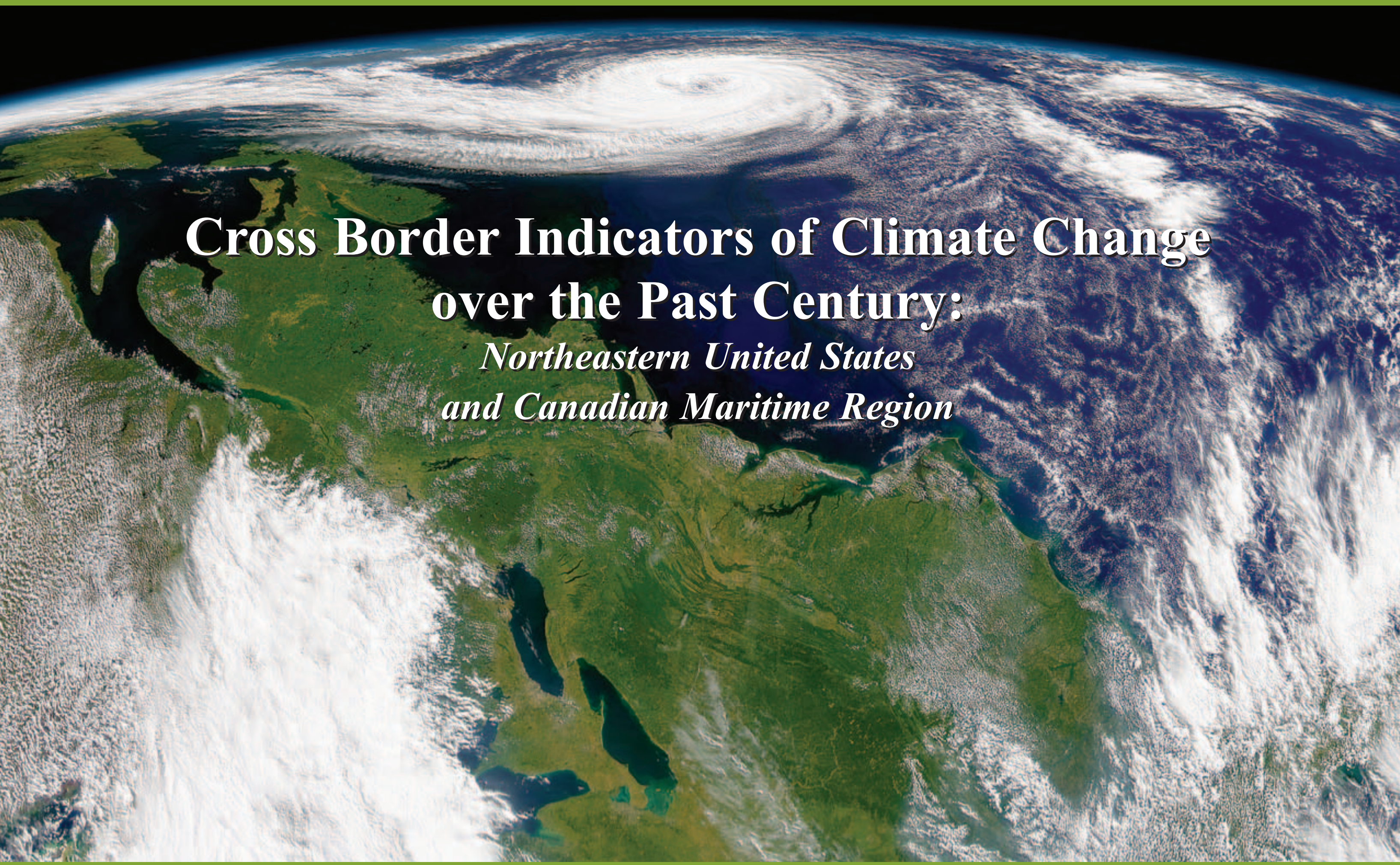

Cross Border Indicators of Climate Change over the Past Century:

Northeastern United States and Canadian Maritime Region

The Climate Change Task Force of the Gulf of Maine Council on the Marine Environment in cooperation with Environment Canada and Clean Air-Cool Planet

Cross Border Indicators of Climate Change over the Past Century:
Northeastern United States and Canadian Maritime Region

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Acknowledgments

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Preface – Climate Change Network Task Force

The Gulf of Maine Council on the Marine Environment has long had an interest in the future impacts of climate change on the health of the Gulf of Maine, so much so that in its 2001-2006 Action Plan it stated…

#8. Convene those working on climate change impacts to develop adaptation strategies, encourage research and disseminate information to managers.

As a result, a Climate Change Network Task Force was set up in 2003 within the Gulf of Maine Council Working Group to move climate change issues important to the Gulf of Maine forward. It became a topic of an Emerging Issues forum in June of 2005 and during that event it was recognized that developing climate change indicators, especially targeted at the Gulf of Maine marine environment, would be instrumental in advising the Council as to the appropriate emphasis to place on the impacts of climate change.

In 2005, it was determined that a comprehensive cross-border report on indicators of climate change in the Gulf of Maine region would be a useful tool for the Council and the public. This first indicators report is intended as a baseline, setting out the current state of understanding and the most commonly used data for understanding climate changes in the Gulf of Maine watershed and region. Because of the importance of changes to the regional ecosystem – for instance, the potential for the spread of a particular pathogen now seen only in Long Island Sound – we have included an area considerably larger than the Gulf of Maine watershed, and indicators reaching beyond the coastal and marine habitats.

As the Task Force moves forward, by setting up a Climate Change Network under the auspices of the Gulf of Maine Council, it will continue to promote climate change indicators as an important element of understanding the health of the Gulf of Maine region.

Introduction

Leading scientists world-wide have identified climate change as the primary threat to the health and sustainability of our natural environment and our social systems. Combine this threat with the impact that human habitation and land-use has had on our environment, especially in the past 50 years, and it becomes obvious that natural ecosystems will be highly stressed over the next 50 to 100 years, with some ecosystems likely collapsing entirely.

To understand the vulnerability of these ecosystems to human activities, our natural environment, including the marine environment, has to be monitored. Engaging in this activity allows us document the changes when they occur and provides the basis for us to study why those changed occur.

But what aspects of the natural environment should we monitor? Is climate change part of that process? Weather in the northeastern United States and the Canadian Maritime region (which we refer to in this report as the cross-border region [CBR]) is as diverse as it is variable as a result of many factors. The most important considerations include the position of the Gulf half-way between the equator and the north pole, both warm (Gulf Stream) and cool (Gulf of Maine and the Labrador Current) water off our the coast, relatively steep elevational gradient, and our position downwind of the rest of continental North America (1).

It is clear that we must help the public and policymakers differentiate the variations in our weather from the trends in climate over the annual to decadal time scales, if we are to work effectively to reduce the threat of global warming. This report is, therefore, designed and written with a general audience in mind, and we have taken pains to make it as available to a range of readers with as broad a background as possible, while maintaining the scientific integrity of the document and research.

As we learn more about the impacts of climate change on our marine environment, it becomes necessary to track climate change to help identify and prioritize those impacts that will have the most effect on that environment. This means we have to choose those indicators of climate change in the environment that will give us a broad measures of change. Some of them are obvious. Temperature has long been a proxy for climate change both globally and regionally. As well, changes in the amount and type of precipitation have been used to identify that change.

In the marine environment, we have to concern ourselves with both the physical and biological indicators that will lead us to better understanding of the overall health of that environment. The primary indicator of physical change is sea surface temperature. As well, we should consider the temperature in the entire water column to get a complete sense of any change that may be occurring. Finally, we should combine these indicators with biological evidence, population decline, population shift within the geographical confines of the Gulf of Maine and the overall health of marine life and the water environment in which it exists.

If we follow these indicators, they will provide us with the information that will inform our decisions in the future and lead us to take action. But this may not be enough. Simply tracking change will only allow us to be reactive to any negative impacts that result. In order to be proactive we will also have to determine what lies ahead by utilizing models and other scientific tools to highlight those aspects of the marine environment most under threat.

To move forward to that goal, the Ecosystem Indicators Partnership was set up to provide information on all indicators of change in the Gulf of Maine marine environment, including climate change. As well, the

Climate Change Network Task Force will be forming a climate change network focused on providing relevant climate change information to the Gulf of Maine Council. This information would include indicators as well as projections of future climates and their potential impacts.

This study is a crucial step toward creating that core of information on climate change indicators. It was recognized, following earlier work, that such indicators had to be viewed regionally, i.e. including portions of Canada, to best describe the results and make them relevant to the Gulf of Maine.

The following work therefore emphasizes that regionality and provides a much more accurate picture of those indicators for use by anyone concerned about the on-going health of the Gulf of Maine.

We have in each indicator used the longest consistently available and most recent sets of data in constructing the analysis. For instance, most of the trends presented here are for the 103-years period from 1900 to 2002, which represents the period for which there are reliable instrumental records for the region from the US HCN and Canadian climate data to investigate regional trends.

We also calculated trends starting in 1970, as that is the time when the global average temperature record begins a warming trend that continues today (Figure 2). This warming trend is likely to have been due to an increase in greenhouse gas concentration in the atmosphere (IPCC, 2001)

Temperatures and other units of measure are presented in centigrade and meters and, in brackets [], Fahrenheit and feet. We have also tried to keep the language as accessible as possible, including where necessary terminology more commonly used in “every day” language along with the scientific terms.

Gary Lines
Cameron Wake
September, 2006

1. Average Temperature 1900 - 2002

Indicator Overview

Temperature is one of most frequently used indicators of climate change and has been recorded at more than 100 stations in the northeastern United States (the New England states [Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont], New York, New Jersey and Pennsylvania) and the Canadian Maritime region (New Brunswick, Nova Scotia, and Prince Edward Island) (Figure 1.1). A few records extend back several hundreds of years; however monthly temperature records from a significant number of stations are only available over the period from 1900 – 2002. These records are used here as one measure of the variability, over time and geography, of the region's changing climate over that time period (1).

Cross Border Region

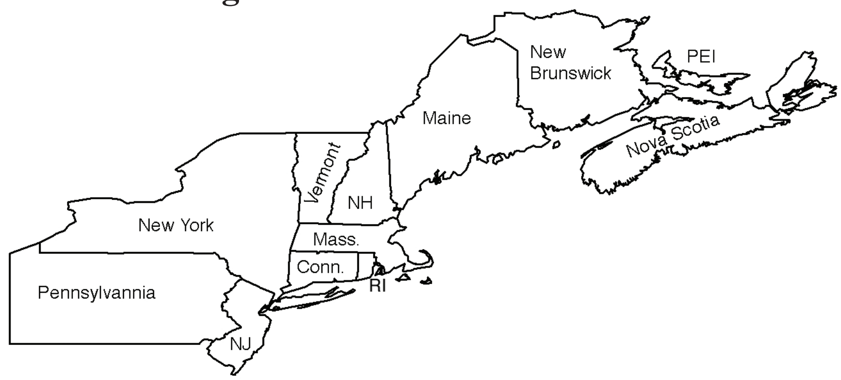

Figure 1.1: The northeastern states and Canadian Maritime provinces that make up the cross-border region (CBR) that is the focus of this report.

Regional Importance

Changes in temperature are the determinant in a range of natural cycles and human impacts. They affect numerous aspects of our daily lives and our region's economy, including emergency management, human health, viability and consistency of electrical power generation and transmission, fuel consumption for heating and cooling, tourism, transportation, and agriculture. Temperature is the determining factor in the length of the growing season, the type and quantity of pests and weeds that can overwinter, the amount of winter snowfall, the number of heat related deaths, and the makeup of the region's terrestrial and marine ecosystems. The National Oceanographic and Atmospheric Administration's National Climatic Data Center (in the United States) and Environment Canada (in Canada) have maintained temperature records from various stations across the region. In the CBR there are 143 stations that have been operating since about 1900, 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 atmospheric concentration of greenhouse gases and other pollutants. Over the last century, average global temperature has increased by about 0.6ºC [1.08° F], in part due to increasing greenhouse gases from human activities (2). Analysis of temperature trends in North America over the past 100 years found that the warming from 1950 to 1999 cannot be explained by natural climate variation(3). Rather the observed trends are consistent with anthropogenic forcing from increasing levels of greenhouse gases and sulfate aerosols.

The average temperature of the CBR reflects the same global influences, but regional temperature is also influenced by regional and local aspects of the climatic system including the passage of different weather systems, storm tracks, fluctuations in the jet stream, topography, changing ocean currents and sea surface temperatures, amount of snow on the ground, and the state of the North Atlantic Oscillation (NAO). The NAO is a large-scale fluctuation in wintertime atmospheric pressure in the North Atlantic ocean between a semi-permanent high-pressure system near the Azores and a semi-permanent low pressure system near Iceland that affects weather patterns in eastern North America and Europe.

Indicator Trend – Average Annual Temperature

Annual average temperature for the CBR shows considerable variability on interannual and longer time scales (Figure 1.2). For example, note the cooler years in 1904, 1917, and 1926 and the relatively warm years in 1949, 1953, 1990, 1998, and 1999. Extended warm periods are also evident, such as the middle of the last century and the 1990s. Cool periods occurred at the beginning of the century and the late 1960s. Over longer periods, there is a clear warming trend over the period of record (4). Based on the linear trend (represented by the red line), the CBR average annual temperature has increased by about 0.8ºC [1.4° F] since 1900 (an average temperature increase of 0.09 ºC [.162° F] per decade). The 1990s were the warmest decade on record. Over the last 33 years, annual average temperatures have increased 1.0 ºC [1.8° F] (an average temperature increase of 0.30 ºC [0.54° F] per decade), a rate three times higher than for the entire century.

The meteorological station data also allow for an investigation of temperature change on a finer spatial scale over specific time periods. As illustrated on the map of the entire CBR (Figure 1.3), almost all of the stations across the region (the exception being a few stations

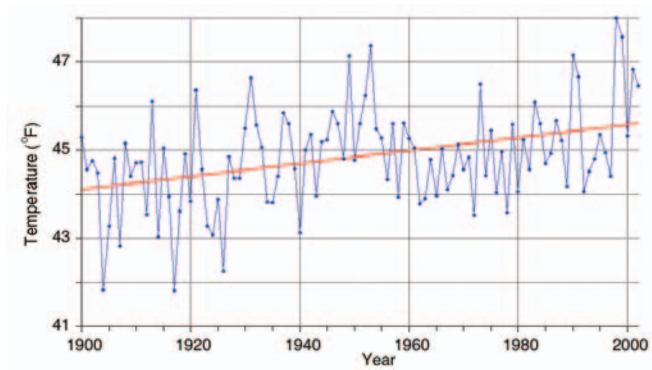

Figure 1.2: Average annual temperature for the CBR, 1900 through 2002. This time-series is a spatially averaged temperature record from 136 stations in the region representing 92 percent of the region's climate zones.

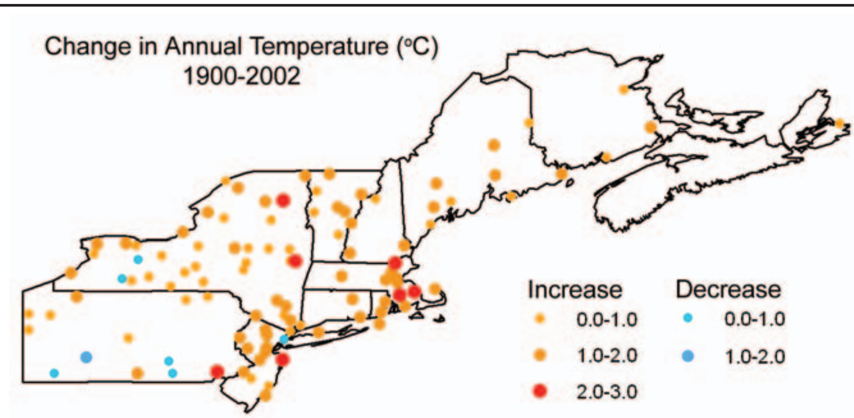

Figure 1.3: Map illustrating the linear trend in annual temperature (°C), 1900-2002 for the CBR. Cooling trends are shown with blue dots, while warming trends are shown with red dots. The change was estimated from a linear regression of annual average temperature for each station.

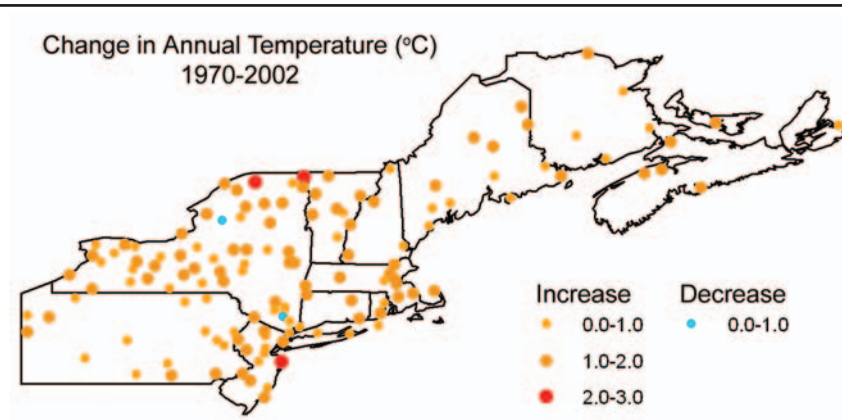

Figure 1.4: Map illustrating the linear trend in annual temperature (°C), 1970-2002 for the CBR. Cooling trends are shown with blue dots, while warming trends are shown with red dots. The change was estimated from a linear regression of annual average temperature for each station.

in southern Pennsylvania and western New York) have experienced an increase in temperature over the 103 year period from 1900 to 2002.

The largest amount of warming over the last century occurred in the coastal region extending from New Hampshire to New Jersey (except for New York City) and in the Adirondacks in the northeast region of New York state. The spatial pattern over the 33 year period from 1970 to 2002 (Figure 1.4) shows remarkably consistent warming temperatures across the region with similar trends in coastal and interior portions of the entire region. If emissions of greenhouse gases continue to increase, it is likely that the Northeast's average annual and seasonal temperatures will also continue to rise. However, due to the uncertainties of future greenhouse gas emissions and the complexity of the response of the climate system, the ecosystem, and our social systems, it is difficult to predict what the exact impacts will be for the region.

Indicator Trend – Average Winter Temperature

The monthly data also allow for the investigation of seasonal trends in temperature. Winter has shown the most significant warming over the past 100 years with average December through February temperatures increasing by 1.4ºC [2.5° F] (Figure 1.5). Even more striking is the 2.4ºC [4.3° F] increase in winter temperatures over the last 33 years (1970-2002). This amount of warming is comparable to the average wintertime temperatures of Halifax, Nova Scotia, being shifted more than 250 km [150.34 mi.] (two degrees of latitude) southward to the "average" wintertime temperatures of Boston, Massachusetts, or of the average wintertime temperatures in Boston being shifted southward to the "average" wintertime temperatures of Philadelphia, Pennsylvania (Table 1).

Almost all of the stations across the region have experienced an increase in winter temperature over the 102 years from 1901 to 2002 (Figure 1.6), with enhanced

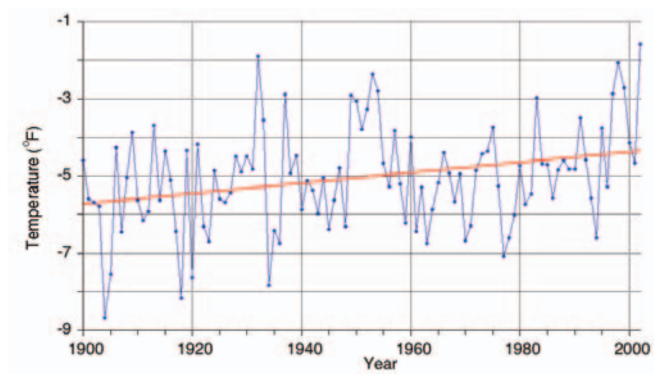

Figure 1.5. Average winter (December – January – February) temperature for the CBR from 1900 through 2002. This time-series is a spatially averaged temperature record from 136 stations in the region representing 92 percent of the climate divisions in the region.

Table 1. Comparison of monthly and winter mean temperatures (ºC) for three coastal cities in the cross border region.

City	Latitude (N)	Dec	Jan	Feb	Mean
Halifax	44.65º	-2.0	-4.5	-5.0	-3.8
Boston	42.32º	0.0	-2.5	-1.5	-1.3
Philadelphia	40.00º	2.5	0.5	1.0	1.3

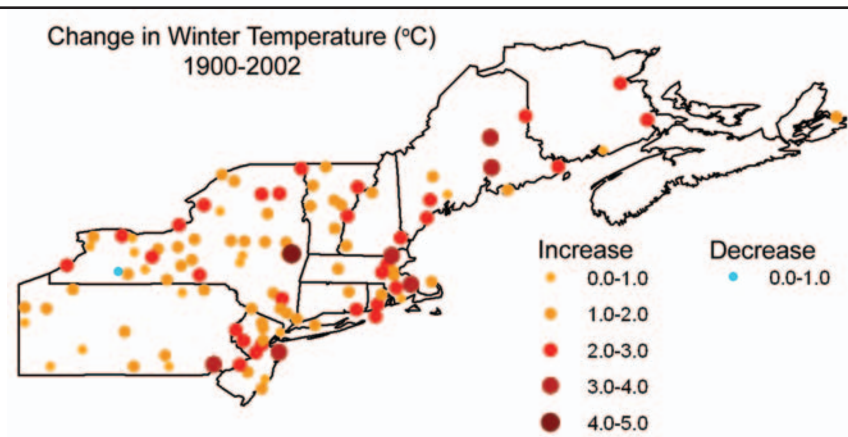

Figure 1.6. Map illustrating the linear trend in winter temperature (°C) from 1900-2002 for the CBR. Cooling trends are shown with blue dots, while warming trends are shown with red dots. The change was estimated from a linear regression of average winter temperature for each station.

warming in the coastal regions. The spatial pattern over the 33-year period from 1970 to 2002 (Figure 1.7) shows remarkably consistent warming temperatures across the entire region. These warmer winter temperatures represent one of the most significant changes in climate over the last three decades in the CBR and are consistent with other winter and spring trends presented later on in this report, including decreasing snowfall and days with snow-on-ground, earlier lake ice-out dates and peak spring flow in unregulated rivers.

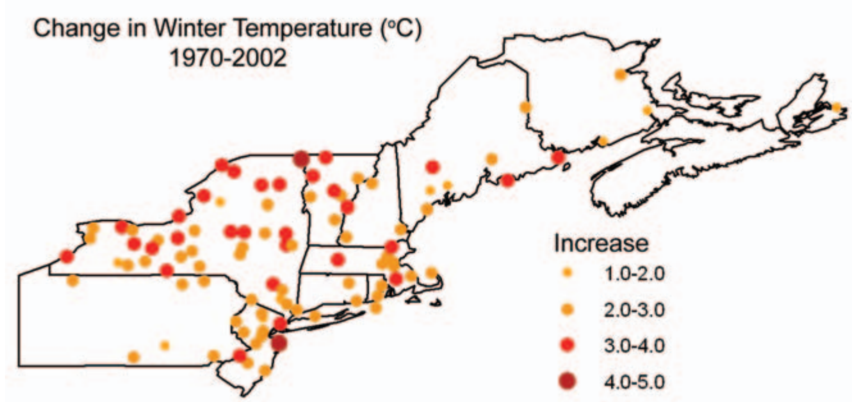

Figure 1.7. Map illustrating the linear trend in winter temperature (°C) from 1970-2002 for the CBR. Cooling trends are shown with blue dots, while warming trends are shown with red dots. The change was estimated from a linear regression of average winter temperature for each station.

The warmer winter temperatures hold important consequences for humans, both economically in terms of winter tourism and recreation, and in public health, as pathogens and pests that were once killed by frost may now "overwinter," expanding their virulence and range. One example of the economic impact is that many smaller ski areas in the southern region of New Hampshire have closed over the past four decades, partially in response to changes in climate (5). An example of the likely public health impact is the expansion of prevalence and range of such diseases as Lyme and West Nile Virus.

2. Average Annual Precipitation 1900 - 2002

Indicator Overview and Regional Importance

Precipitation is critical for sustaining human populations and ecosystems around the world, and this is also the case in the CBR. In our region, precipitation comes in a variety of forms including rain, snow, ice pellets, and freezing rain. Ecological systems depend on precipitation for hydration and human communities depend on the replenishment of water sources for residential, municipal and industrial water supplies and for growing crops. In addition, precipitation is important for the region's tourism economy. More snow in winter is better for winter tourism, and fewer rainy days during the warm season is better for summer tourism. Here, total annual precipitation in the CBR is considered from 1900-2002. This includes rain, freezing rain and frozen precipitation in all its forms as the amount of water equivalent. Previous work has shown that precipitation has been increasing over the past 70 years (1).

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 of the atmosphere because warmer air holds more moisture. (2). Water vapor in the atmosphere is also a critical greenhouse gas. Thus temperature and precipitation are intricately linked in the climate system. Over the past century there has been a 2 percent increase in global precipitation, but that change has not been uniform over time or geography.(3). Precipitation tends to be much more variable over short distances when compared to temperature, and this is reflected in both global and regional records.

Indicator Trend

Precipitation in the CBR has increased by an average of 129 mm [5 inches] (12 percent) over the past century (Figure 2.1). However, just as with temperature, there is significant year-to-year variability in the average annual amount of precipitation that falls in the region. For example, the most significant drought over the past century was during the early 1960s. That drought affected regional agriculture, water quality and quantity, forest health, and human health (4). 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. Since the early 1960s, annual precipitation appears to have become increasingly variable. Despite a decreasing trend in annual precipitation since 1970, this period has also experienced the only four years on record with precipitation greater than 1400 mm [55.12 inches], and eight of the ten wettest years on record. Drought was also an issue during the summer of 2001.

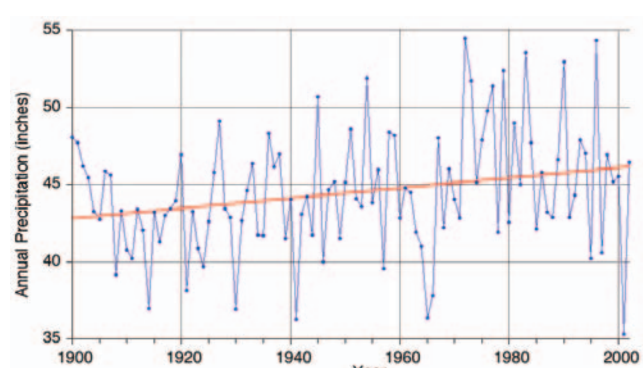

Figure 2.1. Average annual precipitation (mm) for the CBR from 1900 through 2002. This time-series is an aerially weighted average of precipitation records from 133 stations in the region representing 87% of the region's climate zones. Note the drought conditions in 1965-66.

There exists considerable geographic variability in the precipitation records over the past 103 years (Figure 2.2). Some stations adjacent to the Atlantic ocean or the Great

Lakes have experienced an increase of 200 to more than 300 mm [7.8 to 11.8 inches] of precipitation (an increase of 20 to 30 percent), while those in the interior sections of the region show more modest increases or decreases. It is important to note, however, that over the most recent 33 years, almost all of the stations have experienced a slight decrease in annual precipitation (Figure 2.3).

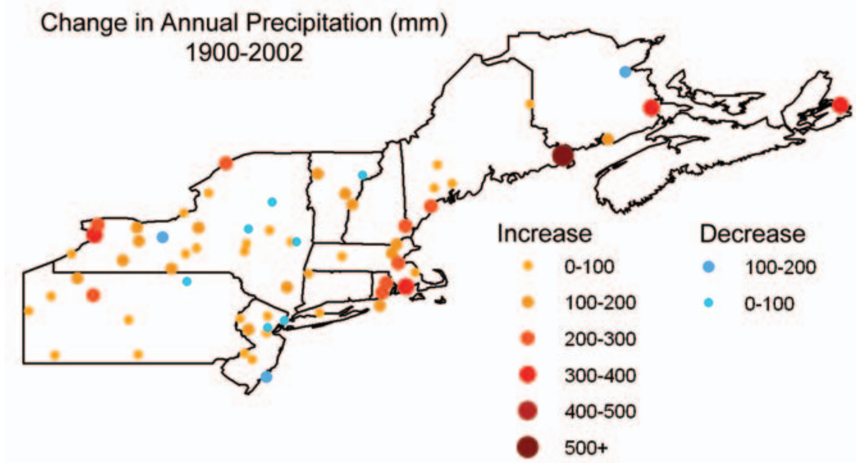

Figure 2.2. Map illustrating the linear trend in annual precipitation (mm) from 1900-2002 for the CBR. Decreasing trends are shown with blue dots, while increasing trends are shown with red dots. The change was estimated from a linear regression of average winter temperature for each station.

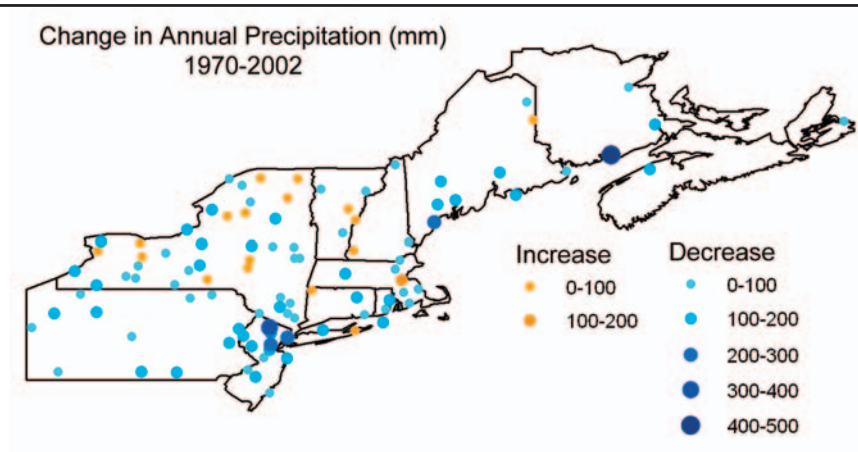

Figure 2.3. Map illustrating the linear trend in annual precipitation (mm) from 1970-2002 for CBR. Decreasing trends are shown with blue dots, while increasing trends are shown with red dots. The change was estimated from a linear regression of average winter temperature for each station.

3. Extreme Precipitation Events 1950 – 2002

Indicator Overview and Regional Importance

The number of precipitation events that resulted in more than 50 mm [two inches] of rain (or water equivalent if the storm results in snowfall) during a 48-hour period is counted for each year for all meteorological stations with daily data. Most of the stations have daily data extending back to 1949. Intense precipitation events, such as those that result in more than 50 mm of rain of precipitation, have the potential to affect significantly agriculture, the built environment, wastewater treatment, and the region's streams and rivers. The average number of extreme precipitation events for the entire region is 2.6 events per year; however this varies across the region with more than four events per year occurring at several coastal sites in Massachusetts and Rhode Island, and some sites in upstate New York, New Brunswick and Nova Scotia (Figure 3.1).

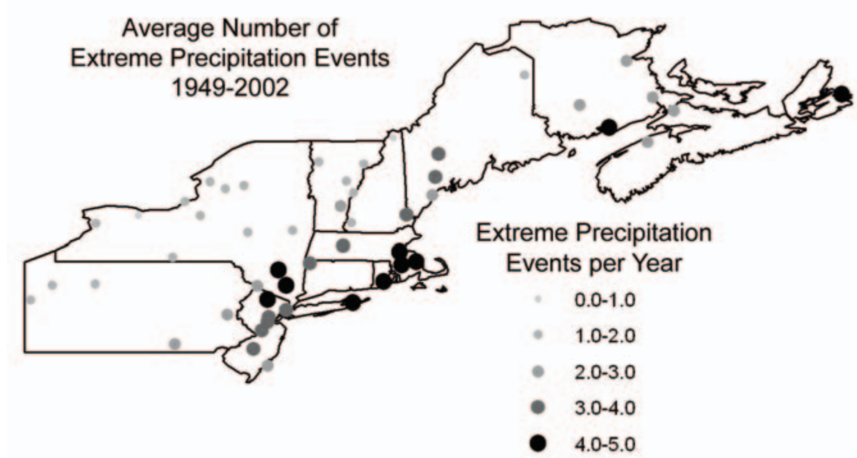

Figure 3.1. Map illustrating the average number of extreme precipitation events by station over the time period from 1949 – 2002.

Sensitivity to Climate and Other Factors

Intense precipitation events are complex phenomena that can result from several different types of weather events. Examples include strong frontal systems where there is a large temperature contrast between air masses, tropical systems (including hurricanes), which gain their energy from warm sea surface temperatures, and air mass instability leading to the buildup of large cumulonimbus clouds (along with thunder and lightening and the possibility of tornadoes), all of which can result in localized heavy precipitation events. 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 an increase in extreme precipitation events (1).

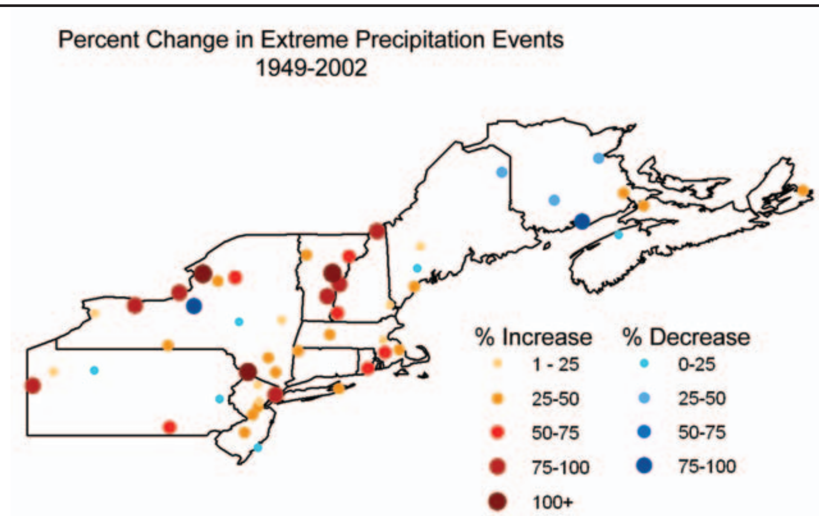

Figure 3.2. Map illustrating the linear trend in extreme precipitation events (percent change over 54 years) from 1949-2002 for the CBR. Decreasing trends are shown with blue dots, while increasing trends are shown with red dots. The change was estimated from a linear regression of extreme precipitation events per year for each station.

Indicator Trend

There is considerable variability in the trend in the number of extreme precipitation events per year across the region (Figure 3.2). Of the 51 stations that contain data for greater that 90 percent of the years since 1949, 36 stations showed an increase of greater than 10 percent in the number of extreme events, while eight stations showed a decrease of greater than 10 percent. Most of the stations showing a decrease are located in the northern part of the region. Conversely, most stations in the southern part of the region showed the most significant increase in extreme precipitation events.

An examination of the records for each station (not shown) reveals a pattern of increasing extreme precipitation events in 1980s and 1990s that is consistent with increases experienced in most of the country (2). 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 (3). However, many stations in the U.S. experienced a frequency of storms in the late 1800s and early 1900s that was comparable to that of the 1980s and 1990s (4). 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.

4. Snowfall and Days with Snow on Ground 1970 – 2002

Indicator Overview and Regional Importance

Total winter snowfall is an important indicator of winter weather. For those living in the CBR, snow is an important factor of everyday winter life. For much of the region, snow is of vital importance to the tourism industry and also represents a key aspect of the region's culture. Many areas rely heavily on income from skiers, snowboarders, and snowmobilers during the winter season, especially in northern New England. Snow removal represents a significant expense for homeowners, municipalities and state/provincial governments across the region, as well as a hazard for transportation. While there are difficulties associated with producing accurate measurements of winter snowfall, our analysis of the best available data indicates there have been changes in snowfall amount in the CBR over the past three decades, with most stations experiencing a decrease in total annual snowfall amounts.

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. 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 (1).

Sensitivity to Climate and Other Factors

Snowfall is a complicated aspect of winter storms. Forecasters often experience difficulty predicting how much snow will fall in a coming storm. This is because snowfall amounts are dependent on complex relationships between the availability of moisture and the temperature at various altitudes, as well as the physical geography in the storm-affected area. Often snow will encounter a warmer (above 0ºC [32° F]) layer in the atmosphere and melt. Once melted, the precipitation may reach the ground as rain, sleet, freezing rain, or ice pellets.

Number of days with snow-on-ground is a useful indicator of overall winter severity. 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.

Indicator Trend – Snowfall

Over the past 33 years, all of the stations in the northern half of the region extending from northern New York through Vermont and New Hampshire and over to New Brunswick and Nova Scotia have experienced a decrease in annual snowfall (measured as snow) of 25 to 75+ cm [9.8 to 29.5+ inches] (Figure 4.1). This decrease in snowfall has important consequences for winter tourism, especially for those outdoor sports that have little capacity to adapt to warmer winters with less snow (e.g., cross-country skiing, snowmobiling, ice fishing). Overall, the southern portions of the region have experienced more modest changes ranging from increases in some regions (e.g. northwestern Pennsylvania) to decreases in other regions (e.g., southwestern New York).

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 snow-to-precipitation ratio (S/P ratio) has been decreasing (2) – that is, the amount of snow, as a percentage of total precipitation, has been decreasing. 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.

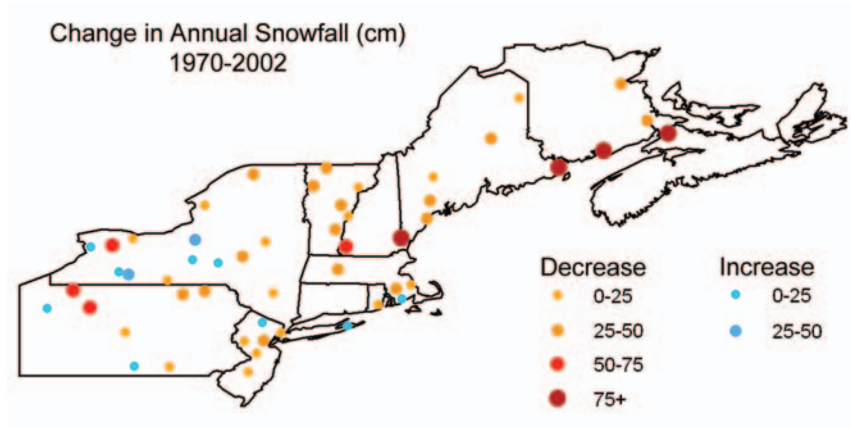

Figure 4.1. Map illustrating the linear trend in snowfall from 1970-2002 for the CBR. Decreasing trends are shown with red dots, while increasing trends are shown with blue dots. The change was estimated from a linear regression of winter snowfall each year for each station.

Indicator Trend – Days with Snow on Ground

Satellite records indicate that snow-cover extent in the Northern Hemisphere has decreased over the past three decades, and the decrease is strongly related to increases in temperature (3). The data from stations in the CBR are generally consistent with the hemispheric trend and reveal a decrease in the number of days with snow on ground (Figure 4.2). Some stations, such as Durham, NH, 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 CBR have experienced an increase in snowfall, the number of days with snow on the ground has decreased.

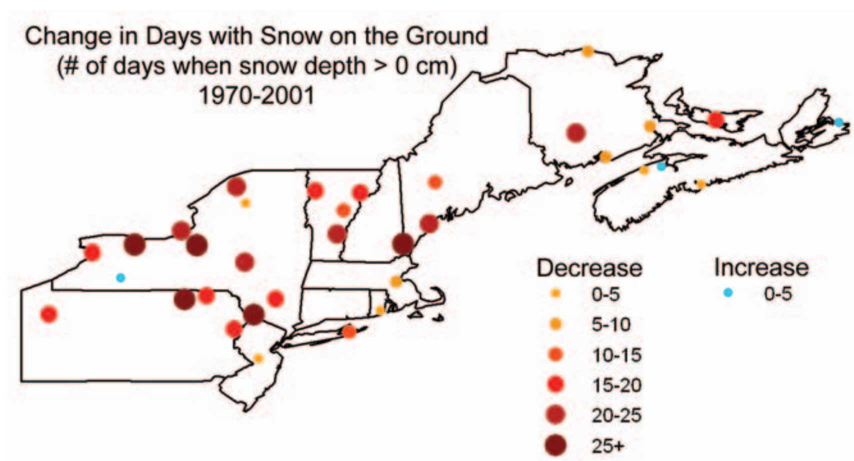

Figure 4.2. Map illustrating the linear trend in days with snow on the ground from 1970-2002 for the CBR. Decreasing trends are shown with red dots, while increasing trends are shown with blue dots. The change was estimated from a linear regression of winter snowfall each year for each station.

5. Timing of High Spring Flow

Indicator Overview

Measurements associated with river discharge make it possible to rigorously and consistently record the timing of high spring flow across the CBR. This data has been collected by the U.S. Geological Survey and Environment Canada using consistent methods for many years on a substantial number of rivers that are free from any significant flow regulation (dams, flood control, sluiceways, impoundments) by human activities. The date marking the point where 50 percent of the water flow occurs during the period January 1 to May 31 (termed the "center-of-volume" date) represents an integrated measure of the response of hydrological systems to climate change in the winter and spring. Here we discuss data for 17 of the longest river discharge records for rural, unregulated rivers in the CBR (1).

Regional Importance

The timing of the delivery of freshwater to estuaries and near coastal marine waters affects 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 (lowest water) 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 (2).

Changes in seasonal flow regime may also influence the timing of migration of anadromous fish. Furthermore, if spring peak migration of juvenile salmon from freshwater rivers (which is controlled by a combination of photoperiod [length of daylight], temperature, and flow) becomes out of phase by as much as two weeks with optimal environmental conditions in rivers, estuaries or the ocean, salmon survival could be adversely affected (3).

Sensitivity to Climate

The date on which half of the total volume of water for a given period has flowed by a river gauging station (the center-of-volume date) is more sensitive to changes in the timing of bulk high-flows in a season than is the date of peak flow. This center-of-volume date, which is determined after the spring flow ends, 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. Warmer temperatures in winter and spring result in earlier winter/spring seasonal center-of-volume dates because of an increased ratio of rainfall to snowfall and an earlier snowmelt.

Indicator Trend

While there is substantial inter-annual variation in the timing of high spring flow, most rivers studied show significantly earlier center-of-volume springtime flows in recent decades.

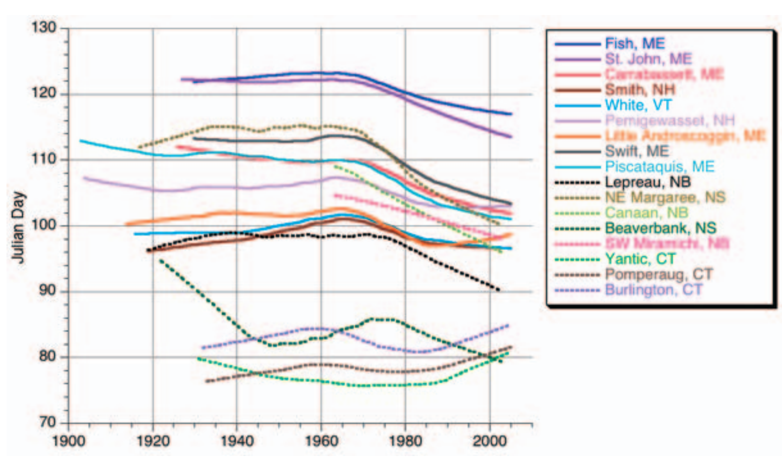

Figure 5.1. Smooths of winter/spring (January 1 to May 31) center-of-volume dates for the 17 longest-record, rural, unregulated rivers in CBR.

The date marking the point where 50 percent of the water has flowed during the period January 1 to May 31 has occurred significantly earlier at all of the sites studied in northern New England and eastern Canada (14 of 17 rivers) for periods ranging from 40 to 95 years through the year 2003 (Figure 5.1). In the northern half of the CBR, where snowfall is highest, the center-of-volume date became earlier by one to two weeks, with most of the change occurring since 1970. Three rivers in Connecticut, a region where rivers are less influenced by winter snowmelt, show a different trend with a recent shift to later center-of-volume flows.

These results are consistent with a recent study of 27 rural, unregulated river gauging stations in New England with an average of 68 years of recording the center-of-volume date, in which 14 sites had statistically significant earlier timing (4). All of the remaining stations were trending towards earlier dates, but these trends were not statistically significant. The center-of-volume date are inversely correlated (r=-0.72) with March/April surface air temperature as expected. The center-of-volume date was not correlated with March/April precipitation, but was weakly correlated with January precipitation.

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. This suggests that these New England spring geophysical and biological changes all were caused by a common mechanism–temperature increases.

6. Lake and River Ice

Indicator Overview

Observations of lake and river ice are tangible, readily available, and technically feasible indicators of local climate conditions in a geographic area (1). Observing the freezing and thawing of lakes and rivers has long been a popular measure of the change in seasons. As well, in an era when scientific monitoring of the environment is suffering from significant funding cuts, this is an observation that can continue to be recorded reliably by non-scientists and volunteers and is thus likely to provide a continually updated indicator of climate change in the region.

There are a variety of measures of ice-in (e.g., start of freezing, majority ice cover, full ice cover, minimum thickness) and ice-out (first open water to appear, major break-up or movement of ice sheets, complete ice loss) While the exact definition may vary from place to place, the definition of ice-in and ice-out for any particular location discussed here has remained consistent over time. In addition, measures of days with ice affected river flow are also available.

The United States Geological Survey office in Augusta, Maine maintains a record of lake ice-out dates for 29 lakes in New England (2). Ice-in dates are available for Lake Champlain from the National Weather Service office in Burlington, VT (3). In addition, other on-line databases offer historical data on ice-in, ice-out, and other aspects of ice for lakes, rivers, and harbors across the CBR (4).

Regional Importance

Used for local commerce and transportation, lakes have been important to people living in the region for centuries. Traditionally, freezing and thawing of water bodies signaled a change in transportation mode and certain economic activities. Today, it is primarily recreational activities (such as ice fishing, cross-country skiing, skating, sled dog racing, snowmobiling, boating, all of which are important for the Northeast's tourism economy) that are affected. Some modes of transportation (e.g., ferries and other lake or river crossing modes) are also affected by the timing of freezing and thawing, while roads and bridges may be affected by associated threats from flooding. Regardless of activity, safety concerns and public interest keep river and lake ice monitoring ongoing, so ice-in and ice-out dates should continue to be a reliable and widespread indicator of our changing climate into the foreseeable future.

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. It is uncertain what the long-term ecological effects of an earlier ice-out date will be. One potential effect of these trends in river ice involves more frequent formation of anchor ice – ice that reaches the bottom of a water body. 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 can restrict or even eliminate bottom water 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(5). 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.

Ice and snow covered lakes and rivers also have a higher albedo (reflecting more sunlight) than open water, so shorter frozen durations could lead to greater heating of these water bodies and adjacent land regions. In addition to the ecological implications, this could also create a positive climatic feedback, helping to accentuate or accelerate climate change and resulting in later ice-in dates in future years.

Sensitivity to Climate and Other Factors

The timing of the freezing and melting of lakes and rivers is primarily driven by the temperature of the air and the water. Other climatic factors affecting the ice-in and ice-out dates include wind speed and direction, and type and amount of precipitation. Ice-in and -out dates may also be sensitive to other factors such as surface and ground water inputs and lake and river circulation patterns.

The methods used to determine the official ice-out day differ from lake to lake and river to river, but generally refer to the last day the lake has significant ice cover, or the last day river flow is significantly affected by ice. The ice-in day is the first day the majority of the lake or river 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 M/S Mount Washington, can safely leave port and motor, unobstructed by ice, to the ports in Center Harbor, Alton Bay, Wolfeboro, and Weirs Beach.

New England Lakes Ice-Out Dates
1925-2005

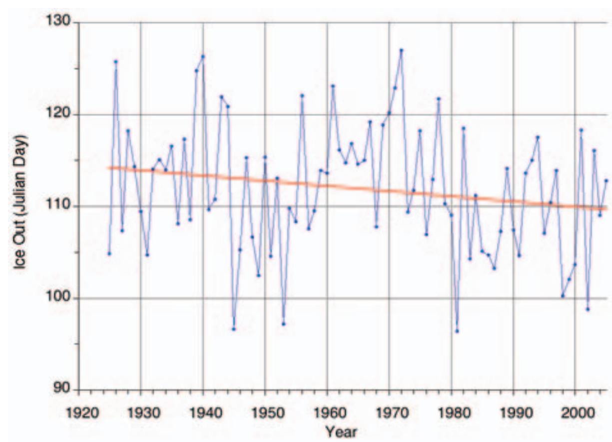

Figure 6.1.: Regional record of mean ice-out dates shows a trend of four to five days over the last 80 years.

Indicator Trend

In New England, every lake with ice-out data shows a trend towards earlier ice-out dates over the length of their record (1). Many of the ice-out records began in the 1920s. The long-term trend of mean lake ice-out dates for New England lakes from 1925-2005 is shown in Figure 6.1. On average, ice-out in the year 2005 occurs four to five days earlier than in 1925, and eight days earlier than in 1970.

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, located in the coastal Maine flood plain 15 miles from the Atlantic ocean, shows an ice-cover decrease of 14 days when comparing the period 1851-1900 to 1951-2000. In addition, Sebago Lake has failed to completely freeze nine times since 1807. Seven of these ice-free years occurred in the last 55 years. The average ice-out date on Lake Winnipesauke, located just south of New Hampshire's White Mountains, occurs almost eight days earlier today than it did in the late 1800s. From 1951-2000, ice-out averaged April 20, a full week earlier than the 1851-1900 average of April 27. Both Moosehead Lake and Rangeley Lake, located at higher latitudes in Maine, have been breaking up earlier.

Lake Champlain Ice-In Dates
1816-2005

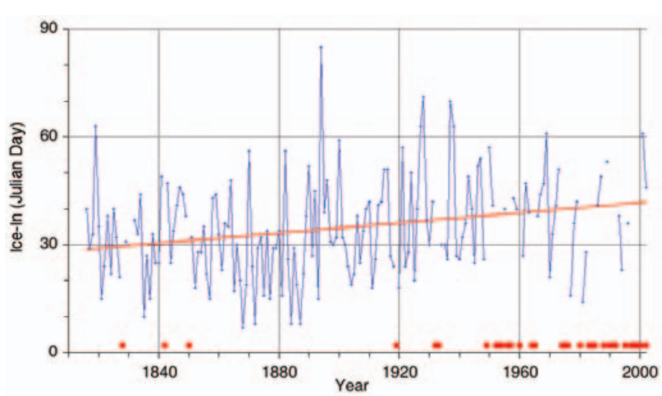

Figure 6.2.:Ice-in date 14 days later over last 190 years. Of 33 years lake has not frozen (•), 18 have occurred since 1970 and 26 since 1950.

Only ice-in records are available for Lake Champlain (Figure 6.2) in Vermont and upstate New York. The ice-in dates have changed over the past 150 years. Today, Lake Champlain freezes over 14 days later than it did in the early 1800s. The most remarkable part of the record is the occurrence of winters when the lake did not freeze at all. Over the 190 year record, the lake has not frozen over in 33 winters, 55 percent (18 years) of which occurred since 1970 and 80% since 1950 (years the lake did not freeze are denoted in the figure with red points). Since 1970, all lakes in New England show earlier ice-out dates, ranging from less than ten days later to greater than 30 days later (Figure 6.3), indicating that the rate of change towards earlier ice-out dates has increased since 1970. In general, lakes farther from the ocean and at higher elevations show smaller decreases in ice-out dates.

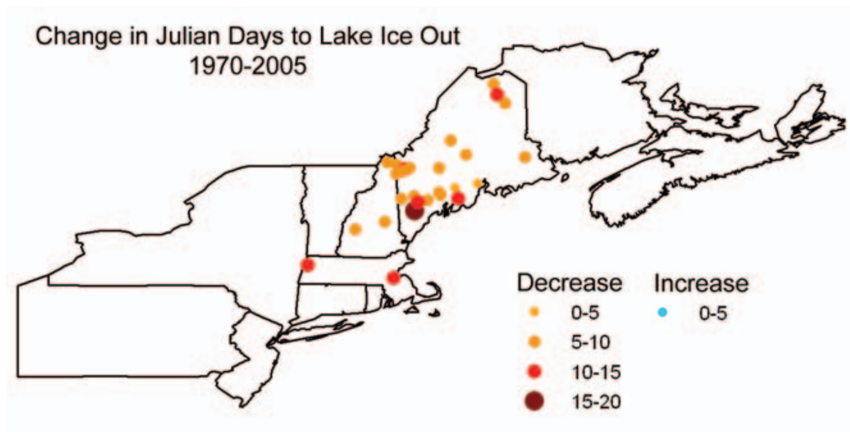

Figure 6.3.:

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. Analysis of lake ice and climate variability indicates that a 1°C increase in air temperature would result in a two to three day delay in ice-in and earlier ice-out (6).

The total annual days of ice-affected flow decreased significantly over the 20th century at 12 of the 16 rivers studied (7) (data not shown here). 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 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 6.1). 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.

7. Growing Season

Indicator Overview

The 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. For our analysis, we have used –2.2 ºC [28 ºF] as the criterion for a hard frost.

Regional Importance

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(1). 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 longer 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 yet longer growing season (2). 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 (3). It is possible that a significant change in the length of the growing season could alter the ecology of the Northeast landscape, including an increase in transpiration, the loss of water vapor from plants, and a consequent decrease in water yield (4), perhaps necessitating more use of irrigation.

Sensitivity to Climate and Other Factors

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

There are two types of frost events, radiative and advective frosts (5). 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 radiative frost. This type of frost generally impacts relatively small geographic regions and occurs mostly in

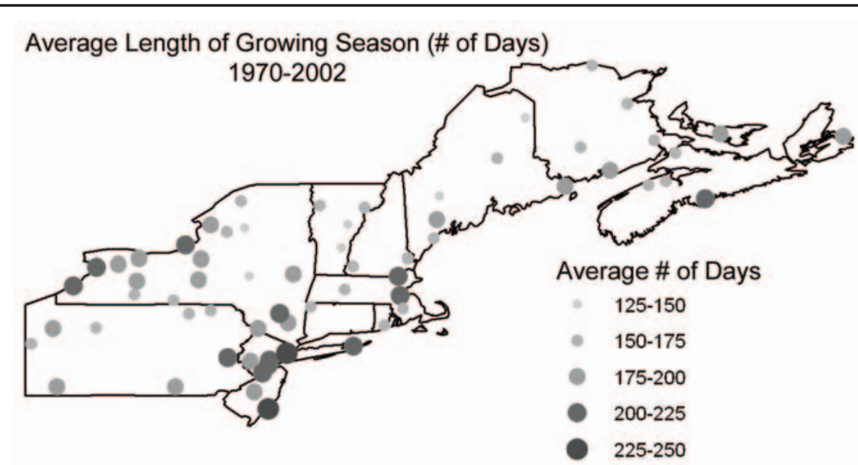

Figure 7.1. Average length of growing season in days across the region.

valleys. Advective frosts are caused by a cold, polar air mass 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 air mass moves through and cools down a region, after which the winds slow down and can create ideal conditions for a radiative frost.

Indicator Trend

Relatively complete (6) daily minimum temperature records are available for the period 1949 to 2002 for 69 stations in the CBR (Figure 7.1). Over the past 33 years, 49 stations have experienced an increase in the length of the growing season by one to 33 days (Figure 7.2). Fully one-quarter of these stations now have a growing season that is, on average, 20 days longer compared to 1970. Twenty stations show a decrease in the growing season length ranging from one to 20 days shorter; 60 percent of these stations showed a decrease of 10 days or less. Overall the data indicates that the growing season is getting longer in western New York state adjacent to Lake Ontario and Lake Erie, in New Jersey, coastal Massachusetts, Maine, and the Canadian maritime region. The longer growing season, in part because of earlier last frost dates in the spring, has resulted in earlier lilac bloom dates in the northeast US, and earlier grape and apple bloom dates in upstate New York (7)

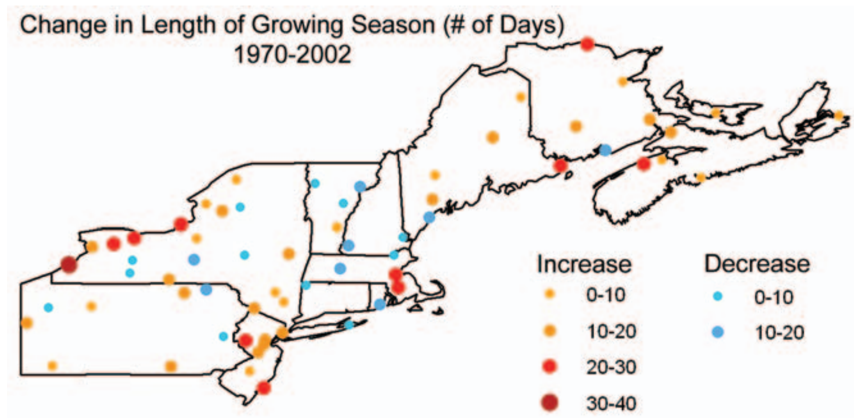

Figure 7.2. Change in the length of the growing season in days over 33 year period from 1970 – 2002.

8. Sea-Level Rise 1856 - 2003

Indicator Overview

Sea level may be influenced by climate in two ways: directly by transfer of heat to the oceans, resulting in thermal expansion of water, and indirectly by accelerating the rate of fresh water input from melting glaciers and ice caps. As the climate warms, both processes will contribute to increasing the volume of water in the oceans and the continuing rise of their surface levels.

Although sea level may change in an absolute sense in response to climate (eustatic, or global, sea level change), relative sea level may also be changing in areas where land level is rising or sinking. This relative sea level change is generally a result of crustal motions up or down following retreat of glaciers. In the Gulf of Maine region, the crust has concluded its post-glacial rebound and is now subsiding again. Thus to use observed sea level rise as an indicator of climate change one must first account for relative sea level changes from crustal movement.

Sea level has been measured in this region using tide gauges at many sites, since the late 19th and early 20th century (1). Other observable and datable measures of sea level change are available. For example, a mooring ring believed to be placed at high tide at the Fortress of Louisbourg on Cape Breton Island in 1743 is now a measurable distance below the current high tide level (Figure 8.1). Clearly, relative sea level has increased considerably over the past 250 years.

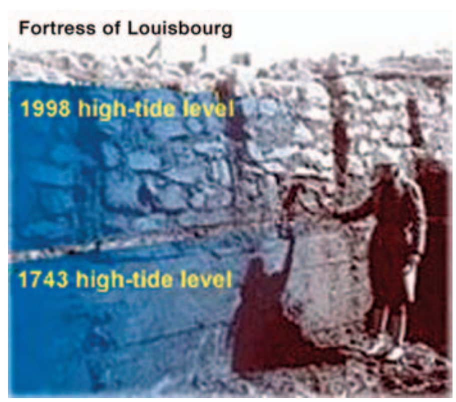

Figure 8.1. Photograph of sea wall at Fortress of Louisbourg in Nova Scotia showing the high-tide level in 1783 compared to the high tide level in 1998. Note the significant rise in the high-tide level over the past two centuries.

Estimates of pre-instrumental sea level rise may be obtained using proxy data (e.g. rates of salt marsh accretion derived from foraminifera [a protozoan common to the region], pollen, and radiometric dating from radioactive decay rates) (2). Using these and other techniques, present rates of submergence or emergence may be estimated. New work (3) by Koohzare et al. suggests the rate of submergence is significantly less than previously thought, with the dividing line between submergence and emergence running though central New Brunswick and along the coast of Maine (Figure 8.2)

Warmer temperatures in the future will likely contribute to the thermal expansion of ocean water and further melting of continental glaciers, raising world-wide sea level even further. Projections for sea-level rise (SLR) in the 21st century are not generally viewed as reliable because there is considerable uncertainty in the likely responses of the Greenland and West Antarctic Ice Sheets to a warming climate.

Regional Importance

As much of the CBR is heavily populated along the thousands of miles of coastline, it is especially vulnerable to a rising sea level. For example, well over 2000 km^2 [about 1,243 square miles] of land in the Northeast US is less than 1.5 meters [almost 5 feet] above the present sea level (4). Rising sea level in the CBR will impact many coastal communities by threatening low lying coastal infrastructure (roads, rail lines, bridges, buildings, wharves, sewage treatment plants, etc.) and possibly inundating coastal aquifers and surface water supplies. Changes in sea level can also contribute to increased erosion and saltwater contamination of freshwater ecosystems (5) and loss of salt marshes and cordgrass. Low-lying shorelines such as sandy beaches and marshes are likely to be the most vulnerable to rising seas. In addition, all of the shoreline glacial deposits in the CBR are vulnerable to undercutting by a rising sea level, possibly resulting in landslides.

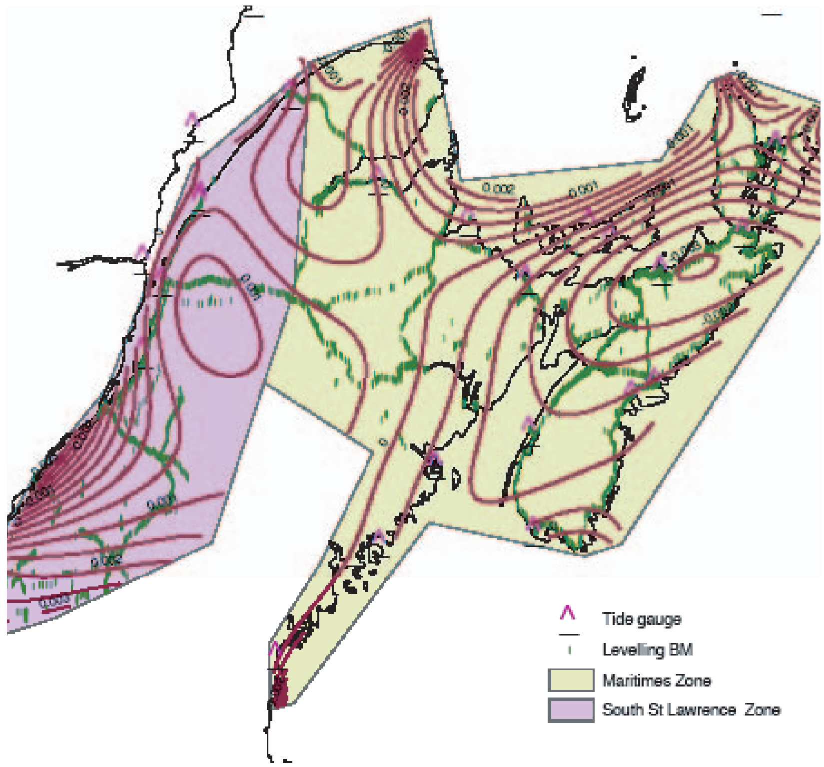

Figure 8.2: Map of vertical crustal movements (m per year) in Eastern Canada compiled using cubic spline polynomials. Figure from (2).

According to a study done by the Geologic Survey of Canada (6), much of the coast line of the Canadian Maritime region is moderately to highly sensitive to sea level rise. This sensitivity can arise from factors such as shorelines made of poorly consolidated (and thus easily erodable) rock, shallowly sloping coastlines (allowing small amounts of sea level rise to travel farther inland), and tectonically submerging land. The upper Bay of Fundy has two locations (Tantramar Marsh and the Grand Pré area) with an additional vulnerability: they are currently below sea level at high tide, as the land was diked by early Acadian settlers several hundred years ago. Coastal communities are more populous and sensitive land is more common on the New Brunswick side of the Bay of Fundy than on the Nova Scotia side. New Brunswick is implementing a coastal protection policy that may help to deal with the expected impacts of sea level rise.

The Bay of Fundy's unusually high tidal range may mask some of the associated impacts of a rising sea level. Because projected sea level rise over the next century is expected to be well within the current tidal range of the upper bay, storm surges, coastal flooding and coastal erosion will only impact previously invulnerable land and infrastructure when they occur at the peak of the tidal cycle. Otherwise, increased impacts will be limited to the intertidal zone. Increasing storm frequency expected with a warming climate may make the confluence of these two events more probable, although the net impacts will still likely be lower than in the outer Bay of Fundy and other regions of the Gulf of Maine with a much lower tidal range.

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 subsidence (sinking or settling) or uplift, thermal expansion, deposition of sediment, and thawing of permafrost are important. In response to warmer global temperatures, the rate of melting of ice sheets and glaciers in the northern hemisphere is increasing and contributing to sea level rise. More important is the expansion of water as it warms.

Indicator Trend

Sea level has risen worldwide more than 120 meters [393.70 feet] since the end of the last ice age, about 18,000 years ago. As the continental ice sheets melted, massive quantities of water were added to the sea. From geological data, it appears that global sea level has been rising at the rate of about 5 mm [.039 inches] per decade for the past 6,000 years – or some 300 mm [about two feet].

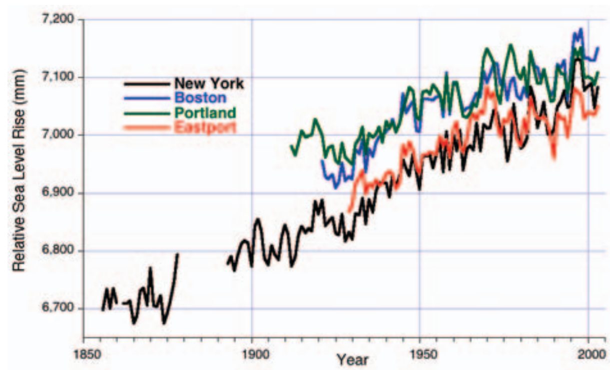

Figure 8.3. Relative sea level rise measured by tide gauges at four cities in the northeast United States.

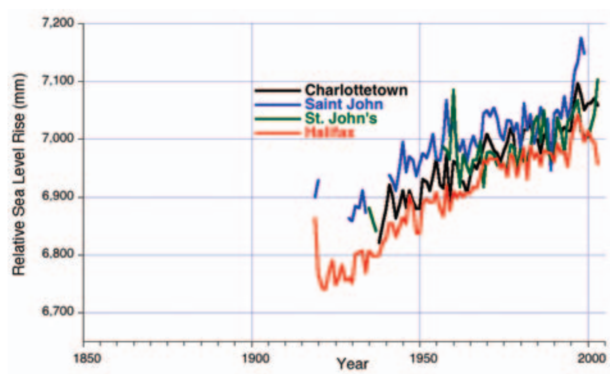

Figure 8.4. Relative sea level rise measured by tide gauges at four cities in the east coast Canadian cities.

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 400 mm [15.74 inches] since 1850 at a rate of about 27 mm [about 1 inch] each decade, with small interannual fluctuations (Figure 8.3). Sea level in Atlantic Canada has risen approximately 250 mm [9.84 inches] since 1920 (Figure 8.4), at a rate similar to that for the northeastern United States. While part of the relative rise in sea level in the coastal areas of the CBR is likely due to the slow geological subsidence of the region (2) part of the relative rise is due to thermal expansion of the upper layers of the ocean due to the 0.4 ºC [.72° F] warming of the past century (7) and net melting of snow and ice worldwide. 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 over the next century lies in the range of 90 to 880 mm [3.54 to 34.6 inches](7), although measurement and analysis of recent significant changes in the dynamics of the Greenland Ice Sheet suggest that sea level may rise much more rapidly than previously predicted (8).

9. Sea Surface Temperature

Indicator Overview

Sea surface water temperature data from buoys, ships, and other platforms from the mid- to late 18th century have been assembled, quality controlled, and made widely available to the international research community (1). This is a review of sea surface temperature (SST) readings from 1854-2002 for four significant ocean regions: south of New York City – Long Island, the Gulf of Maine, south of Nova Scotia and the Gulf of St. Lawrence (Figure 9.1).

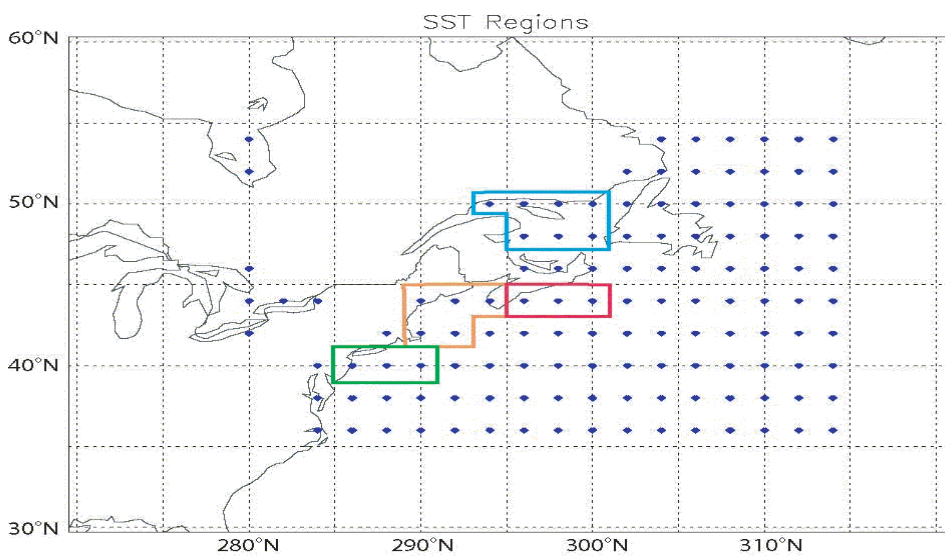

Figure 9.1. Location of the four ocean temperature regions examined here. From north to south they are: Gulf of St. Lawrence (blue), southeast (SE) of Nova Scotia (red), Gulf of Maine (orange), and NY&NJ (green).

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. Over the past century, ocean temperatures have been warming, on average, as a result of heat exchange and flux with the atmosphere. From the mid-1950s to the mid-1990s, global volume mean temperature increase for the 0- to 300-meter layer of the world's oceans was 0.31°C [.56° F] (2). Recent model studies indicate that the Earth (primarily the oceans) is now absorbing more energy from the Sun than is emitted to space (3).

It is generally understood that the oceans respond slower to warming than the atmosphere but, once warmed, are relatively slow to release that heat back to the atmosphere. This creates a lag in response and has led researchers to conclude, as a result of testing various scenarios with global climate models, that heat from the oceans could continue to warm the atmosphere long after greenhouse gases have stabilized.

Sea surface temperature also plays a key role in storm tracking and intensity. For example, warmer than normal surface water south of Nova Scotia likely helped to sustain Hurricane Juan as it crossed water south of Halifax in 2003 (4).

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.

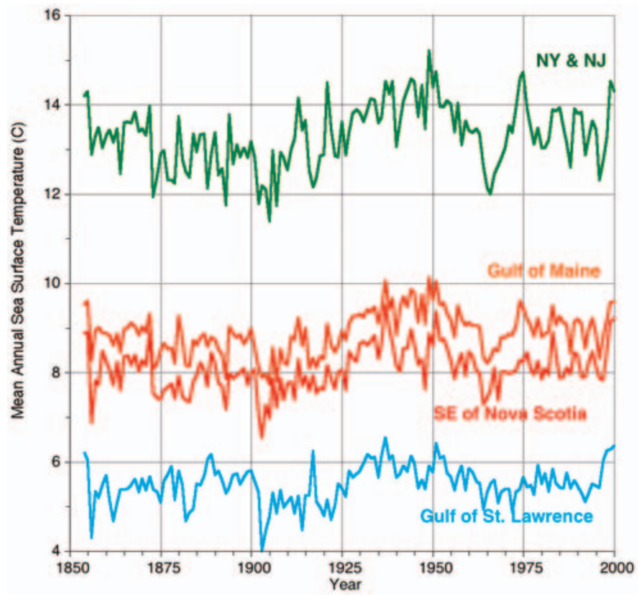

Figure 9.2. Temperature trends over the past 150 years in mean annual sea surface temperature in the four regions.

Indicator Trend

All four marine regions in the western Atlantic examined here have experienced significant annual to decadal scale variability in temperature. (Figure 9.2). From 1880 through the early 1920s, the three most southern regions (SE of Nova Scotia, the Gulf of Maine, and New York and New Jersey) experienced below-average temperatures. Sea surface temperatures then increased during the first half of the 20th century, cooled from about 1950 to 1970, and have then warmed again since 1970. Since the 1970s, the more northern regions (Gulf of St. Lawrence and SE of Nova Scotia) display a higher warming trend compared to the two southerly regions. Also note the cool period in the mid-1960s that is apparent in the three more southerly regions.

Over the past 100 years, the surface water temperature in the four regions has warmed on average from 0.50 to 0.66 ºC [0.90° to 1.18° F] (Table 1), which represents a tremendous amount of excess energy that is being taken up by the ocean's surface waters. The warming trends are higher in the three regions south of the Gulf of St. Lawrence.

Table 1. Trends in sea surface temperature by region.

Location	103 year trend (ºC)	33 year trend (ºC)
Gulf of St. Lawrence	0.50	0.69
Southeast of Nova Scotia	0.59	0.56
Gulf of Maine	0.61	0.21
NY & NJ	0.66	-0.02

10. Landfalling Hurricanes

Background

Tropical cyclones have been a common feature of the Atlantic Basin for hundreds of years. Tracking and forecasting these tropical entities has been the responsibility of the National Hurricane Center (NHC) in Miami, Florida, formed during the preparations for US National Aeronautic and Space Administration's Apollo Moon missions in the 1960s. The NHC not only tracks and forecasts these features but archives information on each storm.

In 1985, after being affected by the remnants of Hurricane Gloria, Environment Canada formed the Canadian Hurricane Centre (CHC), co-located with the Storm Prediction Centre, in Dartmouth, NS. The Centre coordinates with the NHC on tracks of tropical cyclones that could impact Atlantic Canada in order to better advise the general public on the location and strength of tropical features in their area.

Since that time, both the NHC and CHC have been building archived information on storm track and intensity. In the summer of 2005, the Canadian Hurricane Centre released "A Climatology of Hurricanes for Canada". Most of the information originated with the Hurdat database maintained by NHC; it also included storm track information in an easily accessible form and large numbers of tables and graphics for use by clients. Figures 10.1 to 10.5 are taken from that climatology.

Technical Description (from the Canadian Hurricane Centre website)

Tropical cyclones (known as hurricanes and tropical storms in the Atlantic Ocean, typhoons in the Pacific Ocean and cyclones in the Indian ocean) can be very powerful and destructive storms. This type of storm usually develops over oceans 8° to 15° North and South of the equator.

An intense tropical cyclone is an almost circular storm of extremely low pressure and high winds. Winds spiral inward at high speed, accompanied by heavy rainfall. Tropical cyclones can range in size from only a few hundred kilometers [less than 200 miles] across to more than 1000 kilometers [621 miles] across for a monster hurricane. Tropical cyclones have three distinctive parts: the eye, the eye wall and spiral rain bands.

A tropical cyclone will progress through a series of stages. It begins as a tropical disturbance: a large area of organized thunderstorms that maintain their identity for more than 24 hours. If the area of thunderstorms organizes so that a definite rotation develops and winds become strong, the system is upgraded to a tropical depression. At this point, a low pressure centre exists and it is given a number.

If winds continue to increase to 63 kilometers [39 miles] per hour, the system becomes a tropical storm and is given a name. The storm becomes more organized and the circulation around the centre of the storm intensifies. As surface pressures continue to drop, the

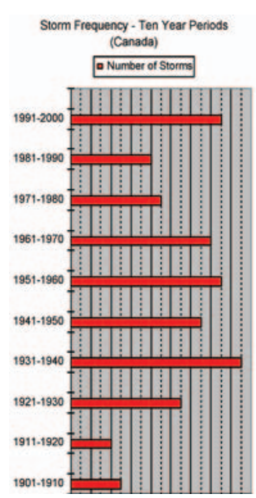

Figure 10.1. Decadal Storm Frequency

storm becomes a hurricane when wind speed reaches 118 kilometers [74 miles] per hour. A hurricane will begin to dissipate when the storm passes over cooler waters and will continue to dissipate as it moves over land because its energy source (the warm water) is missing.

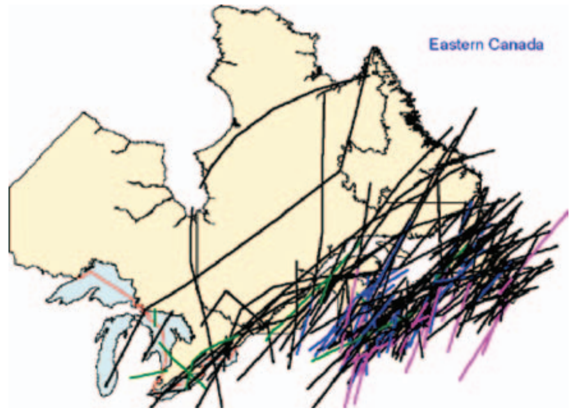

Figure 10.2. Storm Tracks Eastern Canada

Historical Frequency

The entire region has experienced tropical cyclones since 1950. Figures 10.1 and 10.2 provide evidence that tropical cyclone frequency has been variable over the length of record. Figure 10.1 provides a look at the decadal variation in that occurrence and, over the 100 years of that record, suggests a cyclical pattern. No specific trend can be extracted from the record other than to say that the Atlantic Basin is currently experiencing an active period that, based on the record, can be expected to continue for about another ten years.

Figure 10.2 provides some geographical perspective on the tracks of these cyclones over Eastern Canada. Once again no specific trend is indicated but it is clear that Eastern Canada and the northeastern US are vulnerable to landfall from these events.

Landfalling Hurricanes as Indicator

Atmospheric scientists are in agreement that the Atlantic Basin has returned to an extended period of heightened hurricane activity, as evidenced by the decade 1995 to 2005 recording the highest frequency of tropical cyclones of any decade on record.

Tropical storms of hurricane strength receive considerable media and public attention when making landfall. These storms carry winds in excess of 63 knots (117 km/h [73 m/h]) and some wind-related damage is expected. For example, deciduous trees are vulnerable during the warm weather months where full leaf provides surface area that allows the wind to exert considerable force. This is combined with the fact that, during hurricane season, the ground is not frozen, making trees more vulnerable to uprooting. All tropical and extra-tropical storms can result in heavy rainfalls over short periods of time with flooding being a common problem.

Hurricane intensity is identified by number utilizing the Saffir-Simpson scale. These numbers were calculated from archived maximum wind speeds.

Current maps of the occurrence of these landfalling hurricanes only exist as separate documents for Canadian and US locations. Figure 10.3 illustrates the points at which hurricanes have crossed provincial boundaries over the entire record (1851-2003). Figure 10.4 is a close-up look at the province of New Brunswick. While these maps are designed to illustrate the impacts to New Brunswick, the tracks and provincial entry

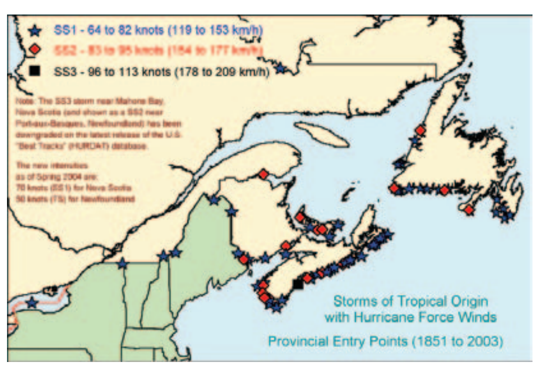

Figure 10.3. Provincial Entry Points – Hurricane Force Winds (1851-2003)

points also apply over the State of Maine.

Information on landfalling hurricanes is also available through the US National Oceanographic and Atmospheric Administration in the US. Figure 10.5 illustrates the specific storms that have made landfall since 1950.

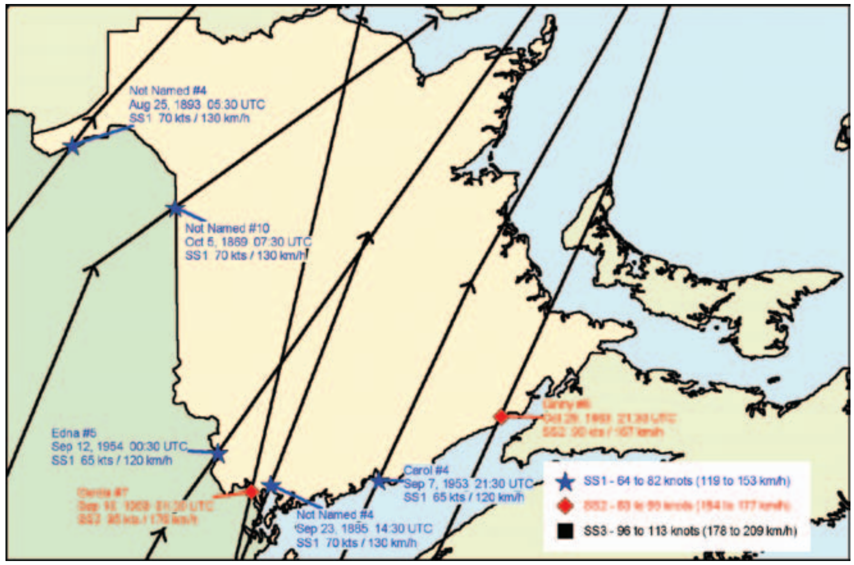

Figure 10.4. NB Entry Points

All of this information provides us with an historical view and suggests our current vulnerability to the impacts of these storms. However it does not provide information on how many more hurricanes we can expect in the future or where they will specifically occur. Work has been done to calculate statistics on where the highest probability of occurrence will be (Tropical Meteorology Research Project, Colorado State University) but these statistics have not taken climate change into account.

At this time, the scientific consensus is that the intensity of hurricanes will increase with increasing global warming. This is predicated on the understanding that the oceans will continue to be heated by an ever-warming atmosphere and that heat will be transferred as energy to tropical systems.

Figure 10.5. Continental US Landfalling Hurricanes (1950-2004)

However there is no consensus or any specific indication that the number of storms, including landfalling hurricanes, will increase in the future with global warming. There is also no specific indication that tracks of these storms will change.

Following the intensity of the storms from one season to the next may provide some insight into the impact of climate change on the nature of these storms.

11. Sources of Meteorological Data and Data Analysis

US Historical Climatology Network Data – Temperature and Precipitation Records

The temperature and precipitation data used in this report for stations in the US are a subset of the United States Historical Climatology Network (USHCN) (Karl et al., 1990; Easterling et al., 1999; Williams et al., 2005). USHCN data represent the best available data for investigating changes in temperature and precipitation since 1900 as the stations were selected based on length and quality of data, which includes limiting the number of station changes. In addition, monthly data have undergone numerous quality assurances and adjustments to best characterize the actual variability in climate. These adjustments take into consideration the validity of extreme outliers, time of observation bias, changes in instrumentation, random relocations of stations, and urban warming biases (2). Missing data are estimated from surrounding stations to produce a nearly continuous data set for each station.

US HCN data are available online from the US NOAA National Climatic Data Center (ftp://ftp.ncdc.noaa.gov/pub/data/ushcn/) or from the US Department of Energy http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html.

Canadian Climate Data – Temperature and Precipitation Records

A database of homogenized and long-term temperature time series has been specifically designed for climate change analyses over Canada. For this indicator analysis, the data consist of daily maximum, minimum, and mean temperatures for 15 stations across Atlantic Canada. Series extend back to 1895 where possible. The original data include daily station temperatures extracted from the National Climate Data Archive. It was necessary in some cases to join short-term station segments to create long-term series.

Using a technique based on regression models (3), annual maximum and minimum temperature series were tested for relative similarity (homogeneity) with respect to surrounding stations. The methodology involves the identification of dissimilarities (inhomogeneities) in the temperature series, which are often non-climatic steps due to station alterations (including changes in site exposure, location, instrumentation, observer, observing program, or a combination of these). Monthly adjustments were derived from the regression models, and adjustments were applied to bring each homogeneous segment into agreement with the most recent homogenous part of the series (4). Daily adjustments were derived from an interpolation technique using the monthly adjustments (5). Whenever possible, the main causes of the identified inhomogeneities were retrieved through historical evidence such as the inspector reports.

For daily precipitation, the methodology for correction of systematic biases can be improved when performed on daily rain gauge and snow ruler data. Part of the adjustment methodology was based on procedures developed for six hourly synoptic station data by Metcalfe et al.(1994). Since their methodology was designed for a different time-step and purpose, several modifications had to be implemented. (6)

Station history files were searched thoroughly for: date of any relocation; installation date of all rain gauges; introduction date of the six hourly measurement program and; introduction date of hourly weather type measurement program. Computerized metadata files were created for each station to aid in the task of correction. For the selected stations, daily total rainfall (gauge) and snowfall (ruler) measurements were extracted from the Canadian National Climate Data Archive for the maximum available interval. The data was then corrected based on changes in observational techniques, measurement apparatus and application of rain-snow density conversions in order to remove non-climatic inhomogeneities. (7)

Monthly data can be downloaded from the Adjusted Historical Canadian Climate Data web site noted below.

http://www.cccma.bc.ec.gc.ca/hccd/

Spatial Averaging

Annual and seasonal temperature and precipitation trends for the northeast states (Connecticut, Maine, Massachusetts, New Hampshire, New York, New Jersey, Pennsylvania, Rhode Island and Vermont) and eastern Canadian provinces (New Brunswick, Nova Scotia, and Prince Edward Island) were calculated using the monthly mean data. First, an arithmetic mean was calculated using the monthly temperature data for all the USHCN stations in each of the National Climatic Data Center climate divisions, of which there are 38 in the study region, ranging from 1 to 10 per state (Figure 11.1)(8). We treated PEI and Nova Scotia as single climate divisions, and we separated New Brunswick into a coastal (land below 400 meters [1312.34 feet] above sea level [asl]) and an inland (land above 400 m asl) climate divisions. Next, we calculated a single region-wide mean for the entire CBR based on the mean values for each climate division, with proportional weighting based on the area of each of climate division (Table 1). No weight was given to climate divisions with no stations.

Figure 11.1. NCDC climate divisions for the NE states, used here as the basis to calculate NE-wide mean temperature and precipitation values.

Table 1. Area of climate divisions used for developing regional averages.

State or Province	Climate Division	sq. miles	sq. km	State or Province	Climate Division	sq. miles	sq. km
CT	1	1014	2625	NY	8	2950	7637
CT	2	3251	8416	NY	9	7303	18907
CT	3	744	1926	NY	10	4918	12732
ME	1	17916	46382	PN	1	3269	8463
ME	2	10307	26684	PN	2	1922	4976
ME	3	4992	12924	PN	3	4384	11350
MA	1	1578	4085	PN	4	2770	7171
MA	2	4217	10917	PN	5	4851	12559
MA	3	2462	6374	PN	6	4035	10446
NH	1	2864	7415	PN	7	4397	11383
NH	2	6440	16672	PN	8	3595	9307
NJ	1	2877	7448	PN	9	8205	21242
NJ	2	4381	11342	PN	10	7906	20468
NJ	3	578	1496	RI	1	1214	3143
NY	1	4298	11127	VT	1	4854	12566
NY	2	9062	23460	VT	2	3177	8225
NY	3	7050	18252	VT	3	1579	4088
NY	4	1814	4696	NB	coastal	22829	59198
NY	5	6375	16504	NB	inland	2131	5527
NY	6	2732	7073	NS		18732	48574
NY	7	3074	7958	PEI		1962	5087

Analysis of Trends in Climate Indicators

Most of the trends presented in this report cover time periods of the last 103 years (1900 to 2002), or the 33 years (1970-2002). The 103-year trends represent the period for which there are reliable instrumental records for the region from the US HCN and Canadian climate data to investigate regional trends. We also calculated trends starting in 1970, as that is the time when the global average temperature record begins a warming trend that continues today (Figure 11.2). This warming trend is likely to have been due to an increase in greenhouse gas concentration in the atmosphere (IPCC, 2001)

Any time a specific year is

used to calculate a long-term trend, there is a chance that the choice of year may influence the magnitude of the trend. This can be especially problematic if the year chosen to begin the trend was a period of very high or very low temperature or precipitation. In order to determine how sensitive the trends we have calculated over the two time periods are to the start year, we performed a "sensitivity analysis" by calculating trends over 98 to 108 years, using a range of start years from1895-1905, and for trends over 28 to 38 years using a range of start years from 1965-1975. Sensitivity analyses were performed for annual temperature, winter temperature, snowfall, the number of days with snow on the ground, and precipitation. A trend was considered robust if the sign and magnitude of the trend remained consistent regardless of the year the time series was started. The criteria we used to define "consistent" for each of the climate indicators we investigated are listed in Table 2. If these criteria were not met for a particular station for a particular indicator, the data for that station is not shown in the figures and is not used to calculate the regional trend.

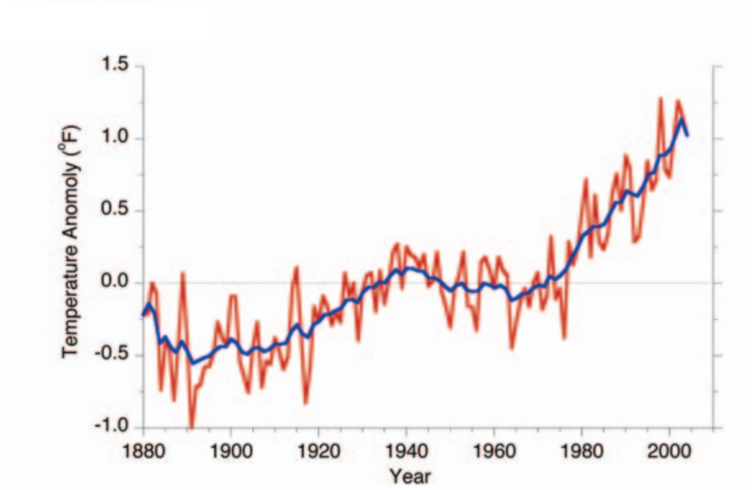

Figure 11.2. Global average annual temperature from meteorological stations. After Hansen et al., 1999. J. Geophysical Res. Vol 104, p. 30,997. Data from http://www.giss.nasa.gov/data/update/gistemp/

The robustness of the regional 103-year trends for annual temperature and winter temperature was evaluated by comparing trends using a range of start years, 1895-1905. The robustness of the 33-year trends was evaluated using the range 1965-1975. The trend (Δ ºC over time) was estimated from the slope of linear regression applied to the time series. The same was done for the 103-year individual station trends for annual temperature and winter temperature.

In general, all of the trends for regional temperature (annual and winter temperature over 103 and 33 years) are robust and show consistent increasing annual and winter temperature trends regardless of in which year the time series began. Individual station trends were also found to be robust for both annual and winter temperature trends over the past 103 years, with fewer than no exceptions. The regional and individual station 33-year annual and winter temperature trends were also found to be robust, again with few exceptions at 13 individual stations for mean winter temperature, and at 6 individual stations for mean annual temperature.

Table 2. Criteria used to determine robustness of trends in climate indicators

Indicator	Criteria: 103 year trend	Criteria: 33 year trend
Regional Averages		
annual temperature (°C)	± 0.1	± 0.1
winter temperature (°C)	-0.4 and +0.1	-0.1 and +0.5
annual precipitation* (mm)	-9 and + 23	-46 and + 68
Individual Stations:		
annual temperature (°C)	-0.3 and +0.2	-0.4 and +0.6
winter temperature (°C)	-0.7 and +0.2	-0.8 and +1.4
annual precipitation* (mm)	-90 and +110	-90 and +110
snowfall (cm)	n/a	-30 and +60
days with snow on ground (days)	n.a	+ 13

* for precipitation, sensitivity analysis did not include 1965, which was a year of very low precipitation at the core of the 1960s drought.

The 33-year trends in the number of days with snow on the ground were found to be robust at the individual station level, with the exception of three stations (two in New Jersey and one in Pennsylvania). The 33-year trends in winter snowfall were less robust. Of the 67 stations with relatively complete data, 16 were not used because the records were not robust.

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