capacity throughout the atmosphere.[30] Water vapor in the atmospheric is also a climatically critical greenhouse gas.[31] Thus temperature and precipitation are intricately linked in the climate system.

Indicator Trend

Over the past century there has been a 2 percent increase in global precipitation, but that change was not spatially or temporally uniform.[32] Precipitation in the Northeast has increased by an average of 3.3 inches (8 percent) over the past century (Figure 1). There has been a significant increase in precipitation following the drought that affected the region in the early 1960s, which is clearly visible in Figure 1. That drought impacted regional agriculture, water quality and quantity, forest health, and human health.[33] By 1965, that drought reached critical levels and resulted in widespread forest fires, crop failures, fish kills, water shortages, harmful algal blooms, and heat-related deaths. Following the 1960s drought, precipitation has increased. Of the ten years with the most precipitation, eight have occurred since 1970.

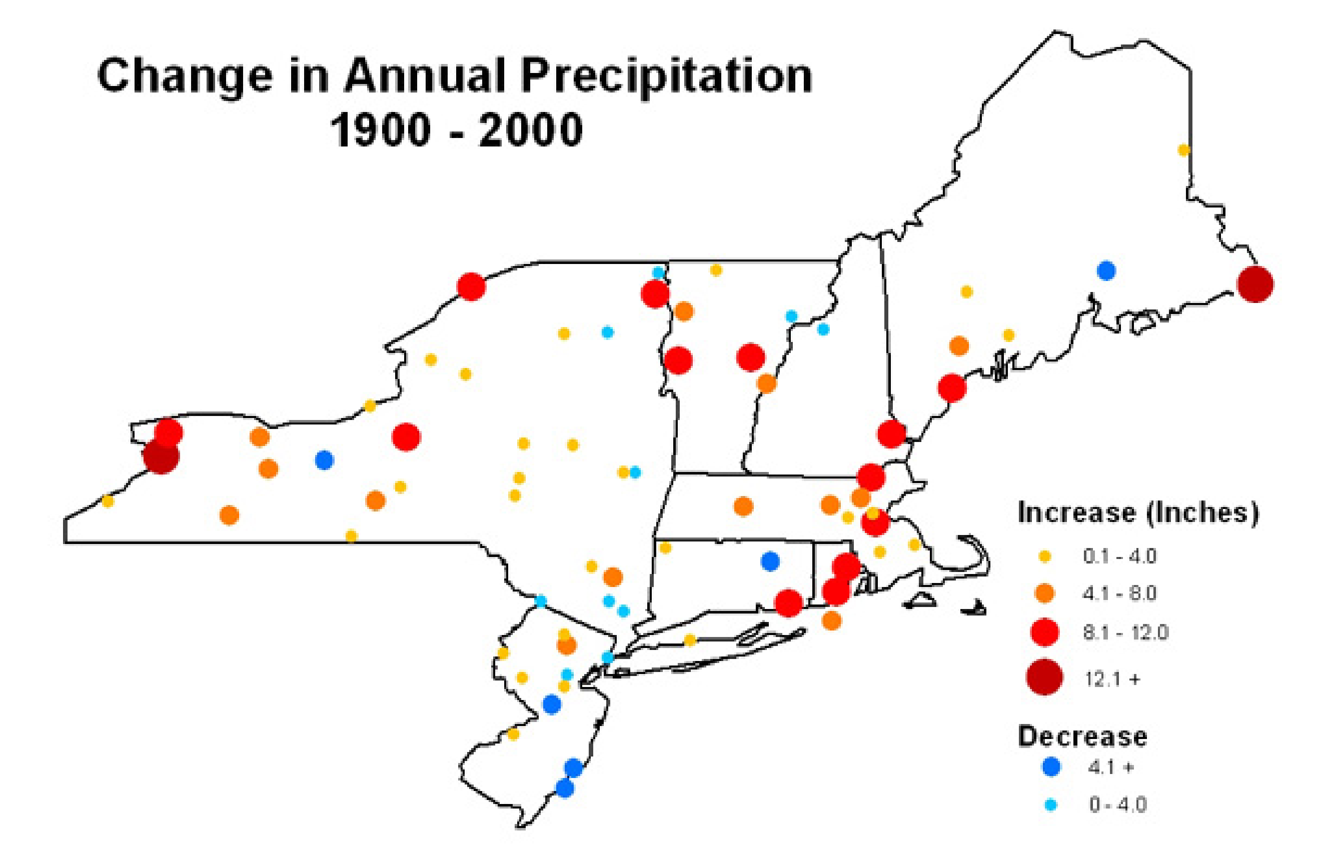


Figure 2: Map illustrating change (from linear regression) in total average annual precipitation for stations from 1900 to 2000. Points labeled red or orange indicate stations that have experienced an increase in total annual precipitation; blue indicates a decrease.

Despite the overall increase in precipitation, significant spatial variability exists (Figure 2). Some stations have experienced up to a 60 percent increase in precipitation over the past century, while others have experienced a slight decrease. The stations with the greatest increases tend to be either near the Atlantic Coast or major bodies of water (the Great Lakes and Lake Champlain).

Another indicator of hydrologic response sensitive to climate variability is the ratio of snow to total precipitation (*S/P* ratio). Changes in the *S/P* ratio over time could influence the magnitude and timing of spring runoff and the amount of winter snowcover. In a warmer climate, even without changes in total precipitation, one would expect the relative amount of snowfall to decrease, resulting in a decrease in the *S/P* ratio. Analysis of daily US Historical Climatology Network data at 21 sites across New England from 1949 to 2000 has shown that at 11 stations, concentrated in northern New England and coastal/near-coastal regions, the annual *S/P* ratio has been decreasing.[34] These annual trends are predominantly a result of decreasing snowfall over the past 30 years (see Snowfall, pages 24 - 25). The other 10 sites show weak decreasing *S/P* ratio. None of the sites had even a weak increasing trend. When the data are aggregated, the entire New England region and the northernmost region had significant decreasing trends in *S/P* ratio for annual and winter periods.

Intense Precipitation Events 1888 - 2000

Indicator Overview and Regional Importance

The number of precipitation events that resulted in more than two inches of rain (or water equivalent if the storm results in snowfall) during a 48-hour period is counted for each year for six stations going back as far as 1888.

Intense precipitation events, such as those that result in more than two inches of precipitation, have a great impact on the Northeast.

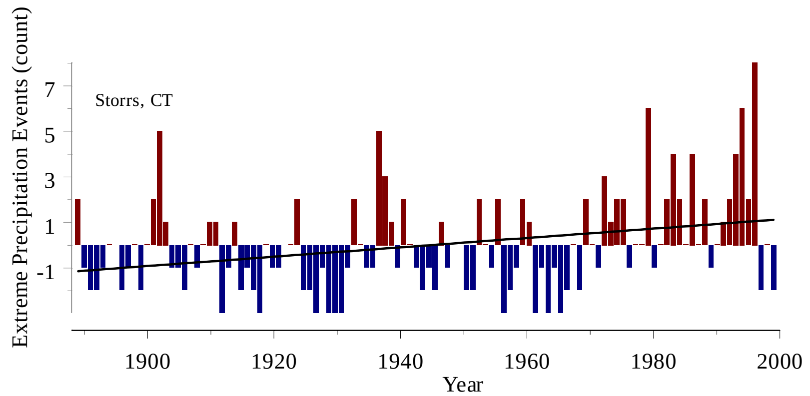


Figure 1: Extreme precipitation events (>2 inches in 48 hours) anomaly for the Storrs, CT, 1888-1999. In the graph, zero represents four events, the average number over this time period. Years in red experienced more than average extreme events, while years in blue experienced less. The black line is a linear regression of the data showing an increasing trend.

Sensitivity to Climate and Other Factors

Intense precipitation events are complex phenomenon that are dependent on many atmospheric processes, such as the temperature of various atmospheric layers, presence of moisture and atmospheric capacity to hold it, high- and low-pressure centers, location of storm track, and others. In general, a storm with more energy and more moisture will tend to increase its severity and therefore amount of precipitation. Climate change models suggest that a warming planet will likely experience increasing storm intensity and frequency.[35]

Indicator Trend

Every station investigated reveals an increase in extreme precipitation events during the 1980s and 1990s, as compared with the early 1900s. Storrs, CT, which has data available back to 1888, averaged about three intense storms each year prior to 1970 (Figure 1). Since 1970, however, Storrs has averaged 5.5 intense storms per year. The five other stations included here: Amherst, MA; Boston, MA; Farmington, ME; Hartford, CT; and Kingston, RI, all have a similar history of intense storm events (Figure 2).

The increase in the 1980s and 1990s is consistent with increases experienced in most of the country.[36] For example, the contribution to the total annual precipitation of one-day storms exceeding two inches increased from 9 percent in the 1910s to 11 percent in the 1980s and 1990s.[37] However, many stations in the U.S. experienced a frequency of storms in the late

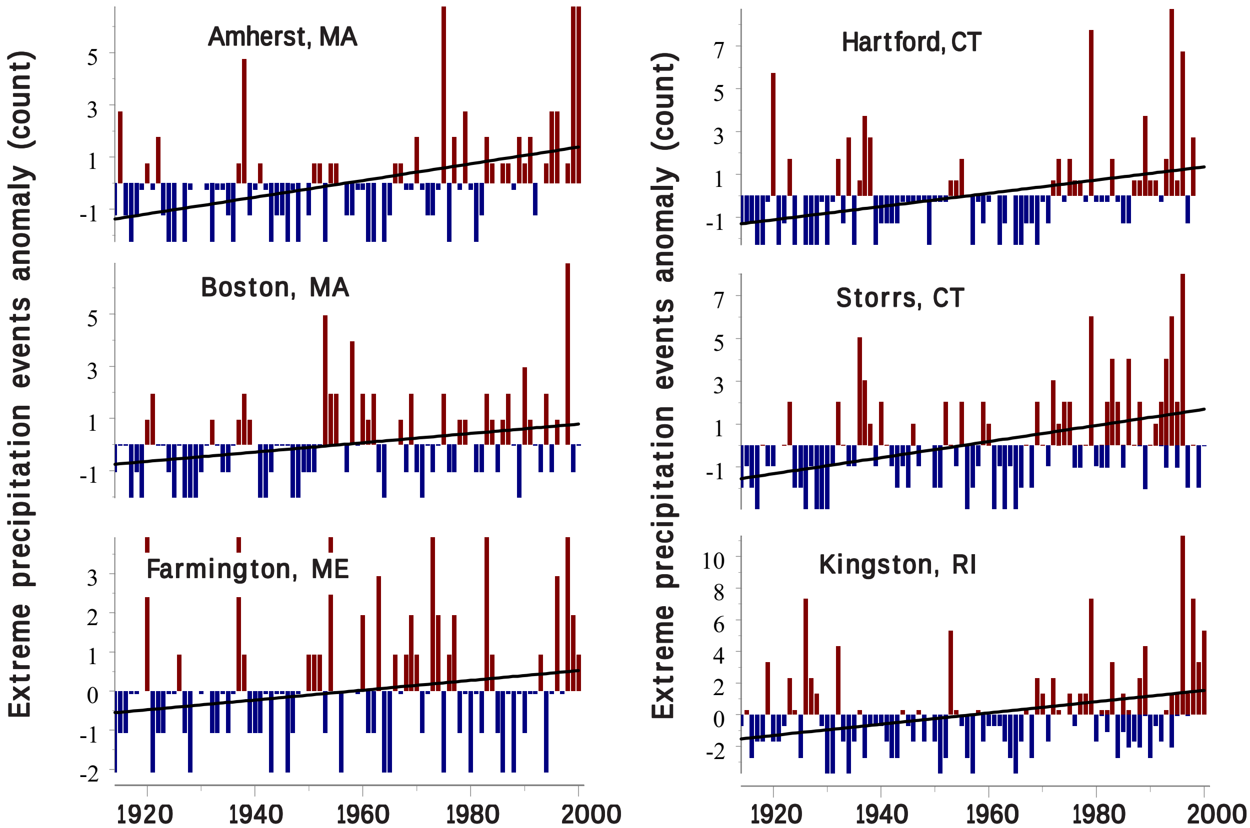


Figure 2: Extreme precipitation (>2 inches) events anomaly for six cities, 1914-2000. In the graph, zero represents the average number of events over this time period. Years in red experienced more than average extreme events, while years in blue experienced less. The black line is a linear regression of the data showing an increasing trend.

1800s and early 1900s that was comparable to that of the 1980s and 1990s.[38] This suggests that the recent increase in intense precipitation may be due to natural variability, but the effect of human induced climate change cannot be ruled out.

The longest running station reviewed here (Storrs, CT) did not experience an elevated frequency of storms in the early 1900s. Thus the record of intense precipitation there suggests a recent increase that corresponds to the recent increase in temperature. Unfortunately, the pre-1914 data for the other Northeastern stations is currently unavailable.

Sea Level Rise
1856-2000

Indicator Overview

Mean sea level at the coast is the "height of sea with respect to a local land benchmark, averaged over a period of time, such as a month or a year, long enough that fluctuations caused by waves or tides are largely removed."[39] For the past 150 years, sea level has been monitored at New York City, NY, Boston, MA (Figure 1) and other major ports in the Northeast. From these records it is clear that the relative sea level has risen, due to a combination of natural processes and human influences. Warmer temperatures in the future would likely further melt continental glaciers and contribute to the thermal expansion of ocean water, raising world-wide sea level even further.

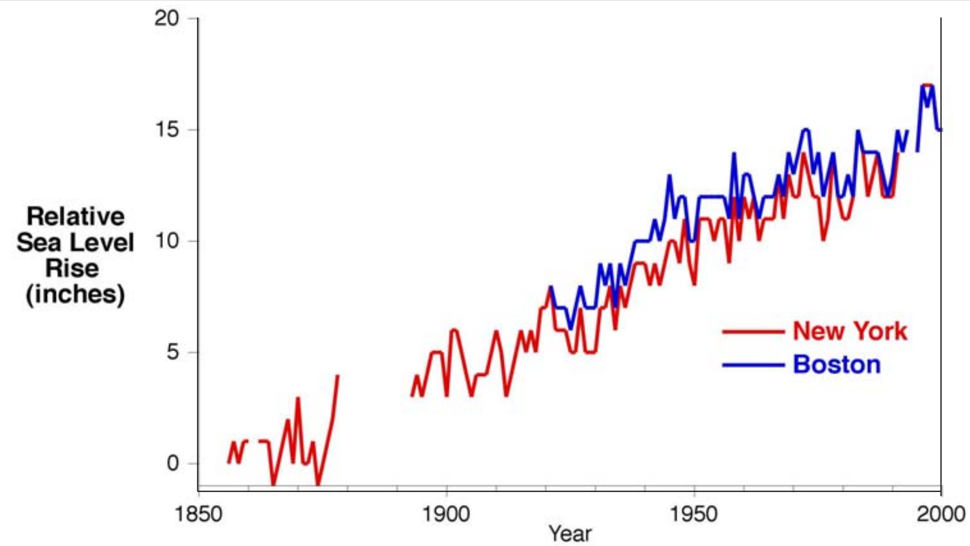


Figure 1: Sea level as measured at New York City, NY (from 1856, in red) and Boston , MA(from 1922, in blue) through 2000 in inches. The 1856 sea level was set to zero to illustrate the amount of increase over the past 150 years. Sea level has been increasing in the Northeast since it was recorded, due to natural phenomenon and perhaps human influence on climate. Human induced warming threatens to accelerate the rising sea level. Data from Permanent Service for Mean Sea Level, United Kingdom, http://www.pol.ac.uk/psmsl/

Regional Importance

As much of the New England coast is heavily populated, it is especially vulnerable to a rising sea level. It is estimated that well over 2,000 km^2 of land in the Northeast is less than 1.5 meters above the present sea level (Figure 2).[40] If sea levels were to continue to rise, people in these areas would be forced to relocate or adapt. Changes in sea level can also contribute to increased erosion and saltwater contamination of freshwater ecosystems[41] and loss of salt marshes and cordgrass.[42] Low-lying shorelines such as sandy beaches and marshes are likely to be the most vulnerable to rising seas. In addition, all of the glacial deposits in coastal New England, regardless of elevation, are vulnerable to undercutting by a rising sea level, possibly resulting in landslides. This is important, as coastal areas tend to be heavily developed.

Sensitivity to Climate and Other Factors

Sea level is affected by numerous factors on a range of timescales, from geological processes working over millions of years to the changing tides over the course of hours. As an indicator of a changing climate, we are interested primarily in changes on the scale of decades to centuries. Over this time period, factors such as changes in the size of ice sheets and glaciers, geological settling or uplift, thermal expansion, deposition of sediment, and thawing of permafrost are important. All of these factors are sensitive to changes in climate. In warmer temperatures, the rate ice sheets and glaciers melt may increase and contribute to sea level rise. In addition, when large ice sheets melt, the loss of mass can cause the landmass underneath to redistribute, causing uplift in some areas and settling in others. Another important factor is the expansion of water as it warms.

Indicator Trend

Worldwide sea level has risen more than 400 feet since the end of the last ice age, about 18,000 years ago. As the alpine and continental glaciers melted, massive quantities of water were added to the sea.[43] From geological data, it appears that global sea level has been rising at the rate of about 0.2 inches per decade for the past 6,000 years. The average rate of global sea level rise has been greater in the 20th century than the 19th century, based on the few long-term tide-gauge records. In New York City, where sea level data has been collected for about 150 years, sea level has risen about 16 inches since 1850 at a rate of about 1.2 inches/decade, with small interannual fluctuations. The majority of the change is likely due to the slow geological settling of the region, but at least part of it can be explained by the thermal expansion of the upper layers of the ocean due to the 0.7 °F warming of the past century.[44] As human activity continues to influence global climate, it is likely that the rate of sea level rise will increase over the coming century. The predicted global average sea level rise from 1990 to 2100 lies in the range of 4.3 to 30.3 inches.[45]

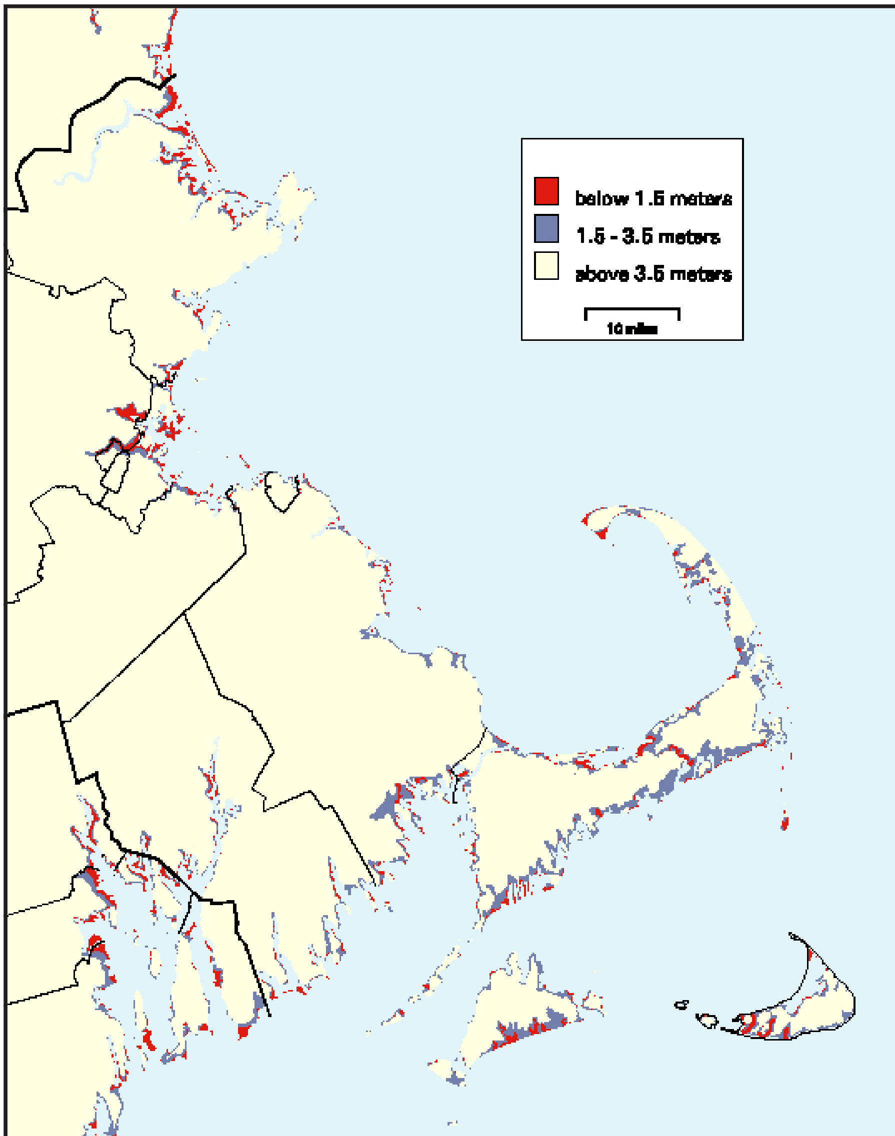


Figure 2: Map of areas in the Northeast vulnerable to a rising sea level. Elevations based on computer models, not actual surveys. Coastal protection efforts may prevent some low-lying areas from being flooded as sea level rises. The 1.5-meter contour depicted is currently about 1.3-meters above mean sea level, and is typically 90 cm above mean high tide. Parts of the area depicted in red will be above mean sea level for at least 100 years and probably 200 years. The 3.5-meter contour illustrates the area that might be flooded over a period of several centuries. This map does not include coastal areas composed of glacial sediment, which are prone to erosion regardless of elevation.

Sea Surface Temperature
1855 - 2001

Indicator Overview

Surface water temperature data from buoys, ships and other platforms from the late 18th century have been assembled, quality controlled, and made widely available to the international research community. This indicator is a review of the historical sea surface temperatures (SST) from 1860-2001 for the Gulf of Maine and the South Shore of New England.[46]

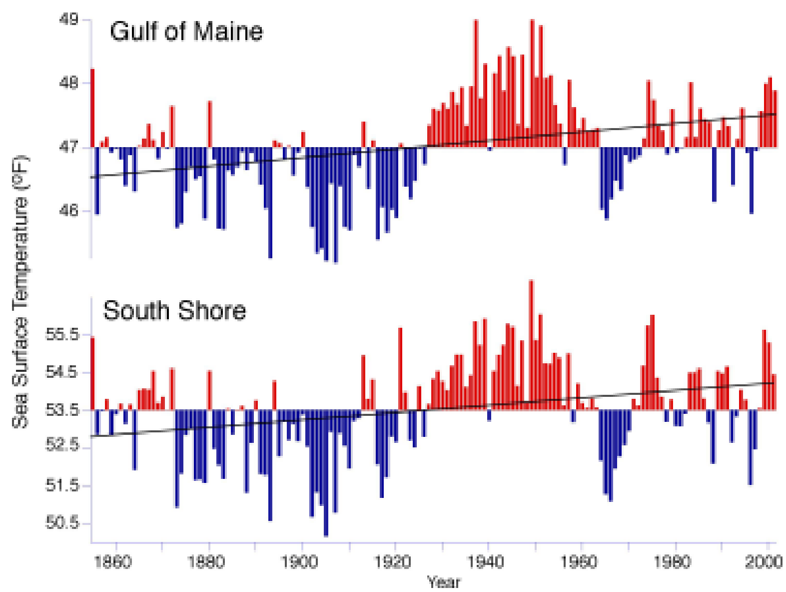


Figure 1: Sea surface temperature anomaly for the Gulf of Maine and South Shore, 1855-2001. Years in red experienced higher than average temperatures; years in blue experienced lower. The black line is a linear regression of the data showing an increasing trend.

Regional Importance

Sea surface temperature is an important moderator of regional climate. Areas near the coast generally experience warmer winters and cooler summers due to the vast heat storage capacity of the ocean. SST also plays a key role in storm tracking and intensity. Here SST is presented for two marine regions; the first is the Gulf of Maine, off the coast of Maine and New Hampshire. The second region is the South Shore, which extends from Cape Cod, Massachusetts to Long Island, New York.

	Gulf of Maine					South Shore				
Season	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
Average (°F)	47.1	40.5	39.7	55.4	52.5	53.4	42.6	43.2	66.7	61.5
Change (°F)	1.1	0.4	1.3	1.8	0.9	1.6	0.5	1.8	2.5	1.4
% Change	7.7%	5.2%	19.1%	7.8%	4.5%	7.6%	5.1%	18.0%	7.4%	4.9%

Table 1: Summary of statistics for changes in sea surface temperatures in the Gulf of Maine and South Shore, 1880-2001. Average is the average temperature over the period 1880-2001. Change is the estimated change in annual temperature from 1880 to 2001, from linear regression. For example, the annual SST in the Gulf of Maine was 1.1°F warmer in 2001 than it was in 1880. Percent Change is the change divided by the 1880 average value and represents the significance of the change. For example, the spring SST temperature on the South shore was 18% warmer in 2001 than it was in 1880.

Sensitivity to Climate and Other Factors

The world's oceans are continually circulating, moving heat from the tropics to the polar regions at about the same rate as the atmosphere. The oceans are huge reservoirs of heat and thus have a strong influence on global and regional temperature. Because of its size, the ocean changes temperature very slowly and can act as a heat sink or source, depending on the temperature of the air above it. While air temperatures can vary dramatically over the course of hours, ocean water takes months to warm up or cool down significantly. In this way, any change in SST represents changes in temperature on a seasonal, annual, or multi-annual timeframe.

Indicator Trend

Both marine regions have experienced significant variability since the 1880s. From 1880 through the early 1920s, the Gulf of Maine and the South Shore experienced below average temperatures. From the late 1920s to the early 1950s, SST was warmer than average. Since that time, SST has mostly remained above average in the Gulf of Maine and the South Shore.

Overall the SST in these regions has warmed significantly, with an increase of 1.1 ^{o}F (8 percent) in the Gulf of Maine and 1.6 ^{o}F (8 percent) on the South Shore. Most of this warming has taken place in the spring and summer months, where there has been an increase of about 1.3 to 1.8^{o}F in both locations (Table 1).

These regional trends are generally consistent with global records of SST, which reveal a rapid warming from 1905 to 1940 followed by a slight increase from 1940 to 2001.[47]

Snowfall
1880 - 2001

Indicator Overview

Total winter snowfall is an important indicator of winter weather. There have been significant changes in snowfall amount in the Northeast over the past century. Most areas have experienced a decrease in total snowfall amounts.

Regional Importance

For those living in the Northeast, snow is an important factor of everyday winter life. Snow in New England is of vital importance to the tourism industry and also represents a key aspect of New England culture.

Many regions rely heavily on income from skiers, snowboarders and snowmobilers during the winter season, while snow removal represents a significant expense for municipalities and state governments across the region.

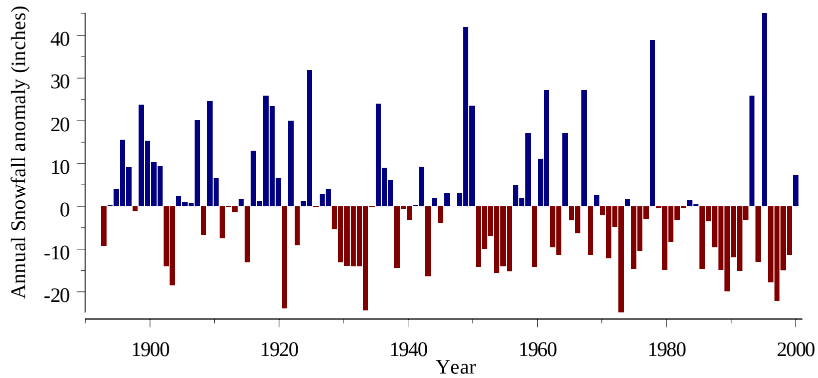


Figure 1: Total annual snowfall anomalies in Central Park, New York, New York, 1880-2001. In the graph, zero represents 27.3 inches, the average annual snowfall in the park. Years in blue experienced higher than average snowfall, while years in red experienced less. Notice the increased frequency of years with below average snowfall in recent decades.

Sensitivity to Climate and Other Factors

Snowfall is a complicated aspect of winter storms. Even weather forecasters have difficulty predicting how many inches will fall in a coming storm. This is because snowfall amounts are dependant on complex relationships between the availability of moisture and the temperature at various altitudes. Snow is formed high in the clouds, but must remain below freezing as it falls to the ground. Often snow will encounter a warmer (above 32°F) layer in the atmosphere and melt. Once melted, the precipitation may reach the ground as rain, sleet, freezing rain, or hail.

Indicator Trend

The longest running, high-quality record of snowfall in the northeast is from Central Park in New York City, which has been in continual operation since 1890. Snowfall there ranged from a maximum of 72.5 inches in 1996, to a minimum of 2.5 inches in 1973, with

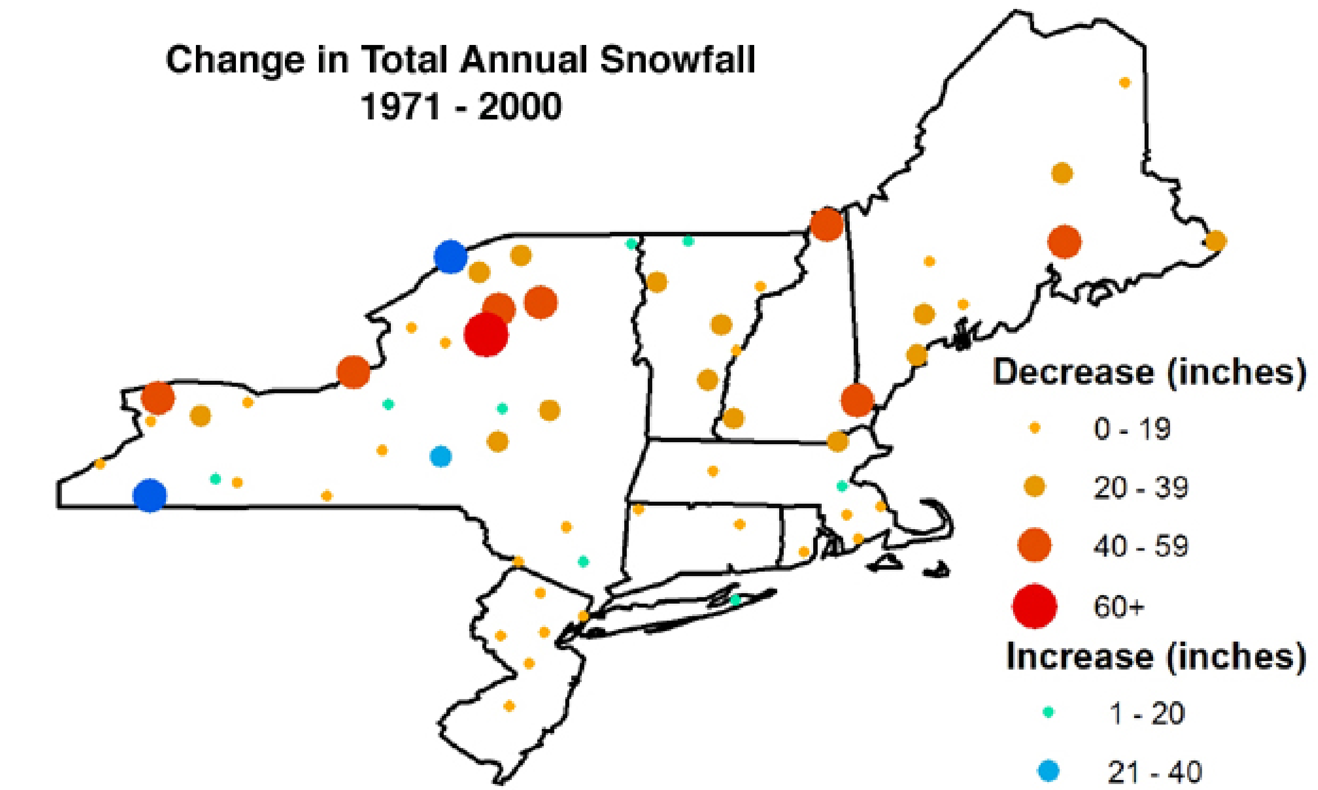


Figure 2: Map illustrating percent change (from linear regression) in total annual snowfall for stations 1971 to 2001. Points labeled with in yellow to red indicate stations that have experienced a decrease in total annual snowfall, while blue indicates an increase in snowfall.

an average snowfall of 27.3 inches. On average, New York is getting about 10 inches less snowfall each winter than it did in 1890. These results are consistent with recent data from other nearby stations on the coast. However, there is still significant year-to-year variability and these measurements may have been influenced by increased urbanization during this time period.

Meteorological stations in many other areas of the Northeast have also collected snowfall data. Over the past 30 years, stations in northern New York and northern New England have experienced significant decreases in snowfall, with several locations showing a decrease of 60 or more inches (Figure 2). Overall, the southern portions of the region have experienced a decrease in snowfall, although the decrease is smaller compared to northern regions. This decrease in snow has important consequences for winter tourism in northern New England.[48]

Days with Snow on Ground
1970 - 2001

Indicator Overview

Like total snowfall, total days with snow on the ground are an important indicator of winter weather. Unfortunately, few meteorological stations have been recording the presence of snow on the ground for very long. As a result, this indicator is only available for many stations back to 1970.

Regional Importance

This indicator is perhaps more relevant to outdoor recreation than total snowfall, because it is a measure of the length of the winter recreation season. While the total amount of snow is important, the length of time it stays is also a significant factor. Many forms of winter recreation, such as skiing and snowmobiling, rely on snow cover. In addition, snow affects ecological systems. Snow depth and persistence of snow cover are important factors in the reproduction and growth of plants.[49]

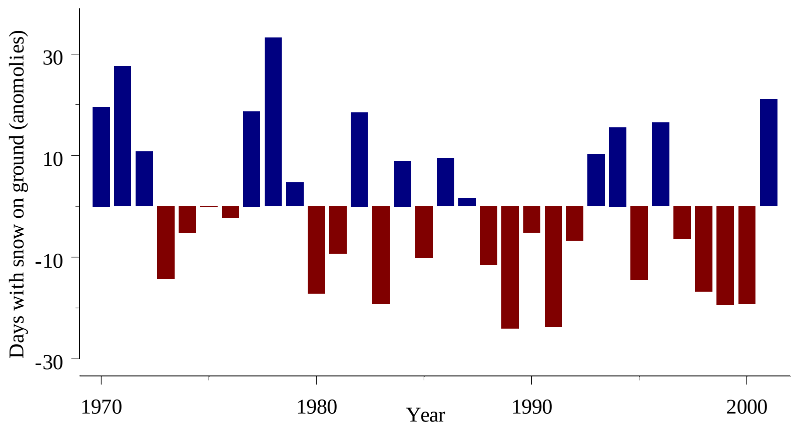


Figure 1: Total days each winter with snow on the ground at 36 stations in the Northeast, 1970-2001. In the graph, zero represents 80 days, the average number of days with snow on the ground. Years in blue had more than average days with snow on the ground, while years in red experienced fewer. Notice the increased frequency of years with below average snowfall in recent decades. On average, in 2001 the Northeast had 16 fewer days with snow on the ground each year than it did in 1970.

Sensitivity to Climate and Other Factors

The total number of days with snow on the ground for a given year is sensitive to both snowfall amounts and temperature fluctuations. For example, a single storm may drop two feet of snow in a region, but it could melt in three days of warm weather. Thus snow-on-ground is a useful indicator of overall winter severity.

Indicator Trend

Satellite records indicate that snow cover extent (SCE) in the Northern Hemisphere has decreased by about 10% since 1966 and is strongly related to increases in temperature.[50] Snowfall in the Northeast is extremely variable, with some stations receiving only a few inches of snow and others receiving more than 100 inches every year. Thus the number of days with snow on ground will also be variable across the region. The data from stations in the Northeast are generally consistent with the hemispheric trend and reveal a decrease in the number of days with snow on ground. When averaged, the Northeast stations reveal that there were, on average, 16 fewer days with snow on ground in 2001 than in 1970. However, there are several large areas that do not have snow depth data (such as most of

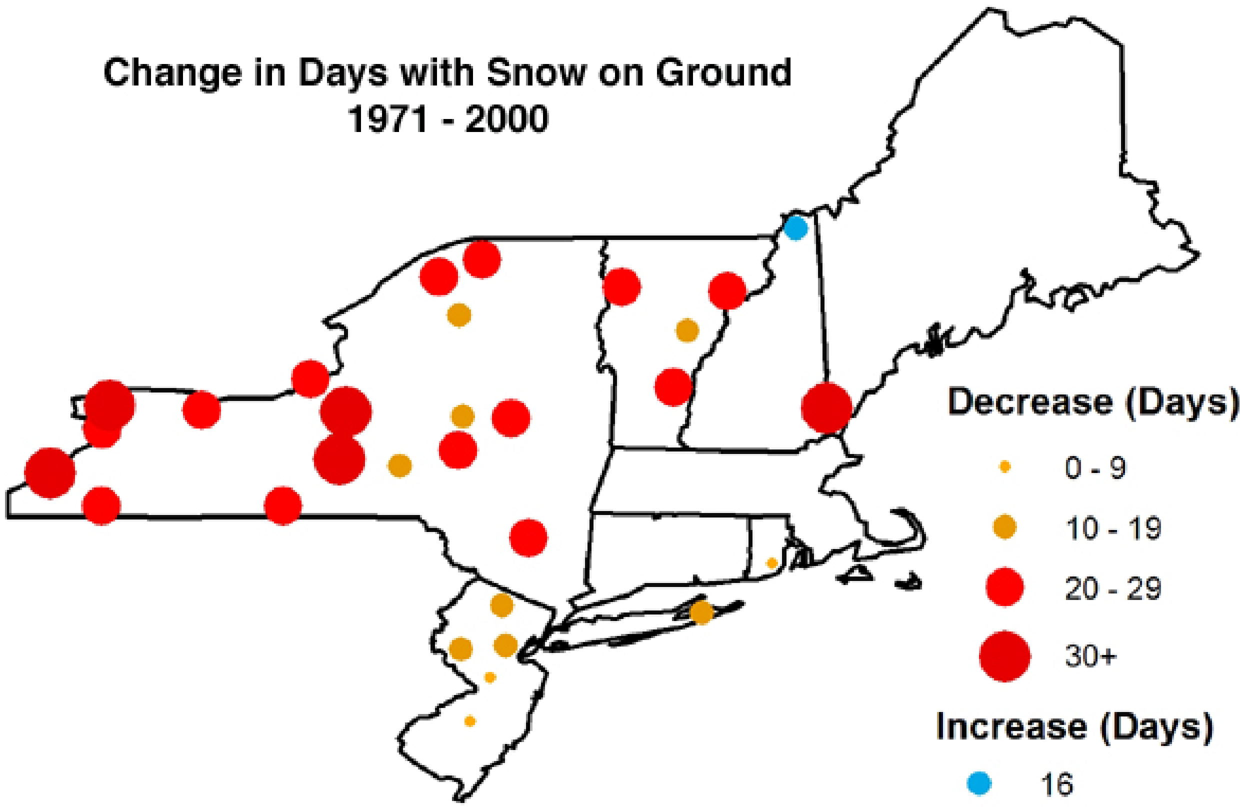


Figure 2: Map illustrating change (from linear regression) in the number of days with snow on the ground for stations 1971-2000. Points labeled in red or yellow indicate stations that have experienced a decrease in total annual snowfall, while blue indicates an increase in snowfall. Stations labeled in black did not experience much change.

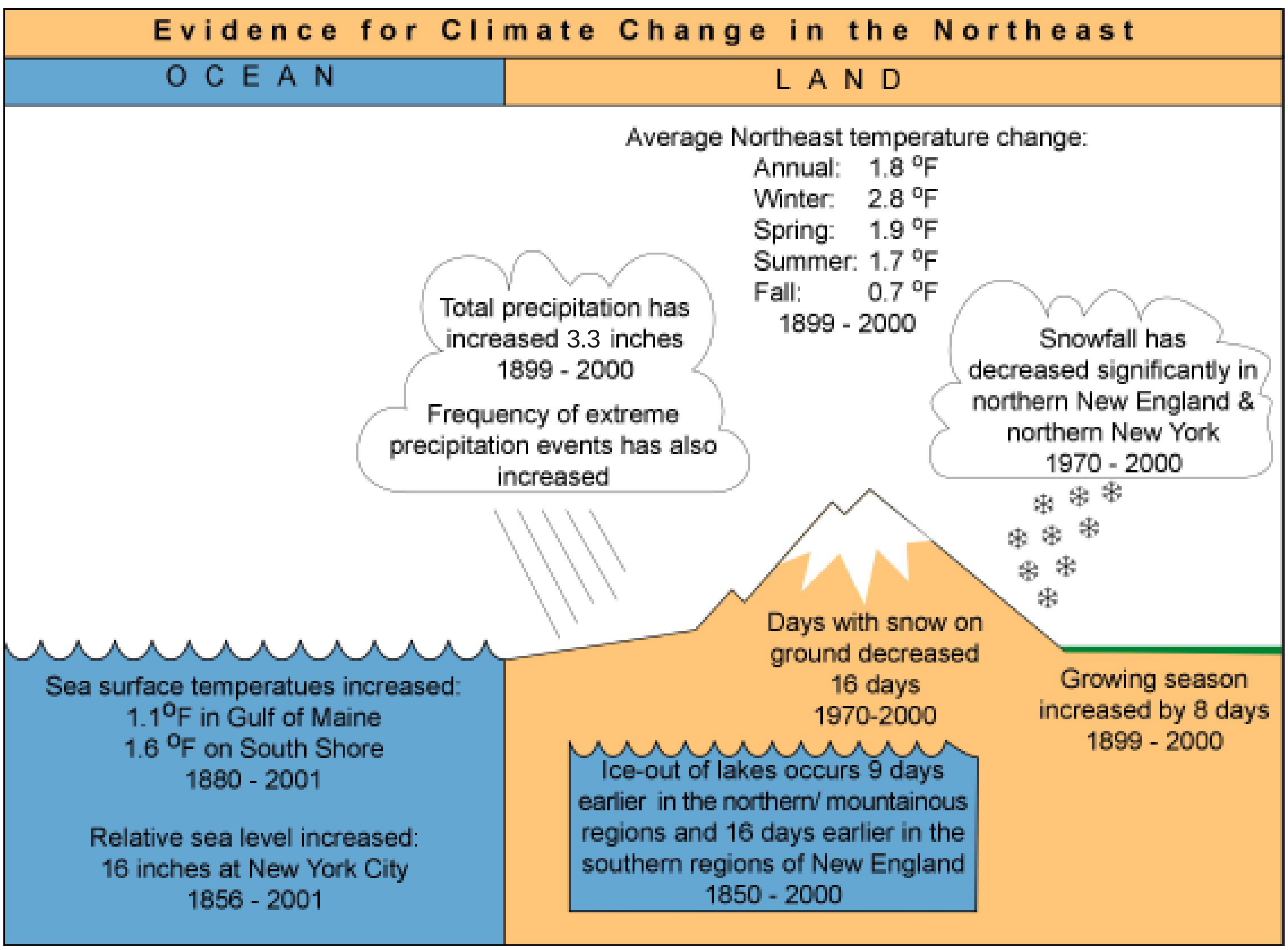
Maine, Massachusetts, and Connecticut). Some stations, such as Durham, NH, and Fredonia, NY, are experiencing almost a month of fewer days, on average, with snow each year. These trends are consistent with the measured increases in temperature over this time period. While the western areas of the northeast have experienced an increase in snowfall, the number of days with snow on the ground has decreased.

SUMMARY

Weather and climate in the Northeastern U.S. are arguably among the most variable in the world. This variability on time scales from hours to years is the result of several factors that relate to the physical geographical setting of the region, including its latitude, topography, and coastal orientation.

Despite this variability, the indicators of the Northeast's changing climate presented in this report provide a coherent set of evidence of a region that is warming, especially over the last thirty years. This evidence comes from a wide range of environments – the atmosphere, the biosphere, the oceans, and snow and ice. Additional research is required to better understand our changing climate, and to determine why it is changing. There are additional indicators that will be collected in the coming years that report not only on changes in the region's climate, but also the impact those changes are having on the region's environment, economy, and quality of life.

However, the remarkably consistent signal of a warming trend across the region cannot and should not be ignored. We now have our canary in the coal mine.



References

[1] The data used in this analysis is from the National Climatic Data Center (ftp://ftp.ncdc.noaa.gov/pub/data/ushcn/). The series for the New England region comprises areally weighted values. The station data were first averaged by climate division. Then the climate division data were averaged, giving proportional weight to the larger divisions. The mean of the series is 44.6 ^{O}F. Keim, B.D., A. Wilson, C. Wake, and T.G. Huntington. 2003. Are there spurious temperature trends in the United States Climate Division Database? Geophys. Res. Lett. 30(27), 1404, doi:10.1029/2002GL016295 30:1404, doi:10.1029/2002GL016295.Trombulak, S.C., and R. Wolfson. 2004. Twentieth-century climate change in New England and New York, USA. J. Geophys. Res. 31:L19202, doi:10.1029/2004GL020574.

[2] "Speech on the Weather" was given at the New England Society's seventy-first annual dinner, in New York City on December 22, 1876. From *The Family Mark Twain*, New York: Harper & Row, 1975.

[3] Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. http://www.ipcc.ch

[4] Frich, P., L.V. Alexander, P. Della-Marta, B. Gleason, M. Haylock, A.M.G. Klein-Tank, and T.C. Peterson. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Clim. Res.* 19:193-212. Kunkel, K.E., Easterling, D.R., Hubbard, K., Redmond, K., 2004. Temporal variations in frost-free season in the United States: 1895–2000. *Geophys. Res. Lett.* 31, L03201, doi: 10.1029/2003 GL0186. Cooter, E.J., and S. LeDuc. 1995. Recent frost date trends in the Northeastern U.S. *Intl. J. Climatol.* 15:65-75.

[5] US National Assessment of the Potential Consequences of Climate Variability and Change Educational Resources Regional Paper: The Northeast. US Climate Change Science Program. http://www.usgcrp.gov/usgcrp/nacc/education/northeast/ (2003). Parmesan, C., and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42. Walther, G.-P., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.-M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. *Nature* 416:389-395.

[6] Ricklefs, R. *The Economy of Nature, 4th ed.* W.H. Freeman and Company. New York. (1997)

[7] Baron, W. and D. Smith. *Growing Season Parameter Reconstructions for New England Using Killing Frost Records, 1697 - 1947*. Maine Agricultural And Forest Experimental Station Bulletin 846, University of Maine, Orono. (1996).

[8] The stations included in this average are Atlantic City, NJ; Blue Hill, MA; Burlington, VT; Eastport, ME; New Brunswick, NJ; Central Park, NY; and Storrs, CT. All data from the United States Historical Climate Network daily dataset, which is available at: http://www.ncdc.noaa.gov/oa/climate/research/ushcn/daily.html

[9] Wolfe, D.W., M.D. Schwartz, A.N. Lakso, Y. Otsuki, R.M. Poole, N.J. Shaulis. 2005. Climate change and shifts in spring phenology of three horticultural woody perennials in the northeastern United States. International Journal of Biometeorology (in press).

[10] Weltsin, J.F., R.T. Belote, N.J. Sanders. 2003. Biological invaders in a greenhouse world: will elevated CO_2 fuel plant invasions? *Frontiers in Ecology and Environment*1(3):146-153. Thomas, C.D. et al. 2004. Extinction risk from climate change. *Nature* 427: 145-148.

[11] Van Vliet, A.J.H., A. Overeem, R.S. Groot, A.F.G. Jacobs, and F.T.M. Spieksma. 2002. The influence of temperature and climate change on the timing of pollen release in the Netherlands. *Intl. J. Climatology* 22:1757-1767. Jager, S, 2003, Global warming: trends in start, duration and intensity of the pollen seasons in Europe. *Allergo J.* 12:314-315. Ziska, L.H., D.E. Gebhard, D.A. Frenz, S. Faulkner, B.D. Singer, and J.G. Straka. 2003. Cities as harbingers of climate change: Common ragweed, urbanization and public health. *J of Allergy and Clinical Immunology* 111:290-295.

12 Ziska L, F. Caulfield. 2000. The potential influence of rising CO_2 on public health: pollen production of the common ragweed as a test case. *World Research Reviews* 12: 449-457.

13 Aono, Y. 1998. Climate change in March temperature deduced from phenologocal record for flowering of cherry tree in Tokyo since the late 18th century. *Bull. Osaka Prefecture University*, Ser.B 50:11-19. Aono, Y., and Y. Omo. 1994. Estimation of temperature at Kyoto since the 11th century using flowering data of cherry trees in old documents. *J. Agric. Meteorology* 49:263-272.

14 Walther, G.-R. et al. 2002. Ecological responses to recent climate change. *Nature* 416:389-395.

15 Bradley, N.L., A.C. Leopold, J. Ross, W. Huffaker. 1999. Phenological changes reflect climate change in Wisconsin. *Proceedings National Academy of Sciences USA* 96:9701-9704.

16 Abu-Asab, M.S. et al. 2001. Earlier plant flowering in spring as a response to global warming in the Washington D.C. area. *Biodiversity and Conservation*. 10:597-612.

17 Hopp, R.J. 1974. Plant phenology observation networks. IN: Leith, H. (ed.) *Phenology and Seasonality Modeling*. Springer-Verlag, Heidelberg, pp. 25-43.

18 A. Lakso, Cornell University, personal communication

19 Zhou, L. et al. 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981-99. *Journal Geophysical Research* 16:20069-20083. Zhou, L., R.K. Kaufmann, Y. Tian, C.J. Tucker, and R.B. Myneni. 2003. Relation between interannual variations in satellite measurements of northern forest greenness and climate between 1982 and 1999. *J. Geophys. Res. Atmos*. 108(D):4004, doi:10.1029/2002JD002510.

20 See: European phenology network site: www.dow.wau.nl/msa/epn; UK site: www.phenology.org.uk; and lilac phenology site in development for the U.S.: www.uwm.edu/~mds/markph.html.

21 Prowse, T. D.: 1994, 'Environmental significance of ice to streamflow in cold regions,' *Freshwater Biol*. 32:241–259.

22 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.

23 Hodgkins, G A, R. W. Dudley, and T. G. Huntington. In Press, Changes in the number and timing of ice-affected flow days on New England rivers, 1930-2000. *Climatic Change*.

24 Huntington, T. G., G. A. Hodgkins, B. D. Keim, 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.

25 IPCC, *Climate Change 2001:The Science of Climate Change*. Cambridge University Press, NY, NY. 2001

26 New England Regional Assessment Group, *Preparing for a Changing* Climate, New England Regional Overview, U.S. Global Change Research Program, 96 pp., University of New Hampshire. (2001)

27 Hodgkins, Glenn A., Ivan C. James II, and Thomas G. Huntington, 2002: Historical changes in lake ice-out dates as indicators of climate change in New England, 1850-2000. *Int. J. Climatol.,* 22 (15), 1819-1827.

28 http://www.erh.noaa.gov/er/btv/climo/lakeclose.html

29 Keim, Barry D., Fischer, Michelle Russo, Wilson, Adam M. 2005. Are there spurious precipitation trends in the United States Climate Division database? *Geophys. Res. Lett.*, Vol. 32, No. 4, L04702 10.1029/2004GL021985.

30 Held, I.M., and B.J. Soden. 2000. Water vapor feedback and global warming. *Annual Review of Energy and the Environment* 25:441-475.

31 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. Section 2.5.1. http://www.ipcc.ch

32 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. Section 2.5.2.1. http://www.ipcc.ch

33 *The New England Regional Assessment: Key Issues and Relevant Case Studies*. US Global Change Research Program. http://www.necci.sr.unh.edu/reports.html

34 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.

35 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001.pp 572-576. http://www.ipcc.ch

36 Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, and J. Lawrimore. 2004. Contemporary changes of the hydrological cycle over the contiguous United States: Trends. *J. Hydrometeor*. 5:64–85.

37 Karl, T. R., R. W. Knight, D. R. Easterling, and R. G. Quayle, Trends in U.S. climate during the twentieth century, *Consequences*, 1, 3 – 12, 1995.

38 Kunkel, K. E., D. R. Easterling, K. Redmond, and K. Hubbard, Temporal variations of extreme precipitation events in the United States: 1895–2000, *Geophys. Res. Lett.*, 30(17), 1900, doi:10.1029/2003GL018052, 2003.

39 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. http://www.ipcc.ch

40 J.G.Titus and C.Richman, 2000, "Maps of Lands Vulnerable to Sea Level Rise: Modeled Elevations Along the U.S. Atlantic and Gulf Coasts." *Climate Research* (in press)

41 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. http://www.ipcc.ch

42 Donnelly, J.P., and M.D. Bertness. 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. *Proc. Natl Acad. Sci*. 98:14218-14223.

43 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. http://www.ipcc.ch

44 Barth, M. and J. Titus. *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation.* Van Nostrand Reinhold Company Inc, (1984)

45 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001. http://www.ipcc.ch

46 NOAA Extended Reconstructed SST data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, www.cdc.noaa.gov. For details on the dataset, see Smith, T.M., and R.W. Reynolds, 2003: Extended Reconstruction of Global Sea Surface Temperatures Based on COADS Data (1854-1997). *Journal of Climate, 16, 1495-1510.*

47 Smith, T.M., and R.W. Reynolds, 2003: Extended Reconstruction of Global Sea Surface Temperatures Based on COADS Data (1854-1997). *Journal of Climate, 16, 1495-1510.*

48 Hamilton, L.C., D.E. Rohall, C. Brown, G. Hayward, and B.D. Keim. 2003. Warming winters and New Hampshire's lost ski areas: An Integrated Case Study. *International Journal of Sociology and Social Policy* 23: 52-73.

49 Post, E., and N. Stenseth. Climatic variability, plant phenology, and northern ungulates. *Ecology* 80:1322-1339 (1999)

50 *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change. Cambridge University Press, UK. 2001.pp 123-124. http://www.ipcc.ch

CLEAN AIR COOL PLANET

100 Market Street, Suite 204, Portsmouth, NH 03801
161 Cherry Street, New Canaan, CT 06840
603-422-6464 • 203-966-5429
www.cleanair-coolplanet.org