Executive Summary

Purpose

The New England Regional Assessment (NERA) is one of 16 regional assessments, conducted for the U.S. Global Change Research Program (USGCRP), as part of the National Assessment of climate change impacts on the United States. The National Assessment was conducted in response to the Congressional Act of 1990, at the request of the President's Science Advisor. The purpose of this regional assessment of potential climate change impacts on the New England Region (the six New England states plus upstate New York) is to provide a local perspective on a global issue. The intent in producing this *Foundation* document is to provide the most current insight on the topic of climate change, focused on local issues and concerns, in a relevant and accessible format of use to the public.

The overall goal of the NERA was to determine the potential impacts of future climate change by evaluating selected sectors (Forests, Water Resources, and Human Health) considered to be of importance to the New England region. For each sector we considered:

- the *current stresses* on these key sectors;
- how *additional stresses* associated with potential climate change and/or variability would impact these sectors;
- the *missing pieces* (knowledge and/or data) needed to more fully understand the potential impacts and how best to adapt to them;
- reasonable *adaptive strategies* that could be employed to reduce these impacts; and
- where possible, win/win approaches to adaptation, so that the impact of climate change is minimized and additional benefits are realized.

From the beginning, one of the goals of the assessment was to engage as many stakeholders as possible in the process. In so doing, a dialogue was initiated between research scientists, policy makers, and the general public. Regarding the important issue of climate change (past, present, and future) and its impact on the New England region, stakeholder feedback was instrumental in the identification of key sectors, specific regional concerns, perceived vulnerabilities, knowledge/data gaps, research needs for the future, and possible adaptive strategies. Well over 300 stakeholders, representing a broad range of interests, participated in the NERA effort.

The New England Regional Assessment (NERA)

The New England Regional Assessment (NERA) was initiated in September 1997, with the *New England Climate Change Impacts* Workshop, held at the University of New Hampshire (UNH). Additional Sector-specific Workshops were held in 1999. As defined by the National Assessment, the New England Region includes the six New England states (CT, MA, ME, NH, RI, and VT) and upstate New York. The NERA effort has been supported by the National Science Foundation, and focused on the analysis of existing data rather than initiating new studies.

Much of the region is heavily forested, but also includes some of the most productive agriculture (NY), especially cold-crop production, in the nation. The region has several major population centers, such as Buffalo, Albany, and Boston, but is noted for its rural setting and natural landscapes. When people think of the region, they envision spectacular fall foliage displays, winter activities such as skiing, and maple syrup production – all of which are highly sensitive to climate variables. While the common perception is of clean mountain air and sparkling streams and lakes, the reality is a region plagued by frequent episodes of poor air quality, polluted rivers, and seasonal red tides.

Stakeholders participating in the NERA identified the three key Sectors (Forestry, Water Resources, and Human Health) for detailed consideration, and three key concerns or issues likely to affect these Sectors if climate change continues (Air Quality, Seasonal Dynamics, and Extreme Weather Events). The Final Report of the NERA is offerred in two forms: A *Foundation* document (this report) consisting of peer-reviewed research papers, and an *Overview* document consisting of summary statements and concepts taken from the *Foundation* document. Both documents are organized as follows. Following an introduction to key concepts (Chapter 1), necessary background information is provided on those factors which characterize the region's notorious weather (Chapter 2). The factors, both natural and anthropogenic, known to affect climate at the global and regional scale are presented in Chapter 3, and the two global climate models selected for use in this assessment are presented in Chapter 4. Detailed treatments of the Sectors are presented in Chapters 5 (Forests), 6 (Water Resources), and 7 (Human Health). Chapter 8 presents an analysis of the social and economic impacts that climate change will likely have on three regionally-important issues: the fall foliage display, regional tourism, and human health.

The Format

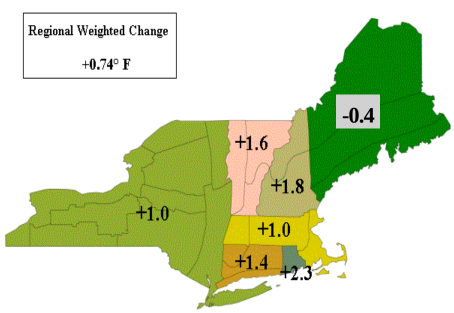
The format of this *Foundation* document of the NERA Final Report is designed to convey maximum information content in a technical and detailed manner. Each Sector Chapter is divided into *current stresses, additional stresses associated with potential climate change, missing pieces,* and *adaptive strategies.* Illustrative Case Studies are included in each Sector Chapter, again to provide the reader with a detailed treatment of how the Sectors are affected by present or future climate change. While many additional Case Studies could have been included, we selected only those which were illustrative of the effects of air quality, seasonal dynamics or extreme events. For the sake of readibility, temperatures are given in °F.

The Key Findings

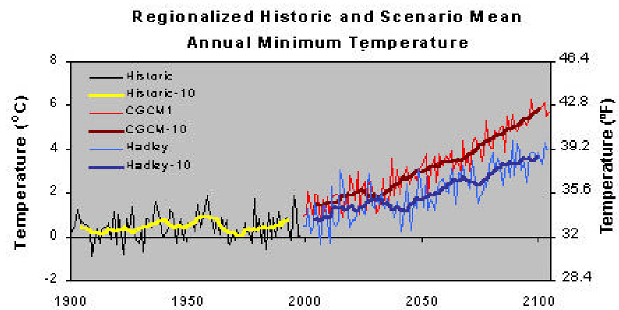
In the process of conducting the NERA, key findings were clearly identified.

- **The Regional Climate Has Changed Over the Past Century –** In an analysis of the historic temperature and precipitation records, by region and by state, the evidence indicates that the climate *has* changed over the past century (1895-1999). Overall, the region has warmed by 0.7° F, yet some states (RI, NH) have warmed by two to three times the regional average and one state (ME) has cooled. Warming in winter months (a regional increase of 1.8° F) has been greater than summertime warming (0.5° F increase for the region). Regional precipitation has exhibited a modest (4%) increase over the same time period, but as with temperature, the change has not been uniform across the region. While Maine's precipitation has decreased by 12%, Massachusetts' has increased by nearly 30%. We do not understand the heterogeneous nature of these historic trends.

New England & New York Temperature Changes (°F) Between 1895 and 1999



- **The Models Project Significant Warming Over the Next Century** – The two models used in this regional assessment project varying degrees of temperature and precipitation increase by 2090. The Hadley Model projects a warming of 6° F in annual minimum temperatures and a 30% increase in precipitation for the region, while the Canadian Model projects a 10° F warming in minimum temperatures and a 10% precipitation increase (punctuated by periodic, long-term droughts) over the next century. Both models project a significant warming and a moderate to significant increase in precipitation. It is important to recognize that these models provide "what if" scenarios for us to consider. Either temperature increase would be greater than any climate variation experienced by the region in the past 10,000 years. If either scenario occurred, the climate of the New England region would be profoundly different than the climate of today.



- **The Impact of a Few Degrees Temperature Increase** – Although a 6-10° F increase may not seem to be very significant, a comparison of present-day temperatures is instructive. If 6 °F were added to Boston's 30-year average annual temperature (an average of 51.3 °F between 1961-1990), the resulting temperature would approximate the 30-year annual average for Richmond, VA (57.7° F). If 10° F were added to Boston's 30-year average, the 30-year average for Atlanta, GA (61.3° F) would result! An annual average increase of 6-10° F would have a profound impact on the climate of the region.

- **Human Activities are Affecting Climate -** Our understanding of the factors, both natural and anthropogenic, which influence climate has improved dramatically over the past several decades. There is now strong scientific evidence that the global warming experienced in the last half of the 20th century is attributable to human factors including the build-up of greenhouse gases in the atmosphere. This finding is consistent with the idea that continued build-up of greenhouse gases will lead to additional climate change in the future.

- **The Past and Present Changes Have Clearly Impacted the Region** - Many changes (milder winters, earlier maple sap flows, reduced snowfall, etc.) are likely to have occurred as a result of a "minor" increase in wintertime temperature (1.8° F for the entire region). The 6-10° F temperature increases projected for the region by either climate model used in this assessment must be viewed as serious.

- **Regional Air Quality May Worsen –** Stakeholders identified air quality issues as the single most frequent regional concern. One significant finding of the assessment is that physical climate and chemical climate are closely related. Hot, dry summer months are ideal for converting nitrogen oxides (NO_X) from automibile traffic and volatile organic compounds (VOCs) into ground-level ozone, a major component of smog. The same conditions provide the environment for power plant emissions of sulfur oxides (SO_X) to form sulfate haze. Both SO_X and NO_X combine with atmospheric water vapor to produce acid clouds and acid rain. If the climate becomes hotter and wetter, and automobile and power plant emissions remain the same or increase, regional air quality and acid rain problems will become worse in the future.

- **Such Future Warming Trends Would Profoundly Change the Sectors** – All three sectors analyzed in this assessment would be significantly impacted under the scenarios of climate change presented by the models. The human health impacts - both direct (health effects of poor air quality) and indirect (warmer winters facilitating expansion of Lyme disease-carrying deer tick habitat) - of physical and chemical climate change are likely to be the most significant. The Forest Sector, already under stress, will likely continue to be the most flexible and adaptive. The potential droughts (in the Canadian scenario) and/or flooding (the Hadley scenario) would have profound impacts on regional water quality and warming coastal waters will experience species shifts and toxic algal blooms. Sea-level rise will become a significant problem for low-lying coastal regions (Cape Cod, coastal areas of CT, RI, MA, NH, and ME), affecting both human infrastructure and coastal wetlands.

- **The Economic Impacts –** A very limited assessment of the economic impact of climate change was conducted on natural resources, tourism, and health care industries. The major conclusion from this intitial economic analysis is that the impacts of climate change will vary and be significant. The economic impacts will be greatest on the Human Health sector, intermediate on tourism and least severe on the Natural Resource Sector. This initial economic assessment has identified the need for a more extensive analysis of a broader range of Sectors.

Missing Pieces

In the process of conducting the NERA, it was found that often something was missing, that if present, would have allowed a more complete assessment. Some missing pieces are technical and will require additional research, other missing pieces are simply a matter of needing to analyze existing datasets. Together these include:

- **A Regional Climate Model -** The National Assessment required each region to use two global climate models (Hadley and Canadian) as a minimum basis for their assessment of potential future conditions. However, because of their coarse scale, these models were down-scaled to better fit each region. Since the models were designed as global climate models, they do not capture important fine-scale characteristics of the region (land cover, topography, etc.). A regional climate model parameterized for the New England region was not available for this assessment, but was recognized as a very important missing tool for future assessments. A significant research effort will be needed to produce a regional model from the ground up.

- **A Focused Research Effort –** The heterogeneity, both spacial and temporal, characterizing the current warming trend for the region is not well understood. A focused research effort is needed to identify and quantify those factors responsible for this heterogeneity.

- **An Expanded Economic Analysis –** A more thorough economic impact analysis, focusing on all sectors and accounting for expanded multiplier factors, is needed. The limited economic assessment conducted for the NERA had a narrow focus on only a few segments of the Forest, Tourism, and Human Health Sectors.

- **Public Knowledge about Climate Change –** The general public is often skeptical regarding climate change issues. The public believes that: 1. scientists don't agree on how and if climate change is happening; 2. the problem, if it occurs, will be 50-100 years in the future; and 3. the problem has no solution. All of these are false assumptions and must be addressed in a responsible and understandable way.

- **The Need for Educational Materials –** There is a present lack of clearly-stated (in plain English), well-documented educational materials for both the general public and the K-12 classroom. Such materials are key to informing the residents of the region about the potential impacts of climate change in the future. Such materials, once developed, must be made available to teachers, informal educators, policy makers, and the general public. Education was a recurring theme at all workshop discussions. It was agreed that education must start early if we are to change people's understanding, attitudes, and behavior – when you educate a third grader, you also educate the parents and grandparents of that student.

Adaptive Strategies

Given the nature of these findings, it will be important to identify and prioritize strategies for reducing uncertainties and mitigating potentially adverse impacts. Some actions that accomplish these goals may have other benefits to the region and are called "win-win" strategies. A partial list of "win-win" actions includes:

- Promoting the development of more extensive and efficient use of regional forests as carbon sequestration (enhanced CO_2 uptake and storage) tools, as well as more productive sources of wood products.

- Improving air quality by reducing CO_2, NO_X, and SO_X emissions, thus improving the human health and forest health, as well as lowering greenhouse gas emissions.

- The development of high efficiency/alternative energy sources that not only reduce CO_2 emissions but also other by-products (air pollutants).

- Investing in "green technologies" that reduce both CO_2 emissions and industry/business liabilities, thus strengthening their good neighbor image and creating a stronger regional manufacturing presence.

Next Steps

To address the above issues and concerns, a positive approach should be taken. By focusing on win-win strategies and avoiding "gloom and doom" predictions, we must begin to present a clear and compelling message to the public. Appropriate next steps include:

- **Development of an Expanded Regional Assessment –** Based on the results from this limited assessment, it would be prudent to conduct an expanded assessment that considers more sectors and improved tools, such as a regional climate model. Given the pace of the problem and the rapid developments in science and technology, such an expanded assessment should be conducted every 5-10 years. This assessment should include a more extensive economic analysis.

- **Reduction of CO_2, SO_X, and NO_X Emissions (Better Air Quality) –** Most steps taken to reduce CO_2 emissions will also reduce air pollutant emissions (SO_X and NO_X) as well. Such improvements in air quality across the region will bring benefits to human health and forest health. Such reductions will not only improve air quality, but would also reduce acid rain impacts, further improving forest health. Hybrid automobiles and alternative home energy systems offer such benefits.

- **Promotion of the Forests of New England as Potential Carbon Sinks (Sequestration) –** Forests are potentially significant carbon storehouses and the heavily forested New England Region could contribute to national efforts to reduce atmospheric CO_2 levels. The actual extent to which regional forests are able to act as CO_2 sinks in the future will depend on air quality, soil nutrient status, tree species sensitivity to temperature and moisture regimes, and other factors. Additional research is needed on this issue in order to fully understand the extent to which forests can provide carbon sequestration capabilities.

- **Development of Forest Management Practices to Maximize Carbon Sequestration –** Recent studies have identified the significant role that past land use practices have played in contributing to the present carbon storage capacity of regional forests. Developing future strategies to maintain or enhance current carbon storage capacity will be important. Not only will carbon storage capacities be improved, but economic benefits to the region would also result.

- **Development of Economic Incentives to Promote Alternative Energy Options –** Serious efforts need to be focused on creating economic incentives to promote the development of alternative energy options appropriate for the region. Solar-based and wind-based strategies should be considered and past regional reliance on water-power could be re-introduced. Due to our coastal location tidal action could prove to be a significant source of energy generation. These and other options will need to be supported by tax credits, subsidies, etc.

- **Development of Land Cover Strategies Which Minimize Climate Impacts –** Since forested land cover can act as strong absorbers of solar energy, a more focused effort is needed to educate the general public on the multiple benefits of maintaining and enhancing the region's forests.

- **Conduct Impact/Risk Assessments to Minimize Potential Climate Impacts –** As with other potential risks (flooding, fire, storms, etc.) state and regional efforts are needed to address climate change risks identified in this report. Even in the face of perceived or real uncertainties, appropriate steps must be taken to reduce the risks posed by future climate change and variability.

- **Provide Broad Public Access to Information –** A series of hardcopy documents (such as this NERA report) are needed for distribution to a wide range of audiences. These hardcopy documents should include colorful, descriptive and compelling materials, designed for the public, not the scientist. Multifold Sector-specific brochures are needed, providing key graphics, major findings, and main take-home lessons in plain English for distribution to a general audience. A list of "Things You Can Do" must be provided at both the general level as well as for specific Sectors.

- **Make Difficult Decisions in the Face of Uncertainties –** While there are uncertainties associated with climate change issues, there is still a great deal of consensus among the scientific community regarding these issues. The uncertainties should not lead to inaction. Rather, rational steps should be taken to identify risks and make efficient decisions. Decision making in the face of uncertainties about the future is commonplace in people's daily lives and businesses.

- **Focus on the Things We Can Change –** While many factors, both natural and human-induced, are known to affect the climate, we have no control over the natural factors. We do have control over the human-induced factors and must now consider what direction our future climate will take. The future is in our hands.

The New England Regional Assessment of The Potential Consequences of Climate Variability and Change

A Final Report

Appendices

Chapter 1

The New England Regional Assessment – An Introduction

By: Barrett Rock

1.1. The New England Regional Assessment

The purpose of this "*Preparing for a Changing Climate - The Potential Consequences of Climate Variability and Change; New England Regional Foundation*" document is to provide regional examples of positive and negative impacts of both recent and future climate events. Our regional climate has changed over the past century and the changes are likely to intensify over the 21st century. This report also provides examples of local strategies that may be necessary if the current climate trends continue. Taking a local view of the potential impacts that a changing climate may have on the New England region (including upstate New York) is an important first step in identifying local needs and coping strategies, improving public understanding, and identifying local and regional issues that need further study.

One way of assessing the impact of potential change in climate conditions for the New England region is to identify the current stress factors (climate-related or otherwise) impacting the region today. By looking, sector by sector, at the current stressors, one can better evaluate future climate impacts by asking the questions "How would a change in climate (warmer, wetter) influence these sectors in the future?" and "Would the change improve the current conditions, or in combination with the current stressors, would conditions worsen?" We also offer appropriate coping strategies useful in dealing with the impacts of climate change if it occurs, and identify areas where more information would be needed to better understand impacts and how to adapt. We will use this approach in the New England Regional Assessment.

This assessment of the current and potential future impacts of climate change on the New England region has been conducted as part of a larger National Assessment effort, entitled "*Climate Change Impacts on the United States – The Potential Consequences of Climate Variability and Change.*" The National Assessment was mandated in 1990 by the U.S. Congress, and has been coordinated and conducted by the U.S. Global Change Research Program (USGCRP), a multi-agency effort, in response to a request from the President's Science Advisor. The National Assessment *Overview* document was published in December 2000. The findings of the New England Regional Assessment (NERA) are presented in the following chapters.

The New England Regional Assessment effort began with the New England Regional Climate Change Impacts (NECCI) workshop, held at the University of New Hampshire on September 3-5, 1997 (*www.necci.sr.unh.edu*). The purpose of the NECCI Workshop was to initiate a dialogue with the general public, regional and national experts, and governmental agencies on regional climate change issues and the potential impacts on the six New England states and upstate New York. The NECCI Workshop, and a follow-on series of NERA Workshops, were conducted to assess our current state-of-the-science understanding of the potential consequences of climate variability and change on the New England region, as well as to identify areas for which more information is needed. In addition, it is our intent to present our findings in terms that are relevant and meaningful to the general public.

Often, when climate change issues are considered, examples given are either not relevant to the citizens of the region (melting glaciers and permafrost in Alaska, disastrous flooding in Venezuela, droughts in the southwestern United States, etc.), or seen as unrelated to regional concerns (tropical deforestation). One of the suspected culprits in the climate change debate is the emission of man-made greenhouse gases, and people assume that these greenhouse gases come from industrial sources located in mid-western states, and thus, are beyond regional control. In addition, a common view is that global warming is global in scale and it is not obvious to the average person how local action could have any impact on such a large-scale problem. Finally, for the citizens of the New England region, global warming might not be so bad, since few other than winter sports enthusiasts would mind milder winters and longer growing seasons. This NERA Final Report has identified climate change impacts on the New England region that go well beyond the effect on human comfort. Climate change, if it does occur as projected, will fundamentally change both the character and the quality of life in the New England region; and thus, these potential changes must be seriously considered.

To generate the New England Regional Assessment Final Report, we have directly involved regional experts/stakeholders as active participants and contributors in discussions of climate change and its potential impacts on the region. Regional issues were identified by participants during the regional assessment workshops. The Regional Assessment Team and Steering Committee (see Appendix 1) have prioritized the regional issues and identified important regional Sectors (Forests, Water Resources, and Human Health) considered to be especially sensitive to climate variability.

Three of the four Sectors were addressed in separate regional workshops focused on Forests, Water Resources, and Human Health. These workshop summaries are presented as Appendices. Findings focused on current stresses, potential climate impacts, coping strategies, and missing pieces, and are organized into Sector Chapters (Forests, Chapter 5; Water Resources, Chapter 6; and Human Health, Chapter 7). In addition to assessing the current impacts of a changing climate, the NERA has analyzed future possible climates using the climate scenarios (Chapter 4) provided by the National Assessment Synthesis Team (NAST), as well as socioeconomic scenarios for the New England Region (Chapter 8).

The key issues identified by stakeholders are illustrated using relevant Case Studies in each of the Sector Chapters. In order to be included, each key issue or Case Study needed to meet three criteria: (1) they are important to the New England region; (2) they exhibit a clear connection to either physical or chemical climate impacts; and (3) each Case Study was well-documented and well-understood, based on existing data. The key regional issues and illustrative Case Studies are presented in Table 1.1 below.

Chapter 2 gives the reader a better understanding of the geographic, topographic and climatic conditions which make the New England Regional weather so unique. Chapter 3 presents our current understanding of those natural factors (variations in solar output, planetary position relative to the sun, etc.) and anthropogenic factors (greenhouse gases, land cover change, etc.) which are known to influence our weather and climate. Chapter 9 presents the key findings of this New England Regional Assessment.

The New England Regional Assessment is available in two versions. The NERA Final Report is published in a detailed version, subjected to scientific peer review and entitled the *Foundation* Document (this document). A much shorter version, called the *Overview* Document, contains the key points and major highlights of the NERA Foundation Document. Both are available to the general public, both in hard copy form and on the Web at www.necci.sr.unh.edu.

1.2. The National Assessment

Overall Goal: The overall goal of the National Assessment was to analyze and evaluate what is known about the potential consequences of climate variability and change for the Nation in the context of other pressures on the public, the environment, and the Nation's resources. A large emphasis was also put on public engagement to improve understanding of the needs and concerns of the average citizen, as well as how best to educate the public about the potential impacts of climate change.

The main purpose of the National Assessment is to prepare citizens for possible future changes in climate. By involving a broad range of stakeholders, scientists, and the general public in addressing the effects of climatic change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems and biodiversity, the USGCRP was charged with producing an assessment of the current scientific knowledge and potential impacts for the US Congress and the American people. The National Assessment report will then be used as a baseline for developing future research needs and policy. In addition, the outcomes of this assessment provided input to the Third Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC).

To implement the National Assessment, the USGCRP selected five national-level sectors and 16 regions (including the New England region) to begin the task of assessing climate change and variability impacts. The five sectors chosen by the National Assessment (Agriculture, Forests, Human Health, Water Resources and Coastal) were selected based on their national importance and the 16 regions determined based on common geography and socioeconomic characteristics. For this reason, the National Assessment Office determined that upstate New York should be com-

Table 1.1. Key Issues and Relevant Case Studies

Key Issues	Case Studies
Air Quality	Forest Health Impacts (ground-level ozone) - Chapter 5 Human Health Impacts (Hiker Health Studies) - Chapter 7
Seasonal Dynamics	The Maple Syrup Industry - Chapter 5 The Effects of Warming on Snow - Chapter 6 Climate Impacts on Lyme Disease - Chapter 7 The Relationship Between the Winter NAO and Streamflow - Chapter 6 Climate Variability and Winter Flounder Abundance - Chapter 6 Species Migration - The Loss of Sugar Maple in New England - Chapter 5
Extreme Weather Events	The 1998 Ice Storm Damage - Chapter 5 The 1960's Drought - Chapter 6

bined with the New England States. The USGCRP was charged with synthesizing the outcomes of the various sectors and regions to produce the National Assessment report for President Clinton and Congress that was released in 2000.

- **Regions:** Regional activities have focused on the issues of most importance to each region across the United States. The New England regional effort began with a scoping workshop (NECCI), followed by three activities: (1) follow-on sector-specific workshops to conduct quantitative analyses of the 3 key issues; (2) continuous engagement of regional stakeholders; and (3) the publication of the *Overview* and *Foundation* documents of the New England Regional Assessment report in 2001.

- **Sectors:** Sectoral assessments were focused on issues that are national in scope and related to the goods and services on which people, society, and the economy of each region depend. The National Assessment focused on five sectors: **Agriculture, Coastal Areas and Marine Resources, Forests, Human Health,** and **Water Resources**, while the New England Assessment focused on the **Forests, Water Resources,** and **Human Health** Sectors.

- **National Synthesis:** A Synthesis Report (the National Assessment *Overview* and *Foundation* documents) was produced which integrated key findings from the regional and sectorial assessments and addressed overarching questions related to implications of climate variability and change over the next 100 years, as called for in the 1990 Congressional mandate. Both National Assessment documents, are available on the Web at: www.nacc.usgcrp.gov.

1.3. Important Climate Change Concepts for the New England Region

The New England region is dominated by ever-changing weather and physical climate, and residents have come to expect to be able to "work around" their weather. They also expect their weather forecasts to be reasonably accurate, and their weather predictable. Recent weather-related events have raised public awareness that the "typical" New England weather may be changing, as evidenced by recent mild winters, changing seasonal patterns (earlier springs and later falls), and what seems to be an increasing occurrence of extreme weather events (heavy rains and flooding of October 1996 and June 1998, ice storms in January 1998, and the summer droughts of 1995 and 1999.)

Some basic concepts underpin our current understanding of New England's weather (day-to-day and week-to-week patterns of temperature, precipitation, and cloud cover) and climate (longer-term seasonal to decadal weather patterns). To more fully appreciate the potential climate change impacts on the region, these basic concepts are discussed below.

- **New England is Downwind From the Rest of the Country**

As we have come to know from watching the evening weather on TV, high and low pressure systems, storms and associated precipitation patterns move rapidly from west to east across the United States (Figure 1.1). Weather affecting the west coast and mid-west soon affects the New England region. We are in the unenviable position of being downwind from the rest of the country and parts of Canada. Our position places us in the path not only of the weather from the rest of the country, but, due to long-distance transport, also in the path of air pollution from upwind. It has been said that New England represents the tail pipe for the United States.

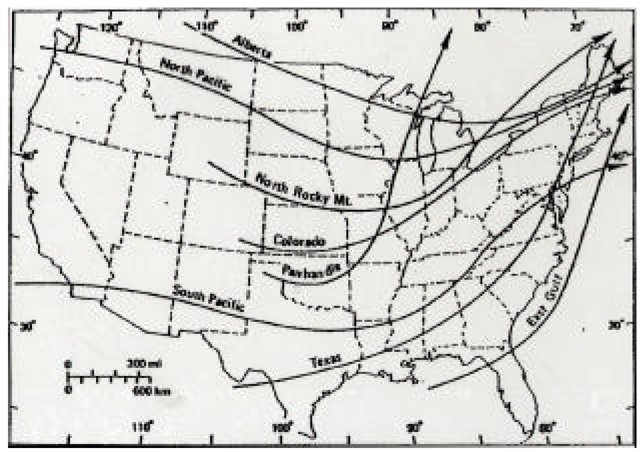


Figure 1.1. A plot of the major storm patterns for the United States, showing the impact that continental weather phenomena and airborne chemical pollutants have on the New England region.

- **Climate Change Refers to both Physical Climate and Chemical Climate Change**

It is important to recognize that the term "climate" can refer to both physical climate (temperature, precipitation, and cloud cover) and chemical climate (including the chemical composition of the atmosphere and precipitation). Changes in the regional chemical climate are well known to the public, resulting in changes in air quality and the acidity of rainfall, snowfall, and cloud chemistry. Public concern is high for the potential impacts of ground-level ozone (smog) on both the environment as well as on human health, and the New England region is well-known for the acid rain which continues to be a problem for high-elevation lakes and forests. Only recently has the public become aware of the impact that such chemical climate may be having on hikers in the Adirondacks (NY), the Green Mountains (VT), and the White Mountains (NH).

Because the two types of climates are interconnected, a change in one may lead to a change in the other. Hot summer days are known to be conducive to the formation of elevated levels of ground-level ozone or smog. This smog results from the interaction of nitrogen oxides (NO_x - produced largely from automobiles), and volatile organic compounds (VOCs which in New England often come from natural sources such as forests) in the presence of sunlight (see Figure 1.2). In addition to smog, emissions of sulfur dioxide (SO_2) and NO_x from the combustion of fossil fuels can combine with cloud moisture to form acidic cloud and precipitation chemistry (sulfuric acid - H_2SO_4 and nitric acid - HNO_3 respectively). In general, SO_2 is produced in the combustion of coal or fuel oil, often in the process of generating electricity, while NO_x is produced when atmospheric nitrogen and oxygen are combined by contact with hot surfaces, such as automobile exhaust systems. The interconnection between physical climate and emissions from the burning of fossil fuels has led to the changes in the chemical climate currently impacting the New England region. If such emissions continue or increase in the future and anticipated changes in temperature and precipitation occur, chemical climate conditions will become worse across the region.

- **Physical Climate and Chemical Climate are Connected**

When we think of climate change it is only natural to think of physical climate factors such as temperature and rainfall. However, as noted above, it is important to realize that physical climate factors have an influence on the chemical climate as well, in the form of changing air quality. Poor air quality is one of the key concerns identified by participants attending NERA workshops. The following discussion illustrates a connection between physical and chemical climate here in the New England area.

In July of 1997 the Environmental Protection Agency (EPA) implemented a new National Ambient Air Quality Standard (NAAQS) for ground-level* ozone pollution (smog). With the previous standard, a 1-hour average value equal to or greater than 0.125 ppm (125 ppb) of ozone was considered an exceedance. The new standard is more stringent and measures ozone concentrations over an 8-hour average, and cannot exceed 0.080 ppm (80 ppb). According to this standard, a monitoring site has an exceedance if the 3-year average of the four highest annual daily maximum 8-hour average ozone concentrations are greater than 0.080 ppm. Therefore, for any particular year, if the fourth-highest ozone value is greater than 0.080 ppm the monitoring site is out of compliance for that year; but it takes three years of being out of compliance of the EPA standard before there is a violation. This standard tends to account for more chronic low-level ozone concentrations which can be a significant health and environmental hazard. These chronic low-levels were not considered in the original NAAQS.

Table 1.2 compares the number of exceedance days in New Hampshire for 1997 for the two standards. As you can see, based on the comparison, there are more exceedances recorded when using the 8-hour NAAQS standard. There is a similar trend for other New England states—a far greater

*Ground-level ozone, a component of smog, should not be confused with the ozone layer in the stratosphere of our atmosphere. Stratospheric ozone naturally occurs and acts as a filter for ultraviolet (UV) radiation, protecting life on Earth's surface. Ground-level ozone is harmful to living systems and is anthropogenic (human) in origin.

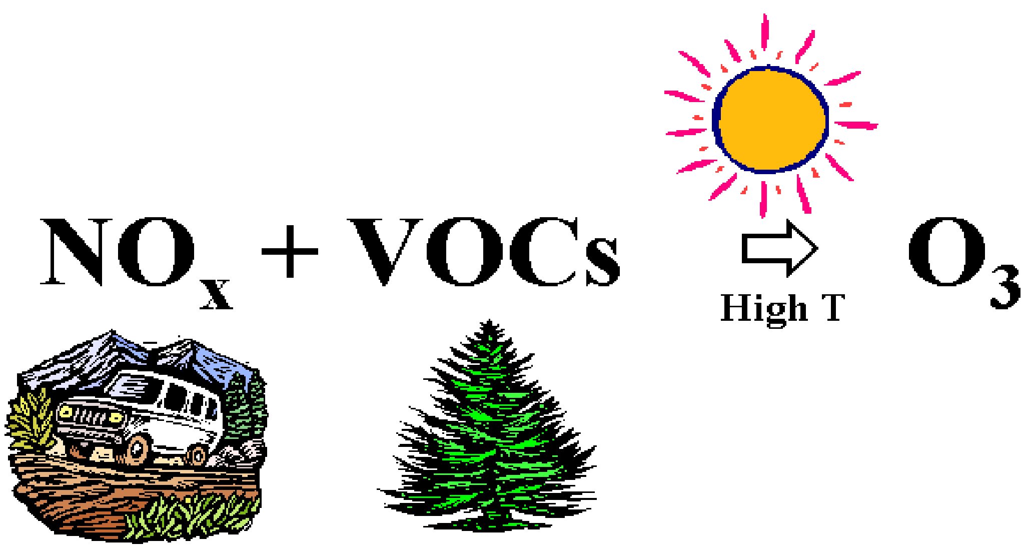


Figure 1.2. The relationship between NOx, VOCs, Temperature, and sunlight in the formation of ground-level ozone.

Table 1.2. Number of Exceedance Days in New Hampshire of the NAAQS Ozone Standard

Year	1-Hour Standard	8-Hour Standard
1990	1	9
1991	3	13
1992	0	7
1993	1	8
1994	1	9
1995	3	9
1996	0	6
1997	3	10

number of exceedances are recorded under the new standard. If states are successful in meeting the new standards then risks due to long-term exposure to medium or high levels of ground-level ozone will be reduced. Recently, the oil and coal industry challenged the EPA 8-hour standards, arguing that inadequate scientific evidence was available to support the standard, resulting in a return to the older, 1-hour standard. The Hiker Health Case Study (Chapter 7) challenges this decision and supports the adoption of even stricter air quality standards in the future.

Figure 1.3 shows the number of 1-hour (.120 ppm) and 8-hour (0.080 ppm) exceedance days, compared with the number of days the temperature was at or above 90° F, as monitored at Bradley Airport, north of Hartford, CT, for the period from 1980-2000. Clearly, the years in which there were a greater number of days at or above 90° F, were also characterized by a greater number of ozone exceedances for both the 1-hour and the 8-hour standards. The years 1983, 1988, 1991, 1993, 1995 and 1997 were characterized by such exceedances. It can also be seen that a trend toward fewer days at or above 90° F leads to fewer exceedances over the same time period. As noted above, hot, dry summers provide the physical climate conditions conducive to ozone formation.

Figure 1.4 is a map of July 16, 1999, one of the worst ground-level ozone days of that year. The map is based on an interpolation of the actual maximum 8-hour average ozone concentration values at approximately 200 ground-level ozone monitoring sites from Maine to North Carolina. As can be seen in this regional portion of the overall map, unhealthful levels of ozone (8-hour concentrations of ozone above 80 ppb) occurred throughout much of the New England region. The highest ozone concentrations are commonly associated with urban centers or heavily traveled transportation corridors. Note from Figure 1.3 that in 1999

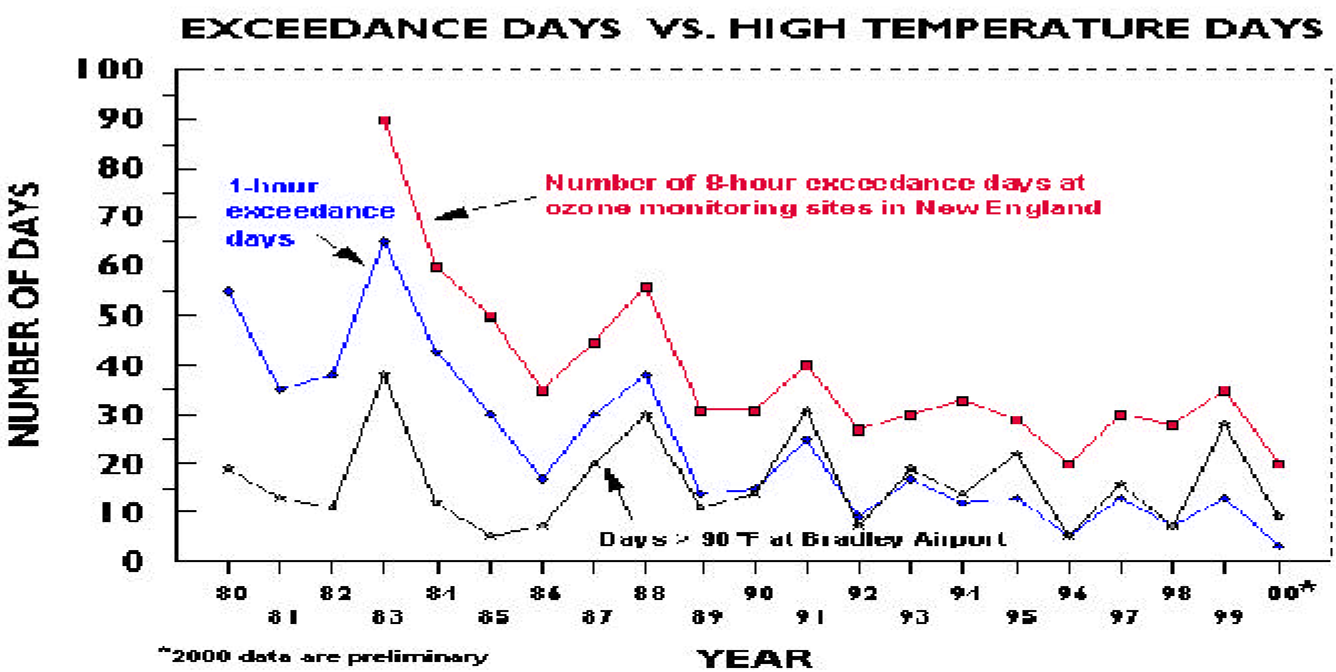
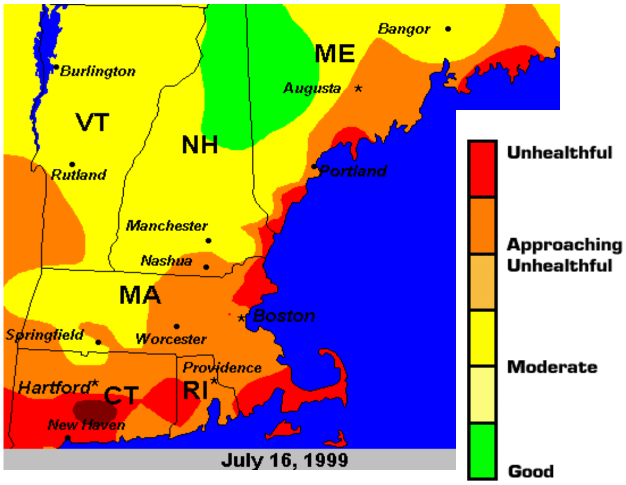
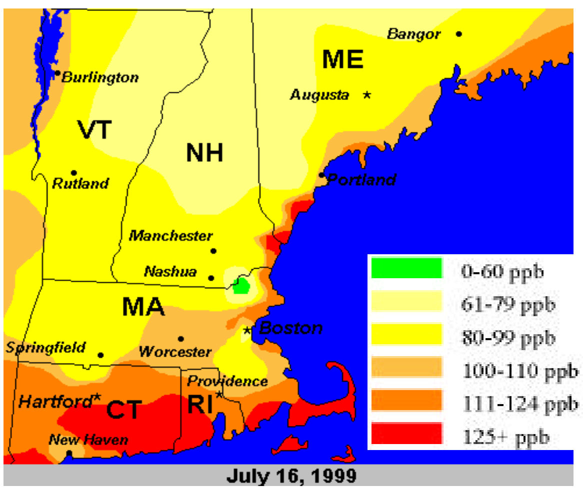


Figure 1.3. Number of 1-hr and 8-hr ozone exceedance days, as well as the number of days at or above 90°F at Bradley Airport, Hartford, CT.

A Bad Ozone Day



8-hour peak values



1-hour peak values

Source: http://www.epa.gov/

Figure 1.4. A high ozone day, July 16, 1999. Due to the black and white format, the ocean areas may appear to be exceeding air quality standards. While coastal regions are frequently in exceedence, the open water is not.

there were a total of 35 8-hour ozone exceedance days similar to July 16th. Also note that there were far fewer exceedance days in the year 2000.

As will be seen in the case studies in Chapters 5 (Forests) and 7 (Human Health), elevated levels of ground-level ozone have a negative impact on forest health and human health alike. Since the forests of the New England region are a major source of VOCs, innovative strategies focused on reducing NO_x emissions are needed to reduce ground-level ozone exposures across the region.

- **The Forests of New England Sequester Carbon**

Recent studies have shown that forests store (sequester) large amounts of carbon in the form of both structural and functional carbohydrates. Wood is composed of several types of structural carbohydrates (including cellulose and hemicellulose), along with other complex chemical compounds derived from metabolism of atmospheric carbon dioxide (CO_2). Wood represents atmospheric CO_2 stored in a stable form that is no longer able to function as a greenhouse gas.

Although the forests of the New England region currently store 20 million metric tons of carbon per year, it is significant to understand that poor air quality adversely impacts potential photosynthetic capacity, especially in sensitive species. Exposure of white pine to ozone, a species shown to be sensitive to exposure to ozone in exceedance of 60-80 ppb, will result in a 15-20% reduction in annual wood production. If air quality can be improved for the region, wood production (carbon sequestration) would increase. Reducing CO_2 and NO_x emissions by improving gas mileage and reducing automobile traffic would effectively reduce ground-level ozone, and thus improve the carbon sequestration capabilities of regional forests. More details on this aspect of addressing the impact of regional air quality on forest health are presented in Chapter 5.

- **Why Climate Models are Used**

Understanding what the future climate will be like requires the consideration of many factors, including local conditions (geography, topographic, the types of land cover, etc.), natural climate forcing factors (solar output, volcanic activity, ocean circulation patterns, atmospheric circulation patterns, etc.) and anthropogenic climate forcing factors (greenhouse gas emissions, land cover changes, etc.). The use of climate models allows us to vary one or more of the factors known to impact climate and project the consequences. The two climate models used, the Canadian General Circulation Model (CGCMI) and the Hadley Climate Model (HadCM2), produce future scenarios as a starting point for discussing our climate future. Each scenario presents a "what if" condition for the future, based on increasing CO_2 levels and sulfate aerosols over time. Other variables that cannot be anticipated (solar output, volcanic eruptions, land cover change) are kept constant in both models.

- **How the Climate Models Used in this Assessment Were Chosen**

The models used in this regional assessment provide dramatically different projections or scenarios. Both the Canadian General Circulation Model (CGCM1) and the Hadley Climate Model (HadCM2) and their respective scenarios are presented in Chapter 4. Both models were selected for several reasons, including the fact that they would provide the public with a reasonable range of scenarios or "what if" projections about future climate patterns. In addition to intentionally selecting models which would provide a range of different scenarios, these models were considered robust enough to be tested at a regional scale. Since most climate models are global climate models (GCMs) which need to be scaled-down to a regional level (see Chapter 4), the CGCM1 and HadCM2 versions were considered to be capable of such a de-scaling approach. Since all GCMs differ one from another on the basic assumptions made for producing future projections, it was decided to present two models which were considered to be based on the most reasonable assumptions.

Thus, it is important to understand that just because these models present different scenarios, there is no reason to disregard either or both. They were selected specifically because they give different scenarios, and in the process suggest two possible "what if" futures for the region. We should not (and can not) expect either one of these models to be correct in projecting regional climate conditions 100 years into the future. By considering a reasonable range in "what if" scenarios, we are better able to develop possible adaptation strategies for the future. Although the two models provide two different projections, both project warming by 2090 (approximately 6^{o} F or 3.2^{o} C suggested by HadCM2; 10^{o} F or 5.6^{o} C by the CGCM1 for minimum temperatures). In either case, a 6-10 ^{o} F warming over the next 100 years would represent an unprecedented warming in such a short time, based on historical data (see Chapter 3). The two models also differ in their projections of precipitation, with the CGCM1 suggesting a 10% increase in precipitation by 2090, but also projecting significant periods of drought, while the HadCM2 projects nearly a 30% increase in precipitation over the same time period. In either case, the New England region would be significantly impacted by such changes. The New England we know today would not be the New England of 2090.

- **A Few Degrees are Significant**

The projections of a 6-10^{o} F (3.2-5.6^{o} C) warming of minimum temperatures in the next 100 years may not seem to be very significant, since tomorrow is likely to be at least 6-10^{o}F warmer or colder than it is today. A few degrees, either Celsius or Fahrenheit, don't seem to be that significant. However, it is very important that we understand what a few degrees in global or regional average temperature means in terms of climate. Approximately 20,000 years ago, parts of the New England region were under nearly 2 miles of ice. At that time, the northern hemisphere of Earth was experiencing a period of maximum glaciation (see Chapter 3). Within 1,500 to 2,000 years, the region had entered a period of warming known as an interglacial period. The current climate conditions today are very similar to those conditions characterizing the beginning of the interglacial period. The global average temperature difference between the last glacial maximum (2 miles of ice) and the current interglacial period is only 10-12^{o} F (5-6^{o} C)! Thus, a change of 10^{o} F over the next 100 years (as suggested by the Canadian model) would represent a potentially catastrophic period of climate change, especially since such a change might occur over a period of 100 years, rather than over 1,500 to 2,000 years.

As an illustrative example of the difference that a change in climate of just a few degrees can make, a comparison of two New England regional cities is made with cities from other parts of the United States. The information on the average temperature values cited (annual monthly averages) for these cities comes from the NOAA Historical Climatology Series "*Climatic averages and extremes for U.S. Cities*". This work presents as "normal", temperatures for major U.S. cities compiled over the 30-year period from 1961-1990. The "normal" Boston, MA monthly average temperature for the 30-year period is 51.3^{o} F and the "normal" Portland, ME monthly average temperature is 45.4^{o} F. Using the two climate model scenarios presented in Chapter 4 (the Canadian model and the Hadley model), we can look for cities that are, on average, 6^{o} F warmer (the Hadley model projection for 2090) and 10^{o} F warmer (the Canadian model projection) than the present conditions for these two cities. This will allow us to develop a sense of what Boston and Portland might be like 100 years from now if either of these scenarios occurred. If a 6^{o} F warming occurs over the next 100 years, Portland's "normal" temperature would be like present temperatures in Boston, and Boston's "normal" temperature would be more like today's Richmond, VA (57.7^{o} F). If a 10^{o} F warming occurred for the coastal region as the Canadian model projects, then Portland's temperatures would be similar to current temperatures in Baltimore, MD (55.1^{o} F), and Boston's temperatures would be similar to those in Atlanta, GA (61.3^{o} F).

Of course, there is much more to climate than simply the temperature, but these comparisons are useful in relating the impact of just a few degrees increase in average temperature in the future. One can only imagine what would become of our ski industry, the maple syrup industry and our fall colors, if Boston becomes more like Richmond, VA or Atlanta, GA. If either of these scenarios were to actually occur, the New England region would be a very different place in 2090. Now is the time to begin to give serious thought to what climate change could mean to future generations living in a future New England region.

- **Climate is very Complex and Current Understanding is Limited**

It is very important to understand how incredibly complex the Earth's climate system is. We are only now beginning to fully understand the extent to which both natural and anthropogenic factors influence our climate. One of the great challenges for this and the next generation will be to develop better measurement tools and improved climate models to provide insight into how natural and anthropogenic factors interact to impact the climate, as well as to understand how a changing climate may impact the New England region. The remaining chapters in this New England Regional Assessment Final Report will help us understand this complex climate system, the current impacts of climate, both physical and chemical, potential climate scenarios of the future, and how best to adapt to a changing climate. In particular, Chapters 2 and 3 deal with factors which affect the region's climate and thus, contribute to this complexity.

- **Uncertainties about the future should not result in inaction**

It is also important that we recognize the great regional variability and unpredictability (Chapter 2) in attempting to forecast future regional climate trends. Certainly, using a global model "down-scaled" for use as a regional model is not the ideal way to do this. At present there are no widely-used regional-scale climate models available for our use. One of the key findings of the NERA effort is that such regional models, which take into account local geography, topography, land cover conditions, etc., are sorely needed. In light of their absence, the down-scaled Global Climate Models such as the Canadian and Hadley are the best that we have to work with. The Hadley model does a very respectable job of hindcasting past temperatures (Chapter 4), as long as both natural and anthropogenic forcings are incorporated into the model.

The biggest uncertainties about future climate projections are not due to model failings, but rather in our inability to predict future levels of greenhouse gases such as CO_2, methane (CH_4), and others, the cooling effects of sulfate aerosols from both human and natural sources, as well as other forcings (solar output, land cover change, etc.). Since we can't control the natural forcings, we need to address those things that we can control. We can control CO_2 emissions from the burning of fossil fuels. We can control land cover changes within the region. Now is the time to begin to take actions that will reduce the risk of climate change in the future.

Finally, we make informed decisions to protect valuable items (our homes, car, and possessions) by purchasing insurance policies. We buy fire insurance on our homes, even though the likelihood of our home burning down is very small. We buy such insurance, "just in case." We make medical decisions based on uncertainties – removal of a "suspicious" lump is a common medical practice, "just in case." We make such important decisions often based on far greater uncertainties than we have about the likelihood of climate change in the future. We need to take the same approach with confronting future climate change, "just in case."

Chapter 2

New England's Changing Weather and Climate

By: Barry Keim and Barrett Rock

2.1. Introduction

When people think of the New England region (the six New England states plus upstate New York), they think of crisp, clear fall days enhanced by spectacular fall foliage, hot, sunny summer days and cool summer nights, or pristine winter snowscapes with snug cabins and bustling ski slopes. While the regional weather can change on short time scales ("If you don't like the New England weather, wait a few minutes"), we tend to think that our climate is more stable. Just how stable is our climate, and are we seeing evidence that our climate is changing?

New England regional weather and climate are arguably some of the most varied in the world. This climate variability holds true at time scales of from days to weeks, years to decades, and thousands to millions of years. Regional variability includes extremes of both hot and cold temperatures, droughts, heavy rainfall, hurricanes, tornadoes, blizzards, and more. Such variations in New England regional weather are influenced by many factors which relate to the region's physical geographic setting, including its latitude and coastal orientation, its topographic variability, and its position relative to the North American continent and prevailing storm tracks.

To discuss possible climate change in the future, it is useful to look at how our climate has changed in the past, as well as the dominant factors that influence the New England regional climate today. This chapter will consider climate variations known to have characterized the region during the last two million years, the region's physical geographic setting, and some trends suggesting what, if any, climate change may have occurred based on climate records for selected sites.

2.2. Primary Components of the New England Regional Climate

The four components that dominate the modern climate of the New England region are: (1) latitude; (2) coastal orientation; (3) position within the zone of the westerlies; and (4) great changes in elevation. These factors interact to provide the New England region with its characteristic weather and climate patterns. These are treated in greater detail elsewhere (Climate Change Research Center, 1998).

First, the region is located about halfway between the equator and the north pole (45^{o} N), which results in frequent interaction between warmer, moist air from the south and colder, dry air from the north. The surface air mass boundaries are made up of warm, cold, and stationary fronts, which frequently traverse the region from west to east (Figure 1.1, Chapter 1) taking us from one air mass to another in rapid succession.

Second, the region is dominated by a cold ocean current along its east coast, and a warm water current along the south shore of Connecticut and Rhode Island, as well as Long Island (NY). These currents, and the corresponding water temperatures associated with them, impact summer recreation, swimming comfort, etc, and also create a notable sea breeze in spring and summer. The sea breeze circulation, particularly along the east coast, tends to mitigate frequencies and intensities of thunderstorms in the coastal zone while bringing relief in the form of mild temperatures in the peak summer heat. In winter, these waters remain warm relative to land areas, thereby influencing snow-rain boundaries, which are very difficult for weather forecasters to predict.

Third, since New England falls primarily in the zone of the westerlies, the area is dominated by drier continental airflow from various areas across North America (Figure 1.1, Chapter 1), rather than having a prevailing flow off the Atlantic Ocean. Despite the coastal orientation of New England, it is not a maritime climate like those found on the west coast of the United States. Due to this continental airflow pattern, the New England region is downwind from much of the rest of the continent, and with that airflow comes varying degrees of air pollution from both the mid-west and from along the eastern urban corridor.

Fourth, New England has mountainous topography that also influences weather patterns. Such mountain topography enhances precipitation on the windward side of the mountain, and creates drier conditions known as rainshadows on the downwind slopes. However, the prevailing storm tracks can take storms all around the region. Hence, a south-facing slope may be in the rain shadow on one day, while the next, it could be on the windward side. Increases in elevation also lead to cooler air temperatures. The summit of Mount Washington (NH) is known for some of the most severe weather on Earth, weather so severe that hiker deaths due to exposure and hypothermia in summer months are not uncommon. Mount Marcy and the High Peaks region of the Adirondacks (NY) are also notorious for severe weather.

As a result of a combination of New England's geographical location, its continental climate, its coastal orientation, and its mountainous topography, the region's weather is notorious. It is known for its diversity over short distances and changeability in a matter of minutes. To document the diversity and changeability of the region's weather, we will now discuss several aspects of climate.

2.3. Temperature

New England average annual temperature is 44° F, and ranges from approximately 40° F to the north, and about 50° F along the south shore of Connecticut and Rhode Island. However, when we factor in elevation, temperatures are generally cooler (Mount Washington has an annual average temperature of 26° F). The range in temperature at both diurnal (daily) and seasonal scales is smaller along the coastal zone and larger inland, away from the stabilizing influence of the ocean. Absolute extreme temperatures in New England have been recorded to be as high as 107° F and as low as –50° F. The record 107° F high is hotter than the all-time high temperature recorded in Miami, Florida, and the –50° F low is colder than the record low temperatures in Anchorage, Alaska or International Falls, Minnesota (commonly cited as the coldest location in the conterminous United States). The region is also plagued with a great abundance of freeze-thaw cycles during the winter months, which can be detrimental to the health of forest trees.

Based on the Historic Climate Network data (HCN-see Section 2.5), there has been a modest (0.7° F) regional trend toward increasing annual temperatures since 1895 (Figure 2.1). As can be seen in the figure, a good deal of year-to-year variation (grey line) characterizes the regional

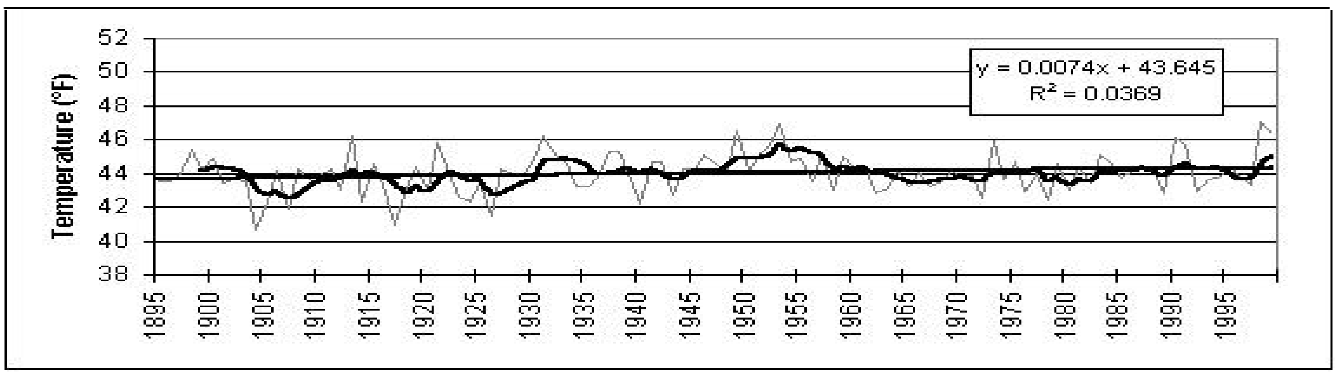


Figure 2.1. Regional Weighted Annual Temperature - New England and upstate New York, showing an overall regional increase of 0.74° F.

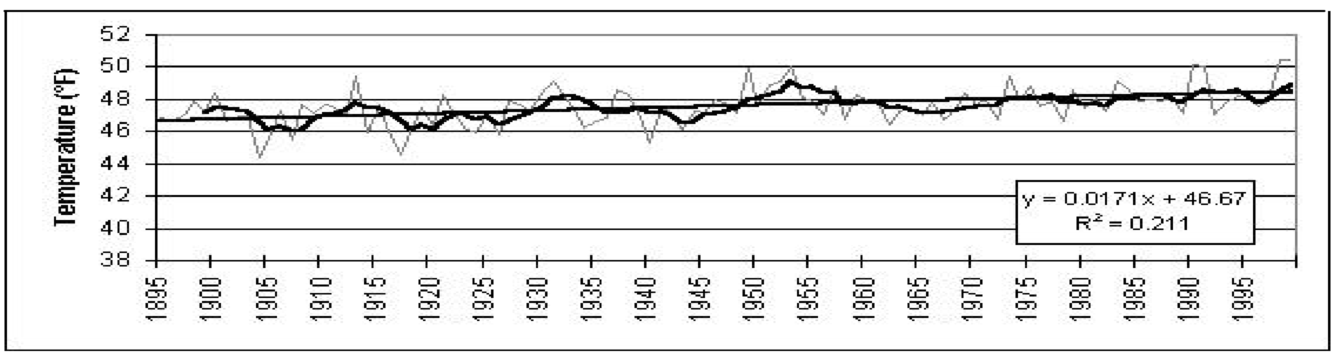


Figure 2.2. New England (Coastal) Yearly Weighted Average Temperatures, showing an overall coastal increase of 1.71° F.

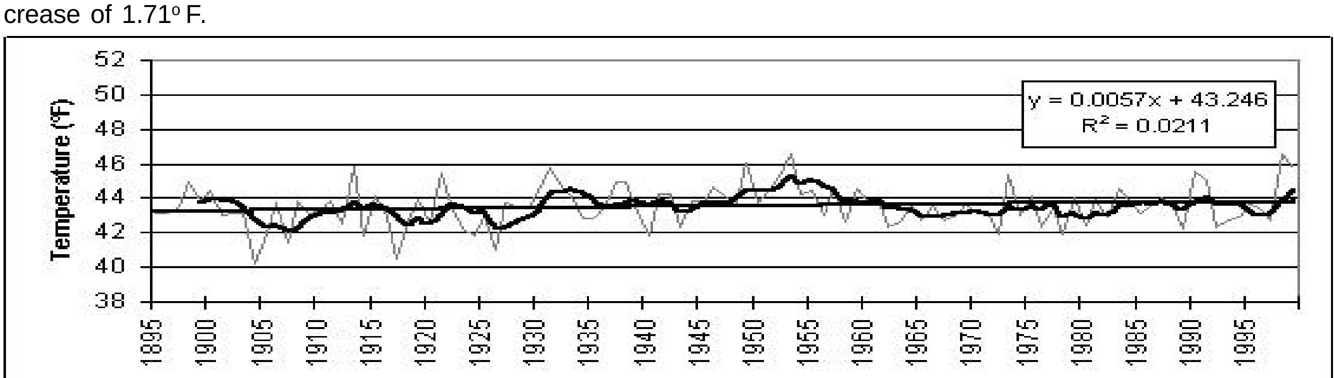


Figure 2.3. New England Region (Interior) Yearly Weighted Average Temperature, showing an overall increase of 0.57° F.

record. A 5-year running average (heavy black line) smooths out some of the variation and the regression line (straight black line) illustrates the overall trend. The coastal zone of the region has warmed by 1.7° F over the same time period (Figure 2.2) while the interior has warmed by only 0.6° F (Figure 2.3). There are two possible explanations for these differences. First, the coastal region has experienced rapid population growth over the past century and the warming could be the effects of urban heat islands. Second, there is speculation that the sea surface temperatures around New England may have warmed, thereby warming the climate of the coastal zone.

2.4. Precipitation

The average annual precipitation for the region is approximately 40 inches per year and ranges from approximately 35 inches in the northern reaches, with higher values, to over 50 inches, along the southern coastal zone. Since elevation tends to enhance precipitation totals, Mount Washington averages approximately 99 inches of "liquid equivalent" precipitation per year. Across the New England region, there are significant shifts in the seasonal distribution of rainfall. For example, Burlington, Vermont has its seasonal peak in precipitation during the summer, with minimal values found in winter. Portland, Maine displays the exact opposite seasonality, with peak precipitation occurring in late autumn and winter, with minimal precipitation in summer.

Similar to the change-over-time patterns noted with temperature, there is a trend of increasing precipitation for the entire region based on the HCN data (a 3.7% increase - Figure 2.4). A greater increase (16.8%) has occurred in the

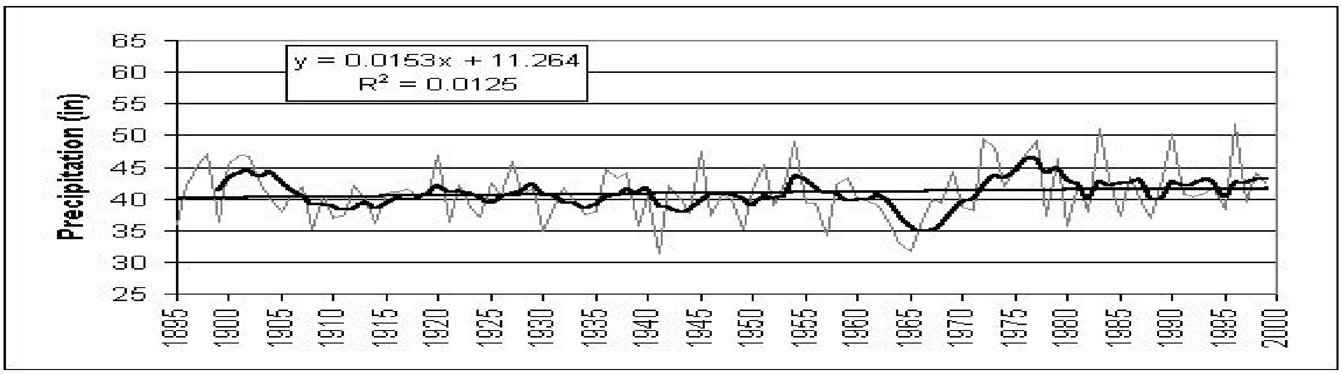


Figure 2.4. Regional Weighted Annual Precipitation in New England and upstage New York showing an overall increase of 3.7%.

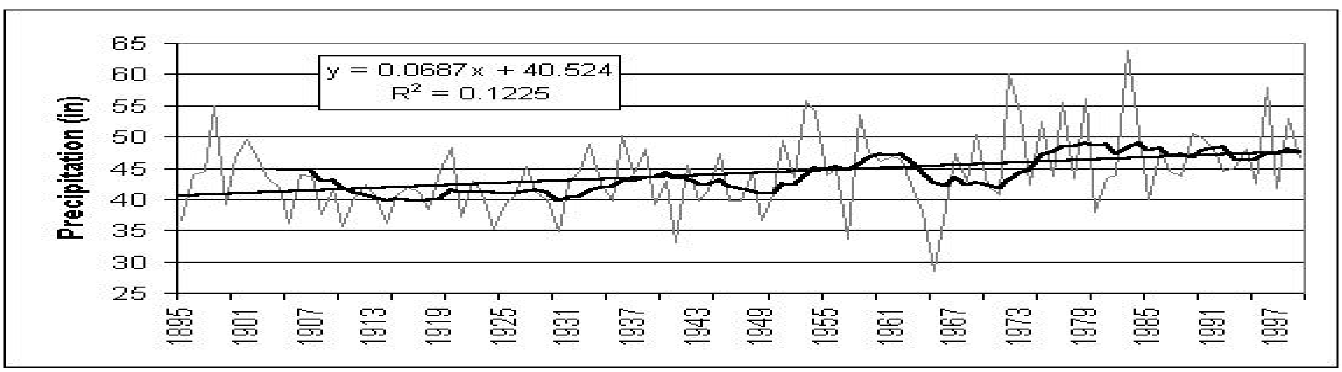


Figure 2.5. Annual Weighted Coastal Precipitation shows a 16.76% increase.

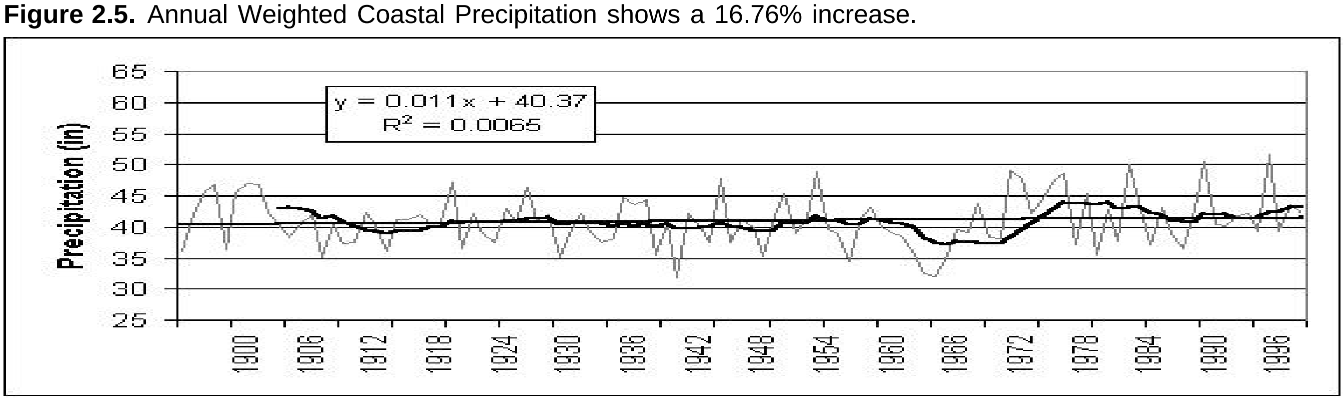


Figure 2.6. Annual Weighted Interior Precipitation Data shows a 2.7% increase.

coastal zone over the past century (Figure 2.5), with less (2.7% increase) long-term change in the interior (Figure 2.6). In addition, there appears to be an increase in heavy rainfall events in the east coastal region, where three precipitation events with greater than 50-year return period have occurred between October 1996 (Keim, 1998) and October 1998. In addition to these rain events, a significant ice storm was experienced by a large part of the region in January, 1998 (See Chapter 5). At a minimum, the 1998 ice storm has been classified as a 200-year return event, and possibly a 500-year return event, resulting in the loss of 17 lives in the US (a total of 26 lives were lost in Canada) and an economic loss well in excess of 1 billion dollars (DeGatano, 2000).

Although the New England region is not considered to be water-limited, several periods of significant drought have occurred that were region-wide. The affect of the mid-1960s drought (covering 4-5 years) can be seen in Figures 2.4, 2.5 and 2.6. Significant regional droughts were also experienced in 1995 and 1999. As can be seen in Chapter 3, shifting patterns of high and low pressure systems over the Atlantic Ocean (the North Atlantic Oscillation or NAO) appear to correlate well with drought periods in the New England region. An improved understanding of the relationship between the NAO and periods of drought may allow us to predict such adverse conditions in the future.

2.5. Annual and Spatial Temperature and Precipitation Variation within the New England Region

Annual temperatures for the entire New England region (including upstate New York - Figure 2.7) have been monitored at over 450 weather stations operated by the National Climate Data Center (NCDC), as part of the Historic Climate Network (HCN). Many of these monitoring stations have been in continuous operation since 1931, and in some cases since 1895. The data provided by the NCDC/ HCN constitute the most reliable long-term record of temperature and precipitation for the region available.

As noted in Sections 2.3 and 2.4, using the historic records from this network, the annual average temperature for the entire region has increased by 0.7^{o}F, and the average annual precipitation has increased only slightly (1.5 inches, or approximately 4.0% of the amount measured in 1895), over the past 105 years (1895-1999).

The entire United States has shown an increase in temperature of approximately 1.0^{o} F over the same period , while the global average temperature increase is often cited as 1.2^{o} F. Thus, the New England Region has warmed slightly less than the nation, and approximately half of the overall global increase. The region's 4% increase in precipitation is slightly below the 5-10% average precipitation increase nationally over the 105 year period (National Assessment Synthesis Team, 2000).

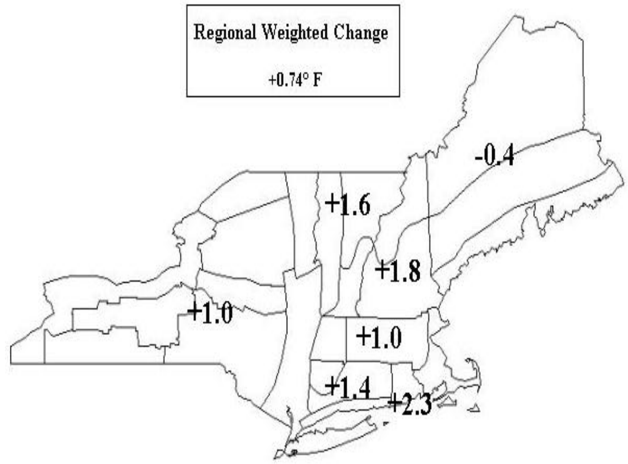


Figure 2.7. New England and New York Temperature Changes (^{o} F) Between 1895 and 1999. The faint lines within the states represent the various climate zones recognized by the National Climate Data Center.

It is important to note that there is a good deal of variation within the region in both temperature change and precipitation over the past century. This heterogeneity is at both spatial (varies state to state) and temporal (seasonal). As can be seen in Figure 2.7, some states have warmed more than the regional average and others less. Rhode Island has warmed the most (2.3^{o} F), likely due to its coastal location and heavy urban development. New Hampshire's annual temperatures have increased (1.8^{o} F) at nearly three times the regional average (0.7^{o} F) while Maine has exhibited a slight cooling (-0.4^{o} F) over the same time period. Section 2.8 presents the New Hampshire data to show that, even within a single state, there has been significant temporal and spatial variation. Figure 2.8 presents the 1895-

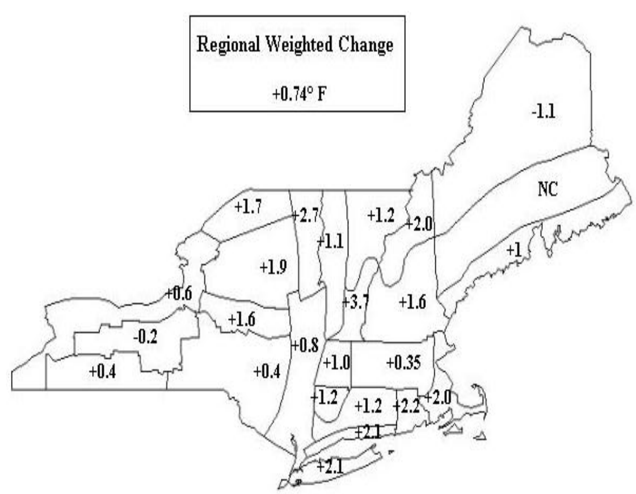


Figure 2.8. New England & New York Climate Division Temperature Changes (^{o}F) Between 1895 and 1999.

1999 temperature changes for the region by climate zones within each state.

While the overall region has warmed, based on annual average temperatures by 0.7°F, the regional wintertime months (December, January and February) have warmed by 1.8° F (Figure 2.9). Summer months (June July and August) exhibit an increase of 0.5° F, similar to the annual regional increase (Figure 2.10). Thus, for the region, wintertime warming has been nearly three times the annual warming.

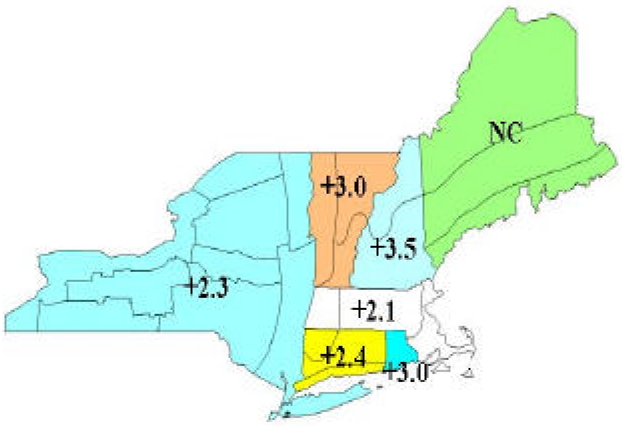


Figure 2.9. Wintertime Temperature Changes

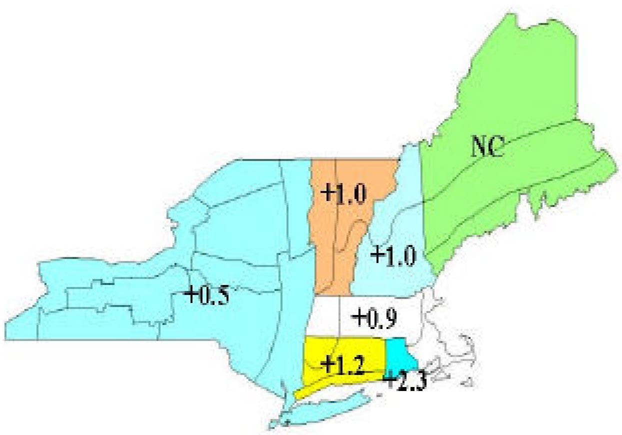


Figure 2.10. Summertime Temperature Changes.

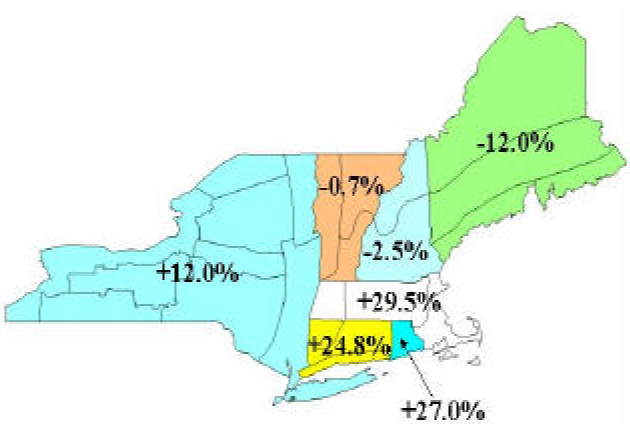


Figure 2.11. Precipitation pattern variability.

Precipitation patterns across the region also show a high degree of variability (Figure 2.11). While southern New England (MA, CT, and RI) have experienced a nearly 30% increase in precipitation, the three northern states (VT, NH, and ME) have experienced as much as a 12% decrease (ME). Upstate New York has experienced a 12% increase in precipitation. The entire region has experienced a modest increase in precipitation (3.7%).

2.6. Snowfall

Snowfall is highly variable in the New England region, both spatially and temporally. Southern New England receives the lowest snowfall totals on the average with approximately 35 inches per year. Northern New England region receives substantially more snowfall, with large regions in and near the White, Green and Adirondack mountains averaging well over 100 inches per year. Due to their locations on the shore of Lake Erie and the direction of prevailing winds, Rochester and Buffalo, NY are cities known for their heavy winter "lake effect" snowstorms. Elevation enhances snowfall totals and Mount Washington averages 254 inches of snowfall per year. As seen in Figure 2.12, there has been a nearly 15% decrease in snowfall in Maine, New Hampshire, and Vermont since 1953. The past several winters have been unusually mild, resulting in lost revenues for the ski industry. The winter of 00/01 has been a more typical winter for the region in terms of snowfall, although temperatures were relatively mild.

Although snowfall, snowpack, and duration of snow-on-ground data have been acquired by many organizations (State Offices, the Army Corps of Engineers, etc.), only a

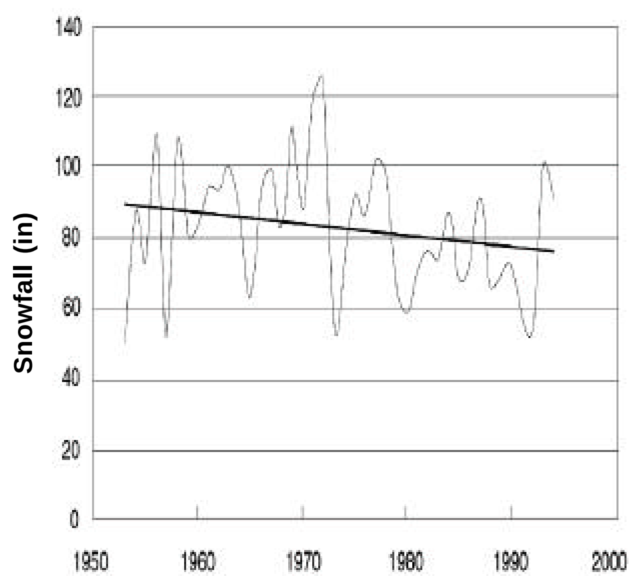


Figure 2.12. Annual snowfall data for Vermont, New Hampshire, and Maine between 1953 and 1994.

limited number of these datasets have been analyzed. The duration of snow cover on the ground has decreased by approximately seven days over the past 50 years (Figure 2.13). As noted with temperature and precipitation data, the results are spatially varied. Snowpack has decreased significantly in some parts of the region (the northern climate zone in New Hampshire has decreased by 14.5 days) while showing no change in Maine's northern climate zone. These variations are correlated with the heterogeneous winter-time temperature variability across the region. Both snowfall and snow-on-ground data were provided by *Climatological Data*.

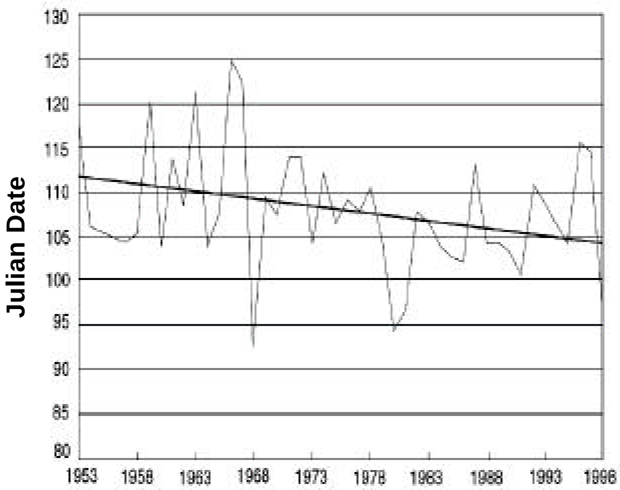


Figure 2.13. Annual snow-on-ground data for Vermont, New Hampshire and Maine between 1953 and 1998.

2.7. Ice-out dates for Regional Lakes

Accurate records of ice-out dates (the earliest date for ice-free lake surfaces) for selected New England region lakes provide some evidence of a changing climate, when viewed with air temperature and precipitation records. Ice-out records have been kept for Lake Winnipesaukee (Figure 2.14), where ice is an important consideration for ferry traffic on the lake, as well as for ice fishing, snow mobiling, and cross country skiing. Ice-out data are also available for Rangeley Lake (Figure 2.15) in northeastern Maine. Magnuson *et al.* (2000) also provides ice-out records for several New York lakes (Oneida, Otsego, Schroon, and Cazenovia) and one additional Maine lake (Moosehead). Data for Lake Winnipesaukee show ice-out dates that average four days earlier for the 1885-1999 period, while ice-out dates on Rangeley Lake are also four days earlier since 1870. The Winnipesaukee and Rangely Lakes results are similar to those reported for the New York lakes (ice-out occurring on average 4 days earlier per 100 year period), while the Magnuson *et al.* (2000) data on ice-out times found for Moosehead Lake are earlier by 5.6 days/100 year period.

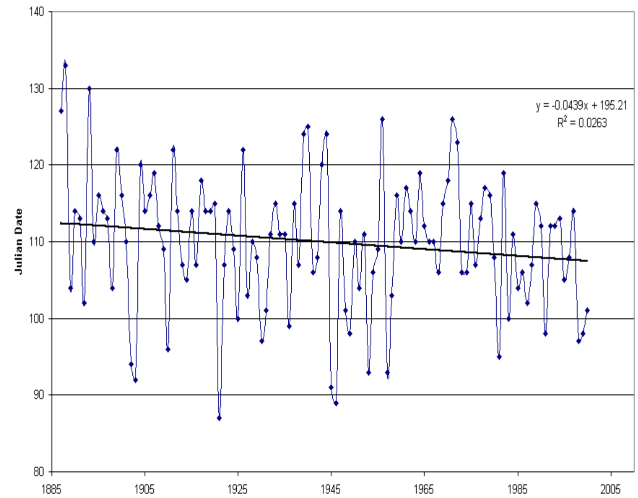


Figure 2.14. Lake Winnipesaukee Ice-Out Dates since 1885, showing a decrease of four days.

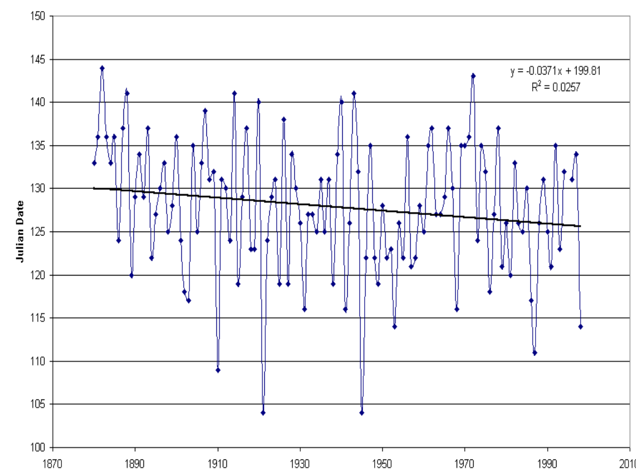


Figure 2.15. Rangeley Lake Ice-Out Dates since 1870.

These results suggest that the New England regional is warming trend in winter and spring has resulted in earlier ice-out dates for those lakes for which long-term records exist. It is clear however, that a more detailed analysis of available data is needed before more significant conclusions can be drawn.

2.8. The climate of New Hampshire has changed over the past 100 years

The state of New Hampshire is divided into two climate zones by the NCDC, a northern climate zone which includes the White Mountains and Coos County, and a southern climate zone which includes everything else (Figure 2.8). There are a total of 44 NCDC/HCN stations in New Hampshire, 13 in the northern climate zone and 31 in the southern climate zone.

Surprisingly, the annual average temperatures in New Hampshire have increased significantly more than the region (or the nation and the globe), increasing by 1.8° F since 1895 (Figure 2.7). Even more surprising is the annual average temperature increase of 2.0° F for the northern climate zone (Figure 2.8). The southern climate zone has increased by a lesser amount (1.6° F) since 1895. The annual precipitation for New Hampshire has decreased by approximately 2.5% (Fig. 2.11), a reversal of the 4% increase for the region and the 5-10% increase for the nation.

A look at the winter months provides an even bigger surprise, in regard to temperature and precipitation. In New Hampshire's northern climate zone, average temperatures for December, January, and February have increased by 3.8° F! At the same time, precipitation amounts for those same three months have dropped by 24%! No wonder the ski industry in New Hampshire has been having a very difficult time. The southern climate zone has also warmed in the winter months (by 3.2° F) but no change is seen in the monthly precipitation data over the 105 year period.

Summer months (June, July, and August) in New Hampshire have not warmed as much (approximately 1.0° F in both climate zones) as the winter months. Thus, there is very strong evidence that New Hampshire winters are warming at 3-4 times the rate of summertime warming. In addition, New Hampshire's annual temperatures have increased at nearly twice the national rate. Clearly, New Hampshire is behaving differently when compared with the globe, the nation, and the region regarding the temperature records over the past century. The globe, the nation, and the New England region have experienced a warming trend over the past 104 years, but New Hampshire, especially the northern climate zone, has experienced a significantly greater warming trend.

Figure 2.7 provided information on the temperature changes for each of the states within the New England region. The wide range of variation in temperatures between the states (Maine cooling slightly, while New Hampshire has warmed by nearly 2° F) is difficult to explain and may be due to the differing patterns (both spatial and temporal) of deforestation experienced by the two states during the past century. Such an explanation is speculative at this point and will require considerably more study in order to provide a definitive answer.

2.9. Extreme Events

In recent years, extreme events may have become more common in the United States, particularly in the Northeast. Note the following extremes in the region since 1996.

- Region-wide blizzard with storm snowfall totals in excess of 30 inches (January, 1996)
- Coastal New England Rainstorm producing over 19 inches of rainfall (October, 1996)
- Warmest single-day February temperature record in Seacoast of New Hampshire (1997)
- Boston's 24-hour snowfall record broken (April 1997).
- Severe Ice storm strikes northern New England, New York, and southeastern Canada (1998)
- Warmest single-day March temperature ever recorded in New Hampshire (1998)
- Longest snow-free period ever recorded at Boston's Logan Airport (304 days – 1999/2000)
- The 1999/2000 winter was the mildest on record (replacing the 1998/1999 winter as the previous record, which in turn replaced 1997/1998)
- One of the hottest and driest summers on record in southern and western New England (1999)
- One of the coolest and wettest summers on record for southern New England (2000)

Evidence of increases in extreme events is provided by Changnon *et al.*, (1997) in the form of increasing trends in weather-related insurance claims. Using insurance claims to document an increase in storm severity may not be related so much to weather extremes, as to the fact that human population in the US is increasing, and more people are building more expensive homes in weather-sensitive areas (coastal property susceptible to hurricanes, and floodplains vulnerable to flooding). Work by Karl *et al*. (1994a, 1994b, 1996) documents national temperature and precipitation trends and suggests that the proportion of annual rainfall contributed by 1-day extremes has increased in the US over the past century.

While the "Top Ten Most Memorable Weather Events for the New England Region" (See Sidebar, page 16) span the 20th Century, from the infamous 1927 flood in Vermont to the 1998 ice storm across much of New York, Vermont, New Hampshire and Maine, it is interesting to note that two of these "Top Ten" events occurred in the 1990s. While it is difficult to say with certainty that extreme events are on the increase in the New England region, it is clear that the decade of the 1990s has been characterized by an unusual number of extreme events.

Perhaps the most memorable weather-related event in the region was the "Year Without Summer" in 1816, a year characterized by snow falling in every month, across the New England region. This highly unusual (and memorable) event followed a major volcanic eruption (Tambora, in 1815) by one year, which injected large amounts of sun-blocking dust and debris into the upper atmosphere, cooling the climate worldwide. As can be seen in Figure 3.2, Chapter 3, the "Year Without Summer" also coincided with a sunspot minimum which extended from 1800 to 1830. Very likely, the two concurrent natural factors known to affect weather resulted in an amplification of this extreme weather event. A look at any of the temperature records for the region (Figures 2.1-2.3) identifies the period between 1991 and

Top Ten Most Memorable Weather Events for the New England Region

Compiled by Barry Keim

1. **The Hurricane of 1938 - September 21, 1938.** A hurricane, named appropriately as the "Hurricane of 1938," made landfall in southern Connecticut and given the storm's path and power, impacted the entire region. Attributed to this storm were over 600 deaths, caused primarily by the 17 foot storm surge along the Connecticut and Rhode Island Coasts. However, high winds and rain caused large stands of trees to be blown down all the way up into the White Mountains and flash flooding was problematic in MA, VT, and NH.

2. **The Blizzard of 1978 - February 5-7, 1978.** The Blizzard of '78 was caused by an intense coastal nor'easter that produced winds in excess of hurricane force and very high snow totals. Northern Rhode Island received over 50 inches of snow, with most of southeastern New England buried beneath 3 or more feet. The region was paralyzed for over a week.

3. **Hurricane Diane - August 17-19, 1955.** Hurricane Diane produced a 24-hour rainfall total of 18.15 inches (the New England record) and a storm total of 19.75 inches rainfall. These impressive totals caused massive flooding as they fell on saturated grounds — Hurricane Connie visited the area only days prior to Hurricane Diane to soak the area.

4. **The "All New England Flood" - Mid-March 1936.** Two heavy rain events fell on greater than normal snowpack to produce the "All-New England Flood" which led to the most serious widespread flooding ever experienced in New England. Hookset, NH had 18-20 feet of water flowing down main street and the Amoskeag Mills were badly damaged with record flood crests on the Merrimack River and beyond.

5. **The 1998 Ice Storm - January 5-9, 1998.** Northern New England experienced the worst ice storm (see Ice Storm Case Studies; Chapter 6) in recorded history with loss of life, widespread power outages that took months to fully restore and damage to forests that may require decades to recover.

6. **The Worcester Tornado - June 9, 1953.** The Worcester Tornado touched down as a F4 tornado, with wind speeds between 200-260 mph. It carved a path of 46 miles from Petersham, MA to Southboro, MA, while persisting for 1 hour and 20 minutes, killing 90 people. That same day, tornadoes also touched down in Exeter, NH and Sutton, MA.

7. **Highest Recorded Windspeed on Earth - April 12, 1934.** Mount Washington (NH) measures a windspeed of 231 mph, which still stands as the highest windspeed ever recorded in the world.

8. **Record Rainfall in Maine and New Hampshire - October 20-21, 1996.** A persistent rainstorm produced the all-time state rainfall records for both Maine and New Hampshire. A storm total of 19.2 inches was produced in Camp Ellis, Maine which ranks as the second largest rain event in New England recorded history — estimated to be a 500-year rainfall event for the Maine-NH coastal area. New Hampshire also broke its all-time 24-hour rainfall total with 10.8 inches measured at Mount Washington.

9. **The Nor'easter of '69 - February 22-28, 1969.** A nor'easter produced over 3 feet or more of snow across large portions of ME, NH, MA, and RI, with totals of 98 and 77 inches recorded at Mount Washington and Pinkham Notch, respectively. These values are unprecedented snowfall totals for any single storm event in this region. This storm was also preceded by yet another impressive snowstorm on February 8-10 which produced between 1 and 2 feet across most of New England. The combination led to incredibly high "snow on ground" totals and large snow drifts.

10. **The Flood of '27 - November 3-4, 1927.** A frontal system was assisted by tropical moisture to produce rainfall totals near 10 inches across central VT, leading to massive river-basin flooding. Eighty-four Vermonters perished and to this day, this storm is still considered the worst weather catastrophe in the state.

1997 as a cool period. This corresponds to the period following the Mount Pinatubo eruption.

Predicting future extreme events in a dynamic region such as New England has proven to be a difficult task. Most of what is known about future climates is derived from general circulation models (GCMs). The various GCMs [e.g. the Canadian Global Coupled Model (CGCM), the Goddard Institute for Space Studies (GISS) model, the Geophysical Fluid Dynamics Laboratory (GFDL) model, and the Hadley (HadCM2) model from the United Kingdom Meteorological Office] generally agree that global temperature and precipitation should increase as concentrations of atmospheric greenhouse gases increase, but regional impacts remain unclear. Furthermore, most extreme events (e.g. intense precipitation events, tornadoes, hurricanes, high winds, etc.) are too small in scale for GCM recognition and therefore the GCMs are of limited value in predicting extremes.

Though the GCMs are of little assistance in directly projecting future extreme events, possible global warming in the future has implications relating to severe events. First, global warming would likely translate into warmer global sea surface temperatures (SSTs), and in fact, global SSTs have warmed by nearly 1.0^{o} F in the last century. It has been found that warmer SSTs are strongly correlated with increases in tropical storm frequencies, at least in the north Atlantic Basin (Wendland, 1977). Such changes in the North Atlantic Basin impact storm frequencies in the eastern United States, including the New England region. Similarly, Emanual (1987) reports that hurricane intensity is likely to increase under warmer conditions globally. A time series analysis of annual hurricane frequencies over the past 100+ years fails to show increasing frequencies of hurricanes in New England (Climate Change Research Center, 1998). Furthermore, hurricane intensities do not appear to be increasing as evidenced by the most powerful storms to strike the eastern United States over the past century. These events occurred, in descending order of intensity, in: 1935, 1969, 1992, 1919, 1928, 1960,1900, 1909, 1915, and 1961.

A possible explanation for the above apparent contradiction may be found in the assumption of most GCMs that warming is most likely to occur to a greater extent at the higher latitudes, which are predicted to warm more than lower latitudes. If this were to occur, and there is strong evidence that this is already occurring (Weller *et al*., 1999), there would be a reduction in the temperature gradient between the tropics and poles. It is this gradient that drives most of the severe weather in the mid-latitudes and such a gradient reduction would likely lead to a reduction in atmospheric mixing, thereby reducing severe weather associated with mid-latitude storms like Noreasters and Alberta Clippers.

Predicting extremes in New England is also complicated by the region's geographic location. The region is exposed to both cold and dry airstreams from the north and warm and moist airstreams from the south. The interaction between these opposing air masses often leads to turbulent weather across the region. Also, because of the propensity of storm tracks to move across this region, the jet stream is frequently positioned overhead. The complicating factor here is that very small shifts in storm tracks and jet stream location lead to highly differing weather conditions region-wide. Currently, GCMs do not have the capability to predict how these storm tracks and jet stream locations may shift in a warmer climate.

Regarding extremes of the past in this region, cursory examination suggests slightly warmer extreme cold conditions in southern New Hampshire, and an increase in the frequency of extreme precipitation events has occurred in southern New England. Both of these are in general agreement with increases in annual temperature and precipitation found across the region (Karl *et al*., 1994a; 1994b). In addition, Davis and Dolan (1993) report that over the past 50 years the total number of East Coast nor'easters appears to be decreasing, but that the most powerful ones seem to be increasing in frequency. It is clear that we need to better understand the complexities and interrelations that result in the complex system known as weather and climate.

2.10. Summary

The weather and climate of New England have proven to be highly variable over long and short time scales and across short distances. Much of this variability can be attributed to the region's unique geographic location. In a given year, the region can experience hurricanes, blizzards, drought, and more. Over the past century, there has been an indication that temperatures are warming, especially in the coastal zone and for selected states. Clearly, more warming has occurred during winter months, and earlier ice-out dates for regional lakes suggest the seasonal warming has had an effect.

There is limited evidence from insurance claims that extreme events have been on the rise, but a more thorough analysis of more than just the number and value of claims filed is needed. Furthermore, climate models are not yet sensitive enough to yield reliable information at a scale associated with most extreme events.

At this point, we clearly need more data and research to assess the true impacts of a changing climate on weather phenomena, both routine and extreme, in an area as dynamic as the New England region.

References

Changnon, S.A., Changnon, D., Fosse, E.R., Hoganson, D.C., Roth, Sr. R.J.,Totsch, M. 1997. Effects of Recent Weather Extremes on the Insurance Industry; Major Implications for the Atmospheric Sciences. Bulletin of the American Meteorology Society 78:425-435.

Climate Change Research Center. 1998. New England's Changing Climate,Weather, and Air Quality. Institute for the Study of Earth, Oceans, and Space. University of New Hampshire, Durham, NH.

Davis, R.E., Dolan, R. 1993. Nor'easters. *American Scientist* 81:428-439.

DeGaetano, A.T. 2000. Climatic perspective and impacts of the 1998 northern New York and New England ice storm, Bulletin American Meteorology Society, 81.

Emanuel, K.A. 1987. The Dependence of Hurricane Intensity on Climate. *Nature* 326:483-485.

Karl, T.R., Easterling, D.R., Knight, R.W., Hughes, P.Y. 1994a. U.S. National and Regional Temperature Anomalies. In: T.A. Boden, D.P. Kaiser, R.J Sepanski, and F.W. Stoss (eds.), *Trends 93: A Compendium of Data on Global Change*. ORNL/CDIAC-65, pp. 686-736. Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN.

Karl, T.R. Easterling, D.R., Groisman, P.Ya. 1994b. United States Historical Climatology Network- National and Regional Estimates of Monthly and Annual Precipitation. In: T.A. Boden, D.P. Kaiser, R.J Sepanski, and F.W. Stoss (eds.), *Trends 93: A Compendium of Data on Global Change*. ORNL/CDIAC-65, pp. 830-905. Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN.

Karl, T.R., Knight, R.W., Easterling, D.R., Quayle, R.G. 1996: Indices of Climate Change for the United States. *Bulletin of the American Meteorology Society* 77:279-292.

Keim, B.D. 1998. Record Precipitation Totals from the Coastal New England Rainstorm of October 20-21, 1996. *Bulletin of the American Meteorological Society* 79(6):1061-1067.

Magnuson, J.J., Robertson, D.M., Benson, B.J., Wynne, R.H., Livingstone, D.M., Arai, T., Assel, R.A., Barry, R.G., Card, V., Kuusisto, E., Granin, N.G., Prowse, T.D., Steward, K.M. and Vuglinski, V.S. 2000. Historical trends in lake and river ice cover in the northern hemisphere. *Science* 289:1743-1746.

National Assessment Synthesis Team. 2000. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. U.S. Global Change Research Program. Washington, D.C.

Weller, G., Anderson, P and Wang, B. 1999. Preparing for a Changing Climate. *A Report of the Alaska Regional Assessment Group*, Center for Global Change and Arctic System Research. University of Alaska, Fairbanks, 42 pp.

Wendland, W. 1977. Tropical Storm Frequencies Related to Sea Surface Temperatures. *Journal of Applied Meteorology* 16:477-481.

Chapter 3

Natural and Anthropogenic Factors of Global and New England Climate Change

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3.1. Introduction

New England weather is highly variable for a number of reasons. Our regional climate is also quite variable. The winters of the past decade are milder than they were in the 1960s and 1970s but as the ice-out and snowfall data show (Figs 2.5 and 2.6), the patterns of change appear to be cyclical. The mid-1960s were marked by a period of severe drought while recent severe storm events, such as the heavy flooding in November, 1996 and the ice storms of 1998, all serve to remind us that living in the New England region is never dull. With the advent of Earth-orbiting satellites to monitor our planet and spacecraft that study the sun, an active International joint project to monitor the Sun – Earth (Solar Terrestrial) environment has evolved. Coupled with an ever increasing computational capability, we are now able to study the many factors which influence our weather (the day-to-day variations in temperature, precipitation, and storm activity) and climate (seasonal and annual patterns of weather), which characterize the New England region. In addition to recorded data and observations from space, recent advances in the study of ice core data, tree rings, lake and bog sediments, and other forms of proxy data now allow us to understand how our global and regional climates have changed in the past.

In this chapter, we discuss some of the factors which are known to have affected New England climate in the past, so that we can better understand potential consequences of future climate variability and change. First, we discuss solar factors which operate on times scales from days to millennia and the consequences of these variations in New England. In many cases the magnitude of solar radiative forcing variations is small, but a number of mechanisms including changes in greenhouse gas concentrations may amplify the effects of solar variations on the Earth's climate (Chambers et al., 1999; Shindell et al., 1999; Andreae, 2000). Variations in volcanic activity and distribution of aerosols can also affect global and regional climate (National Research Council, 1998), and are discussed here, along with a brief consideration of the impact of changing land cover types. Finally we consider the recent rate of greenhouse gas increases due to human activity, and the possible consequences of altered atmospheric patterns such as the North Atlantic Oscillation (NAO) on climate in the New England region.

3.2. Variations in Solar Forcing and Consequences on Earth

The Sun affects Earth in many ways. Phenomena on the Sun can impact the local space (near Earth) environment, resulting in changes in "space weather." These variations can in turn affect our everyday lives. Very energetic solar events like solar flares and coronal mass ejections (CMEs) release charged particles that affect communications on Earth, including radio and television, navigational systems, Automatic Teller Machines, and even "pay-at-the-pump" operations. Not only are electronics on orbiting satellites at risk of damage because of these charged particles, but their orbits are also often altered due to increases in solar UV radiation, UV absorption by ozone in the stratosphere and resulting expansion of the Earth's atmosphere.

Humans at high altitudes, e.g. plane passengers and astronauts, are at risk of dangerous radiation exposure after significant solar events. In fact, the Federal Aviation Agency often assesses radiation risks and alerts flights in potential danger to reduce altitude to minimize exposure. One such event occurred on November 7, 1997 where very energetic solar particles were detected by the neutron monitor atop Mt. Washington in New Hampshire (Figure 3.1).

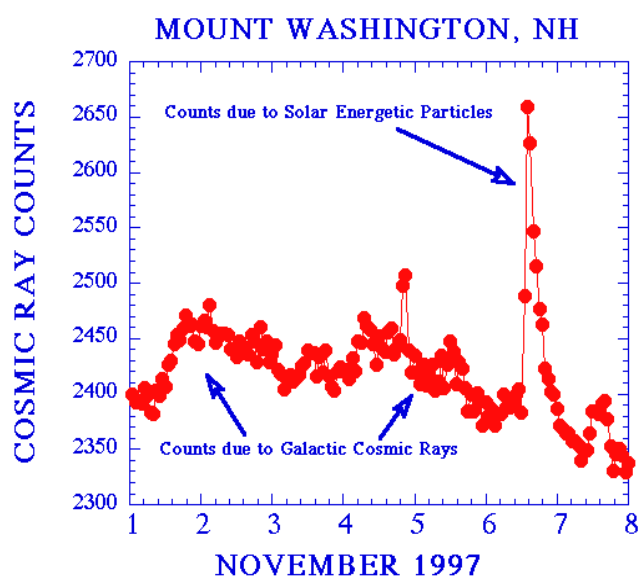


Figure 3.1. Solar energetic particles detected by the neutron monitor atop Mt. Washington, NH.

The Earth's rapidly fluctuating magnetic fields stimulated during periods of solar activity can induce currents in long pipelines, affecting flow meters and pipeline corrosion. These geomagnetic storms also induce currents in power grids that are harmful to transmission equipment, sometimes resulting in power outages. In March 1989, New Hampshire experienced a power outage due to such a solar storm. In fact, due to geographical location and geologic makeup, the region is highly susceptible to the effect of these geomagnetic storms. A natural extension of these relationships is to ask if these phenomena affect climate changes on Earth as well. Next we consider the consequences of millennial variations in solar input due to Earth orbital variations that are associated with global and regional climate changes.

3.2.1. Orbital Variations and Glacial and Interglacial Cycles

Climate variations in New England during the past two million years were highly influenced by local geography. New England was located at the southern end of one of the major northern hemispheric regions of continental ice sheet growth. Multiple times this major ice sheet has had its origin in eastern Canada and gradually expanded southward to cover much of the landmass now known as upstate New York and New England. This latest period of glaciation is known as the Pleistocene epoch, a period of approximately 2,000,000 years characterized by oscillations between glacial maxima or ice ages (colder periods in which the glaciers extended over New England) and interglacial ages (warmer periods in which the ice sheets retreated and/or disappeared). Glacial maxima were characterized by an average global temperature about 7-8^{o} F (~4.3^{o} C) **(**Bush and Philander, 1999**)** colder than the current interglacial values, and persisted for durations of about 90,000 years each. In contrast, previous warm interglacial periods experienced temperatures near modern levels and persisted for about 10,000 years, resulting in a cycle of roughly 100,000 years (Agaudo and Burt, 2001) between ice ages.

Figure 3.2 presents data derived from the Vostok ice core from the Antarctic ice sheet for the past 160,000 years. Measured concentrations of CO_2 and CH_4 (methane) are plotted over time, along with a proxy record of temperature derived from oxygen isotope ratios measured in the ice. Note the periods of portions of two glacial maxima and two intervening interglacial periods. Also note that at no time during the past 160,000 years have CO_2 levels been above 300 ppm (parts per million). These past climate fluctuations are believed to be related to changes in Earth-Sun relationships known as *Milankovitch* cycles, as well as possible cyclical variations in the energy output of the Sun, but the physical mechanisms explaining these co-variations are not completely understood.

The *Milankovitch* cycles include changes in: 1) eccentricity - the shape of Earth's orbit around the sun which varies between circular and slightly elliptical thereby affecting the distance between the Earth and the Sun (associated with less than 1 percent variation in solar heat flux, a full cycle completed in approximately 97,000 years); 2) tilt of Earth's axis of rotation relative to the orbital plane - influences the latitudinal distribution of the Sun's rays reaching Earth's surface on approximately a 41,000 year cycle, and 3) precession - the distance between the earth and the sun at a given point of the year (such as the equinoxes), on approximately 21,000 years (Barron, 1994). At the present time, Earth is actually closest to the Sun during the winter months in the Northern Hemisphere, but due to the tilt of the Earth's axis away from the Sun, less direct rays reach the surface of the Northern Hemisphere during the winter months. In another 14,000 years, the Northern Hemisphere will experience summer in December and winter in June. The total length of these orbital cycles (approximately 100,000 years) matches well the length of cycles between ice ages.

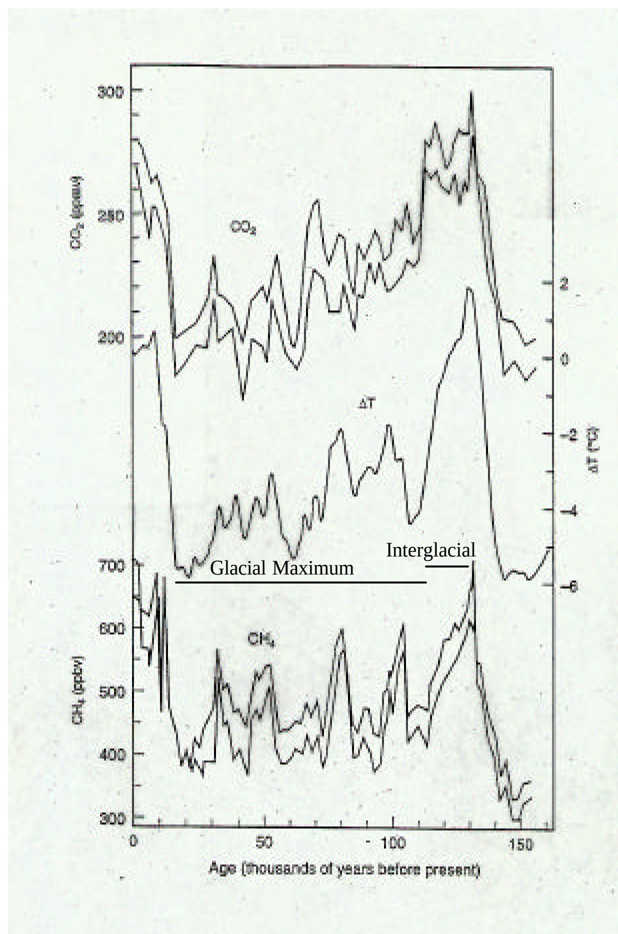


Figure 3.2. Data on concentrations of CO_2 and CH_4, as well as temperature inferred from O_2 isotope ratios. Modified from the Ice Core Working Group (1998).

The impacts of these past glacial and interglacial climate changes on the modern New England regional landscape are profound. Progressing from interglacial to glacial, then back to interglacial, many erosional and depositional features were produced that characterize our present landscape. Erosional features include Niagara Falls and Letchworth State Park (NY); Tuckerman's Ravine on Mount Washington (NH); the U-shaped or glaciated valleys of the "Notches" in the northern White Mountains (NH - Franconia, Dixville, and Crawford Notches); and lakes such as the Finger Lakes (NY), Lake Champlain (VT), Lake Winnipesaukee (NH), and Squam and Sebago Lakes (ME). Some notable depositional land features include Bunker Hill and Beacon Hill (MA), which are drumlins; Nantucket, Martha's Vineyard, and parts of Cape Cod (MA), which are all relict terminal morraines, and the stagnant ice topography of much of western New York. Clearly, the impact on New England and upstate New York of the advance and retreat of glaciers has played a very significant role in shaping the familiar aspects of our landscape.

3.2.2 Variations in Solar Activity During Recent Centuries

Variability in solar output may also have important consequences on global and regional climate. More recent changes in the energy output of the sun during the past few centuries may be an important factor that has contributed to global and regional climate variations. Galileo used his primitive telescope to describe large numbers of sunspots as early as 1610AD. However, during the period from approximately 1645-1715AD, very little sunspot activity was recorded, a period known as the Maunder Minimum (Figure 3.3). The Maunder Minimum coincides loosely with the onset of a longer period known as the "Little Ice Age" (see below). The return to "normal" sunspot activity at the end of the Maunder Minimum (1715) very roughly corresponded to a return to more normal temperatures and climate patterns in Europe.

Figure 3.3 shows the sunspot cycle from 1610 to 1998. This periodic solar behavior is echoed in some locations by cycles in tree ring growth, yearly rainfall in the Northern Hemisphere, and in variations of dust and chemical residues found in ice cores.

The timing of the Maunder Minimum and the initiation of the Little Ice Age is of particular interest. There is active debate regarding the actual timing of the Little Ice Age, but a date from 1500 to 1800 is generally accepted (Thompson, 1992; Bradley, 1999**).** Also, this pattern of climate change was spatially heterogeneous, affecting different locations with somewhat different starting and ending times (Mann et al., 1999). Unfortunately, there are no sunspot records prior to 1610. While the end of the Little Ice Age does loosely correspond to a resumption of sunspot activity in the early 1700s, many scientists agree that the Maunder Minimum is only a partial explanation for that period of cooler temperatures. During the Little Ice Age, Eskimos extended as far south as Scotland, it snowed in Ethiopian mountains and orange groves in China died. Norse colonies established on Greenland during the Medieval Warm Period (900-1400 AD) failed during the Little Ice Age due to heavy pack ice which prevented supply ships from reaching them.

In addition, 11-year and 22-year sunspot cycles appear to be associated with some global temperature variations in the past. However, there is controversy about the physical significance of these associations since the 11 year sunspot cycle is associated with very small changes (0.05-0.1 % in the energy output of the sun). During the 11-year (on average) sunspot cycle, the number of sunspots on the Sun increases to a maximum, then declines to a minimum number of few, or no, sunspots. As the number of dark spots increases to a maximum, so does the overall output of the Sun. In addition to the dark sunspots, bright features called faculae contribute to the increase in overall solar brightness. Collections of these sunspots make up active regions where

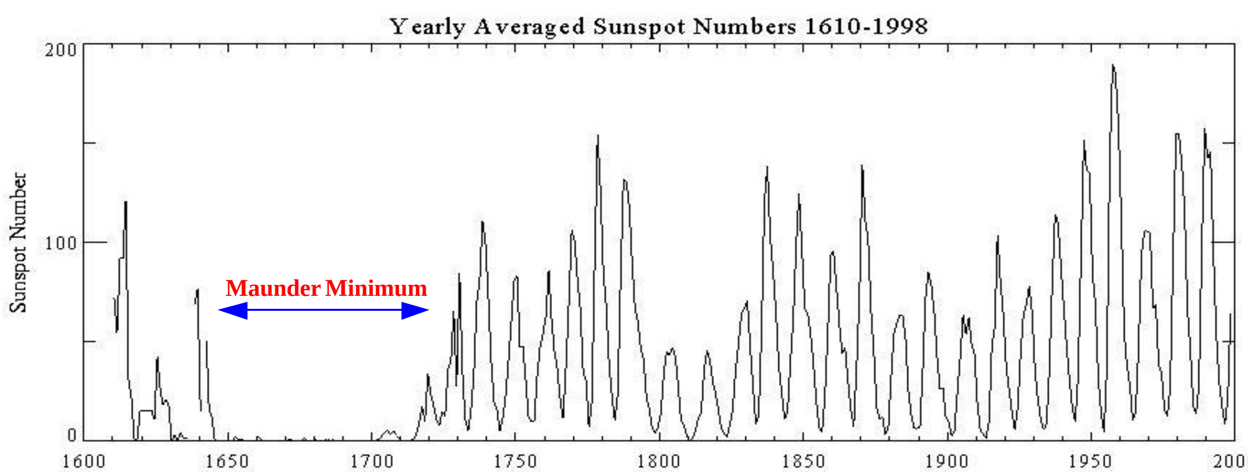


Figure 3.3. The Solar Cycle, yearly averaged sunspot numbers as a function of time. From http://wwwssl.msfc.nasa.gov/ssl/pad/solar/images/.

flares and CMEs originate. Therefore, during sunspot maxima, solar activity and solar output are at a maximum as well.

Although there appears to be a statistical correlation between sun spot cycle and weather patterns, no satisfactory explanation provides a clear physical mechanism for these associated changes. To develop a mechanism that tests these correlations, three main solar variables are currently under investigation: 1) Solar brightness, seen as affecting Earth temperatures; 2) UV rays from the Sun, affecting pressure gradients, winds and ozone production in the Earth's upper atmosphere; and 3) the Sun's magnetic fields and charged particles, which may affect rainfall and amount of cloud cover. It is also possible that minor variations in solar forcing could be amplified due to various feedback mechanisms (Chambers et al., 1999, Andreae, 2000). Recent research suggests particularly interesting relationships among observed variations in solar cycle UV radiation, observed changes in stratospheric ozone concentrations in the stratosphere, and dynamic coupling between the stratosphere and the troposphere (Shindell et al., 1999). Shindell and colleagues (1999) suggest that variations in solar UV forcing, and stratospheric ozone concentration could affect atmospheric pressure gradients in both the stratosphere and troposphere. Such changes, known as Arctic Oscillations, could affect the strength of polar wind vortices in the stratosphere and associated shifts in mid-latitude windfields at Earth's surface during the winter.

As we improve analysis methods, our knowledge of the Sun's role in global climate change promises to increase. Collectively, various solar and planetary cycles appear to have led to many of the dramatic climate shifts associated with past glacial cycles, as well as the varying intensities of past glacial and interglacial components of individual cycles. The Sun's role in climate change is best investigated through interdisciplinary, collaborative work. An example of such a program is "Living With a Star" (http://sec.gsfc.nasa.gov/lws.htm). While *Milankovitch* and solar cycles may explain much of the cyclical climate during the Pleistocene, there are other important climate forcing mechanisms both natural and anthropogenic which influence climate as well.

3.3. Land Cover and Land Use Change Affect the Impact of Solar Forcing

When sunlight strikes the land surface, one of several things can happen, depending on the surface condition. When the surface is extremely bright, much of the sunlight is reflected back to space through the atmosphere. This happens when the land surface is covered with snow, for instance, or when the surface is obscured with cloud cover. Little surface heat is produced when sunlight strikes a bright surface. If the surface is dark, however, much of the sunlight is absorbed and the molecules of the surface material become excited. The excited molecules exhibit an increased molecular vibration and via kinetic energy, generate heat and the dark surface warms. Dark surfaces such as soil and rock are warmed by incoming sunlight, becoming heat sources which return heat to the atmosphere, even after sunlight is no longer shining on them. Some dark surfaces behave differently, as in the case of forest cover. The forests absorb much of the sunlight as part of the process of photosynthesis, in which light energy is converted into chemical energy. In the process of light absorption by leaves, heat is also produced but evaporation of water vapor in the leaf's interior and the loss of that water vapor through stomates (transpiration) cools the leaves. Thus, although fairly dark, a forest canopy actually cools the surface, rather than warms it. Forests represent a land cover type that acts as a heat sink (cooling the surface) rather than a heat source (warming the surface and surrounding atmosphere).

As will be seen below (Section 3.5) greenhouse gases are gases that are transparent to sunlight, but are not transparent to heat energy, thus trapping heat within an atmosphere containing greenhouse gases. Land surfaces that are bright (i.e. snow, ice) reflect sunlight and do not produce much surface heat, while forested land surfaces are also cool even though they absorb sunlight. Land surfaces that are dark (i.e. cleared areas, soil and exposed rock, parking lots, urban areas) generate heat by absorbing sunlight, the heat is then trapped by the greenhouse gases in our atmosphere. Thus when we cut down large tracks of forests, and replace them with urban land cover (shopping malls, parking lots, buildings, roadways, etc.), we are converting a heat sink into a heat source. The concept of an urban "heat island" is well known, and changes in land cover and land use over time can contribute significantly to local and regional warming trends. Conversely, the reforestation of previously cleared areas (as in the case of abandoned farmland across much of the New England region) can have an overall cooling effect locally and regionally, affecting our weather and climate.

Thus, the type of land cover that characterizes an area can significantly affect the impact that solar variation and atmospheric greenhouse gas concentrations have on climate variability, both in the past and in the future. As inhabitants of the New England region, decisions about land use become potentially important in determining, in part, what the regional impact of future climate change may be. In addition to affecting impacts of solar forcing, land use changes (e.g. in flood plains and low lying coastal areas) may enhance the risks associated with climate variability and change.

3.4. Sulfate Aerosols Have a Cooling Effect on Climate

Fine droplets of sulfuric acid in the atmosphere (sulfate aerosols) develop when sulfur compounds such as sulfur dioxide (SO_2) combine with atmospheric water vapor. The sulfur in the atmosphere can be either natural in origin (typically from volcanic eruptions) or anthropogenic (typically from the combustion of fossil fuels rich in sulfur, such as fuel oil or coal). The sulfate haze that limits visibility during summer months in the New England region is typically the result of SO_2 emissions from coal-fired power plants in the mid-West combining with humid air (Figure 3.4).

Just as bright land surfaces reflect sunlight back through the atmosphere, sulfate aerosols act as a reflective component in the atmosphere, limiting visibility and reflecting sunlight. The overall effect of sulfate aerosols is to cool an area by limiting the amount of sunlight that reaches the surface. As is often the case with volcanic eruptions, sulfate aerosols produced enter the stratosphere and can remain in the atmosphere for prolonged periods of time. As noted in Chapter 2, 1816 – "The year without summer," was characterized by snowfalls in every month of the year across the New England region. This followed by one year the eruption of Tambora, in 1815, which ejected large amounts of debris (including sulfate aerosols) into the stratosphere, cooling the climate worldwide. More recently, the eruption of Mount Pinatubo in 1991 provides a likely explanation of the mid-1990s cooling trend seen in the New England regional temperatures presented in Chapter 2.

3.5. Variations in Greenhouse Gas Concentrations Amplify Effects of Other Forcings

Variations in atmospheric greenhouse gas concentrations may amplify the effects of variations in solar forcing as well as land cover change. With increasing anthropogenic emissions of greenhouse gases, we are affecting this amplifier. To help put recent human-induced increases in atmospheric CO_2 into perspective, it is instructive to consider past variations in greenhouse gases (particularly CO_2) and climate. Instrument measurements of climate variables (temperature, precipitation, storm patterns, etc.) date back to the mid to late 1800s (some temperature records go back to the 1860s), and thus provide information about climate variability over the past century or more. Direct measurements of atmospheric CO_2 concentrations in the troposphere (the lowest layer of the atmosphere) began in 1958 at an observatory on Mauna Loa in Hawaii. Most measurements of other greenhouse gases in the atmosphere such as CH_4 (methane - which is twenty times more powerful at trapping heat energy than CO_2), go back only a few decades. The shortness of the modern time-series observations, the complexity and chaotic nature of some atmospheric processes, computational limitations of modern computers used in coupled ocean-atmospheric general circulation modeling, and gaps in our understanding of climate and ocean dynamics all contribute to uncertainty about global and regional-scale climate change.

Fortunately, our understanding of how modern changes in concentrations of greenhouse gases, such as CO_2 and CH_4, may impact climate can be improved by studying past variations in atmospheric gases and climate. Air becomes trapped in accumulating snow in areas of glacier formation. As layers of glacial ice form, air bubbles are sealed in each layer of ice and these bubbles contain traces of the air (consisting of nitrogen, N_2; oxygen, O_2; and trace gases such as CO_2 and CH_4). Analysis of bubble composition from different layers can be used to discern concentrations of atmospheric gases at the time when the ice was formed. If the ice formed 50,000 years ago, the bubbles in that ice contain traces of 50,000-year-old air. Since ice formed from winter and summer snow have different optical properties, the resulting ice

8/14/81

6/26/80

Figure 3.4. The view from the summit of Mount Washington, NH on a clear day (8/14/81) and the same view on a hazy day (6/26/80). The light scattering haze is caused by sulfate aerosols that limit visibility and present a health hazard to people and forests alike. (Photos courtesy of Timothy Perkins.)

contains visible annual layers. By counting layers and using other isotopic techniques, the age of the ice can be determined (Ice Core Working Group, 1998). Ice cores collected from the Greenland ice sheet are up to 110,000 years old, while cores from the Antarctic are up to 420,000 years old. The Antarctic cores encompass up to four full glacial/interglacial cycles (Petit et al., 1997). The climatic significance of the deeper part of the Greenland Ice Sheet Project (GISP2) ice core is a matter of considerable investigation (Mayewski and Bender, 1995; GISP2, 2000), because the older the ice, the more compressed the layers and the more difficult it is to determine the age. In places like Greenland and the Antarctic, analysis of the chemical composition of the ice bubbles permits analysis of past variations in greenhouse gases in both hemispheres. Temperature and ice volume can be estimated by using oxygen-isotope ratios derived from the O_2 trapped in the same ice core bubbles used to measure CO_2 and CH_4 levels (Figure 3.2).

Atmospheric CO_2 levels between 270-290 ppmv (Barnola et al., 1999) are characteristic of our pre-industrial atmosphere, and also occurred during several previous interglacial periods such as the previous (Sangamon aka. Eemian) interglacial about 125-115 years Before Present (B.P.) (Figure 3.2). During the last 130,000 years, as glaciers advanced over mid-latitude continents in the northern hemisphere, the concentration of atmospheric CO_2 gradually dropped to about 190 ppm due in part to gas solubility in water. Colder water holds more of the gas, and less CO_2 occurs in the atmosphere when the ocean surface is cold.

Based on recent analyses of Antarctic ice cores, atmospheric CO_2 concentrations began to increase about 200 years ago. Because CO_2 from fossil fuels has a chemical signature, there is no doubt that the recent increase is due to human activities. As a consequence of fossil fuel use, atmospheric CO_2 concentrations are currently above 370 ppm, about 30% higher than the 280 ppm level typical prior to the Industrial Revolution (1850s). Current levels are the highest in the last 160,000 years (Figure 3.5). Atmospheric CO_2 concentrations could more than double from pre-industrial concentrations by 2100 if emissions continue at the present rate (National Assessment Synthesis Team, 2000). Thus, there is no debate that we are currently engaged in a global-scale alteration of the concentration of greenhouse gases in the atmosphere. The only debate concerns the possible consequences of these greenhouse gases, the appropriate strategies for dealing with their potentially adverse effects, and possible regional adaptations to a varying, and changing, climate.

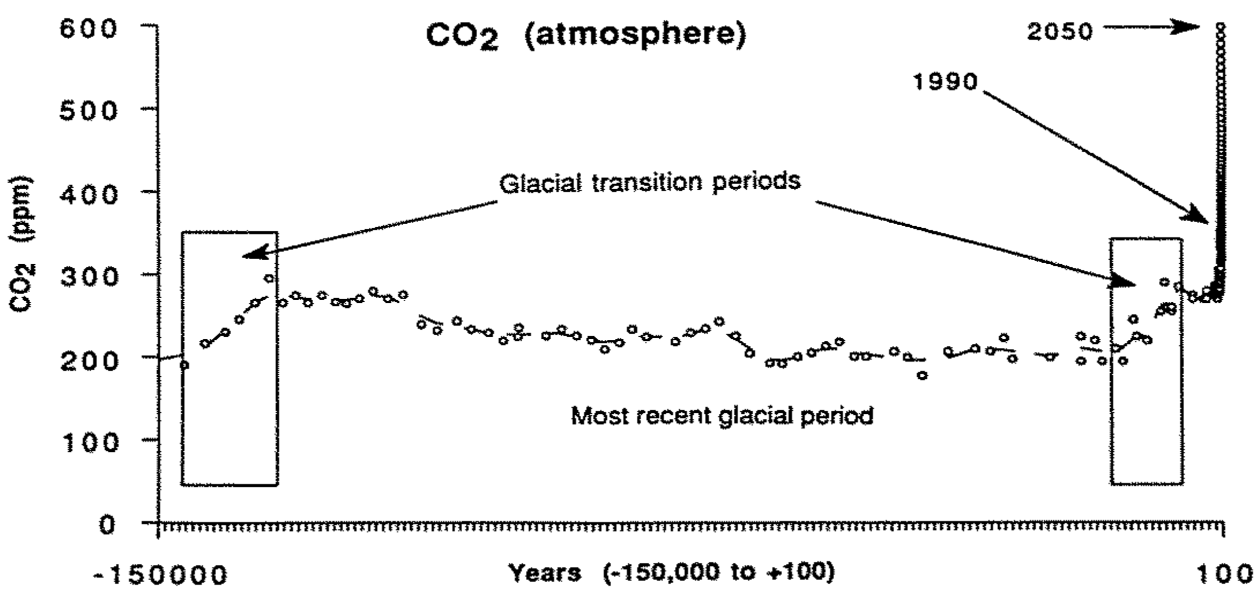


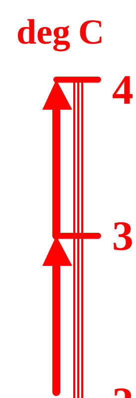
Figure 3.5. Estimates of CO_2 concentrations for the last 150,000 years with a projection to A.D. 2050 based on present-day rates of emission (Longhurst, 1991).

3.6. Evidence of Rapid Climate Change

There have been abrupt periods of warming and cooling during the past 100,000 years particularly in the North Atlantic region, but some of the mechanisms are not well understood (IPCC, 1998). Bond et al. (1999) document periodic abrupt climate changes in the North Atlantic (recurring in cycles of 1,300 - 1,800 years) based on the study of ice rafted debris in deep sea sediments. A possible mechanism for this cycle may be related to an 1,800 year oceanic tidal cycle with periodic variation in vertical mixing and surface ocean cooling. Such an analysis suggests a possible tidal contribution to the observed warming trend in the past century (Chapter 2), which will continue for several hundred years (Keeling and Worf, 2000).

For more recent time periods (within the last 10,000 years B.P.) and more precise age estimates (yearly details), pollen records from annually laminated lake sediments and bogs, and proxy records from tree rings provide great insight. For example, climate reconstructions can be based on tree ring width and density variations in long-lived trees such as bristle cone pine (up to 5000 years old), standing dead trees, and timbers in ancient dwellings. During the growing season, the growth rate of deciduous trees is often limited by available water and serves to record past variations in precipitation. In contrast, woody growth in many of the conifers is often more sensitive to variations in temperature. Thus variations in tree ring width from deciduous and conifer trees can provide information about past variations in precipitation and temperature, respectively. Variations in temperature, precipitation, and atmospheric circulation at the time of wood formation can be inferred in a manner similar to that used in ice cores; by analyzing variations in stable carbon and oxygen isotope ratios in the cellulose of the wood. Carbon isotope variations in tree rings have been related to variations in the amount of precipitation, while oxygen isotope variations in tree rings can record variations in both air temperature and atmospheric circulation changes (Saurer et al., 1998). Historical and paleo reconstructions of past climate variations can then be assembled using information from ice cores, tree rings, lake sediments, marine sediment, and chemical changes in corals that lay down bands similar to tree rings. Longer term perspectives of past climate variations assembled from these proxy records provide a context for understanding the rate of climate change that we have already experienced during the past century.

For the past 1000 years, rates of change in Northern Hemisphere temperature (Mann, 2001; Mann et al., 1999) have been estimated by multi-proxy analysis (Figure 3.6). As a result of these and other recent paleoclimate reconstructions, there is considerably less debate about whether we are currently in a period of rapid global warming. The last 100 years can be seen as a period of rapid warming in the northern hemisphere relative to temperature changes during the last 1000 years. However,



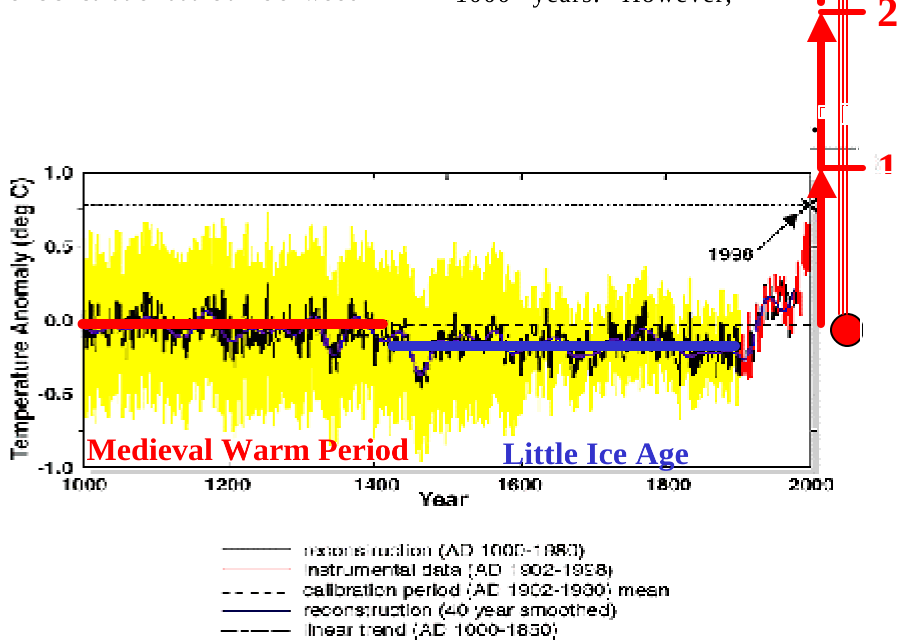


Figure 3.6. Northern Hemisphere temperature changes in the last 1000 years. Modified from Mann et al., 1999.

there have been other notable periods of rapid temperature change in the past millennium. Conditions were relatively warm at the start of the last millennium during the Medieval Warm Period (Hughes and Diaz, 1994), a spatially heterogeneous climate regime with warmer conditions particularly evident in Europe around A.D. 1000-1200 (Lamb, 1965). A subsequent global cooling leading to the Little Ice Age occurred abruptly and synchronously in the South Pacific and North Atlantic at 1400 A.D. (Kreutz et al., 1997), and is reflected in a rapid decline in atmospheric CO_2 concentrations measurable in ice cores. Note that the difference in temperature between the Medieval Warm Period and the Little Ice Age, based on proxy data (Figure 3.6) is only 0.2^o C (0.36^o F).

Greenhouse gas increases due to anthropogenic emissions are expected to result in an additional component of warming. Computer models used in the New England Regional Assessment suggest that the rapid increase in atmospheric CO_2 due to anthropogenic emissions could be followed by a rate of global warming of an additional 3.2 to 5.0º C (6.0-9.5º F) in the next 100 years. This would represent an acceleration in the rate of warming far beyond the warming experienced in the last century or last millennium (Figure 3.6), moving us into a range of global temperatures that have not been experienced in over two million years.

Having discussed atmospheric CO_2 changes in the last 150,000 years and examples of rapid temperature change, consider aspects of interannual climate variability that could have important regional implications to the New England region. Climate variability in New England is determined by New England's mid-latitude location, downwind of a major continent, modified by effects of mountain ranges, land-sea thermal contrasts, and interplay between air masses originating from the four corners of the compass. For reasons described in Chapter 2, New England is blessed with one of the most variable climates in the Northern Hemisphere, a statement which holds true on a broad range of time scales. To more fully understand climate variability in New England, one is forced to consider climate variability at larger spatial and longer time scales in the Northern Hemisphere.

3.7. Modes of Climate Variability and Teleconnections in the New England Region at Larger Spatial and Longer Time Scales

Large-scale patterns of regional climate variation have important effects on the U.S. climate. The El Niño / Southern Oscillation (ENSO) cycle primarily affects low-latitude systems (e.g. the southwestern United States), but is associated with climate variations via teleconnections in other regions of the country and the globe. As noted in the Forest Sector Chapter (Chapter 5), treatment of variability in air quality, poor air quality summers over the past two decades correspond to El Niño years. The ENSO variations can be documented using an index of east-west atmospheric pressure variations across the equatorial Pacific, measured using the Southern Oscillation Index (SOI). Variability in ENSO prior to modern meteorological observations can be documented using various types of proxy records (Mann, 2001) from tree rings, corals, and mountain glaciers.

Significant variations in the mass of the atmosphere and resulting atmospheric pressure gradients also occurs over the North Atlantic, and is a prominent factor in the Northern Hemisphere winter climate (see the Stream Flow Case Study in the Water Resources Chapter). A Chapman Conference in 2000 on the North Atlantic Oscillation (NAO), brought together scientists from many countries and scientific disciplines (The North Atlantic Oscillation. http://www.ldeo.columbia.edu/NAO/) to discuss this important feature of climate variability and change. The atmospheric-pressure oscillations at the sea surface over the North Atlantic during the past century can be documented in a variety of ways. Hurrell (1995; 1996) bases his winter NAO index on measured Sea Level Pressure (SLP) anomalies in Lisbon, Portugal minus SLP anomalies in Stykkisholmur, Iceland. Others compute a monthly NAO index, the simplest involving differences in normalized monthly mean SLP, and north–south differences in SLP between the Icelandic Low (measured at Reykjavik, Iceland) and Azores High (measured at Ponta Delgada, Azores). Still others measure NAO pressure differences between Reykjavik, Iceland and Gibraltar, U.K. (Figure 3.7).

Europe is downwind of prevailing westerly surface winds at mid-latitudes across the North Atlantic. The NAO index is positive when either the Icelandic Low results in a particularly low SLP, or the Azores High results in a relatively

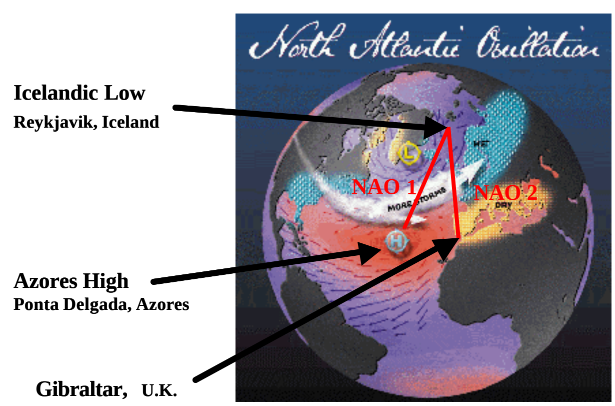


Figure 3.7. Climate patterns when the winter NAO index is in positive phase. Figure illustrates alternative ways to estimate the North to South Pressure gradient over the North Atlantic (e.g. NA01 - SLP difference between Iceland to the Azores, and NAO2 - SLP difference between Iceland and Gibralter). Adapted from http://www.ldeo.columbia.edu/NAO/.

high SLP, or both. The index measures the slope of the atmospheric pressure gradient between two locations. A negative winter NAO index results from relatively weak pressure gradients. A shift from a negative to a positive NAO index moves moisture up into Scandinavia, drawing from the Mediterranean. Positive NAO index phases are associated with increased heat and moisture flux to northern Europe, drought in the Mediterranean, and somewhat wetter conditions along the U.S. east coast, Figure 3.7 (Hurrell, 1995).

Observations indicate that the winter NAO index variation based on SLP variations is a bi-pole, oscillating between two stable states (steep and weak pressure gradients) with periodic fluctuations of varying duration between the two, associated with large variations downwind in European climate. During a positive winter NAO index phase, there is a positive correlation in sea surface temperatures in the northeastern Atlantic and around the southeastern United States. Along with this positive index pattern come significant weather changes, changes in the frequency of Atlantic winter storms and different weather behavior in New England (Hartley, 1996). Negative phases of the NAO index (weak pressure gradients) are associated with a reduction in the frequency of winter storms over the North Atlantic and dryer conditions along the New England coast. Variations in the winter (December through March) NAO index inferred from the difference of normalized sea pressures (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland, (Hurell, 1995) are illustrated since 1864, Figure 3.8 (http://www.intellicast.com //DrDewpoint/Library/1103/drdew11.html). The winter warming trend in southern New England coastal waters correlates well with the transition from a prolonged negative winter index phase to a positive phase between 1950 and 1990 (Figure 3.8B).

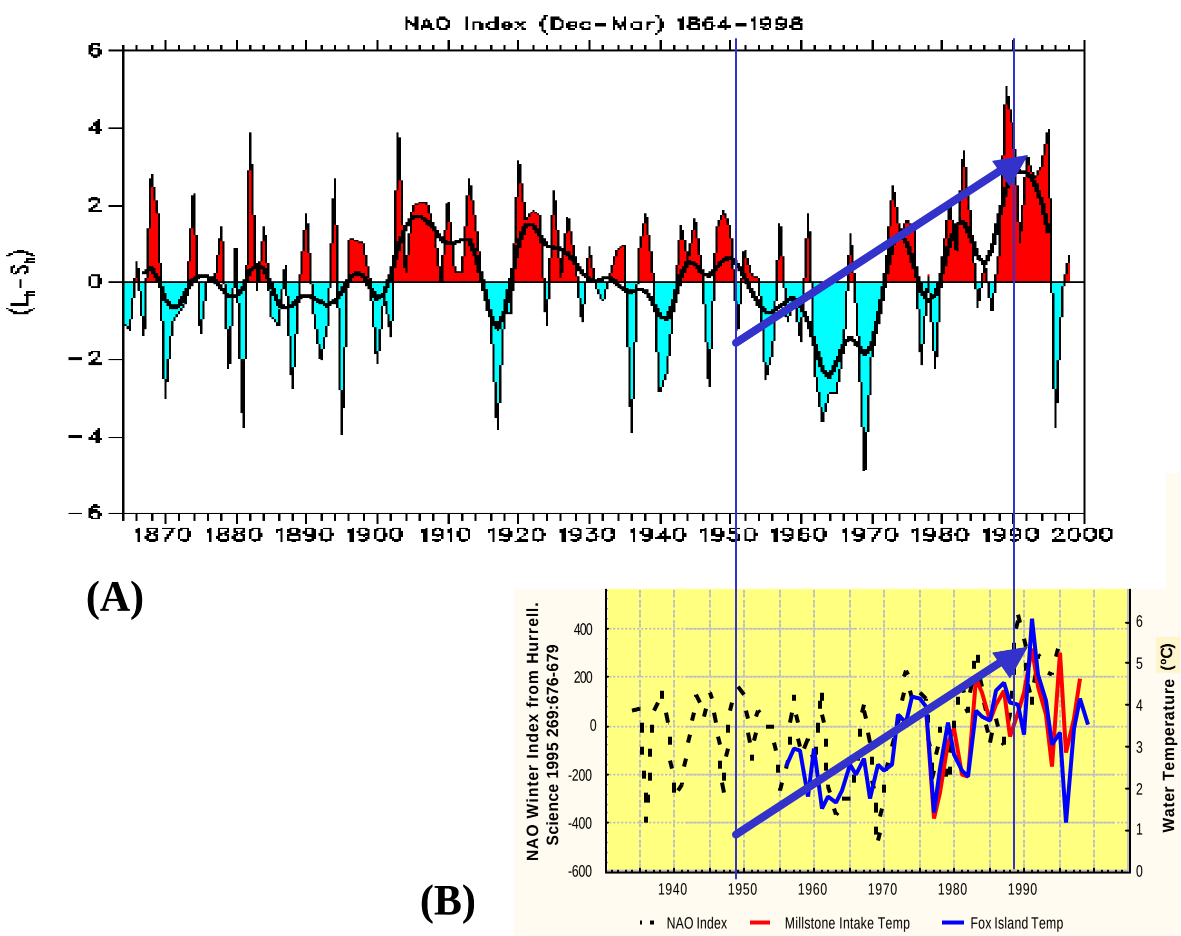


Figure 3.8. The Winter North Atlantic Oscillation index plotted for 1864-1998 (A) and winter coastal water temperatures for southern New England (B). In (A) the red indices are positive, while the blue indices are negative. In (B) the dashed line = winter NAO Index, the blue line = winter water temperature off Fox Island, Narragansett Bay, R.I., and the red line = winter temperature (Jan. - Mar. in Niantic Bay, CT) from Northeast Utilities Millstone Power Plant intake. Sources: (A) geoid.mit.edu/accp/avehtml.html; (B) Hurrell, 1995.

About 49% of the variance in the winter temperature of the Northern Hemisphere over the past 60 years is associated with the SOI and the winter NAO (Hurrell, 1996), with warm El Niño conditions in the Equatorial Pacific and positive winter NAO index phases associated with warmer winters. At present, the full extent of the relationship between the El Niño/Southern Oscillation (ENSO) and the NAO is not understood. Variations in the winter NAO are also associated with larger-scale climate variability around the Arctic (Thompson and Wallace, 1998). Thompson and Wallace view the NAO as a component of a larger feature they refer to as the Arctic Oscillation (AO) or Arctic annular mode. A Principal Component analysis of SLP variations for the Northern Hemisphere (PC1 = AO), and for the Atlantic Sector (PC1 = NAO), reveals a very strong correlation (r = 0.95) between the Arctic Oscillation and the NAO (Deser, 2000).

The emergence of longer-period variations in the NAO, including a persistent negative winter NAO index period in the 1950s and 1960s is not well understood. From the perspective of a 350-year NAO reconstruction based on ice core records from Greenland (Appenzeller et al., 1998), the recent increase in interdecadal variability with more persistent negative and positive phases in the NAO beginning around 1900 is unique. In the North Atlantic, negative NAO index periods may involve aspects of ocean-atmospheric interactions that can weaken or displace the Icelandic low. Although speculative, it is possible that relatively warm conditions and relatively higher atmospheric pressures around Iceland were more frequent during the Medieval Warm Period (1000 to 1400 years AD) (Figure 3.6). Chemical changes in ice cores from Greenland suggest that milder climates during this period were associated with circumpolar vortex contraction, and correspondingly weaker meridional (west to east) circulation (O'Brien et al., 1995).

Currently, scientists are studying proxy evidence from a wide variety of sources to characterize past periods of abrupt climate change around the North Atlantic during the Holocene (11,000 B.P. to today). The frequency and phase characteristics of the NAO during the Medieval Warm Period were probably quite different in character from modes of variability during the subsequent Little Ice Age; an atmospheric circulation pattern that may have persisted into the 20th century (Kreutz et al., 1997), and which may still persist (personal communication Dave Meeker, UNH). Perhaps the climate around the North Atlantic is in the process of flipping back into a circulation pattern with an oscillatory pattern of NAO variability more characteristic of the Medieval Warm Period, or a future pattern of variability which does not have a good paleo analogue. What we should recognize is that such a change in the NAO would be reflected in changes in the strength and trajectory of westerly winds, and could have profound impacts on temperature and moisture fluxes around the North Atlantic including the New England region.

3.8. Summary and Discussion

A number of both natural and anthropogenic factors are known to influence the Earth's climate. Solar output, orbital variations and volcanic eruptions have affected past climate variability and will continue to do so in the future. Land cover type influences how sunlight interacts with the Earth's surface, either reflecting the light back to space or absorbing it, resulting in warming or cooling (in the case of forests). Human activities often result in the alteration of the natural land cover or in the emission of greenhouse gases, factors known to affect climate. Variations in atmospheric pressure systems, such as the North Atlantic Oscillation (NAO), are also known to influence weather and climate patterns in the Northern Hemisphere, including the New England region. All of these climate forcings interact to produce our ever-changing weather and climate.

We are currently in a period of rapid climate warming (e.g. the ten hottest years since the beginning of the last millennium have all occurred since 1983). How much of this recent warming is attributable to anthropogenic factors is still actively debated, but there is a growing recognition that a significant component of the 20th century warming is due to emissions of greenhouse gases (Crowley, 2000; Zwiers and Weaver, 2000; Stott et al., 2000, and the IPCC Third Assessment Report, http://www.ipcc.ch/). As a consequence of fossil fuel use, we could double the concentration of CO_2 in the atmosphere by the middle of the 21st century. Meteorological records indicate that the global surface temperature is rising with the greatest warming during the 20th century occurring over land masses in the Northern Hemisphere during winter (Chapter 2). Analysis of recently declassified data from the U.S. Navy, indicates that Arctic sea ice thickness from the ocean surface to the bottom of the ice pack has decreased by 40% since the first measurements were made in 1958 (Rothrock et al.,1999).

Stratospheric temperatures have cooled, another predicted consequence of increased concentrations of greenhouse gases which absorb outgoing infrared radiation in the lower atmosphere. Recent results from three stratospheric models and two tropospheric models from the Goddard Institute of Space Sciences (GISS) are in general agreement, and indicate that greenhouse gas-induced cooling in the stratosphere and associated changes in stratospheric pressure gradients may be related to observed strengthening of stratospheric wind vortices around both poles (Shindell et al., 1999).

It is becoming apparent that understanding how greenhouse gases in the troposphere affect dynamics in the stratosphere may be fundamental to simulating present warming and future climate change at Earth's surface (Shindell et al., 1999). In the Northern Hemisphere, increased wind speeds in the Arctic stratospheric vortex are associated with stronger midlatitude westerly winds at the Earth's surface and an increased heat flux from the North Atlantic to northern Eurasia

(Shindell et al., 1999). The fact that recent computer simulations do not simulate the rise in the NAO index observed over the past three decades may be due to insufficient resolution of stratospheric processes (Stott et al., 2000). The combined effects of solar forcing, stratospheric chemistry, and tropospheric greenhouse gas increases are only now becoming clear.

We have also learned that the climate is a dynamic system which exhibits bounded instability and can jump between different stable states (Opsteegh, 1998). We know that many natural processes can force the climate, and that several anthropogenic factors also can force the climate. Since we have no control over the natural forcings (solar output, volcanic eruptions, ENSO/NAO patterns), but do have control of many of the anthropogenic forcings (greenhouse gas emissions, land cover changes), it is only prudent for us to begin to consider ways in which the future impacts of anthropogenic forcings can be reduced.

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References

Aguado, E. and J.E. Burt. 2001. *Understanding Weather and Climate*. Prentice Hall. Upper Saddle River, NJ.

Appenzeller, C., T.F. Stocker and M. Anklin. 1998. North Atlantic Oscillation Dynamics Recorded in Greenland Ice Cores. Science 282: 446-449.

Andreae, M. O. 2000. Feedbacks and Interactions between Global Change, Atmospheric Chemistry, and the Biosphere. in Geosphere-Biosphere Interactions and Climate, L. Bengtsson, Editor. 2000, Oxford University Press, Oxford, UK. http://www.mpch-mainz.mpg.de/~biogeo/feedbacks.htm

Barnola, J.M., D. Raynaud, C. Lorius, and N.I. Barkov. 1999. Historical CO_2 record from the Vostok ice core. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Barron, E.J. 1994. Climatic Variation in Earth History, Understanding Global Climate Change: Earth Science and Human Impacts, Global Change Instruction Program #108, UCAR, 23 pp.

Bond, G., W. Showers, M . Elliot, M. Evans, R. Lotti, I. Hajdas, G. Bonani. and S. Johnson. 1999. Mechanisms of global climate change at millennial time scales. Geophys. Monog. 112, Am. Geophys. Union, Washington D.C., pp. 35-59.

Bradley, R.S. 1999. Paleoclimatology: Reconstructing Climates of the Quaternary. Harcourt Academic Press, Burlington, MA, USA, 613 p.

Bush, A.B.G., and S.G.H. Philander. 1999. The climate of the Last Glacial Maximum: Results from a coupled atmosphere-ocean general circulation model. Journal of Geophysical Research 104:24509-24525.

Chambers, F.M., Ogle, M.I. and Blackford, J.J. 1999. Palaeoenvironmental evidence for solar forcing of Holocene climate: linkages to solar science. Progress in Physical Geography 23: 181-204.

Crowley, T.J. 2000. Causes of climate change over the past 1000 years. Science 289: 270-277.

Deser, C. 2000. On the teleconnectivity of the Arctic Oscillation. Geophysical Research Letters. 27:779-782. http://www.gcd.ucar.edu/~cdeser.

GISP2. 2000. The GISP2 Ice Coring Effort. http://medias.meteo.fr/paleo/icecore/greenland/summit/document/gispinfo.htm#GISP2 and GRIP Records

Hartley, S. 1996. Atlantic Sea Surface Temperatures and New England Snowfall. Hydrological Processes 10:1553-1563.

Hughes, M.K. and H.F. Diaz. 1994. Was there a 'Medieval Warm Period' and if so, when and where? Climate Change 26:109-142.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science. 269:676-679.

Hurrell, J., 1996. Influence of variationsin extratropical wintertime teleconnectionson Northern Hemisphere temperature. Geophys. Res. Lett., 23, 665-668.

Ice Core Working Group. 1998. Ice core contributions to global change research: past successes and future directions. National Science Foundation Cooperative Agreement Number OPP-9617009, Univ. of New Hampshire. http://www.nicl-smo.sr.unh.edu/icwg/icwghtml.html#LESSONSLEARNEDFROM

IPCC. 1998. Intergovernmental Panel on Climate Change Workshop on Rapid Non-linear Climate Change. Workshop Report. Noordwijkerhout, The Netherlands 31 March - 2 April. http://www.meto.gov.uk/sec5/CR_div/ipcc/wgl/ipccrep.html.

Keeling, C.D. and T.P. Whorf. 2000. The 1,800-year oceanic tidal cycle: A possible cause of rapid climate change. Proceedings of the National Academy of Sciences 97:3814-3819.

Kreutz, K.J., P.A. Mayewski, L.D. Meeker, M.S. Twickler, S.I. Whitlow, I.I. Pittalwala. 1997. Bipolar changes in atmospheric circulation during the Little Ice Age. Science 277(29):1294-1296.

Lamb, H.H. 1965. The early medieval warm epoch and its sequel. Paleogeography, Paleoclimatology, Paleoecology. 13-37.

Longhurst, A. 1991. Role of the marine biosphere in the global carbon cycle. Limnology and Oceanography 36(8):1507-1526.

Mann. M.E. 2001. Large scale temperature patterns in past centuries: implications for North American climate change. Human and Ecological Risk Assessment. In Press.

Mann, M.E., R.S. Bradley and M.K. Hughes. 1999. Northern Hemisphere Temperatures During the Past Millennium: Inferences, Uncertainties, and Limitations. Geophysical Research Letters 26: 759-762

Mayewski, P. and M. Bender. 1995. The GISP2 ice core record - Paleoclimate Highlights. AGU paper 95RG00498.

National Assessment Synthesis Team. 2000. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. U.S. Global Change Research Program, Washington, D.C.

National Research Council. 1998. Decade to century climate variability and change: a science strategy. Panel on Climate Variability Decade-to-Century Time Scales. Board on Atmospheric Sciences and Climate. Commission on Geosciences, Environment and Resources. National Academy Press. Washington, D.C.

O'Brien, S.R., P.A. Mayewski, L.D. Meeker, D.A. Meese, M.S. Twickler, and S.I. Whitlow. 1995. Complexity of holocene climate as reconstructed from a Greenland ice core. Science 270:1962-1964.

Opsteegh, J.D. 1998. Dynamical non-linearities in the climate system. In: International Panel on Climate Change. 1998. IPCC Workshop on Rapid non-linear Climate Change. Workshop Report. Noordwijkerhout, The Netherlands 31 Shindell, D., D. Rind, N. Balachandran, J. Lean, and P. Lonergan. 1999a. Solar cycle variability, ozone, and climate. Science 284: 305-308.

Petit, J.R., I. Basile, A. Leruyuet, D. Raynaud, C. Lorius, J. Jouzel, M. Stievenard, V.Y. Lipenkov, N.I. Barkov, B.B. Kudryashov, M. Davis, E. Saltzman, and V. Kotlyakov. 1997. Four climatic cycles in Vostok ice core. Nature 387:359-360.

Rothrock, D.A., Y. Yu, and G.A. Maykut. 1999. Thinning of the arctic sea-ice cover. Geophysical Research Letters 26(23):3469.

Saurer, J., R. Siegwolf, S. Borella and F. Schweingruber (1998). Enviornmental information from stable isotopes in tree rings. In: The Impacts of Climate Variability on Forests (eds. M. Beniston, J.L. Innes). Springer Verlag, Berlin, Heidelberg, 241-253.

Shindell, D.T., R.L. Miller, G.A. Schmidt, and L. Pandolfo. 1999. Simulation of recent northern winter climate trends by greenhouse gas forcing. Nature 399:452-455.

Stott, P. A., S.F.B. Tett, G.S. Jones, M.R. Allen, J.F.B. Mitchell, G.J. Jenkins. 2000. External control of 20th century temperature by Natural and Anthropogenic forcing. *Science* 290: 2133-2137.

Thompson, L.G. 1992. Ice core evidence from Peru and China. In: Climate Since A.D. 1500. R.S. Bradley and P.D. Jones, eds., London: Routledge, 517-548.

Thompson, D.W.J., and J.M. Wallace 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys. Res. Lett. 25, 1297-1300.

Zwiers, F.W. and A.J. Weaver. 2000. The causes of 20th 20th Century warming. Science, 290: 2081-2082.

Chapter 4

Historic and Future Climates of New England and Upstate New York

By: George Hurtt, Stephen Hale, and Barrett Rock

It is becoming increasingly clear that significant global climate change will result if the concentrations of greenhouse gases continue to rise (IPCC, 1997). This fact has led the international community to negotiations on the control of the emissions of greenhouse gases (the Kyoto Accord), and has led to the U.S. National Assessment (USNA) of the potential impacts of future climate change on this country. However, local and regional predictions about the timing, magnitude, and nature of future climate changes remain uncertain in part because regional climate models do not exist. The magnitude of future concentrations of greenhouse gas emissions is unknown, and there are scientific uncertainties in our knowledge of the climate system itself, which are largest at a local scale and over short periods of time (decades to centuries).

The New England Regional Assessment (NERA) has attempted to identify and evaluate the potential impacts of future climate change on various components of the New England region (USNA, 2000). Evaluation of potential impacts in the future depends upon the interaction of complex climatic, ecologic, and socioeconomic systems. To address the future climatic conditions, the US National Assessment has provided both historical climate and future climate estimates or "scenarios" for the New England region using two widely respected global climate models (GCMs) modified to provide output scaled to the regional level. The historical climate data for the region is provided for context. The scenarios of possible future climate change have considerable uncertainty and are provided as a minimum basis with which to begin to assess the potential impacts of possible future climate change in New England and upstate New York.

The strategy/approach used to provide reasonable climate scenarios for regional and national impact assessments was based on several key needs. First, an historical climate record is needed as a basis for assessing the impact of past climate events and a baseline for judging the impacts of future climate. Second, the range of future climates used must reflect the range of uncertainty in models and thus, our projections of potential future impacts. Third, the assessment must reflect the range and character of natural variability (like El Niño) and a sense of the spatial variability of climate (such as coastal vs. interior climates). Finally the approach used must allow a scaling of the GCMs to a regional level so that meaningful assessment can be made of potential climate change on a regional scale. The selection of the specific GCMs for use in this assessment process must also recognize both time and human constraints. For these reasons, the same climate scenarios were used by each region and sector, forming the minimum basis for the overall assessment process (Barron, 1999).

There are many aspects of climate that are important to New England. This first assessment has focused its efforts on three climate variables for consideration as impact agents: (1) monthly minimum temperature; (2) monthly maximum temperature; and (3) monthly precipitation.

4.1. Historical Climate Parameters

Understanding the nature and extent of climate historically throughout the New England Region is important for interpreting future climate scenarios. The historical climate data used in this assessment were obtained from the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) Phase 2 historical gridded record (Kittel et al., 1997; VEMAP Members, 1995). Extending from 1895-1993, this regional data set, from well over 300 monitoring stations across New England and upstate New York (Figure 4.1), is comprised of data from the National Climate Data Center's U.S. Historical Climate Network (HCN), and from the USDA's Natural Resources Conservation Service's SnoTel stations for monitoring precipitation at high-elevations. These data have been spatially interpolated onto a 0.5° X 0.5° latitude/longitude grid (Kittel et al., 1997). The New England region consists of 128 VEMAP grid cells. These historical patterns match the historic temperature and precipitation data presented in Chapter 2.

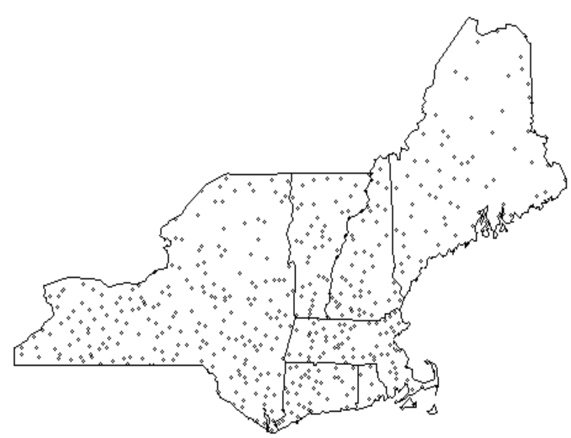

Figure 4.1. Locations of the National Climate Data Center's Historical Climate Network monitoring stations within the New England Regional. Modified from met-www.cit.cornell.edu/nrcc_database.html#daily.

4.2. Climate Scenarios

In the production of scenarios of possible future climate change, the New England Regional Assessment uses the projections from two global climate models used in the National Assessment: the Canadian Centre for Modeling and Analysis's Canadian Global Coupled Model (CGCM1), and the United Kingdom's Hadley Centre for Climate Modeling and Analysis's model (HadCM2). These models simulate climate in response to changes in the concentrations of greenhouse gases over time. Both models assume a 1% (of current levels) per year increase in greenhouse gas concentrations. The cooling affect of sulfate aerosols is incorporated by increasing the Earth's atmospheric albedo. For the US, the projections from these models have been spatially interpolated onto a 0.5^o X 0.5^o latitude/longitude grid (VEMAP Members, 1995). As with the historical gridded data set described above, the New England region is composed of 128 grid cells, and monthly means for all included variables represent the finest temporal resolution used to generate yearly and seasonal means.

About the Graphics

Monthly data were averaged within each year to produce annual mean time-series and averaged within each season to produce seasonal time-series for each parameter. Historical and model output presented for the annual time-series (Figures 4.2, 4.3, and 4.4) include the annual values (thin line) and the 10-year running means (thick line), while seasonal output graphs only present the 10-year running mean (Figure 4.5). The 10-year running mean is calculated using an unweighted average of 10 annual values immediately surrounding the year in question. For example, the parameter value at year 1950 is represented by the average of parameter values occurring from 1945 to 1954. Reporting the running mean in this way filters out short-term inter-annual variation and permits a more generalized view of longer-term trends. It should be noted that precipitation is reported in units of millimeters per month. That is, in the annual precipitation time-series the values represent the average monthly precipitation during that year. For the seasonal time-series the values represent the average monthly precipitation during that season.

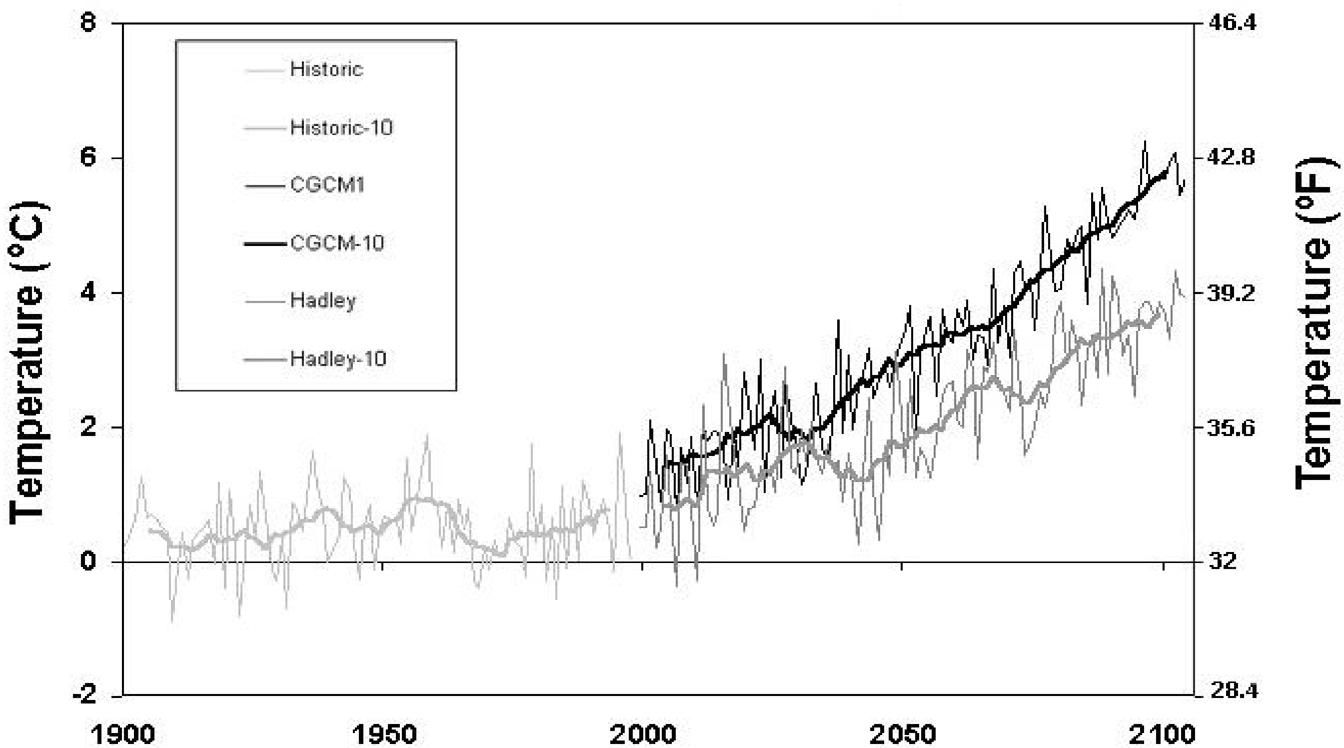

Figure 4.2. Graph of the 10-year running mean of regionalized historic and scenario mean annual minimum temperatures. Historically, there is no indication of a regional increase in minimum temperatures that departs from the range of exhibited variation. Scenario estimates from both models are similar in predicting sustained increasing minimum temperatures into the future. The Canadian CGCM1 model suggests greater increases in minimum temperatures than the Hadley Centre's HadCM2 model. Regionalization was accomplished by averaging the yearly mean values across all 128 VEMAP2 grid cell elements comprising the New England Region. Historic data are from VEMAP2 gridded historical dataset, and the model data are from the VEMAP2 interpolated scenario datasets.

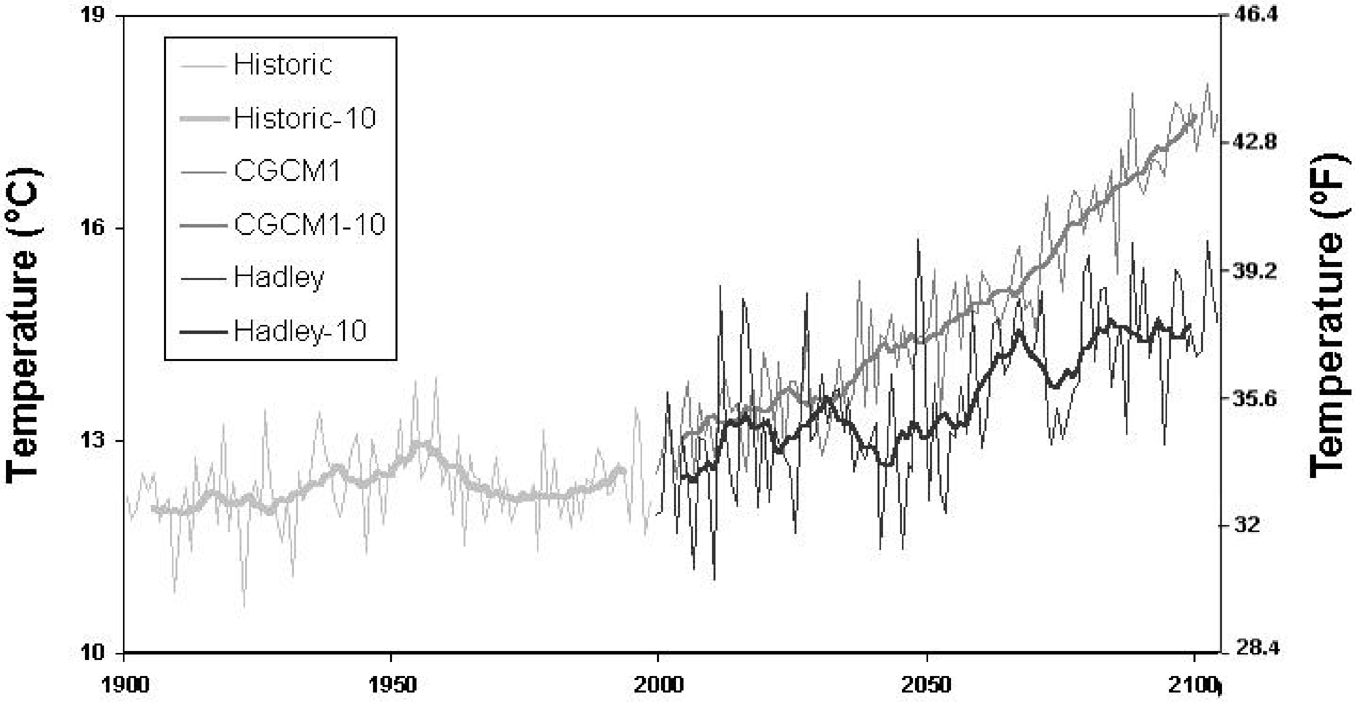

Figure 4.3. Graph of the 10-year running mean of regionalized historic and scenario mean annual maximum temperatures that departs from the range of exhibited variation. Scenario estimates from both models are similar in predicting sustained increasing maximum temperatures into the future. The Canadian CGCM1 model suggests greater increases in maximum temperatures than the Hadley Centre's HadCM2 model. Regionalization was accomplished by averaging the yearly mean values across all 128 VEMAP2 grid cell elements comprising the New England Region. Historic data are from the VEMAP2 gridded historical dataset, and the model data are from the VEMAP2 interpolated scenario datasets.

A gap along the x-axis (year axis) between the historical and scenario curves is produced by this calculation. This gap results at the beginning and end of the time-series data where a centered 10-year running mean can not be computed. A gap in the time-series also occurs along the y-axis (parameter axis) and results from differences in temperature between the historical and modeled outcomes. The modeled results do not include historical values as input for calibration, so model outcomes are not expected to coincide precisely with the historical outcomes.

Seasonal time-series data were used to show parameter variation within a year. Here, Winter is represented by averaging the months January-March, Spring by April-June, Summer by July-September, and Fall by October-December. In addition to the characteristics of the annual time-series graphics, the seasonal time-series graphics have been scaled to facilitate seasonal visual comparison. That is, within panels for a given parameter the y-axis has the same scale. This was done to accommodate the range of absolute temperatures across seasons that would otherwise severely dampen the curves had a single common scale been used. Visual comparison of seasons across parameters should be used with caution, because of the change in y-axis scaling.

The spatial graphs of the New England and upstate New York region are depictions of each grid cell element contained within the region assessment. In these graphics, the long term anomaly (difference) is computed for each grid cell. This anomaly is computed by subtracting the 2090-2099 ten-year parameter mean from the 1961-1990 mean (assumed to be the normal climate). Therefore, the scale is a difference or change in the parameter and not the absolute magnitude of the parameter.

Annual Minimum Temperature

Both the CGCM1 and HadCM2 scenarios suggest that the average annual minimum temperature of the New England region will increase in both the near-term (i.e. 2030) and long-term (i.e. 2100) future (Figure 4.2). However, the models differ in the magnitude of minimum temperature change. Both models suggest the region may increase by 1 ^{o} C (1.8^{o} F) by 2030, more than double the increase seen for the region over the past century. The HadCM2 model indicates a 3.2^{o} C (5.7^{o} F) rise by year 2100, while the CGCM1 indicates a 5.4^{o} C (9.7^{o} F) rise over the same time period. These changes are very large relative to the historical record of minimum temperature variation that has occurred since 1895 and over

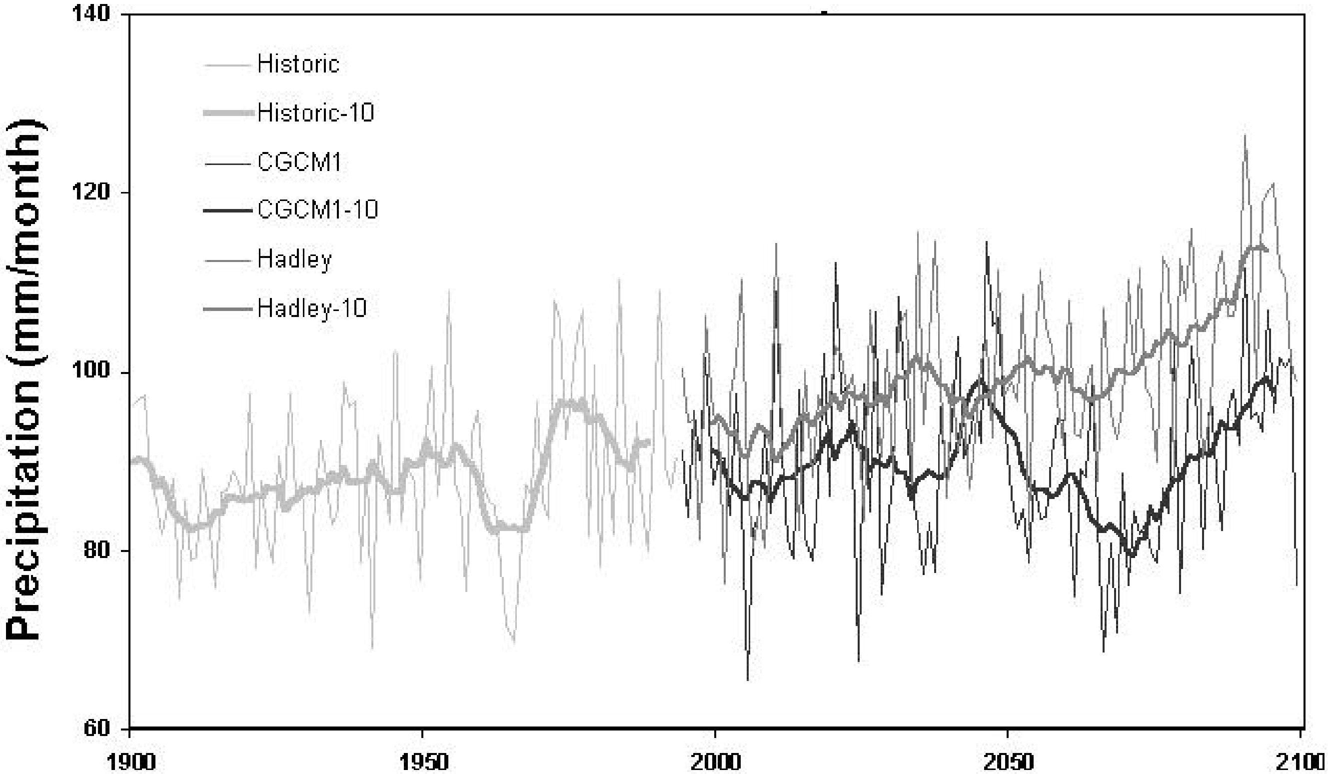

Figure 4.4. Graph of the 10-year running mean of regionalized historic and scenario mean annual precipitation. Historically there is a slight indication of a regional increase in precipitation, however, large, rapid increasing and decreasing departures from any norm have occurred as exhibited by annual variation. Scenario estimates are incongruent in estimating potential future precipitation. The Canadian CGCM1 model suggests lesser increases in precipitation than the Hadley Centre's HadCM2 model. Note further, the massive variability in the CGCM1 model. Regionalization was accomplished by averaging the yearly mean values across all 128 VEMAP2 grid cell elements comprising the New England Region. Historic data are from the VEMAP2 interpolated scenario data sets.

at least the past 1000 years (Figure 3.6, 4.2). Such a change would be similar in magnitude to the change experienced during the last glacial period (20,000 years before present).

Annual Maximum Temperature

Both models suggest that the average annual maximum temperature of the region will increase in both the near-term (i.e. 2030) and long-term (i.e. 2100) future (Figure 4.3). However, as with the minimum temperature, the models differ in the magnitude of maximum temperature change. Both suggest an average annual maximum temperature increase of 1.5^{o} C (2.7^{o} F) by 2030 and from 2^{o} C (3.6^{o} F) to 5^{o} C (9^{o} F) by 2100 (HadCM2 and CGCM1 models, respectively). Both of these scenarios suggest large temperature increases in the future compared to the past 100 year historic record of maximum temperatures and for the past millennium.

Annual Precipitation

Historically, annual precipitation in the New England region has varied widely and has included times of drought (Figure 4.4). Note the prolonged drought that characterized the mid-1960s. Embedded within this range of variability, lies a long-term trend (i.e. 100 years) of a modest (4%) increase in precipitation. The HadCM2 model predicts a continuing increase in precipitation (an approximate 30% increase) without evidence of the type of drought seen in the 1960s. The Canadian CGCM1 model suggests little long-term increase in precipitation (an overall increase of approximately 10%), but large fluctuations in precipitation with events similar to drought of the 1960s. It is interesting to note that the Canadian model suggests a greater warming relative to the Hadley model, while the Hadley model predicts greater precipitation compared with the Canadian model. Either increase in precipitation would be large compared with the regional increase of approximately 4% since 1895.

Seasonality

Most of the seasonal trends were similar to the annual trend for each parameter (Figure 4.5). In every season, both the CGCM1 and HadCM2 models project substantial warming, and the CGCM1 model projects greater amounts of

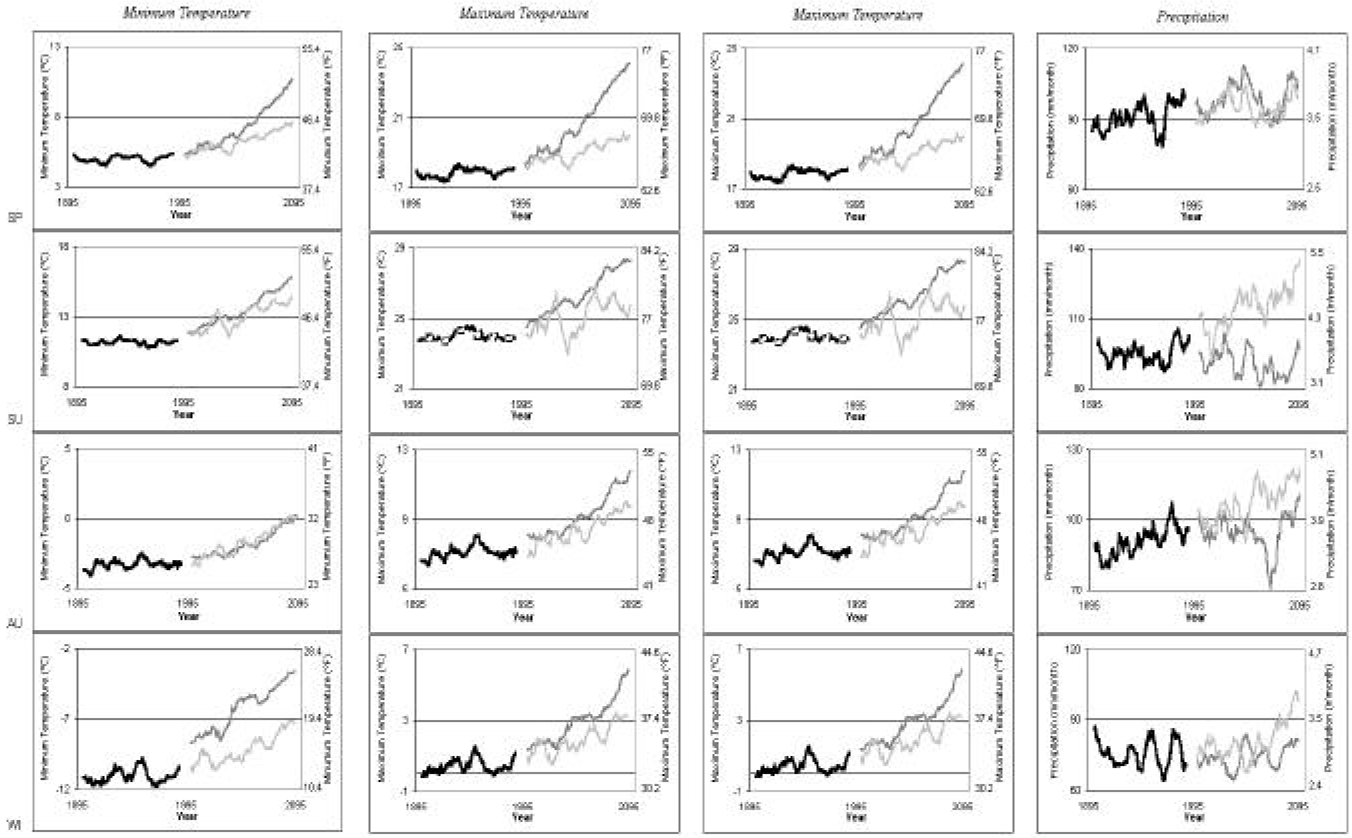

Figure 4.5. Seasonal trend graphs (10 year running means) for the 1895-1993 VEMAP2 historical gridded data and two model “scenario” data sets from 1994-2100. Key: historical = ■; CGCM1 = ■; HadCM2 = ■; SP = Spring; SU = Summer; AU = Autumn; WI = Winter.

warming than the HadCM2 model. Exceptions to this occur in the Summer and Fall minimum temperatures, where the models suggest approximately equal amounts of warming. Precipitation is projected to increase substantially in every season except Spring in HadCM2, and does not have a substantial trend according to the CGCM1 model in any season. Both models illustrate the potential for continued interannual variation in seasonal precipitation of magnitudes that are similar to or larger than variations experienced in the historical record. The months represented by the seasons presented in Figure 4.5 are as follows: Winter = December, January, and February; Spring = March, April and May; Summer = June, July and August; and Fall = September, October and November.

Spatial Variation

The climate models show differing amounts of spatial variation in the parameters investigated (Figure 4.6). Region-wide variation in the long-term temperature anomalies is greater in the CGCM1 model than in the HadCM2 model. The CGCM1 model projects greater temperature increases inland than along the coastal regions, a result in disagreement with current findings (Chapter 2). In contrast, the HadCM2 model shows little to no difference in temperature changes across the entire region. In terms of precipitation regimes, the HadCM2 model shows a greater absolute precipitation difference, but also a greater degree of regional heterogeneity compared with the lesser absolute precipitation and clinal variation exhibited by the CGCM1 model.

GCM Evaluation for the Northeastern US

A qualitative assessment of the performance of the two climate models’ estimates for temperature and precipitation against historical observations has revealed some regional biases across North America (Doherty and Mearns, 1999). The models exhibit greater temperatures than have been observed in the historic record for the northeast region during the Fall and Winter seasons. In addition, both models suggest increased precipitation compared to observed Spring and Summer values. Here, however, the CGCM1 model displays a greater magnitude in bias than the HadCM2 model (Figures 4.5 and 4.6).

The scenario data sets used for the New England Regional Assessment represent some of the best available. However, the down-scaling of much larger-scale global climate models to finer regional scale (used in this analysis) is problematic. Many of the geographic and topographic variables

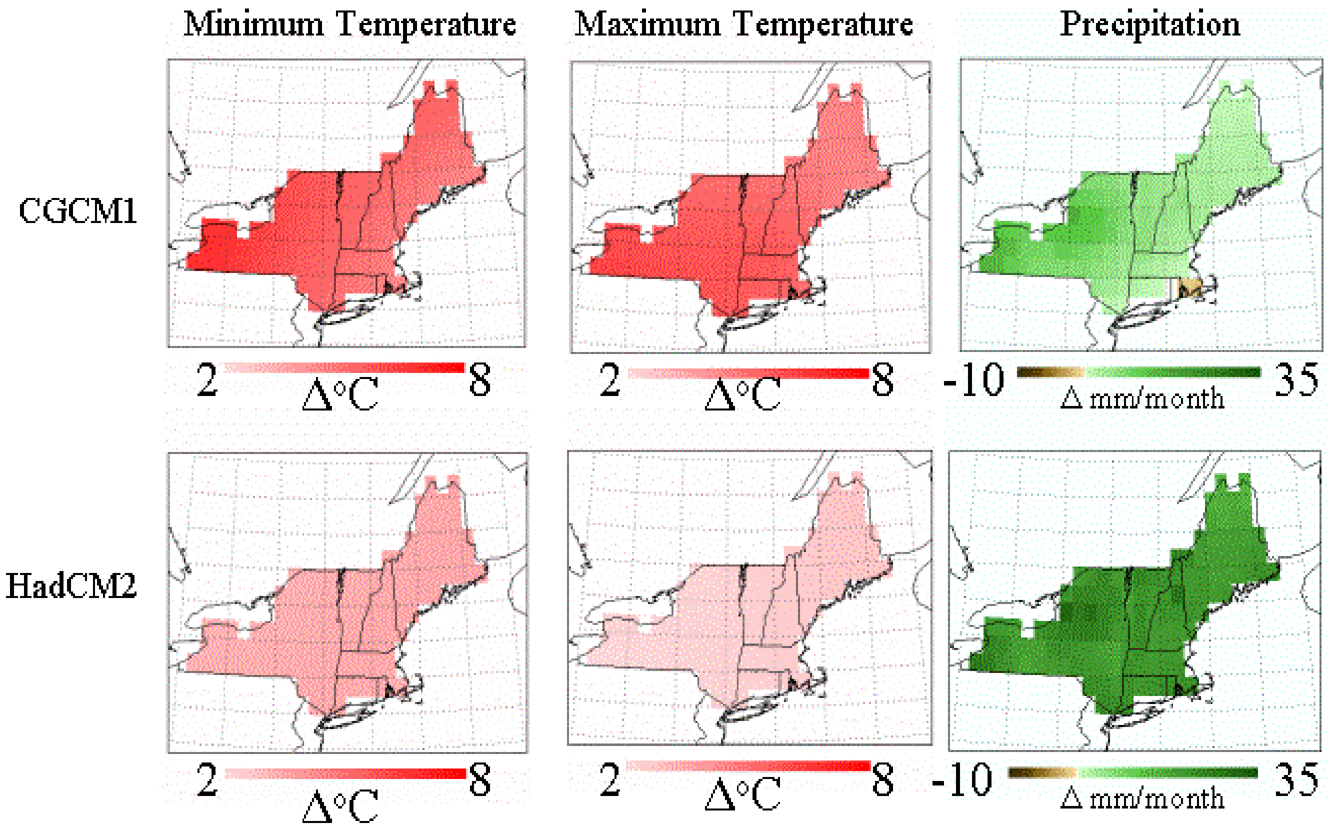

Figure 4.6. Graphs of New England and upstate New York spatial variation of Minimum Temperature, Maximum Temperature and Precipitation for the CGCM1 and HadCM2 models. All differences (anomalies) are computed as the [2090-2099] mean minus the [1961-1990] mean.

that are known to influence our regional weather and climate (Chapter 2) are not considered in global-scale models such as the CGCM1 and HadCM2. For this reason, the regional scenarios presented in this chapter must be considered "best approximations" based on what was available in the late 1990s. Clearly there is a great need for regional climate models to be developed that account for regional variability at a scale known to affect weather and climate.

Newest Climate Models Reproduce the Recent Climate Record and Identify the Human Influences

Recent work by Stott et al. (2000) has used a new version of the Hadley climate model (HadCM3) to simulate recent historic global temperatures and to assess the relative importance of natural and anthropogenic factors on the temperature patterns of the last 140 years (1860-1999). The study shows that the model is able to simulate (hindcast) the global temperature record of this period very well. This is possible only when both natural and human factors that affect climate are included. Changes in natural factors such as variation in solar irradiance and volcanic aerosols are necessary to explain the warming trend observed in the early part of the century. However, human factors such as the increasing concentrations of greenhouse gases in the atmosphere are needed to explain the warming trend over the past 30 years. The ability of the model to accurately simulate the last century of warming gives confidence that models are potentially useful representations of the climate system with which to make projections of the future. The large influence of human factors such as the increases in greenhouse gas concentrations on the climate system in the latter part of the century reaffirms the expectation that further warming will occur with continued increases in greenhouse gases that are assumptions in both models presented in this chapter.

4.3. Summary/Conclusions

Significant climate change in this century is considered an increasingly serious possibility (IPCC, 1997). To provide a basis for an assessment of the potential impacts of future climate change on New England, the regional assessment team has used the regional output from two global climate models as scenarios of possible future climate change in the New England region. These models are not perfect, but represent the best scientific scenarios available, and their projections should be viewed as possible outcomes. Both models project substantial warming and substantial changes in precipitation for the region if greenhouse gas emissions continue to rise at 1% per year into the future. The Canadian CGCM1 model projects a more dramatic warming (10° F increase in minimum annual temperatures) with large fluctuations in precipitation, but with only a modest (10%) increasing long-term trend in precipitation. The Hadley HadCM2 model projects a less dramatic warming (a 6° F increase in minimum annual temperature), and a trend toward dramatic (30%) increases in regional precipitation. The changes from either model, if realized, would be much larger than the climate variation experienced by the New England region in the last 10,000-20,000 years.

References

Barron, E. 1999. Assessment Methods I: Climate Scenarios. Acclimations January/February. (http://www.nacc.usgcrp.gov/newsletter/1999.o2)

Doherty, R. and L. O. Mearns. 1999. A comparison of simulations of current climate from two atmosphere-ocean global climate models against observations and evaluation of their future climates. Report to the National Institute for Global Environmental Change. pp. 56.

IPCC, 1997. The Regional Impacts of Climate Change: An Assessment of Vulnerability. (Watson, R. T., M. C. Zinyowera, R. H. Moss, D. J. Dokken, eds.). Intergovernmental Panel on Climate Change. Pp. 28. (http://www.ipcc.ch/pub/sr97.htm).

Kittel, T.G.F., J.A. Royle, C. Daly, N.A. Rosenbloom, W.P. Gibson, H.H. Fisher, D.S. Schimel, L.M. Berliner, and VEMAP2 Participants. 1997. A gridded historical (1895-1993) bioclimate dataset for the conterminous United States. Pages 219-222, in: Proceedings of the 10th Conference on Applied Climatology, 20-24 October 1997, Reno, NV. American Meteorological Society, Boston.

USNA, 2000. U.S. National Assessment Regions. (http://www.nacc.usgcrp.gov/regions/)

VEMAP Members. 1995. Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochemical Cycles 9*:407-437.

Chapter 5

The Impact of Climate on Regional Forests

By: Shannon Spencer, Gary Lauten, Barrett Rock, Lloyd Irland, and Tim Perkins

5.1. Introduction

This chapter provides an overview of the region's forests as a basis for understanding their relation to climate and climate change. As a region, New England and New York are heavily forested and include the first and second most heavily forested of the contiguous U.S. states (Maine and New Hampshire, respectively). As of 1997, the region contained 51.4 million acres of forestland.

The region's forests form part of a vast ecological transition zone between the true boreal forests of the north in Canada, and the mixed hardwood forests of the south-central United States. The complex mix of forest types, and their distribution across the landscape is determined by a host of factors. Characteristic tree species of this transition zone are the eastern white pine, red spruce and balsam fir and sugar (hard) maple to the north, as well as white oak species to the south. Wetlands are a significant feature of the landscape, and many are forested.

The region's forests include portions of four vegetation provinces:

- Laurentian Mixed Forest Province, dominated by conifers and hardwoods, especially the maple-beech-birch type (northern hardwoods) and spruce-fir. This forest occupies northeastern Maine and a considerable portion of the "southern tier" of New York.

- New England-Adirondack Province, occupying the highlands of the Catskills, Tug Hill, Adirondacks, and the ranges of mountains in New England, and extending along the border of Maine with Canada. This province includes similar species as the Laurentian, and contains the region's examples of alpine and subalpine vegetation.

- The Eastern Broadleaf Forest (oceanic) occupies the coastal portion of this vast hardwood-dominated province. In many biogeographic schemes it is described as the oak-hickory region.

- The Eastern Broadleaf Forest (continental) is the final province, basically consisting of the Lake Ontario plain in New York, which today is largely converted to productive farmland.

The current dominant forest types in the region are presented in Table 5.1. From the human perspective, the region's forests appear to be static and unchanging, but have changed dramatically over the past 400 years and will likely continue to do so in the future with or without climate change (Cogbill, 1999; Irland, 1999).

Table 5.1. Major Types of Commercial Forest Land in the Northeast, 1997 (New England plus New York)

Forest Type	Acres (1,000)	Percent
White/Red/Jack Pine	5,415	10.5
Spruce-Fir	8,525	16.6
Loblolly/Short-Leaf Pine	326	0.6
Oak/Pine	1,254	2.4
Oak/Hickory	5,774	11.2
Oak/Gum	109	0.2
Elm/Ash/Cottonwood	1,838	3.6
Maple/Beech/Birch	24,269	47.2
Aspen/Birch	3,654	7.1
TOTAL	**51,390**	**100.0**

Source: USDA-FS RPA Website.

Forces Shaping the Forest

Forces shaping the forests of the New England region today are diverse and complex. Over most of the region's forest, cutting for timber products has been the primary shaping force in the past. Currently, from 2-4% of the region's forest land is harvested every year, though much of this is partial cutting. The intensity of use of the forest for wood products varies widely, as indicated for pulpwood harvest data in Figure 5.1.

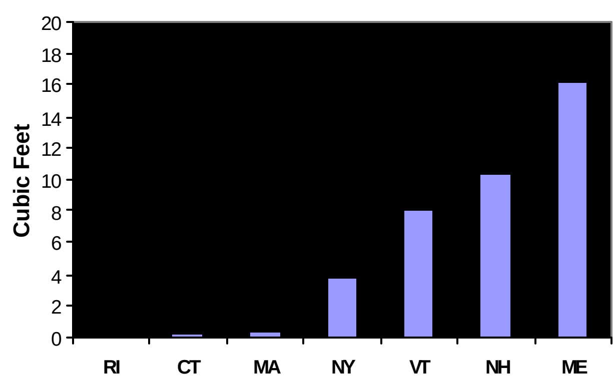

Figure 5.1. Northeastern states pulpwood harvest per acre of commercial forest land, 1994-1996. Source: Widmann and Wharton (1998).

Portions of these harvested areas went through a period of elevated fire frequency in the decades following heavy cutting. The fires affected soils and shaped the species composition of the regrowing forest. Fire has always been an influence in this region, but of fairly low frequency outside of specialized habitats associated with specific human activities (such as the heavy logging in New Hampshire in the early 1900s).

The second most important force was clearing for farming. Millions of acres of land went through a cycle of clearing, pasturing or row cropping, and then returned to secondary forest. Lands subject to this sequence of events display drastically modified soil profiles, in many cases benefiting from elevated organic matter storage compared to their presettlement condition. Frequently, they support early-sucessional types over considerable and near-contiguous areas, in conditions not found in presettlement times. Examples would be stands of aspen on regrown potato land in northern Maine and white pine on old pastures across a wide belt of southern Maine, New Hampshire, Vermont, and New York.

Planting for timber has been locally practiced across the region, and in some areas Christmas tree farms are common, as in Coos County, New Hampshire. Yet, of all the anthropogenic forces shaping the forest, planting has been one of the least important. Even in timber-oriented Maine, less than 10,000 acres a year are planted. In New York, Norway spruce was widely established in fast-growing plantations for timber. This species, technically an exotic, has been so widely planted for so long it is considered naturalized by many foresters. In most instances, the areas planted would have reverted to some other forest condition over time.

As a result of the cycle of farm clearing and then abandonment, the forested area of the New England region has changed considerably over time (Figure 5.2). As the 20th century progressed, the amount of land employed for housing, commercial purposes, industry, and infrastructure increased. By the 1960's, in Connecticut the area of land occupied by forests finally exceeded that remaining in farming.

The region's forests are owned by 1.2 million separate owners. As a result, forest and land management practices vary widely, from active management directed at specific products (Christmas tree farms) to neglect. Thus, forest productivity varies widely as well.

The forest has also been affected by introduced pests. The most famous are the chestnut blight, which eliminated a key component of upland hardwood forests of the region; and the Dutch elm disease. Other introduced pests, such as the white pine blister rust, hemlock woolly adelgid, and gypsy moth have reduced the productivity of native tree species.

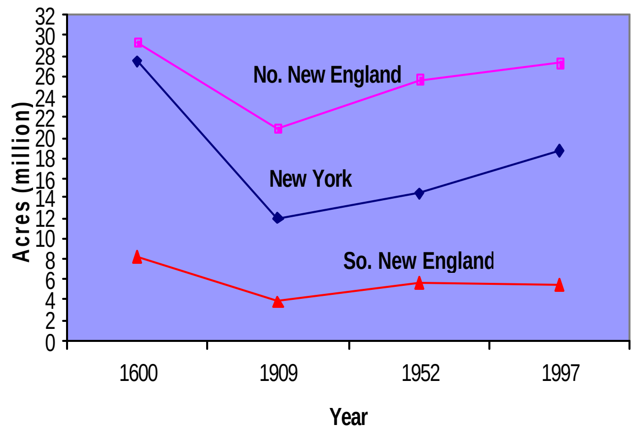

Figure 5.2. Forest land area in the region, 1600-1997.

Extreme weather events obviously affect the forest in the short run. Events such as the 1938 Hurricane and the 1998 Ice Storms are noteworthy. Less dramatic but equally important have been periodic thaw/freeze events in winter months (Auclair *et al*., 1996). How such infrequent events shape vegetation composition and condition over long periods of time has yet to be determined. The impacts of chronic climate change are also poorly understood.

In addressing the potential impacts of climate change on regional forests, current stresses, and how these stresses may be affected by future climate changes will be considered. In addition, coping strategies will be proposed and missing pieces needed to more fully predict impacts will be identified. Four detailed case studies will also be presented that document the impacts of current climate stresses on forests and speculate about future impacts under climate change scenarios.

5.2. Current Stresses and The Impact of Past Climate Change

In a very broad way, the influence of climate is visible today as a stress factor in the region's vegetation provinces. For example, according to one authority, the southerly limit of the boreal province is set by the 18º C July isotherm (Elliot-Fisk, 2000). The fact that oak is uncommon in northern Maine, and native red spruce is uncommon in the "southern tier" of New York is probably a climate effect. Also, the elevational zonation of vegetation in the region's mountain ranges from the Catskills to the Katahdin massif is strongly climate-controlled. Elevation strongly affects growing conditions, adding complexity to the region's vegetation mosaic (Marchand, 1987). Because of the influences of Canadian continental weather in winter, coastal effects, altitudinal effects, and the influence of southerly air masses in summer, the vegetation zonation does not follow a simple north-south scheme. Frost-free seasons, winter thaw/freeze cycles, late frosts, ice storms, and other aspects of climate are important stressors to individual species or in particular locations (Auclair, *et al*., 1996; Boone, 1997; Delcourt and Delcourt, 2000).

Mild temperatures allow insects and diseases to flourish and permit the introduction of exotics not previously found in the region. Currently, the northward spread of the hemlock wooly adelgid is occurring faster than anticipated because of mild winter temperatures during the last decade. This insect has caused major damage to hemlock stands (a favorite home to deer) in southern New England and has recently spread over the northern Massachusetts border, into Portsmouth, New Hampshire. Also with rising temperatures described in Chapter 2 there could be an increase in severity and occurrence of gypsy moth (which attacks the young leaves of oaks and other broadleaf species) and pear thrip (which attacks sugar maple foliar buds) outbreaks, both responsible for periodic defoliation of the deciduous forests in the region.

Air quality also has an impact on tree health and thus ultimately affects forest conditions. Warmer, drier summers possess the ingredients for increased levels of ground level ozone that is known to cause damage in leaves (see Case Study #1). Acid precipitation can cause nutrients such as calcium and magnesium to be leached from both the leaves and the soil. When these nutrients are removed, other harmful elements such as aluminum may injure tree roots. It is important to note here that the increase in carbon dioxide predicted by the climate models may act as a fertilizer and cause greater sugar production during the growing season and thus increased growth. Such a fertilizer effect must be balanced against the damaging effects of poor air quality and nutrient depletion.

Forest fragmentation is a result of a range of human activities, from harvesting and farming, to urban and suburban development. The overall effect of such fragmentation has been a decrease in habitat quality and biodiversity.

Changes in seasonal dynamics (timing and duration of seasonal patterns) may also effect tree physiology and forest health. Case Study #2 evaluates such changes in the past and their impacts on maple syrup production.

Ice storm damage (see Case Study #3) has had a significant impact on selected tree species. Trees with less flexible branches (maples and oaks) tended to be more heavily impacted than those species which were more flexible (pines and birch).

Carbon Storage

Over the New England region as a whole, forests are gaining growing stock, volume, and biomass as a result of regrowth following cutting, and of the return to forests over former farmland. This active regrowth following cutting has been cited as one of the factors which has resulted in the current level of carbon sequestration in New England regional forests (Caspersen *et al*., 2000). This is true with the exception of Maine, where the spruce-fir forest lost volume between 1982 and 1995 due to the joint effects of the range of age class structure, spruce budworm outbreaks, and heavy cutting (Irland and McWilliams, 1997; Irland et al., 2000). While certain species are known to be sensitive to poor air quality (Case Study #1), overall it appears that current regional conditions are promoting forest regrowth and carbon storage.

Traditional forest inventory measurements have concentrated on defining the inventory and growth-removal balance for forests at a state and national level, considered in terms of merchantable wood. In recent years, such measurement has been expanded to develop estimates of the biomass tonnage and carbon content of the entire forest ecosystem, including leaves, roots, dead material, and forest floor and soils (Birdsey, 1992). The total quantity of carbon stored in the forest is partitioned among living and dead biomass, aboveground vegetation, root biomass, forest floor, and soils (Figure 5.3). The trees themselves, including crowns, account for only 26% of the total on each acre.

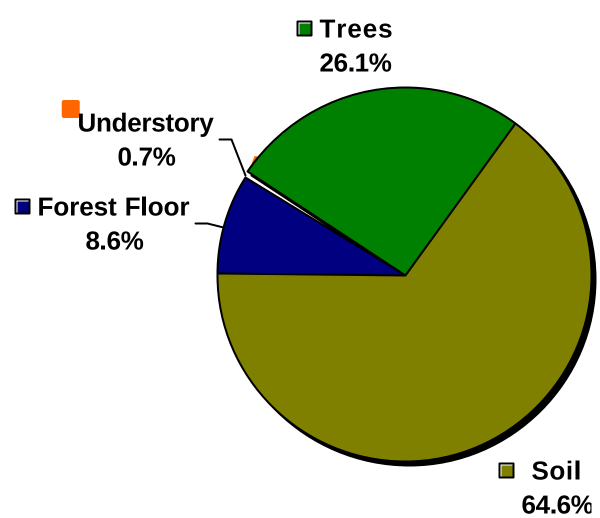

Figure 5.3. Carbon storage in Northeastern forest ecosystem components.

When summed over all forest acres and components, the total tonnage of carbon stored in the forests of the Northeast is 2.8 billion metric tons. As of 1987, these forests were gaining a total annual tonnage of 17 million metric tons of carbon each year (Table 5.2).

Table 5.2. Total Carbon Accumulation in Trees in

State	Metric Tons of Carbon (1,000)
New York	10,811
Vermont	3,426
New Hampshire	3,434
Maine	7,443
Connecticut	849
Rhode Island	196
Massachusetts	1,669
TOTAL	**17,017**

Considering the total flow of wood products harvested through the market system into use, reuse, recycling, incineration, and disposal amplifies our understanding of the role of forest products in the carbon cycle (Irland and Cline, 1998). Overall, carbon storage by forests is small compared to present and future levels of emissions (unless emission controls are implemented).

Air Quality

Tropospheric or ground-level ozone (i.e. not stratospheric ozone) is one of the most pervasive and detrimental air pollutants known to affect forest growth (Ollinger *et al*., 1997). As was noted in Chapter 1, a strong correlation has been shown to exist between changes in physical climate (temperature) and changes in the chemical climate (air quality), notably in the production of elevated levels of ground-level ozone. At a very basic level, studies have shown that the most pronounced affect of ozone on plant carbon uptake is a reduction in net photosynthesis due to a loss of chlorophyll and photosynthetic enzymes (Ollinger *et al*., 1997). Due to the documented effects of tropospheric ozone on both vegetation health and human health (the Hiker Health Case Study, Chapter 7), improving our understanding of the variations in regional tropospheric ozone levels and changes in forest and ecosystem health is a goal of present regional research efforts (Theisen *et al*., 1994; Rock and Lauten, 1996).

Due to the topographic variability typical of the region and the fact that it is downwind from the rest of the country and parts of Canada, upper-elevation sites (generally above 3,000') can be characterized by unhealthful levels of tropospheric ozone. Coastal portions of the region also experience elevated levels of tropospheric ozone, especially during summer months characterized by hot, dry conditions (1991, 1995, 1997, 1999, 2001). Long-distance transport of NO_x, combined with both high levels of naturally-occurring VOCs (terpenes from trees) and sunlight at elevation combine to produce toxic levels of ozone across much of the summer season. These current ambient levels of ozone lead to significant problems for trees, especially in sensitive tree species, such as white pine and red spruce (Moss and Rock, 1991; Rock and Lauten, 1996).

Seasonal Dynamics

Every autumn in the New England region is spectacular as broadleaf trees begin a transformation, their leaves turning brilliant hues of red, purple, orange, yellow, and brown. These brilliant colors occur between mid-September and late October and are responsible for a very busy tourist season throughout the region. This seasonal display is however vulnerable to four components of climate change (air quality, seasonal dynamics, species migration, and extreme weather events) because the quality and brilliance of the display is dependent on tree health, temperature variation, and the species present.

Leaves change color when temperatures become cooler and days become shorter. First, the conduit that allows passage of sugars, nutrients, and water to and from the leaves is sealed, leaving any residual sugars in the leaves and preventing water from the roots entering the leaves. Second, chlorophyll, the pigment in leaves that produces the sugars and give the leaves their green color begins to degrade. Third, other pigments (anthocyanin, carotene, and xanthophyll) in the leaves, whose reds, yellows, and oranges have been masked by the chlorophyll, now show through and produce the brilliant display.

Soil type and moisture, site quality, species characteristics and composition, and tree health are factors known to vary the quality, intensity, and duration of the annual display. However, climatic factors play an even more significant role, since hard frosts hasten the loss of chlorophyll and enhance the colors of the other pigments. All these factors complicate the ability to predict a good or bad foliage season. The year 1998 was the warmest on record, both for this region and the globe. Delayed killing frosts in November or December led to trees keeping their leaves longer than usual, and the colors displayed were muted in many parts of the region.

Extreme Weather Events

Although the links between regional climate patterns and the frequency/occurrence of extreme weather events are not well documented or understood, the present warming trends and altered precipitation patterns may have resulted in more extreme weather events such as the ice storms of 1998. As seen in that ice storm, forest management practices, as well as topography, aspect and species type all contributed to damage levels. See Case Study #3 for more details.

5.3. Impacts of Future Climate Change

Carbon Storage

The impact of future climate change on carbon storage in the region's forests is difficult to quantify. Factors such as poor air quality, acidic deposition, calcium depletion, and continued fragmentation will continue as the climate changes and forest response lead to reduced carbon storage. Even with improved air quality, other factors (soil depletion, insect pests) may continue to limit growth and thus, carbon storage.

A possible win/win scenario could be created if reductions in air pollutants associated with reduced CO_2 emissions resulted in improved forest health. Such improved forest health could result in increased carbon storage. At the present time, the overall impact of increasing levels of atmospheric CO_2 on forest productivity is not clear.

Air Quality

The warming trends projected by either climate model could mean an increase in the number of hot, dry days during summer months, especially in the case of the Canadian Climate Model. Such an increase would likely result in more ozone exceedance days, thus affecting sensitive forest species such as white pine (Case Study #1). Reduced air quality will be a byproduct of a warming climate across the region. The current levels of reduced forest productivity due to poor air quality will increase.

Seasonal Dynamics

Based on the regional projections generated using the Canadian Climate Model and the Hadley Climate Model, the New England region is likely to experience a warming trend and an increase in precipitation over the next 100 years. Both climate models suggest significant warming by 2095, but to differing degrees (an increase of from 3.1^{o} C/6.0^{o}F to 5.2^{o} C/10^{o} F). In terms of precipitation, the models differ as well, suggesting from a 10% to 28% increase. Such changes could have a profound affect on seasonal dynamics across the region: milder winters (especially warmer nighttime temperatures); warmer and wetter summertime conditions; etc. Such changes would have dramatic, potentially negative affects on many current stresses that impact the forests of New England.

Insect Pests

In much the same way as the northward incursion of the hemlock woolly adelgid has occurred, a warming New England region (especially warming winters) will support the introduction and expansion of exotic pests into the region. Insect pests such as the gypsy moth and the pear thrips will likely become more aggressive and have an even greater impact on regional forests than is currently felt.

Plant Species Migration

The increase in air quality impacts, attacks by insect pests, and species sensitivities to climate variables would combine with environmental changes associated with a warming scenario to facilitate species migrations into and out of the region. As shown in Case Study #4, species more tolerant of these conditions would replace less tolerant species over time, resulting in forest composition changes into the future. The current wide-spread occurrence of sugar maple across the northern parts of the region is likely to be much reduced or totally eliminated as a result of either climate scenario presented in Chapter 4.

Species migration due to a changing climate may well be the most devastating impact on regional forests. The climate models predict that by 2100 the major components of the New England forests will be oak and hickory (see Case Study #4). The brilliant reds, oranges, and yellows of the maples, birches, and beeches may be replaced in the landscape by the browns and dull greens of oaks.

CO_2 Fertilization

Finally, while increasing levels of CO_2 in the atmosphere will likely act as a fertilizer enhancing forest growth, recent research has shown that such increased growth is likely to be limited by soil nutrient levels in which elements such as calcium may be leached due to acid rain in the region. Thus, on balance, forests in the region are likely to become less healthy, due to insects, poor air quality, and nutrient depletion, in spite of the CO_2 fertilization affects of enhanced greenhouse gas levels.

5.4. Information and Research Needs

While the forest sector is particularly sensitive to climate change, the public does not fully understand or appreciate the issues involved. One solution to better understanding of the issues is to prioritize research and education programs that focus on the regional impacts of climate change. Some suggestions are as follows:

- Improve the regional resolution of climate models so that climatic variability can be created for specific areas of the region. These models should include physical and chemical climate factors and current land cover and land use change information. Only then can interactive consequences of changes in given factors, such as human land use decisions, have meaning and value to decision makers.

- Create educational outreach programs to improve the public's understanding of the impacts of climate change on forest species important to the region. Expand such programs to schools in the region so students can become better and more knowledgeable stewards of the environment.

- Identify environmental thresholds (critical changes in factors such as temperature, precipitation, air pollutants, etc.) beyond which an individual species or ecosystem can no longer function.

- Quantify, in terms of dollars, the impact to natural and managed ecosystems of various climate projections. If the public can see a projected revenue loss to a state, community, or an industry due to climate change, interest will be heightened.

- Improve current techniques for increasing soil quality in managed forests.

- Determine genetically selected species or varieties with adaptive traits appropriate for changing climatic conditions. This would allow for selection of propagation material tailored to expected environmental conditions.

- Develop appropriate forest management strategies that will promote improved forest carbon storage, given the potentially negative impacts of depleted soils, poor air quality, and increased insect infestations in the future.

5.5. Adaptive Strategies

Since there is very little that can be done to stop the impact of climate change on the forest ecosystem, the most effective approach for coping with change will be to anticipate the effects of that change and initiate adaptation strategies. These strategies will be most important in educating and preparing both the general population and specific forest sector industries for the impending change.

Land use policies and conflicts are major issues now. There will be additional pressure for shifts in land use, whether it be urban sprawl or increased agricultural use, that will encroach on the natural ecosystems. It will be important to maintain contiguous forest regions and minimize the current land use practices that foster fragmentation of the landscape. Community, county, state, and regional planners need to make educated decisions that balance all stakeholder needs.

As previously mentioned, climate change will likely result in more severe and numerous infestations of current pests and pathogens as well as those that will invade in the years to come. Pest management practices will need to be reconsidered and integrated pest management programs revised to fully address these problems. This may well include the need for the increased use of pesticides in order to sustain forests that will be weakened from air pollutants, drought, and warmer temperatures.

A shift in species composition, invasion of exotic species, and loss of habitat will require the most adaptation strategies. While some species, such as oak, hickory, beech, and sweet gum are far from their northern ecological limit, other species, such as fir, spruce, aspen, sugar maple, and birch are near their southern ecological boundary. The forest products industries need to address a number of adaptive measures to insure continued economic prosperity as species composition changes, since these industries traditionally need a 25-30 year lead time on capital investment. Some examples include:

- Consideration should be given to planting different species after harvesting current stands. Warmer climate species have a faster growth rate that would increase productivity.

- Since disturbance seems necessary to maintain positive growth (C-storage), strategies will be needed to promote such positive growth.

- The use of fertilizers may become necessary as forest soils are altered by leaching, drought, and warmer temperatures.

- The industry should look at possible product diversification and more flexible marketing strategies.

Finally, communities and homeowners can change the species of trees they plant. By planting species that are well within their ecological boundaries, there will be less chance for these trees to become unduly stressed from climatic factors. Also consideration should be given to species that are known to be insect and disease tolerant. Diversification can also provide a means to deter total devastation from pests.

5.6. Conclusions

The regional forests have changed over the past several hundred years, and will continue to change into the future. Some of this change will occur independent of climate change in the future. This dynamic nature of the region's forests is likely to make them the most flexible and sensitive to climate changes, of the Sectors considered in this regional assessment.

Increased carbon storage may be one response by the regional forests to enhanced levels of CO_2 in the atmosphere. However, uncertainties about continuing (or increased) air pollution affects, soil nutrient depletion, insect pests, and disease raise questions about this response.

A win-win scenario may be possible if reduced CO_2 emissions are accompanied by reduction in air pollution levels, resulting in improved forest health and increased forest productivity.

5.7. Case Studies

CASE STUDY 1 – Forest Health and Productivity in Response to Ozone Exposure in a Sensitive Species

By: Barrett Rock and Shannon Spencer, Complex Systems Research Center, University of New Hampshire

White pine (*Pinus strobus*) is a forest species that occurs across New England. Commercially, it is an important timber species for the region and is one of our most common low-elevation conifers. Maine, the pine tree state, owes that moniker to the widespread occurrence of white pine across the state. White pine is also known to be a bio-indicator species for exposure to high concentrations of tropospheric ozone, a common component of SMOG (Bennett *et al*., 1986; Treshow, 1986; Sanchini, 1988; Treshow and Anderson, 1991; Theisen *et al*., 1994). Diagnostic foliar symptoms, known as chlorotic mottle and tip necrosis (Fig. 5.4), occurring in the absence of other known causes, are known to result from exposure to ozone levels at or above 80 parts-per-billion (ppb). Such symptomology is the result of varying degrees of chlorophyll loss. Such chlorophyll loss leads to a reduction in net primary productivity (NPP), which in turn can lead to a reduction in wood production in sensitive species such as white pine (Bartholomay *et al.*, 1997). Since up to 45% of the carbohydrates produced in photosynthesis are allocated to wood production, a reduction in NPP due to exposure to elevated levels of ozone (above 80 ppb) across the New England region will result in a loss of timber productivity. Loss of timber productivity is also a loss in the forest's ability to sequester carbon.

Chlorophyll loss can be quantified using spectral reflectance measurements and indices acquired using both field and laboratory spectrometers, as well as with advanced airborne remote sensing tools (Rock *et al*., 1986, 1988; Entcheva *et al*., 1996, 1998, 2001; Zarco-Tejeda, 2000). Field and laboratory data have been used to demonstrate that spectral indices associated with a region of the reflectance spectrum known as the red edge are highly-correlated with chlorophyll content in both hardwoods and softwoods (Rock *et al*., 1986, 1988; Moss and Rock, 1991; Vogelmann *et al*., 1993). Recent work indicates that similar indices can be used on data acquired with airborne imaging spectrometers for assessing changes in forest health (Entcheva, 2000; Entcheva *et al*., 2001; Zarco-Tejeda, 2000).

An on-going science outreach program called *Forest Watch*, developed by researchers at the University of New Hampshire, engages pre-college students across New England in studying forest health, with a specific focus on white pine. *Forest Watch* students collect needle and branch samples from five white pine trees located near their schools for study in their classrooms. Branch collections are made in the spring of each year, resulting in needle samples representing the previous summer's growth. Of the eight *Forest Watch* schools that began the program in 1992, six schools continue their involvement, collecting samples from the same 30 permanently marked white pine trees. In 1992, the students evaluated the health of 1991 needles, and each year, branch samples with the previous year's needles are sent to the University of New Hampshire for spectral characterization using a reflectance spectrometer. One of the spectral parameters, the Red Edge Inflection Point (REIP), is computed for each set of needles sent by the students. Since the REIP is highly-correlated with foliar chlorophyll content (high REIP values correlate with high chlorophyll content, low REIP values correlate with low chlorophyll levels), it may be used as an indicator of needle health.

The eight-year record (1991-1998) of REIP values for each of the school's set of samples provides a basis for comparing the health of current-year needles for the same five trees, at the same six locations, within New Hampshire. The annual REIP values can then be correlated with Summer (June, July and August) ozone values for seven locations monitored by the New Hampshire Department of Environmental Services around the state (Figure 5.5). These monthly maximum values are reported by the Environmental Protection Agency (EPA) on their Web site for each monitoring station.

Figure 5.4. Typical foliar symptoms of ozone damage seen in white pine needles.

Figure 5.5. Seven locations where ozone is being monitored by the New Hampshire Department of Environmental Services.

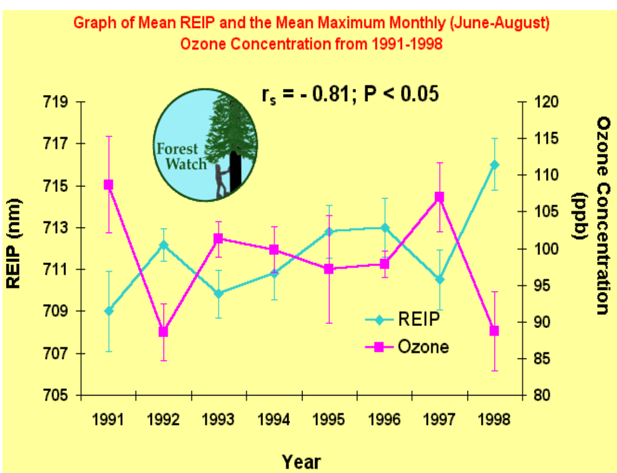

Figure 5.6. Inverse relationship between the REIP and ozone data in New Hampshire for the years 1991-1998.

Figure 5.6 shows the inverse relationship between the Red Edge Inflection Point (REIP) and ozone data in New Hampshire for the years 1991-1998. The resulting correlation coefficient (r_s = -0.81) is *very significant*, and means that 66% of the variation in REIP values is accounted for by the variation in ozone.

The data presented in Figure 5.6 indicate that when average ozone values are high for a given three-month summer period, the REIP values (and inferred chlorophyll levels) are low. Conversely, when ozone values are low for a given year, the REIP values from the same 30 trees are high. The higher the REIP value, the healthier the needle samples *are assumed to be*, based on laboratory studies of REIP vs. chlorophyll concentration (Moss and Rock, 1991; Vogelmann *et al*., 1993). This suggests an adverse relationship between ozone and the health of the needle samples that were sent by the participating *Forest Watch* schools. At this point, we can not be certain that the ozone is the only factor causing the fluctuation in REIP values, but, based on previous work (Moss and Rock, 1991; Theisen *et al.*, 1994), this assumption is warranted. Other climatic factors such as rainfall during summer months and the timing of precipitation patterns have been compared against the REIP values and are not considered to be significant variables. Because high temperatures during summer months and ozone formation are correlated, high temperatures and REIP values show a weaker inverse relationship.

The Red Edge Inflection Point is a spectral index that is calculated by computing the first derivative of the spectral curve between the wavelength range of 680–750 nanometers (nm). The red edge is a steep slope rising from a strong absorption feature in the red spectral region. This absorption of light is due to the presence of chlorophyll, which absorbs red light in the process of photosynthesis. The wavelength of the maximum peak of the first derivative identifies the point along the red edge where the curve experiences its greatest change in slope (the inflection point). As noted above, the inflection point of the red edge is one of several red edge spectral indices that are highly correlated with chlorophyll concentration in the foliage being spectrally characterized.

Ten sets of branches (two branches per tree, five permanently marked trees per school) with current-year needle samples are sent to UNH for spectral analysis by each participating *Forest Watch* school. Each set of current-year needles is measured by a high resolution spectrometer to determine the percent reflectance of the needles from 400-2500 nm. Researchers can determine several parameters (chlorophyll content, state of cellular health and moisture status) related to the health status of the needles using these reflectance data. The REIP value calculated from these data indicated the relative amount of chlorophyll present in the needles at the time of sample collection. Ozone impacts white pine, and other tree species, by entering the stomates and oxidizing (breaking down) the living cellular membranes, along with chloroplast membranes. In previous controlled-exposure studies, exposure of needles to levels of ozone above 80 ppb resulted in cellular degradation (plasmolysis and loss of organelles) and chlorophyll loss that resulted in lower REIP values.

In the recent study by Bartholomay *et al*. (1997), a set of site and environmental variables were evaluated, using tree-ring data collected from white pine trees from a number of sites at Acadia National Park, in Maine. This study used dendroclimatic techniques to investigate the possibility that ozone alone could account for reduced radial growth rates, when compared with climatic and soils factors. The results indicated that stronger negative associations occurred between tree-ring indices and ozone than between tree-ring indices and any climatic (temperature and precipitation) or soil variables.

In a simulation study of the potential impact of tropospheric ozone on forest productivity, Ollinger *et al*. (1997) combined leaf-level ozone response data from a series of ozone fumigation studies of appropriate species, with a forest ecosystem model in an attempt to quantify the affects of ambient ozone on mature hardwood forests across the New England region (including upstate New York). Using ambient ozone data for the region from 1987-1992, predicted declines in NPP ranged from 3-16%, with the greatest reductions occurring in the southern parts of the region characterized by the highest ozone levels (southeastern NY, CT, MA, coastal NH and ME). Reduction in wood production was slightly higher (up to 22%) due to the way in which the allocation of carbon was prioritized for wood production. Since white pine is known to be very sensitive to ozone exposure, and the simulation model dealt only with hardwoods, increased reductions in softwood production would also be expected, based on the findings presented here.

Lessons Learned

The *Forest Watch* program has proven to be a very effective science education outreach project. In addition to students learning the methods of science by doing them, they also have provided valuable data for use by researchers assessing the health of white pine in response to variations in tropospheric ozone levels.

The data presented clearly demonstrate the connections between physical climate change and chemical climate (air quality) change. In addition, the biological impact in a sensitive species is also clearly demonstrated in the *Forest Watch* data.

The year-to-year variation in ozone exposure results in an inverse year-to-year variation in one indicator (chlorophyll/REIP values) of tree health. Trees that exhibit unhealthy values one year can exhibit healthy values the next, with improved air quality conditions.

Forest species are more resilient to improved air quality than is generally appreciated. The *Forest Watch* data suggest that improving air quality would improve the state-of-health of white pine.

Such an improved state-of-health in white pine would result in increased carbon sequestration in this regionally important softwood species.

CASE STUDY 2 – The Maple Sugar Industry

By: Shannon Spencer and Barrett Rock, Complex Systems Research Center, University of New Hamsphire

The maple sugar industry represents an important component of both New England and New York's character and economy. The U.S. maple syrup production presently accounts for approximately 20% of the worldwide production. Prior to the 1950s, the U.S. accounted for 80% of the worldwide maple syrup production. The New England/New York region represents roughly 75% of the total U.S. production and the average value of the New England/New York syrup production was $25 million for 1997-1999 (Figure 5.7) (NEASS, 1999a, 1999b; Allan *et al*., 1995). In Vermont, the highest volume maple syrup producing state in the region, the multiplier affect of the industry to related equipment, manufacturing, packaging and retail sectors equals $105 million annually and represents approximately 4000 seasonal jobs (VDA, 2000a). The maple syrup industry also contributes significantly to the tourism industry and other service sectors within the region (Allan *et al*., 1995; VDA, 2000a, 2000b).

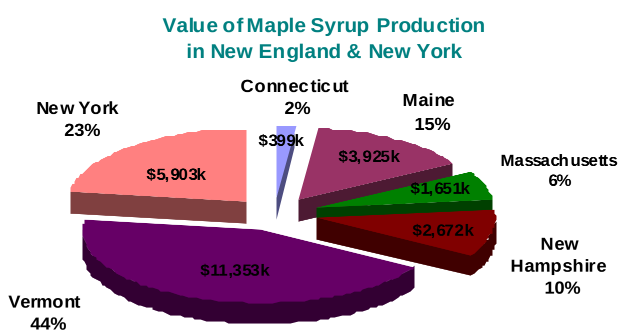

Figure 5.7. Average Production Value for New England states and New York between 1997-2000.

The sugar maple tree (*Acer saccharum*) produces sap flows beginning in late February to early March depending on geographic location and diurnal temperature differences. This occurs due to physiological changes resulting in the conversion of stored starch to transportable sugar (sucrose). Sucrose is required for bud and leaf expansion and prolonged cold periods below 25ºF (cold recharge periods) are required for the enzymatic conversion of starch to sucrose, resulting in high sugar content (3-5%) in the sap. The occurrence of diurnal alternating freeze-thaw conditions causes positive stem pressures, resulting in sap flow (Tyree, 1983). Tapping trees for sap is estimated to remove less than 10% of a tree's sap, and when done properly, has been reported to cause minimal damage to healthy trees (Kramer and Kozlowski, 1979; ACEIS, 2000). Amino acids found in the sap, microbial action and thermal carmelization are responsible for giving maple syrup its distinctive color and taste (Perkins, personal communication).

The successful maple syrup season in New England depends on the proper combination of freezing nights, with temperatures below 25? F, and warm daytime temperatures, with temperatures greater than 40? F (Bloomfield and Hamburg, 1997; Marvin, 1999; Kramer and Kozlowski, 1979; Cook and Myott, 2000). Once a string of days occurs where nighttime temperatures no longer fall below freezing, sap flow stops (Kramer and Kozlowski, 1979). The first sap flow of the season generally has the highest sugar content and the lowest nitrogen content, resulting in the highest quality syrup of a given season (Perkins, personal communication). Therefore, the maple industry in New England depends to a large extent on the timing of these critical climate events. The traditional time to tap trees for the coming season has been around Presidents Day in mid-February, with the season starting after Town Meeting Day (2nd Tuesday in March). Yet, for the last several years the sugaring season and first sap flow have occurred as early as the beginning of February (Marvin, 1999; NEASS, 1999a, 1999b). In addition to the early starts, warmer seasonal temperatures result in reduced sap flow, a shorter tapping season, and a lower grade product. Syrup production and quality during the 1990s has been significantly reduced due to warmer than average conditions during the sugaring season (Marvin, 1999).

The typical tapping season lasts for approximately 30 days (mid-March to mid-April) with good sap runs for 8-12 days. If the weather conditions are not appropriate, the tapping season may only have 2-3 good flow days (Bloomfield and Hamburg, 1997; Kramer and Kozlowski, 1979; Houston *et al*., 1989). Many producers who traditionally "tap by the calendar," have missed the first sap runs (flows) several times in the 1990s (Perkins, personal communication).

The question that concerns New England regional maple syrup producers in the NERA region is: *How will a changing climate affect sap flow and quality?* Initial research looking at the potential impact of climate change and variability on syrup production has begun; some of the results are presented here, but continued research is required to fully understand how a changing New England climate will affect this important New England/New York legacy.

Current Stresses on the Syrup Industry

Tree health issues dominate the concern for most maple syrup producers in the region. In 1987 the North American Sugar Maple Decline Project, now named the North American Maple Project (NAMP), was formed out of concern for an apparent regional decline in sugar maple health. The NAMP now monitors over 7000 trees across the region, as well as trees in other syrup producing states and Canada. A number of biotic and abiotic stresses are of concern. The primary biotic stressors include Pear Thrips, which had a significant outbreak in 1988, and the Forest Tent Caterpillar (Houston *et al*., 1989; Allan *et al*., 1995; Marvin, 1999). These two insects affect the leaves of sugar maple during the spring and early summer which, when the outbreak is severe, can affect photosynthesis and the amount of stored stem and root sugars. The result is a decrease in sap quality and quantity during the following season as well as a reduction in tree vigor. Abiotic impacts to sugar maple include air pollution, acidic deposition, drought, and damage to stems and roots by humans. A bad drought year in 1988 significantly affected tree health for two years (Allan *et al.*, 1995). Drought can also set the stage for secondary insect attacks and may have been a factor in the Pear Thrips outbreak. Certainly a reduced snow pack in the winter of 1987/88, a warm period at the end of the sugar season, and the simultaneous emergence of the Pear Thrips from the exposed soil and leaf litter all contributed to an unhealthy scenario (Vogelmann and Rock, 1989). Allan *et al.* (1995) found that wet deposition of high levels of both sulfate and nitrate had significant impacts on maple health. Freeze injury to roots during periods of little to no snow cover may also be detrimental to tree health (Houston *et al.*, 1989; Auclair *et al.*, 1996; Moore *et al.*, 1997), although more research in the area is needed.

Climatic impacts, such as drought (mentioned above) and ice storms, can cause significant local and regional-scale maple tree damage, which can influence sap flow and syrup production. The Ice Storms of 1998 appear to have had significant impacts on maple syrup production and tree health in the New England/New York region (see Ice Storm Damage Case Study in this chapter). The NAMP in conjunction with the U.S. Forest Service assessed the initial impacts of these storms. In areas where sugarbushes (stands of sugar maple managed for sap collection) were affected by the ice storms, moderate to severe damage occurred on 22% of the trees. Northern New York was severely affected by the ice storms and an average of 26% of the trees within damaged sugarbushes were severely damaged (80-100% crown loss) (Miller-Weeks and Eagar, 1999). The Cornell Cooperative Extension Agency estimated the initial economic impact of the ice storms on syrup production in Clinton County, NY to be $4.5 million (Staats, 1998). The estimated 1998 syrup production loss for NY counties ranged from 20-100%. The damage caused by the storms includes direct structural damage to trees (broken limbs/trunks), damage to sap collection equipment, and a lost opportunity to tap trees where access to the sugarbushes was impeded by downed debris. The full impact of these ice storms will not be known for several years until tree recovery and sap production impacts can be fully assessed.

A recent study of two Vermont sugarbushes evaluated the relative impacts of different growing seasons (1998 vs. 1999) on the root and stem carbohydrate reserves in sugar maple (Perkins, *et al.*, 2000). The 1998 growing season followed the January, 1998 ice storm damage to sugarbushes, while the summer of 1999 was the most severe drought conditions across much of the region since the mid-1960s. Root starch levels were linearly correlated with crown damage from the ice storm in both years ($r^2 = 0.86$). While no clear trends in stem starch or total root/stem sugars were identified, undamaged trees did have higher levels of total carbohydrates than did damaged trees. The year-to-year variations in precipitation between the two growing seasons (normal in 1998, very limited in 1999) resulted in a greater difference in root and stem starch than the effects of the ice storm damage. Approximately 70% less root starch was produced in 1999 when compared with 1998, and stem starch was 50% less in 1999 than in 1998. These results call into question the significance of severe weather events such as the 1998 ice storm, and highlight the importance of inter-annual climate variations in terms of their impact on carbohydrate reserves in sugar maple.

Another current stress to the New England and New York syrup industry is market competition. Canadian production of maple syrup has tripled since the 1970s due to several factors, one of which is aggressive marketing (AgriCanada, 1998/1999; ACEIS, 2000). In addition the Canadian government now offers subsidies for Canadian syrup production. At the same time U.S. production has been constant. Market forces may be making maple sugaring in New England more and more marginal, especially for small producers.

Finally, the advent of tubing-based methods of sap collection has also played a significant role in the Canadian dominance in the world maple sugar production. In the past, the success of the maple syrup industry in Canada was limited by deep snow cover (limiting access to individual trees) and fewer freeze/thaw cycles due to prolonged periods of low nighttime and daytime temperatures (Marvin, 1999). The development of tubing-based sap collection methods that provide easier access to trees and warmer daytime temperatures in Canada, coupled with very early initial flows and warmer nighttime temperatures (fewer freeze/thaw cycles and reduced cold recharge periods) across New England over the past two decades, have resulted in a shift in syrup production to the Gaspe Peninsula of Quebec (Marvin, 1999).

Future Climate Impacts

All of these current stresses have impacted syrup production in the region. Syrup production for both the New England/New York region and other U.S. syrup producing states show a long-term trend in decreased production and a high degree of year-to-year variability (Figure 5.8). Canadian syrup production has dramatically increased since the 1970s, and also shows annual variability. Due to changes in both sap collection technology (the advent of tubing) and climate (very early initial flows, a reduction in enough freeze/thaw cycles and cold recharge periods), the maple syrup industry is migrating from New England into Canada (ACEIS, 2000; Marvin, 1999).

true during drought years (Houston, 1999). Additionally, as will be discussed below, long-term climate warming trends may impact the maple's ability to reproduce and compete with other species.

From a climate perspective, two primary questions regarding the impacts of a changing or variable climate in the future are raised:

1. What affect would a change in climate have on sap production?

2. What affect would climate change have on the health of maple trees in the region?

Weather and climate result in impacts on syrup production. If a trend toward warmer winter minimum temperature occurs, as predicted by both the Hadley and Canadian climate models for the region (see Chapter 4), this would have a negative affect on sap flow. Climate can also affect tree health during the growing season when leaves are producing sugars through photosynthesis—if higher summer temperatures result in greater heat injury and insect damage to maple foliage, sap flow during the following spring will likely be affected. If more intense or more frequent droughts occur, especially during bud break or during the leaf-on period, this will affect photosynthesis as well. Climate can also affect tree health during the winter, as evidenced by impact of ice storms (Allan *et al*., 1995; Miller-Weeks and Eagar, 1999; Houston *et al*., 1989). Ice storms or excessive snowfall during the winter can restrict sap collection by limiting access to sugarbushes (Staats, 1998). Yearly weather conditions and long-term climate tends to control bud-break that marks the end of the collection season. Severe weather conditions during the spring and the growing season tend to affect insect and disease occurrences, which affect sap flow; this is especially true during drought years (Houston, 1999). Additionally, as will be discussed below, long-term climate warming trends may impact the maple's ability to reproduce and compete with other species.

Other factors not necessarily related to climate but important for production include: tree genetic control of sap flow quantity and quality; non-climate stress agents such as disease impacts on tree health; collection methods; and number of trees tapped. The number of trees tapped is affected by a number of factors. Access to sugarbush trees affects the number of trees tapped. The advent of tubing and vacuum systems have allowed more efficient tapping and collection, requiring less person-power and improving daily sap volume. Social and economic factors can also have an affect on the number of trees tapped and sap collected; for instance, the labor pool available for the short but intensive syrup production period can determine how a producer is able to maximize their production potential. Individual tree health is often considered when deciding whether to tap a tree or not. If a tree is over tapped, or if tapped when stressed from other factors, additional tapping may cause further damage. Deciding not to tap a tree in a given year may be beneficial on a long-term basis for tree or stand health, but does affect a single season's production levels. The damage caused by the 1998 ice storms severely limited the number of trees tapped in the 1998 and 1999 sugar seasons (Perkins, personal communication). The low production levels for the US and Vermont for these years is in part due to limited tapping for fear of further damaging ice storm damaged trees (Figure 5.8).

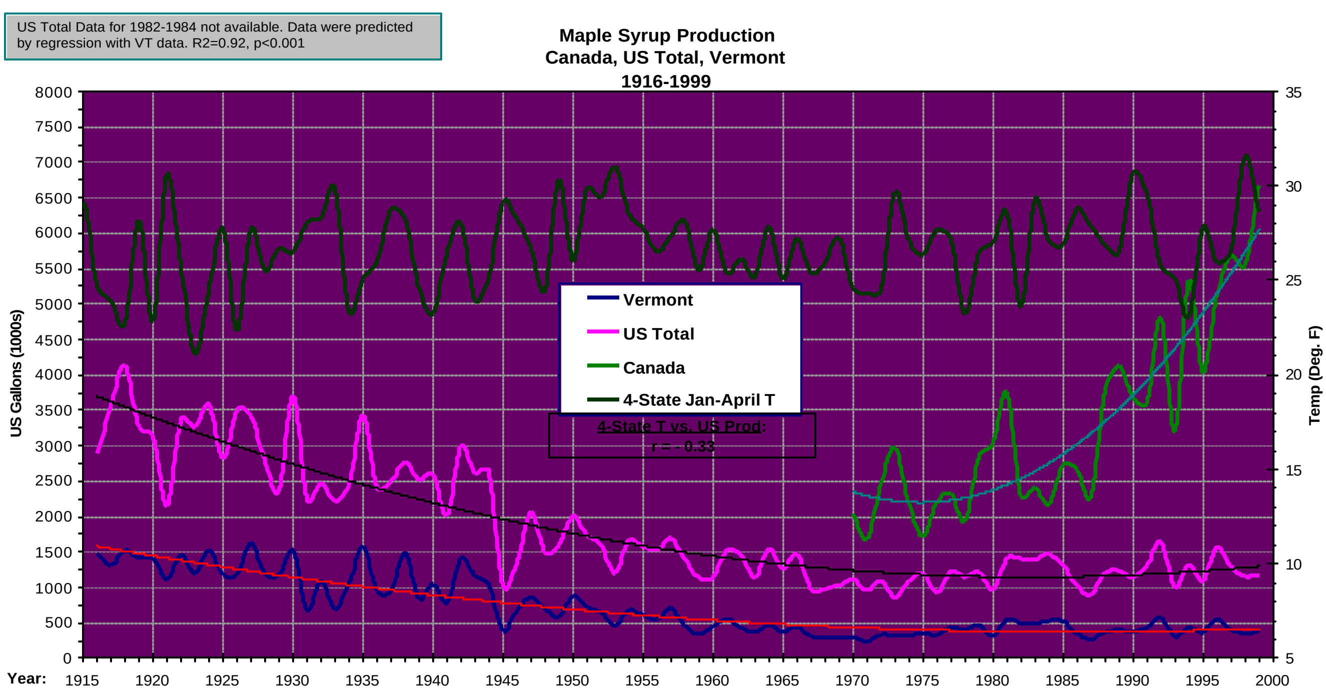

Figure 5.8. Maple Syrup Production Canada, US Total, Vermont 1916-1999

With the above factors under consideration, we can plot syrup production and climate for much of the 20th century. Figure 5.8 shows that U.S. syrup production has decreased dramatically since the early 1900s and has stayed fairly level over the last 30 years. Vermont, the largest US producer, has also seen a decrease but this has been less dramatic than the US total production. Since January to April is the timing for maple tree tapping and sap flow, mean temperature for this 4-month period for the four top producing states in the region (VT, NY, ME, NH in descending order) is plotted in comparison to syrup production. Interesting patterns are seen between the mean temperature data and Vermont, total U.S., and Canadian maple syrup production: In general, years with lower temperatures exhibit an increase in syrup production; this results in a moderate inversely related correlation (r = -0.33) between the mean temperature and total U.S. syrup production. This means that approximately 10% of the variation in syrup production can be explained by variations in January-April temperatures.

Figure 5.9 shows the syrup production and mean winter temperature trends over the last decade. Three different ways of characterizing temperature data are plotted for comparison. The VEMAP2 temperature curve (see Chapter 4 for a discussion of these data) shows the mean of the monthly temperature between January 1 and April 30. Additionally, daily temperature data were acquired from one first-order station from each state and the daily data averaged over two time periods: January 1 to March 15 and February 1 to March 15. A clear trend can be seen in the syrup production data for all states: certain years tend to be "good" years while others tend to be "poor" years. Climate trends show some relationship with syrup production, with 1994 and 1996 "good" years corresponding to low temperature years. However, 1992 was a "good" year, while 1995 and 1997 were poor years, yet all three exhibited very similar temperature regimes. The exact nature of the relationship is still uncertain and will require further detailed analyses to identify the role that climate plays.

To accurately assess the impact of climate on syrup production, production per number of trees tapped is needed. Additionally, precipitation and the previous summer's growing conditions are likely to have important implications for sap flow and syrup production during the late winter and early spring. The temporal analysis of climate data should be investigated further to better understand how climate variables and tree physiology control sap flow and quantity. Additional research should be conducted to look at local syrup production and climate data.

Both climatic and non-climatic factors affect syrup production. For example, if climatic conditions reduce sap flow, syrup production will invariably be reduced; yet, a good flow year could occur but the number of trees tapped could be reduced for any number of reasons. The seasons of 1998 and 1999 were marked by fewer trees tapped due to concerns about ice storm damage "weakening" impacted trees. As noted, the drought of 1994 also had a negative

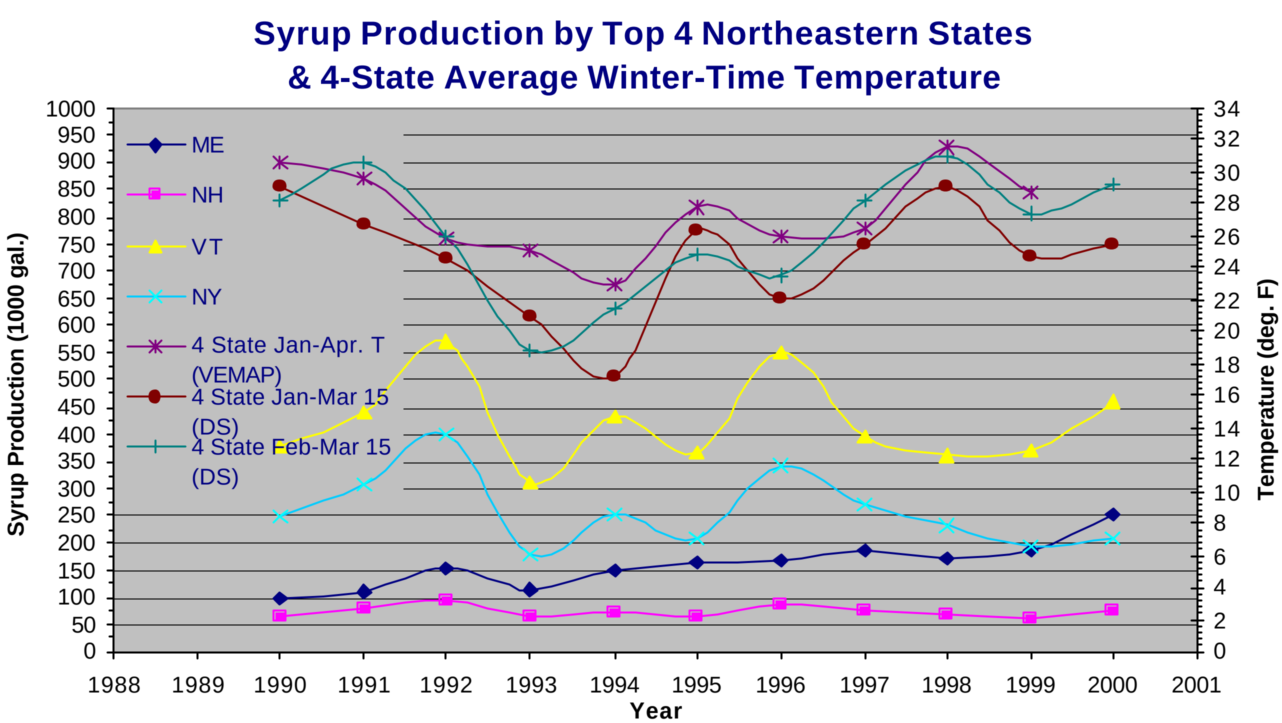

Figure 5.9. Recent Syrup Production & Winter Temperature Trends in VT, NY, ME, and NH.

affect on syrup production even though the temperatures for the region suggests a "good" year for sap flow. To fully understand the impact of climate on syrup production, all of these factors need to be considered — something that current research is just beginning to address.

Lessons Learned

- Sugar maple syrup production is determined by very specific climate and non-climate factors.

- While highly sensitive to climate, maple syrup production is also responsive to changes in demographics, workforce variables (war years), and tree/stand condition.

- Factors affecting sap volume and sugar content include: diurnal temperature differences; previous growing season soil water availability (drought); timing of spring bud-break (the end of the sugar season); tree genetics; previous growing season foliage density and health; and tree health/stress conditions.

- Climate variability has accounted for approximately 10% of the variability in regional syrup production over the past century.

- US syrup production accounted for 80% of the world's production in the 1950-1960s, while now for only 20%. A once viable regional industry is now marginal.

- Future climate change is likely to result in an end of maple syrup production in the region.

Conclusions

The maple syrup industry in the US has exhibited a dramatic decline since early in the 20th century. This decline is due to many factors, including climate. Over the past thirty years, the Canadian Maple industry has shown a dramatic increase also due to many factors, including climate. Some of the climate-related factors include severe ice storm damage to trees and maple sugaring equipment, and increased pest outbreaks with winter warming. Most disturbing are the results of ecological modeling efforts that show the changes in climate could *potentially* remove the sugar maple from the New England region. Continued in-depth research is required to investigate the influence of a variable and changing climate on the region's maple syrup industry. This case study highlights an important sector of New England character, way-of-life, and economy that, because it is highly dependent upon prevailing climatic conditions, may be irreparably altered under a changing climate.

CASE STUDY 3 - 1998 Ice Storm Damage

By: Shannon Spencer and Barrett Rock, Complex Systems Research Center, University of New Hampshire

One concern with a changing climate is the potential for an increase in the frequency and severity of extreme events in the New England region. As the New England Regional Assessment (NERA) process began, the ice storms of January, 1998 occurred, causing extensive economic and social disruption in northern New York, New England and Quebec. This case study identifies and documents the impacts that current severe events, such as ice storms, have on the region.

Ice storms are not uncommon, but the meteorological conditions during the January, 1998 ice storms made them very geographically wide-spread (Figure 5.10) and devastating (DeGaetano, 2000). The area of impact covered 4 states and Quebec, with 37 counties declared Federal disaster areas (Figure 5.10). Extensive damage to forests resulted (Table 5.3). In general, life in the region was disrupted in a number of significant ways. This particular event was categorized as a 200 to 500-year event (Keim, 2000) with 17 deaths in New England/New York and 26 deaths in Canada. Approximately 1.5 million people across the New England/New York region were without power for up to three weeks. The economic impacts were well in excess of $ 1 billion in the US (DeGaetano, 2000), and the long-term impacts of these storms are still being evaluated, especially the effects to natural and managed forest systems.

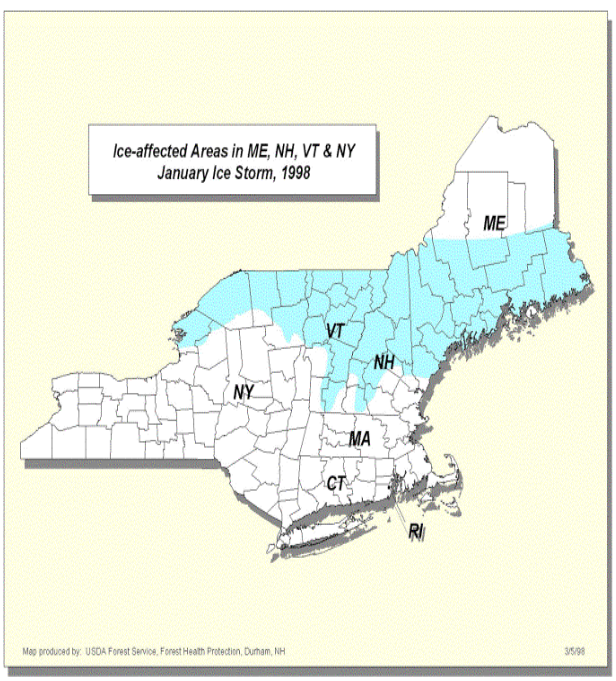

Figure 5.10. Ice-Affected Areas from January, 1998 Ice Storm. From USDS-FS (2000).

Table 5.3. Forest Land Affected by 1998 Ice Storms

State	Area Impacted 1,000 acres
New York	4600
Vermont	951
New Hampshire	1055
Maine	11000

Adapted from Miller-Weeks and Eagar (1999).

The conditions required for an ice event to occur are very specific. A temperature inversion must exist for an icing event to occur: a cold upper layer produces frozen precipitation, this falls through a warm layer at mid-altitude that melts the precipitation, this then enters a layer of cold air near the ground, which is below the freezing point. This super cools the precipitation. When this super cooled precipitation makes contact with the surface it freezes on impact, causing an ice glaze. If air temperatures near the ground are much colder than -3 degrees Celsius (26º F), then the precipitation freezes into sleet. Sleet bounces off surfaces rather than glazing them, and therefore has less impact than freezing rain. Local variations in topography, elevation, aspect, and wind currents and speed influence the occurrence of ice glazing. This can result in patchy areas of ice glazing, as evidenced by the mapping of damage caused by the 1998 ice storms in New Hampshire (Figure 5.11). In most cases, a 3-4 degree difference in surface temperature can regulate the impact

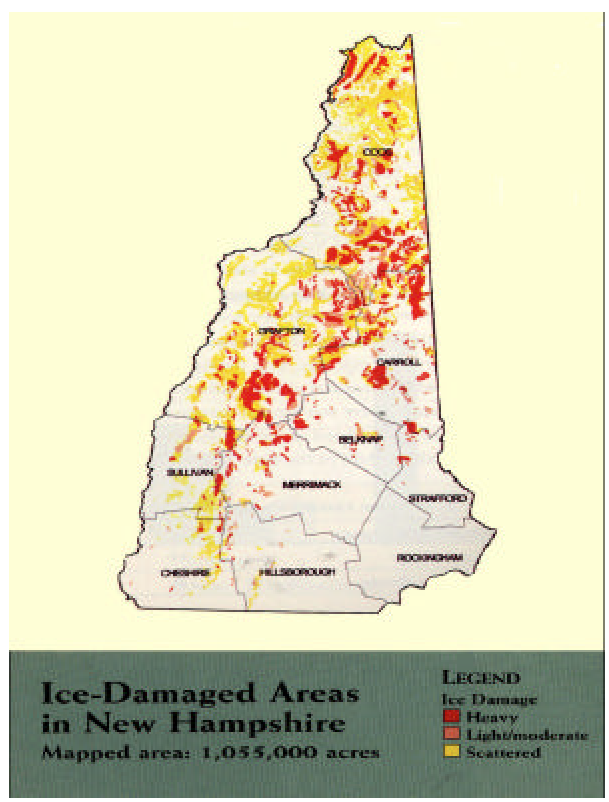

Figure 5.11. Sketch Mapping of NH Ice Storm. From Miller-Weeks and Eagar (1999).

of an ice storm on the local area. Conditions for this inversion to occur include a stationary front that separates opposing air masses. The warmer air mass over-rides the cold air mass creating the cold-warm-cold temperature profile. Therefore, the combination of the temperature inversion and the narrow ground-level temperature range make conditions for severe ice storms very specific.

The National Weather Service (NWS) defines an “ice storm” as the occurrence of freezing precipitation resulting in the accumulation of 6.35 mm (0.25 inches) or more ice. Ice accumulation typically occurs in limited areas traversed by a large storm due to the factors explained above. Generally, the frequency and severity of ice storms increase toward the Northeastern US. Bennett (1959) defined a “glaze belt” which extends from north Texas to New England, in which storms yielding ice accumulations of 6.35 to 12.7 mm (0.25 to 0.50 inches) of ice can be expected once every three years.

Several major ice storms have been recorded in the climate record for the past century, with the following notable storms: 1909, 1921, 1929, 1942, 1950, 1951, 1953, 1956, 1961, 1964, 1969, 1976, 1979, and 1991 (DeGaetano, 2000; Irland, 2000). DeGaetano’s analysis showed that active periods of icing also have occurred between 1929 and 1942 and in the late ‘40s and early ‘60s. Across the US, from 1990 to 1994, ice storms caused a yearly average of 10 fatalities, 528 injuries, and $380 million in damage (Robbins and Cortinas, 1996); and on average, 16 ice storms occurred each year across the US, from 1982 to 1994, making them more frequent than blizzards (Branick, 1997).

DeGaetano (2000) has noted that several of the above mentioned storms were equal in severity to the 1998 ice storms, but that the geographic extent and duration of the 1998 event is unprecedented since reliable records have been kept. His analysis of meteorological conditions of several storms suggests that only the 1921 event approached the magnitude of the 1998 event. The economic and human impacts of the 1998 event far exceed any past event.

Concerns Regarding Ice Storm Frequency & Severity with Climate Change

The timing of the 1998 ice storms corresponded with both the formulation of this New England Regional Assessment of climate change and a period of years in which record average annual high temperatures have been set for the region. The severity and wide-spread nature of the 1998 ice storms have led to questions about whether the New England region might experience increased occurrences of more extreme meteorological events, given a trend toward a warming climate; and, if so, what are potential consequences and/or mitigation steps needed to prepare for these damaging events?

Though the answer to the first question at this point is not at all clear, we attempt here to address the major concerns by looking at our current knowledge of the situation. This analysis is incomplete and it should be looked at as a way to drive future research and monitoring efforts to better understand the impacts of a potentially warming climate.

Ice Storm Impacts on Forest & Natural Resources

Depending on the geographic extent, the duration, and other meteorological conditions of an ice storm, such as ice loading and temperature following the storm, the damage caused to natural and human systems can be significant. Assessing the impact of historic ice storms and the 1998 ice storms can give us an indication as to the overall potential impact to the New England region if these events were to increase in a warming, more variable regional climate.

Significant damage to property, utility infrastructure and forest trees was recorded during the 1921 Great New England Ice Storm (DeGaetano, 2000); over 100,000 trees were severely damaged. In general, impacts to forest resources from past ice storms have been poorly documented. Irland (2000) presents ice storms as a normal occurrence, from an ecological perspective, which have effects on forest species composition on a small geographic scale. Typically, greatest damage occurs in managed stands such as in plantations or sugarbushes (Irland, 2000; DeGaetano, 2000).

In the wake of the January, 1998 storms, an extensive effort was undertaken by state forestry agencies across the region to document forest impacts through aerial photos and ground plots (Irland, 1998). Damage assessment is an inexact science. A common method of quickly assessing forest conditions is to conduct aerial sketch mapping using a trained observer to note crown conditions on a map. This method can produce a quick sketch of the location and the severity of impact to be used for planning and assessment, but observer biases only produces a rough estimate of forest impact. Assessment by analysis of aerial photography is more exact and was conducted for the state of Maine to produce maps of damage intensity and distribution. Figure 5.10 shows the general areas affected by ice in the New England/New York region from the 1998 ice storm, while Figure 5.12 shows the specific damage sketch-mapped for New Hampshire. These maps are useful for informing the public and assisting landowners in management planning. Power outage reports from public utilities can provide a rough proxy of the geographic distribution and severity of damage to forests and trees.

Based on measured impacts on forests, the degree of damage is typically highly skewed by state, due to assessment methodology. The Maine Forest Service initially assessed 1998 storm damage in broad areas based on assumed levels of damage due to a meteorological model, as defined in Table 5.4, and depicted in Figure 5.12. Comparing damage

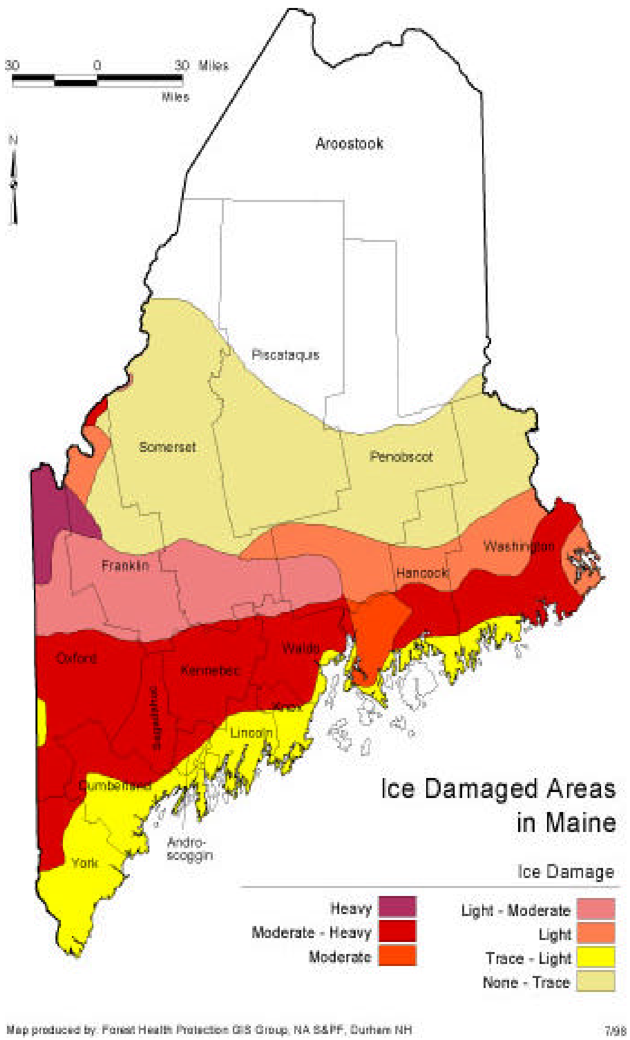

Figure 5.12. Damage Assessment Map of Maine. From USDA-FS, 2000.

assessments for New Hampshire, based on sketch mapping (Figure 5.11), and Maine, based on a meteorological model (Figure 5.12), shows how the methodology can influence results.

Table 5.4 lists the initial estimates of forest damage in Maine. The total area affected by the storm (trace-light and greater) was two-thirds of the state's area. New Hampshire, which used a sketch-mapping method and a different rating system, showed an area of impact much different than Maine's. A standardized method of damage assessment for the entire region is needed. Based on previous work (Vogelmann and Rock, 1989), satellite-based methods may provide such a standard assessment capability.

Field assessment during the following Spring and Summer of 1998 resulted in an improved understanding of the short-term forest damage and the geographical extent of the impact. Table 5.3 lists revised damage estimates from aerial photo analysis and field work, which took up to a year's worth of work following the ice storms. The extensive field work has provided a better understanding of the short-term forest impacts, as described below, but the long-term affects are still not well understood.

Table 5.4. Initial Forest Damage from Sketch-Mapping in Maine.

Damage Level	Acres (1000s)	Percent
None-trace	4,704	35.4%
Trace-light	1,632	12.3%
Light	1,230	9.3%
Light-moderate	1,618	12.2%
Moderate	257	1.9%
Moderate-heavy	3,561	26.8%
Heavy	285	2.1%
Total	**13,289**	**100.0%**

Ice damage to trees can range from mere breakage of a few twigs, to bending stems to the ground, to moderate crown loss, to outright breakage of the trunk (Smith, 2000). In the 1998 ice storms, icing lasted long enough that many trees, which were bent over due to the ice, had their crowns frozen to the snow/crust surface for as long as three weeks. In some instances, trees recovered to an erect posture after release from the snow, but most never recovered. Generally, softwoods seem to suffer less damage from the same degree of ice loading than do hardwoods. In the 1998 storms, it was observed that exotics and trees planted outside their natural ranges, such as *Robinia*, and *Salix spp*. suffered severely while nearby native species suffered far less damage. Bennett (1959) has shown that certain tree species are more resistant to ice damage.

During the January 1998 storms, aspens as large as 15 cm diameter at breast height (DBH) were broken off below the crowns, white pines had stems snapped at their 20 cm diameter point, oaks as large as 50 cm were split along the trunks where divided trunks weakened the stems, and birches as large as 15-20 cm DBH were broken off entirely.

Depending on stand composition, amount of ice accumulation, and stand history, damage to stands can range from light and patchy to the total breakage of all mature stems. In local areas, such complete breakage occurred in the 1998 storm. With moderate degrees of damage, effects on stands could include shifts in overstory composition in favor of the most resistant trees, loss of stand growth until leaf area is restored, and loss of value of the growth due to staining or damage to stem bending. In general, trees are capable of surviving considerable crown damage, and will steadily recover the lost leaf area over time (Irland, 2000). In general, more heavily managed (thinned) stands exhibited more damage than adjacent unmanaged stands (Burnett, 1999). Damage to soils and to residual trees is possible during salvage operations given the likelihood that operations may be conducted in haste. It is possible that damage caused by sloppy salvaging could exceed the damage caused by the storm (basal damage to a tree is far more serious than is branch breakage). This could be because stands recently partially cut have experienced significant widening of crowns, thereby increasing ice loading.

Forest damage tended to increase with increasing elevation and northern exposure; likely due to greater icing at elevations where temperature conditions promoted greater occurrence of freezing rain. Figure 5.13 shows how the ice accumulation on canopy exposed twigs, along a transect at the Hubbard Brook Experiment Station, increased with elevation.

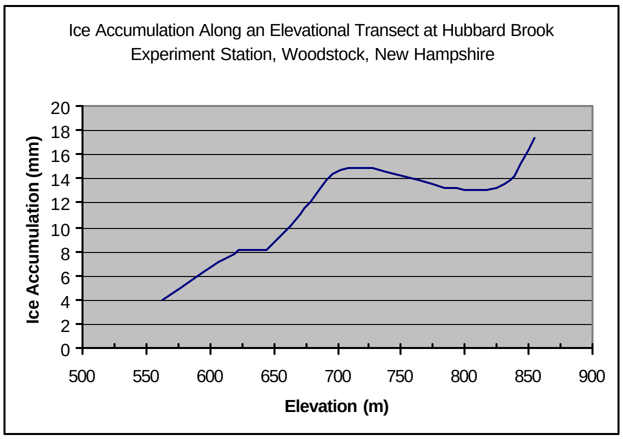

Figure 5.13. Elevational Impact on Icing at the Hubbard brook LTER. Data plotted from Irland, 2000, based on C. Cogbill data (personal communication).

Ice events tend to affect the health condition and number of individuals of susceptible species, but that these events are infrequent and unpredictable (Irland, 2000; Smith, 2000). The above observations and the fact that many other factors affect the susceptibility of forest trees to icing confound the assessment of long-term ecological impact of severe events such as ice storms.

Impacts to Forest Recreation

The ice storms significantly damaged recreational trails in forested areas impacted by the ice storms. In the White Mountain National Forest, 850 miles of trails and roads were blocked with downed woody debris, while 257 miles of trails were impacted in the Green Mountain National Forest (NEFA, 1998). Additionally, 6000 miles of snowmobile trails had damage, at the peak of the season (NEFA, 1998).

The Wonalancet Outdoor Club, which maintains approximately 50 miles of trails in the Sandwich range in the White Mountain National Forest, reported that over 300 person-hours were required to clear even small sections of trail. In many cases trails were completely impassable for up to six months following the storms. Since the most severe damage occurred at higher elevations, the greatest damage was done to trails within Wilderness-designated areas, which prohibits the use of chainsaws or other motorized equipment. In all, over 2700 hours of volunteer labor was required to clear trails in time for the summer hiking season.

The damage caused is anticipated to affect future trail conditions as well. Less canopy cover in some steep portions are likely to result in increased erosion and waterbar washout. Additionally, the opening of the canopy will result in a flush of undergrowth that will require yearly clearing activity to those portions of the trail which were severely damage. On the positive side, the canopy openings the ice storms created have encouraged increased wildlife activity. This has potential benefits to hikers who will have increased wildlife sightings. An increase in neo-tropical migrant bird species due to canopy openings may benefit bird populations. Increased understory forest growth has resulted in greater browsing by deer and moose, which will likely enhance a hunter's recreational experience. Additionally, several new scenic vistas have been created by the openings caused by the storms. In the long-term, the ice storms will likely increase forest diversity which can benefit the recreational use of impacted forests.

Current Findings on Long-Term Effects of the 1998 Ice Storms

Many studies to assess the impact of the 1998 ice storms on wildlife, ecological effects, and forest management activities are ongoing. Interim findings were presented at an Ice Storm Recovery Workshop, held in Dorchester, NH on September 21, 2000. A summary of these findings is presented here.

Understory density has increased in the wake of the storms, as well as a shift in species composition (Woods and Leopold, 2000). Manion *et al*. (2000) are assessing the impacts of the storms on forest health and report that, from a forest system standpoint, the ice damage will not likely alter the health of the system. Burns (2000) reported that recovery has been substantial after two growing seasons on forest monitoring plots in Vermont where significant foliage and crown damage were recorded in the summer following the ice storms. Ruesink and Graves (2000) noticed greater downed woody debris, less canopy cover, less litter, taller herbs, and a greater amount of exotic species on ice storm damaged plots than on non-damaged forest plots, but note that tree mortality is not significantly different. They also observed marked recovery in even highly damaged trees after two years. New Hampshire's aerial analysis of the forest damage has shown an annual recovery of the damaged stands since the storm (Lombard, 2000). Swisher (2000), studying the impacts of thinning on the storm damage to hardwood stands, noted that thinned stands tended to sustain greater amounts of damage, but expects most trees to recover. Smith and Shortle (2000) suggest that the trees at greatest risk to timber quality, growth, and mortality are ones that had basal injury due to logging. All researchers suggested that continued research and data analysis over the next five years will be important to achieve a full understanding of the long-term impact of the January, 1998 ice storms.

Will Climate Model Projections Suggest More Ice Storms?

As reported in the climate modeling section of this assessment report, the prevailing global circulation models predict that the New England/New York region will undergo a steady increase in temperature over the next century. These models predict that the average annual minimum temperature will increase by 6-10? F in 2100, while the average annual maximum temperature will increase by 6-10? F in 2100.

The question is how will these changes in predicted minimum and maximum temperatures affect severe events such as ice storms? The conditions for ice storms are very specific and extremely localized, yet the potential for wide-area impact is certainly evidenced by the most recent event. Climatologists are unable to predict how these model scenarios relate to the frequency and severity of extreme events, because of several factors. For one, the models used in this assessment were originally designed to run at global scales and were not designed for use on regional scales. This is especially the case in New England, where meteorological conditions are based on a number of factors, with the jet stream controlling, to a large extent, the day-to-day weather (see Chapter 2). These global models predict future climate conditions for very large areas where great variability in topography and land type are not considered. Since ice storms are controlled by localized meteorological conditions, elevation, land cover, and aspect, results of the models are not very useful for predicting events at these local scales.

Regional models, which consider regional drivers of climate and which can be designed to resolve local meteorological conditions, are needed in order to even begin assessing the potential impact of a changing climate on extreme events. Global model results could likely feed into these regional models as an overall climate driver, but using their results directly for attempting to assess the likelihood of an increase in occurrence or severity of severe events is not valid. The potential for extreme events to increase in the future should stimulate further research into the development of regional-scale climate models.

Implications for Natural Resources & Research Needs

Ice storms are frequent in the eastern U.S. and Canada. Storms of sufficient intensity to damage trees and forests occur in limited areas once every fifty years or less. In some areas, broken-topped hardwoods provide mute testimony to the effects of previous ice storms. Ice effects have been sufficient to affect stand composition in some areas. In today’s younger, managed forests, the distinct effects of ice storms may be accentuated by management activities (selective thinning sugarbushes, etc.)

Evaluating the impacts of ice storms is complicated by many factors. Even for events of greater than normal proportions (such as the 1998 ice storms) it is difficult to quickly develop accurate estimates of physical and economic losses. A standard assessment methodology, using satellite-based technology, is needed.

At present, it is not possible to predict how future climate change will predict the incidence and severity of extreme weather events such as ice storms. New research strategies, such as regional models, could shed light on this. At this point the best approach to handling the uncertainty in extreme events, such as an ice storm occurrence, is to be prepared to accept some level of risk. In general these events tend to be localized.

Irland (2000), in his analysis of the 1998 ice storm impacts to forest resources, suggests several “coping” strategies, research needs, and practical management ideas. Smith (2000) also presents suggestions for forest stand management, decision criteria, and research needs. Probably the best recommendation, coming from several authors, is to better understand both the ecological and economic ramifications of the 1998 ice storms and how they will continue to affect these two broad areas for the next decade. This will require continued monitoring and research, but will help us better understand the integrated effects of extreme events. In parallel, better damage assessment protocols, damage mitigation plans, and meteorological monitoring need to be implemented to help us better understand how a changing climate might affect the New England region.

Lessons Learned

- The 1998 ice storms were unique in terms of recorded ice storms, due to the large spatial extent (NY, VT, NH, ME and Quebec) of the damage.
- The extent of damage to regional forests was heavy, affecting over 17,000,000 acres in the 4-state region.
- The economic impact on the forestry sector was approximately $400 million, including the $15 million impact on the maple syrup industry (which still continues).
- A standardized method of forest damage assessment does not exist and needs to be developed.
- Regional-scale climate models are needed to assess the impact of climate change on future ice storm frequency and severity.

CASE STUDY 4 - Current & Future Potential Forest Cover Types

By: Shannon Spencer, Complex Systems Research Center, University of New Hampshire

Species migration and forest cover type changes are potential issues in a changing climate. Yet, these are two very complex processes which relate not only to climate factors, but to human changes to the landscape, forest fire dynamics, disease occurrences, and geophysical attribute of the landscape, such as soil conditions, aspect and slope. This section takes a look at the current and potential forest cover type distribution for the New England/New York region.

The current forest types, as depicted in Figure 5.14, are based on a USDA Forest Service publication, which digitized the forest cover types from the Society of American Foresters publication: “Forest Cover Types of the United States and Canada” (USDA-FS, 1993).

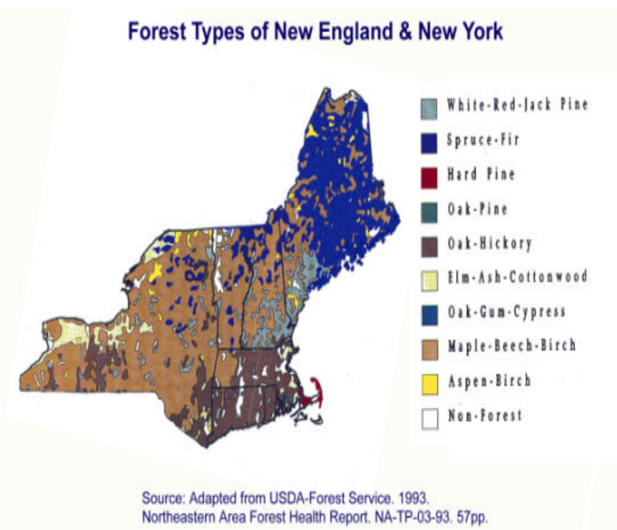

Figure 5.14. Current Forest Types.

Figure 5.14 shows the current forest cover types, as established from USDA Forest Service Forest Inventory and Analysis (FIA) data, and the predicted *potential* forest cover types from modeling conducted by Iverson and Prasad (1998). The model investigates *potential* species importance values under a changed climate (doubled atmospheric carbon dioxide concentrations) using current species distribution and density data for the eastern US. The model is constrained by a species’ ability to occupy an area, based on soil occurrence, landscape variables, land use, elevation, and climate (Prasad and Iverson, 1999). To determine future abundance and distribution of over 80 tree species, the authors integrated a regression model to predict Importance Values (IV) with several climate models (Global Circulation Models [GCMs]).

The IV model is based on several assumptions and uncertainties (such as future forest fragmentation impacts) and is therefore not an absolute prediction of future distribution, but the approach provides a sensitivity analysis for possible ranges of tree distribution in the future based on predicted climate scenarios by GCMs (Iverson et al., 1999). Results from the authors’ research predict that 30 tree species will expand their geographical range by more than 10% whereas approximately the same number of species will decrease their range by 10% or more. Four species move out of the Eastern US, depending on the climate model used to force the Importance Value model. They also found that for almost half of the species modeled, the biological optimum shifted more than 100 km/60 miles, with seven species shifting as much as 250 km/160 miles. The authors note that the historic rates of migration, without human landscape fragmentation, is on the average of 10-50 km/6-35 miles per 100 years, depending on species. Therefore, based on the results presented in Iverson and Prasad (1998) and Iverson et al. (1999), climate change could have very significant impacts on species migration and forest cover type distribution by the year 2100.

Figure 5.15 shows the current forest types as categorized by the FIA data and the IV model’s predicted importance value under a doubled CO_2 atmospheric environment. The

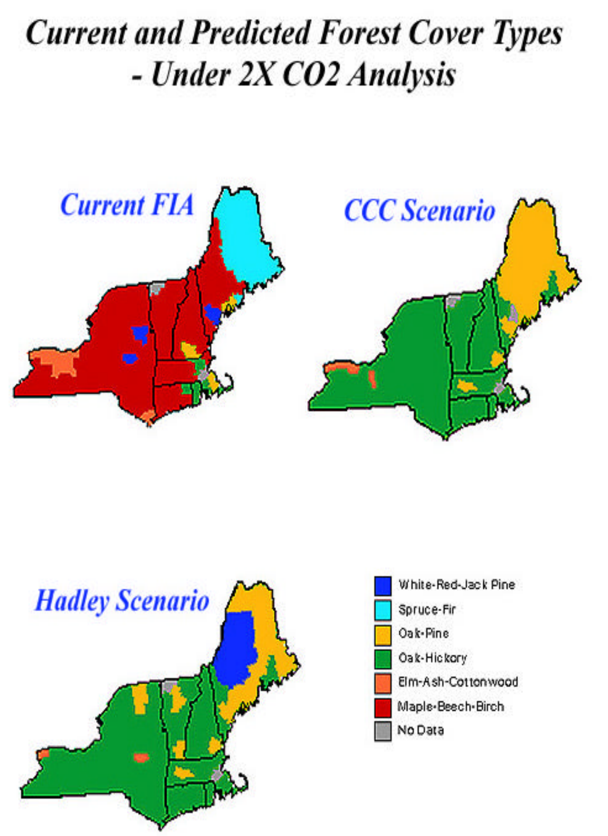

Figure 5.15. IV Model Forest Type Predictions. Adapted from Prasad and Iverson (2000).

results presented are based on the future climate predictions of two well-known GCM models: the Canadian Climate Center Model (CCC) and the Hadley Model. The species importance values are presented for these two GCM models because they are the ones used for the National Assessment on Climate Change. The IV model was forced by five different climate models in all, and Prasad and Iverson (2000) found very strong agreement for predicted potential species Importance Values in New England and New York (Figure 5.16). As can be seen by simple observation, significant changes in forest cover type are likely for the

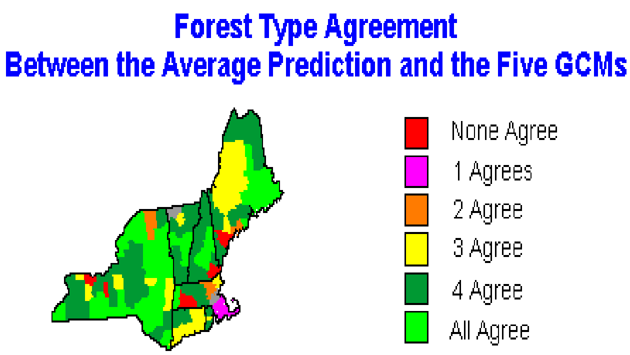

Figure 5.16. GCM model agreement in the prediction of species Importance Values. Adapted from Prasad and Iverson (2000).

New England/New York region, based on the Iverson and Prasad model. Though these model results shouldn't be taken as absolute, they do indicate that the region's forest types may be very sensitive to changes in climate.

Table 5.5 shows the top five dominant species, averaged by state, based on the current FIA data and the predicted dominant species with climate change, as predicted by the CCC and Hadley models GCMs. In all cases maple becomes non-dominant, whereas currently it is the one of the top two dominant species in all states. White pine appears to be relatively climate insensitive: in all states, but New York, where its dominance increases. Oaks also become more dominant in a changed climate, while red oaks become less common.

This change in species dominance is rather dramatic and could have significant implications to both private and public sectors, as well as represent a change in the character and way-of-life of the region. Human land use changes have not been accounted for in this model, as they are difficult to predict, especially in a region dominated by small, non-industrial private landowners. Land use, especially forest fragmentation and development, could have negative impacts on species migration.

Continued research is continuing to look at the effects of human landscape changes on species migration rates

Table 5.5. Top Five Dominant Species by State Based on Predictions from the Importance Value Model using Current FIA data and two GCM Models. Data from Prasad and Iverson, 2000.

		Connecticut		Maine		Massachusetts		New Hampshire		New York		Rhode Island		Vermont	
	Rank	species	IV	species	IV	species	IV	species	IV	species	IV	species	IV	species	IV
FIA Actual Data	1	Acer rubrum	47.1	Abies balsamea	37.0	Acer rubrum	42.0	Acer rubrum	36.0	Acer rubrum	26.1	Acer rubrum	46.0	Acer saccharum	42.6
	2	Quercus rubra	16.6	Acer rubrum	27.3	Pinus strobus	22.0	Pinus strobus	26.1	Acer saccharum	23.8	Quercus alba	27.7	Fagus grandifolia	18.1
	3	Betula lenta	14.5	Pinus strobus	15.1	Quercus rubra	15.2	Tsuga canadensis	15.8	Fraxinus americana	17.7	Quercus coccinea	23.3	Acer rubrum	16.4
	4	Acer saccharum	12.0	Betula papyrifera	10.4	Quercus velutina	14.1	Acer saccharum	13.3	Fagus grandifolia	10.7	Quercus velutina	19.7	Abies balsamea	14.0
	5	Quercus alba	11.1	Tsuga canadensis	9.9	Quercus alba	10.4	Quercus rubra	12.5	Tsuga canadensis	10.1	Quercus rubra	17.7	Betula alleghaniensis	13.0
Canadian Climate Model	1	Quercus velutina	32.8	Pinus strobus	29.8	Pinus strobus	24.4	Pinus strobus	26.4	Quercus stellata	18.7	Quercus velutina	35.7	Pinus strobus	22.6
	2	Quercus alba	26.6	Quercus stellata	23.0	Quercus stellata	21.8	Quercus alba	25.2	Quercus alba	14.6	Pinus strobus	26.0	Quercus alba	18.5
	3	Pinus strobus	26.1	Quercus alba	12.8	Quercus alba	15.2	Quercus stellata	18.6	Fraxinus americana	11.8	Quercus alba	18.3	Quercus stellata	17.5
	4	Quercus stellata	23.9	Quercus velutina	10.7	Quercus coccinea	8.6	Quercus velutina	14.4	Quercus velutina	9.0	Quercus coccinea	14.5	Quercus prinus	12.9
	5	Betula lenta	12.6	Quercus rubra	7.8	Quercus velutina	7.8	Quercus coccinea	12.5	Cornus florida	6.3	Betula lenta	11.7	Quercus velutina	9.2
Hadley Climate Model	1	Quercus velutina	32.8	Pinus strobus	29.8	Pinus strobus	24.4	Pinus strobus	26.4	Quercus stellata	19.7	Quercus velutina	35.7	Pinus strobus	22.6
	2	Quercus alba	26.6	Quercus stellata	15.2	Quercus alba	15.2	Quercus alba	25.2	Fraxinus americana	15.2	Pinus strobus	26.0	Quercus stellata	19.9
	3	Pinus strobus	26.1	Quercus alba	12.8	Quercus stellata	14.6	Quercus velutina	14.4	Quercus alba	14.6	Quercus alba	18.3	Quercus alba	18.5
	4	Quercus stellata	18.5	Quercus velutina	10.7	Quercus coccinea	13.4	Quercus rubra	10.7	Quercus velutina	9.0	Quercus coccinea	14.5	Tsuga canadensis	9.6
	5	Betula lenta	15.6	Tsuga canadensis	9.6	Betula lenta	11.6	Quercus stellata	10.0	Quercus rubra	7.3	Betula lenta	11.7	Quercus velutina	9.2

(Iverson and Prasad, 1998). Clearly, while past climate changes have been shown to affect species migration and forest composition at a regional scale, the question is how will these forest species be effected by the rapid changes in climate predicted to occur in the next 100 years? And, how will changes in forest type distributions affect the region?

5.6. References

Agriculture and Agri-food Canada's Electronic Information Service (ACEIS). 2000. All about Canada's maple syrup industry. Agriculture and Agri-food Canada. Website: http://www.agr.ca/cb/factsheets/maplee.html.

Agriculture and Agri-food Canada's, Market Industry and Services Branch (AgriCanada). 1998/1999. 1998/1999 Maple Products Situation and Trends. Ottawa, Ontario. 5 p.

Allan, D., A. Molloy, Cooke, R., Lachance, D., and Barnett, C. 1995. North American Maple Project: seven year report. North American Maple Project, U.S. Dept. of Agriculture, Forest Service. 57 p.

Auclair, A.N., J.T. Lill, and C. Revenga. 1996. The role of climate variability and global warming in the dieback of northern hardwoods. Water, Air, and Soil Poll. 91: 163-186.

Bartholomay, G.A., Eckert, R.T., and Smith, K.T. 1997. Reduction in tree-ring widths of white pine following ozone exposure at Acadia National Park, Maine, U.S.A. *Canadian Journ. of Forest Research*, 27:361-368.

Bennett, I. 1959. Glaze, its meteorology and climatology, geographic distribution, and economic effects. Quartermaster Res. & Engrg. Command, U.S. Army, Environmental Analysis Branch, Natick Mass. Tech. Report EP-105.

Bennett, J.P., Anderson, R.L., Campana, R., Clarke, B.B., Houston, D.B., Linzon, S.N., Mielke, M.E., and Tingley, D.T. 1986. Needle tip necrosis on eastern white pine in Acadia National Park, Maine:Results of a workshop to determine possible causes. National Park Service, Air Quality Division, Denver, CO. 8pp.

Birdsey, R. A. 1992. Carbon storage and accumulation in the United States forest ecosystems. USDA-FS Gen. Tech. Rept. WO-59. 51 pp.

Bloomfield, J and S. Hamburg. 1997. Seasons of Change: global warming and New England's White Mountains. Environmental Defense Fund. Washington, DC. 33 p.

Boone, R. B. 1997. Modeling the climate of Maine for use in broad-scale ecological analyses. *Northeastern Naturalist* 4(4): 231-230.

Branick, M. L. 1997. A climatology of significant winter-type weather events in the contiguous United States 1982-1994. *Weather and Forecasting* 12: 193-207.

Burnett, J.S. 1999. Detection, assessment, classification, and mapping of differing levels of ice storm damage to northern hardwood forests in the White Mountain National Forest in New Hampshire using hyperspectral airborne sensor Advanced Solid-State Array Spectro-radiometer (ASAS), *Proc. of the International Symposium on Spectral Sensing Conference*, Las Vegas, NV, pp. 121-136.

Burns, B. 2000. Overview of monitoring activities in Vermont related to the January 1998 ice storm (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Caspersen, J.P., Pacala, S.W., Jenkins, J.C., Hurtt, G.C., Moorcroft, P.R., and Birdsey, R.A. 2000. Contributions of Land-Use History to Carbon Accumulation in U.S. Forests, Science, 290:1148-1150.

Cogbill, C. 1999. Presentation on pre-colonial forest conditions in the New England region, NERA Forestry Workshop, March 30, 1999.

Cook, G. and L. Myott. 2000. Maple Information: Backyard Maple Sugar Making. University of Vermont Extension Service. Brieflet 1220. Website: http://www.uvm.edu/~uvmaple/mapleinfo.htm.

DeGaetano, A. T. 2000. Climatic perspective and impacts of the 1998 northern New York and New England ice storm. Bull. Am. Meteor. Soc. 81(2):237-254.

Delcourt, H. R., and P. A. Delcourt. 2000. Eastern deciduous forests. Pages 357-396. *In*: Barbour, M. G. and W. D. Billings (eds.) North American Terrestrial Vegetation, Second Edition. Cambridge, MA: Cambridge University Press. 708 pp.

Elliott-Fisk, D. L. 2000. The Taiga and boreal forest. Pages 41-74. *In*: Barbour, M. G. and W. D. Billings (eds.) North American Terrestrial Vegetation, Second Edition. Cambridge, MA: Cambridge University Press. 708 pp.

Entcheva, P. 2000. *Remote Sensing of Forest Damage in the Czech Republic Using Hyperspectral Methods.* Ph.D. Dissertation, University of New Hampshire, Durham, NH, 278pp.

Entcheva, P., Rock, B., Carter, G., and Miller, R. 1998. Application of multispectral narrow-band videography for forest damage detection in the West Bohemian Mountains of Central Europe. *IEEE Proceedings*, (in press).

Entcheva, P., Rock, B., Lauten, G., and Cibula, W. 1996. Remote sensing assessment of forest health in the Bohemian forests of central Europe. In: *Global Networks for Environmental Information*, ECO-INFORMA '96, Vol. II, pp. 785-790.

Entcheva, P., Rock, B.N., Martin, M., Neefus, C., Irons, J., Albrechtova, J., and Solcova, B. 2001. Detection of initial damage in Norway spruce canopies using hyperspectral airborne data. *Intern. Journ. Remote Sens.* (Submitted).

Houston, D. 1999. History of sugar maple decline. *In* Sugar Maple Ecology and Health: Proceedings of an International Symposium. June 2-4, 1998, Warren, Pennsylvania. U.S.DA Forest Service GTR-NE-261. pp: 19-26.

Houston, D., D. Allen, and D. Lachance. 1989. Sugarbush Management: a guide to maintaining tree health. U.S.DA Forest Service, Northeastern Forest Experiment Station. GTR NE-129. 55 p.

Irland, L. C. 1998. Ice Storm 1998 and the forests of the Northeast: a preliminary assessment. *J. For.* 96(9): 32-40.

Irland, L. C. 1999. The Northeast's Changing Forest. Cambridge, MA: Harvard University Press. 427 pp.

Irland, L. C. 2000. Ice storms and forest impacts. *Sci. Tot. Env*., 262: 231-242..

Irland., L. C. and W. McWilliams. 1997. Maine's 1995 forest inventory: a first look. Northern Logger April, pp. 24,25,52,53.

Irland, L. C. and M. Cline. 1998. Role of northeastern forests and wood production in carbon sequestration. Report to Northeast Regional bioimass Program. processed. 190 pp. Web: www.nrbp.org.

Iverson, L.R., and A.M. Prasad. 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. Ecological Monographs. 68: 465-485.

Iverson, L.R., Prasad, A.M. and M.W. Schwartz. 1999. Modeling potential future individual tree-species distribution in the Eastern United States under a climate change scenario: a case study with *Pinus virginiana*. Ecological Modelling. 115:77-93.

Kramer, P.J. and T.T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, Inc. Orlando, Fl. 811 p.

Lombard, K. 2000. Aerial survey program: mapping the ice storm (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Manion, P., D.H. Griffin and B.D. Rubin. 2000. Ice damage impacts on the health of the forest in northern New York (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Marchand, P. J. 1987. North woods. Boston, MA: Appalachian Mountain Club. 141 pp.

Marvin, D. 1999. *Presentation on the Maple Sugaring Industry at the New England Regional Climate Change Assessment (NERA) Forestry Workshop, March 30th, 1999*. Transcripts from the NERA Forestry Workshop.

Miller-Weeks, M. and C. Eagar. 1999. The Northeastern Ice Storm 1998: A Forest Damage Assessment for New York, Vermont, New Hampshire, and Maine. North East State Foresters Association (NEFA). 32 pp.

Moore, B., B. Rock, S. Spencer, J. Fithian, D. Hart, and C. Kustra. 1997. New England Regional Climate Change Impacts Workshop: workshop summary report. Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH. 150 p.

Moss, D.M. and Rock, B.N. 1991. Analysis of red edge spectral characteristics and total chlorophyll values for red spruce (*Picea rubens*) branch segments from Mt. Moosilauke, NH, USA. Proceedings of IGARSS'91, 1529-1532.

NEFA. 1998. The Northeastern Ice Storm 1998. Northeast Forest Alliance (NEFA). Concord, New Hampshire. 12 pp.

New England Agricultural Statistics Service (NEASS). 1999a. Maple syrup special report. June 11, 1999. National Agricultural Statistics Service Website: http://www.nass.usda.gov/nh/maple99.htm

New England Agricultural Statistics Service (NEASS). 1999b. New England Agricultural Statistics, 1999: Maple statistics 1989-1998. December, 1999. National Agricultural Statistics Service Website: http://www.nass.usda.gov/nh/99maple.htm

Ollinger, S.V., Aber, J.D., and Reich, P.B. 1997. Simulating ozone effects on forest productivity: interactions among leaf-, canopy-, and stand-level processes. *Ecological Applications*, 7:1237-1251.

Perkins, T. 2000. Personal Communication, Maple Producers Annual Meeting, Oct. 26-28, 2000, Burlington, VT.

Perkins, T., Wilmot, T., Baggett, K. and Wong, B. 2000. Effects of the January 1998 ice storm on stem and root carbohydrate reserves in two Vermont sugarbushes. Proctor Maple Research Center Report, University of Vermont, 8p., Burlington, VT.

Prasad, A.M. and L.R. Iverson. 2000-ongoing. A Climate Change Atlas for 80 Forest Tree Species of the Eastern United States [database]. http://www.fs.fed.us/ne/delaware/atlas/index.html, Northeastern Research Station, USDA Forest Service, Delaware, Ohio.

Robbins, C. C., and J. V. Cortinas, Jr. 1996. Climatology of freezing rain in the contiguous United States: preliminary results. 15th AMS Conference on Weather analysis and forecasting. Norfolk, VA. Web: http://www.nccl.noaa.gov/~cortinas/preprints/waf15/climo.html.

Rock, B.N. and G.N. Lauten. 1996. K-12th grade students as active contributors to research investigations. *Journ. Science Educ. and Technology, 5*:15-17.

Rock, B.N., J.E. Vogelmann, D.L. Williams, A.F. Vogelmann, and T. Hoshizaki. 1986. Remote detection of forest damage, *Bioscience, 36*:439-445.

Rock, B.N., T. Hoshizaki, and J.R. Miller. 1988. Comparison of in-situ and airborne spectral measurements of the blue shift associated with forest decline, *Remote Sensing of Enviornment, 24*:109-127.

Ruesink, A. and J. Graves. 2000. A cool disturbance: monitoring ecological effects of the 1998 ice storm at The Nature Conservancy's Shaw Mountain Natural Area in Benson, Vermont (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Sanchini, P.J. 1988. Incidence and spatial patterns of trees with necrotic needle symptoms in *Pinus strobus* populations of nine national parks in 1987. National Park Service, Air Quality Division, Denver, CO. 32pp..

Smith, W.H. 2000. Ice and forest health. North. J. Appl. For. 17(1):16-19.

Smith, K.T. and W.C. Shortle. 2000. Patterns of tree response to storm injury (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Staats, L.J. 1998. Estimated loss of 1998 maple syrup production as a result of the 1998 ice storm in Northern New York. Cornell University Maple Program. Website: http://www.cce.cornell.edu/clinton/ag/ice-storm/nny-maple-loss.html.

Staats, L.J. and C.A. Campbell. 2000. Monitoring recovery and sap production of sugarbushes in northern New York following the 1998 ice storm (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Swisher, J. 2000. Response of trees to ice storm injury in thinned and unthinned hardwood stands (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Theisen, A.F., Rock, B.N., and Eckert, R.T. 1994. Detection of changes in steady-state chlorophyll fluorescence in *Pinus strobus* following short-term ozone exposure. *Journ. Plant Physiol.* 144: 410-419.

Treshow, M. 1986. Tolerance and susceptibility to air pollution, a new direction in sampling strategy: a case study of *Pinus strobus* L. in Acadia National Park, Maine. *Proc. Intern. Symposium on Ecological Aspects of Tree-ring Analysis*, Marymount College, Tarrytown, NY, p. 392-400.

Treshow, M. and Anderson, F.K. 1991. *Plant Stress from Pollution*. John Wiley and Sons, Ltd. P. 283.

Tyree, M.T. 1983. *Maple sap uptake, exudation, and pressure changes with freezing exotherms and thawing endotherms*. Plant Physiol. 73: 277-285.

U.S. Department of Commerce (USDC). 1992. 1992 Census of Manufactures. General Summary, MC92-S-1.

US Forest Service Ice Storm webpage (USDA-FS). 2000. http://www.fs.fed.us/na/durham/ice/index.htm

USDA-FS. 1993. Northeastern Area Forest Health Report. United States Department of Agriculture, Forest Service. Report number NA-TP-03-93. 56 pp.

USDA-FS RPA Website.

Vermont Department of Agriculture, Foods and Markets (VDA). 2000a. The Economic Importance of Maple to Vermont. Vermont Department of Agriculture. Website: http://www.cit.state.vt.us/agric/meco.htm.

Vermont Department of Agriculture, Foods and Markets (VDA). 2000b. Vermont Maple Facts. Vermont Department of Agriculture. Website: http://www.cit.state.vt.us/agric/mfacts.htm.

Vogelmann, J.E., N.J. Defeo, and B.N. Rock. 1989. The use of remote sensing for the study of forest damage.

Proceedings of the International Conference and Workshop - "Global Natural Resource Monitoring and Assessments: Preparing for the 21st Centry," held in Venice, Italy, September 24-30.

Vogelmann, J.E., Rock, B.N., and Moss, D.M. 1993. Red edge spectral characterization of phenological change and insect related damage in sugar maple leaves. *International Journal of Remote Sensing*, 14: 1563-1575.

Widmann, R.H. and E.H. Wharton. 1998. Pulwood production in the Northeast, 1994, 1995, and 1996. USDA-FS NEFES, Res. Bull. NE-140.

Woods, S. and D. J. Leopold. 2000. Response of understory to ice storm disturbance in hardwood forests of northern New York (abstract). *In* Ice Storm Research/Monitoring Workshop Report. Margaret Miller-Weeks, Editor. Workshop held in Dorchester, New Hampshire on September 21, 2000. *See www.fs.fed.us/na/durham/ ice/index.htm.*

Zarco-Tejeda, P.J., Miller, J.R., Mohammed, G.H., Noland, T.L. and Sampson, P.H. 2000. Optical indices as bio-indicators of forest condition from hyperspectral CASI data. Presented at the 19th symposium of the European Association of Remote Sensing Laboratories (EARSeL), Valladolid, Spain.

Chapter 6

Water Resources and Potential Climate Change Impacts

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6.1. Introduction

The New England region (including the 6 New England states plus upstate New York) offers a very diverse geography, matched by an equally diverse economy and human population. Livelihoods throughout the region are based on service industries that depend heavily on communication networks and travel, the manufacture and transport of industrial goods and materials, recreation and tourism, agriculture, and resource extraction (forestry and fisheries). Changes in the future which might affect either the quality or the quantity of water available to the region could have a profound impact on regional economy and populations.

The New England region is not presently considered limited by water availability. While the region was impacted by a serious drought during the mid-1960s, overall, images of a vast network of lush green forests and inviting waterways, extensive shorelines, and a landscape of mountain streams and lakes teeming with fish characterize the region. Water recreation, including fishing, boating, and swimming along with regional seafood such as lobster define the New England region for many. This view assumes that in the future, water will be plentiful and of the highest quality. As we have seen in Chapter 4, the Canadian model projects only a modest increase in precipitation for the region over the 21st century, punctuated by periods of potential drought. The Hadley model projects a significant increase (approximately 30%) in precipitation over the same time period. How would either of these projections, coupled with the warming projected by both models, impact the New England region?

Potential climate change could affect many facets of life in the New England region, with those that are climate-dependent most vulnerable. For example, climate change that would alter either quantity and/or quality of water could directly affect the viability of several regional industries such as agriculture, forestry, fishing, tourism, and outdoor recreation. Changes in climate also could impact human health, and exacerbate existing health stresses posed by air and water pollutants. In the coastal region, infrastructure (the institutions, facilities, and services available to a community) could be impacted by possible climate-induced rise in sea level as well as by water quality issues such as (harmful algal blooms). Other concerns include potential climate impacts on the region's aquatic and terrestrial ecosystems, water supplies, commerce, and infrastructure, including water treatment facilities, surface water management systems (i.e. dams and channel maintenance), and energy generation and transportation systems.

In the New England region, future climate impacts to the Water Sector fall into four general categories: 1) water quality issues, 2) water quantity issues (drought, flooding and sea level rise), 3) the impact of regional land use on water quality/quantity, and 4) the value of wetlands to the region (wildlife habitats, recreation, and pollution impacts). Other water-related issues include the impact of "surprise" events such as the 1998 ice storm. Selected examples of such impacts include warmer, wetter winters, coupled with more moisture year-round (the Hadley projection) leading to flooding and a flushing of sewage and other wastes from urban areas into wetlands and coastal marine waters. The harmful impacts of poor water quality may range from harmful algal blooms to toxification of water supplies. On the other hand, the rapid temperature rise and limited precipitation increases projected by the Canadian model would also lead to poor water quality as well as droughts as significant as (or worse than) the mid-1960s drought. Either projection would also result in significant sea-level rise, which in turn will impact water quality.

This chapter investigates some of the documented impacts (current stresses) of recent climate trends for the region, the potential climate impacts over the next 100 years projected by the climate models, and considers reasonable coping strategies to address the impact. The Chapter identifies significant information gaps and "missing pieces" that are needed to more fully understand just how climate change could affect regional water resources. The content of this chapter has been provided by participants at the New England Regional Assessment initial meeting, held September 3-5, 1997 (NECCI, 1997), and the Water Sector meeting held March 30, 1999. The Chapter begins with a consideration of the current status and stresses on the sector, followed by potential impacts of future climate scenarios, information needs, and adaptive strategies. Finally, illustrative Case Studies are included to provide more details on 1) the regional impacts of the mid-1960s drought, 2) the role of the North Atlantic Oscillation (NAO) on surface hydrology during winter months, 3) impacts of current climate variability on winter flounder abundance, and 4) impact of past and future climate trends on snow pack at Hubbard Brook, NH.

6.2. Current Status and Stresses

Current variability in regional temperature and precipitation

A highly variable climate characterizes the New England region: severe ice storms, summertime heat-waves, spring and fall floods, and long-term and short-term droughts sometimes are the result. The region is famous for its "Nor'easters" along the coast, "lake effect" snowstorms in western New York, and its highly changeable weather. The lush landscape is heavily forested due to the abundance of water. In turn, evapotranspiration associated with the forested landscape results in high humidity and local cloud cover. The periodic droughts, though troublesome, are infrequent. The historic patterns of temperature and precipitation (Chapter 2) have changed over the past century (since 1895), resulting in an overall regional temperature increase of 0.7°F, and a slight increase in regional precipitation (3.7%).

As noted in Chapter 2, the changes in temperature and precipitation across the region since 1895 have been very heterogeneous both geographically and seasonally. The coastal portion of the region has warmed more than the interior portion and has received the greatest increase in precipitation. The average number of days with snow on the ground has decreased by nearly a week over the last 50 years, not surprising since regional wintertime temperatures have warmed more (1.8 °F) than the summertime temperatures (0.5 °F) since 1895. In the case of northern New Hampshire, not only have wintertime temperatures risen dramatically (3.8°F for the months of December, January and February), but precipitation for the same time period has decreased 24% since 1895. Six of the last 40 years have been characterized by significant regional drought, with all six years occurring in the 1960s (see the Mid-1960s Drought Case Study). At the same time, precipitation extremes appear to be increasing with more rain coming in heavy downpours. Changes in the type of precipitation falling during winter months (snow vs. rain), as affected by variations in wintertime temperatures, have a profound impact on water storage vs. runoff, in turn impacting regional hydrology (see Case Study #3).

Clearly, the current climate variability characterizing the region, as well as variability over the past century, constitute a significant stress on the region's water resources. Concerns voiced by workshop participants and the general public include sea-level rise, water quality issues, and the impact of a changing climate on wetlands and wildlife habitat.

Sea Level Rise

As concentrations of greenhouse gases increase in our atmosphere and the planet warms, one of the most likely impacts of the warming will be rising sea levels. Sea-level rise is a result of both the thermal expansion of sea water (as water warms, its volume increases) and the addition of fresh water from melting glaciers, ice sheets, and snow pack. Sea-level rise, which is already occurring, could inundate low-lying areas of the New England region, many of which include densely populated areas (coastal Connecticut and Long Island, Boston, parts of coastal New Hampshire and Maine), as well as popular tourist areas (Cape Cod, Nantucket and Martha's Vineyard, coastal beaches). Because the coast of New England is prime real estate, coastal populations in the region are likely to double by 2100.

Currently, the average rate of sea-level rise on the Atlantic coast ranges from 3.5 inches per century in Boston, Massachusetts, to approximately a foot per century in coastal salt marshes in southern Massachusetts. Different rates of sea level rise occur at different locations due to local rates of subsidence (settling) or uplift. An EPA study suggests a 50-percent chance by 2100 of a 19-inch sea-level rise in Portland, Maine. Already, about 33 acres of land are lost on Massachusetts' Cape Cod each year—73 % of which is due to advancing seawater and 27% to active erosion (NECCI, 1997). The local topography is responsible for determining the rate of submergence, and if unaffected by human activities, much of the submerged land is transformed into salt marsh.

Much of the current rate of sea level rise is due to thermal expansion of the oceans due to the global warming trend that has occurred over the past century. Assuming that uniform global warming of the entire ocean were occurring (instead of the current, spatially heterogeneous warming), a one degree change in ocean temperature would mean a one meter rise in sea level (NECCI, 1997). The current rate of rise is less at present, because the total ocean is not heating uniformly, only the mixed upper layer has warmed to date. The second reason for sea level rise is the melting of glaciers and ice caps. Clear documentation exists of the recession of approximately 80% of mountain glaciers around the world. There is also limited documentation for a small reduction in the Greenland ice sheet (especially in the southern region). A last reason for sea level rise is human activity. As we mine water from aquifers as a source of drinking water, the aquifers recharge more slowly than we empty them, and the mined water finds it's way into the ocean. We also drain wetlands, pumping the water into drainage systems or directly into the oceans. Such direct human activity may account for a third of sea level rise per year (NECCI, 1997).

Changes in the intensity, frequency, and tracks of future storms are uncertain for coastal New England (Chapter 2). However, the potential for altered storm intensities, combined with rising sea levels, could result in increased damage due to more intense storm surges. The threat of an increase in storm intensity or frequency would obviously pose great social and economic concern to coastal residents of this region. Other potential effects of sea-level rise include erosion, inundation, saltwater intrusion, wetland destruction, and impacts on the biology and ecology of coastal systems.

Another result of rising sea level is that the saltwater wedge, vital to the health of an estuary, would migrate upstream unless freshwater runoff increases. This would cause a shift of salinity controlled marine ecosystems upriver. Preserving intertidal habitats is a significant concern, as the wetlands and other intertidal areas (e.g. mud flats) are important nursery grounds for many species of coastal fish and shellfish and important feeding grounds for many migrating waterfowl. If shoreline construction prevents wetland migration, then upslope habitat shifts might be prevented.

Consequences of Climate Change on Coastal Ecosystems

During the past 50 years we have seen large variations in New England regional climate associated with a major shift from a surprisingly persistent negative NAO (North Atlantic Oscillation) phase in the 1950s through the 1960s, into surprisingly persistent positive NAO phase in the 1970s and the 1980s. Within this period, the winter water temperature of Narragansett Bay warmed by 3^{o}C, almost a 1-degree change per decade between 1960 and 1990. Furthermore, it was found that warmer sea surface temperatures off the Atlantic Coast lead to lower snowfall totals in southern New England, though the impact is less noticeable father north.

Such a dramatic wintertime temperature change has probably altered food chains in temperate coastal waters in southern New England. A recent experimentally controlled study (Keller et al., 1999) demonstrated that in warm winters, more of the winter phytoplankton is consumed in the water column, reducing the flux of organic matter to the bottom. Experimental marine mesocosms (controlled tanks of water) were used to evaluate the potential effects of a 3^o C contrast between replicate "warm" tanks (1^o C above ambient), and replicate cold tanks (2^o C below ambient). In the warm marine mesocosms, carbon produced by the phytoplankton was lost primarily by grazing, and to a lesser extent by sedimentation to the bottom. In the cold tanks (in essence a "global cooling" experiment), a larger winter-spring bloom of phytoplankton occurred, and more carbon made it to the bottom as sediment.

The observed reductions in carbon flux to the bottom of the warm experimental tanks suggests the possibility of large scale alteration of marine food webs in southern New England as winters warm. In the past century, there have been large changes in the abundance of bottom-dwelling "ground fish" in New England, largely attributed to changes in fishing pressure. Isotopic analysis of fish scales from certain fish (Haddock, 4 species of flounder, and American plaice) from Georges Bank suggest major changes in trophic structure have occurred in the past century. Statistically significant components of change in the Georges Bank food web were associated with variation in climate (including the NAO), probably having effects at the primary producer level (Wainright et al., 1993). Haddock stocks increased dramatically in the 1960s, a period with cooler winter sea surface temperatures. Although speculative, reductions in the flux of phytodetritus (carbon) to the bottom during warmer winters may have been a contributing factor in the observed declines of commercially important ground fish in southern New England in recent decades.

Current Impacts of a Changing Climate on Commercial Fishing

The winter flounder Case Study describes the effect of recent climate change on the abundance of this important marine species. The winter flounder may well be an indicator species sensitive to increases in water temperatures. Over a 30-year observation period (1959 to 1989), the community composition of Narragansett Bay, Rhode Island, shifted from a resident cold-water, winter flounder dominated community to a migratory, warmer water marine community. Warmer water temperatures appear to have set off a chain of circumstances that began with the loss of the winter flounder population and resulted in increased populations of warmer water invertebrates and migrant fishes (Jeffries and Johnson, 1974; Jeffries, 1994).

During the 30-year period, the winter flounder population collapsed on two occasions. Both instances occurred during a multi-year warming trend in the winter-spring spawning cycle, and a recovery coincided with two successive cold winters. As the number of flounder decreased, large invertebrates—such as crabs, squid, lobster (only in the Bay), and mantis shrimp—moved into the region earlier in the season and in greater numbers. By the third decade of observation, the butterfish, originally a summer migrant species, had increased so much that it ranked fourth in abundance in Narragansett Bay (Jeffries and Terceiro, 1985).

Freshwater Issues

Climate variability in the New England region affects both water quantity and water quality. As will be seen from Case Study #3 (winter NAO Index and Stream Flow in New England), dramatic changes in amounts and forms (rain vs. snow) of precipitation added to the hydrologic system have profound impacts on stream flow and surface water conditions.

Changes in stream flow characteristics can have dramatic affects on water quality - too much water (flooding) could result in overflows of waste water treatment facilities, leading to poor water quality, just as too little water may result in concentration of toxins, also leading to poor water quality. Thus, the impact of extreme events (both flooding and droughts) on water quality is a key concern for the future. Education is a key element of improving public awareness of the impact, as well as in adopting appropriate mitigation strategies for the future. How water quantity is currently measured needs to be considered.

Monitoring Climate Change Impacts on fresh water quality and quantity

Water quality data for New England are not measured as consistently as water quantity. Water quality data vary from state to state, with some states having good, long-term monitoring programs, while others have abandoned their monitoring programs. The best source for long-term water quality records would be the public water suppliers for large areas, where on-going monitoring programs have been in effect for a number of years.

The USGS (U.S. Geological Survey) is well known for its water quantity data, collecting stream flow data at multiple sites across the New England region (http://water/usgs.gov/realtime.html), often done in conjunction with monitoring water usage and flow requirements. Such data are probably the best data set to be used to study climate change and variability effects on water resources. A problem with much of these data is that the data are collected downstream from major impediments or dams – which could influence the characterization of the impacts of climate change.

Another major concern for the USGS is that flood stage and stream height have been changed by upstream development. Adjustments are made for this by quantifying the extent of development — percent of impervious surface in a watershed, for instance. With remote sensing, land cover type and land use change over time can now be measured and quantified. Using remote sensing data, development activity on the land can be documented. Conversely, when measuring large areas of land, change in land use may not have a very measurable effect. Looking at the Pemigewasset stream flow record begun in 1903, following the extensive clear-cutting in the White Mountains, the major land use change involved the re-growth of a heavily deforested landscape. The impact of this dramatic re-growth is not easily seen in the stream flow record. In a number of rivers and streams, flows are not actively managed, making effects of climate variation more evident (Slack and Landwehr, 1992).

The USGS had the National Stream Quality Accounting Network (NASQAN) program — a national effort to look at water quality across the country, which ran from the mid 1970's to the early 1990's. Unfortunately, because few were using the data, the program was discontinued. It was an excellent data set that looked at the water quality at the downstream end of many major river basins across the country. The National Water Quality Assessment program (NAWQA) has since supplemented the NASQAN data (http://usgs.gov/nawqa). This program consists of rotational ground and surface water quality studies, looking at water quality in an area in depth for a while, but not as a long-term trend analysis. There are about 60 long-term collection data sites designated around the country by the NAWQA, which does not provide regional, long-term continuous data. Since the NAWQA data do not provide long-term trends, there is a lack of good, long-term water quality data for the New England region.

The NAWQA program has assessed the coastal drainage from the Kennebec River, in Maine, down to the Blackstone basin in Rhode Island, comparing the current data with historic NASQAN data from the 80's and early 90's. This study used 10 years of data and looked at median values. It shows that the Merrimack basin is one of the largest drainage areas, as well as one of the largest contributors of stream loading of sediments and pollution in the region. The Kennebec and Androscoggin basins (in Maine), though larger, don't contribute as much to loading. More studies, estimating the percent of the total load of sediments and pollutants in the basin that could be from various sources, both natural and anthropogenic, based on the watershed information and GIS (Geographic Information System) data gathering, are needed.

Currently, a regional water quality model does not exist for New England. The Spatial Regressions on Watershed Attributes (SPARROW) is based on a current USGS model — a multi-regression approach to characterizing water quality, based on watershed information (Smith et al., 1997; http://water.usgs.gov/nawqa/sparrow/index.html). Regional applications of SPARROW are being considered by the EPA to: conduct regional water quality assessments, help set nutrient criteria, and assist in establishing the Total Maximum Daily Load process (TMDL), in order to restore impaired waters. It is hoped that this model can be used to better understand water quality conditions in watersheds for which there are little data. Such a model would be used for predictive work (future populations, land use, etc) as well. It would factor in land use, as well as point sources and population estimates. This would all be linked to a network stream database that has flow, relief, and other information associated with it. It would need to be very detailed, using a 1:100,000 scale for stream length.

6.3. The Potential Impact of Climate Change in the Future

Global and regional computer models, although imperfect at describing local conditions, suggest that the current warming trends will continue and the Hadley and Canadian climate scenarios suggest warmer winters. Compared with other regions of the US, the New England region has typical levels of projected future warming (6-10^{o}F) by 2100 (National Assessment Synthesis Team, 2000). Precipitation changes projected by the models are much less certain, and range from 10 – 30% increases. Whether the increase will be greatest in the summer or the winter is as yet uncertain but it is likely that a greater percentage of precipitation will come in heavy downpours. Coastal precipitation is likely to be highly variable and is likely to increase. If greater frequency and intensity of extreme events were to occur, increased frequency of winter thaw events, flooding, and summer droughts could result. Although the region is considered "water rich" because of its high level of precipitation, drought has been and remains a significant concern for this region. As noted, inadequate water storage, and large, aging water supply systems will be challenged to respond to changing water demands.

As temperatures increase in the future, the current levels of variability in regional temperatures and precipitation can be expected to continue, and perhaps increase (Chapter 4). Since much of the current heterogeneity and variability is not well understood, improving our understanding about the cause and effect relationships between regional characteristics (land cover, urban development, topography, etc.) and local climate across the region is needed.

Sea Level Rise

Rising sea levels will have several impacts on the coastal areas of the region. Saltwater intrusion would convert some areas of coastal freshwater wetlands to salt marshes. Near coastal groundwater could also be affected, as brackish water infiltrates aquifers that supply drinking water to coastal communities. This occurred in a number of regional estuaries during the mid-1960s drought (see Mid-60s Drought Case Study). Since saltwater intrusion occurs as a result of low freshwater flow, a higher chloride water content may occur in important aquifer systems and water supplies. Aquifers are vulnerable to future saltwater intrusion because aquifer recharge is by freshwater in-flow. Low freshwater flow, a rise in sea level, or both could contribute to future episodes of saltwater intrusion, affecting the water supplies in coastal regions.

In addition, as sea level continues to rise, the amount of the region's low lying coastal area subject to flooding from coastal storms will increase, especially in areas of low relief. Increases in sea level can cause dramatic changes, as higher sea levels would provide a raised base from which storm surges may sweep inland, allowing for greater and more widespread damage than would occur with stable sea levels. Even if storm strength were not increased, higher sea levels could result in more damage. Vulnerability to coastal structures would result from additional building in low lying areas.

Future Impacts on Coastal Ecosystems

Dramatic wintertime temperature change projected by the climate models will likely lead to altered food chains in temperate coastal waters in southern New England. Similar changes in coastal ecosystems may also occur in northern New England. Although speculative, reductions in the flux of phytodetritus (carbon) to the bottom during warmer winters may become a significant contributing factor in the decline of commercially important ground fish in southern New England in the next 100 years.

Future Impacts on Commercial Fishing

With projected warming, it is probable that the observed downtrend in winter flounder populations will continue. Scientists suggest that a change in the preditor-prey relationship is occurring with warmer late winter-early spring temperatures allowing sand shrimp, one of the invertebrates increasing in number, to feed earlier in the year than usual. They invade the flounder's cold-water, estuarine refuge and feed on its larvae at rates sufficient to reduce the flounder populations. Case Study #4 provides more details on this complex climate-related phenomenon.

It is likely that in addition to experiencing future alterations in coastal food chains, we will also experience other changes such as in predator-prey relationships and competition between exotic (non-native) and native species.

Freshwater Issues

Climate change impacts on freshwater in the New England region will affect both water quantity and water quality. As is seen from the NAO Surface Hydrology Case Study (#3), dramatic changes in amounts and forms (rain vs. snow) of meteorologic water added to the hydrologic system have profound impacts on local and regional stream flow and surface water conditions. Increased storm intensities and drought periods will have even more significant impacts on the region's freshwater supplies. Although the region is unlikely to become water limited as the result of climate change, regional water quality could be reduced under either of the two climate scenarios.

Freshwater Fishing: Environmental Impacts

The potential impacts of climate change on fishing are of concern to recreational anglers. Nearly 50 million people engage in recreational fishing each year in the United States, generating more than $108-billion to the U.S. economy. Nearly 30 percent of the fishing was associated with cold-water and anadromous fish.

A continued warming trend would definitely impact freshwater fishing in the New England region. Significant losses of cold-water species would occur by the end of the next century if climate change results in loss of cold-water habitats.

With climate change, the greatest losses in cold-water species would occur in the southern borders of a species' natural range, where the minimum temperatures are closest to thermal tolerances. Many species are particularly temperature-sensitive during spawning. An EPA study based on thermal modeling that assumes a doubling of carbon dioxide levels, found that the region faces a 50- to 100-percent potential loss of habitat for brown, brook, and rainbow trout—cold-water species that are highly valued by anglers. With the loss of such habitats however, cool and warm water fish could expand their ranges into previously cold-water habitats, thus increasing their availability.

In fact, little change is expected in the numbers of cool-water fish species, which include walleye, northern pike, and yellow perch. Most of the change the climate models project will occur at the southern end of the species' range. Species at the northern end of their range could benefit from warmer temperatures by increasing their growth rates and productivity, which would increase an estimated 10 to 20 percent with each 1.8° F increase in temperature. Maturation rates would also increase if other factors continue to be positive, such as food availability.

Stream flow in the region also would be affected by changes in climate but uncertainties are very large. Regional stream flow changes are much harder to project than changes in temperature. Changes in stream flow rates could affect all species through changing their habitats in numerous ways. The rate of stream flow may change or be uneven, although overall precipitation remains the same, because some of the precipitation may come in the form of downpours rather than gentle rains. If the rate of stream flow is high and causes floods in the spring, eggs could be destroyed and food availability reduced.

Low water levels, in contrast, could decrease the availability and quality of habitat areas, causing crowding, the spread of disease, and stranding. If stream flow is low enough, eggs lying at the bottom of a stream could be encompassed in ice in cold weather or could be scoured off the bottom as water flows by, resulting in their destruction. However, not all fish species would be hurt by less stream flow.

6.4. Information Needs and Data Gaps

The following information and data gaps need to be addressed:

- Uniform and standardized long-term water quality measurements in all seven states in the region;
- A regional geographic information system (GIS) for monitoring and characterizing land cover and land use change over time;
- A regional assessment of total loading of sediments and pollutants to stream systems;
- A resurrection of a standardized national program (such as NASQAN) to look at water quality across the country;
- More studies, estimating the percent of the total load in the basin that could be from various sources, both natural and anthropogenic, based on the watershed information and GIS data gathering;
- A regional water quality model for the New England region;
- An improved understanding of the role that the NAO plays in regional weather is needed; and
- Improved understanding about cause and effect relationships that determine the current levels of variability in regional temperatures and precipitation.

6.5. Adaptive Strategies

We know that New England as a region has suffered both severe drought and flooding in the past. We must be careful about how we manage our water resources under such extreme conditions. Additionally, because of the changes in regional land use due to agriculture and forestry, the impacts of variability in our future climate (even without overall change) are growing. We can do much in terms of developing adaptation strategies by learning to adapt to changing circumstances, and limiting our vulnerabilities to both wet and dry extremes of climate.

Sea Level Rise

The EPA has identified at least three strategies to cope with the effects of climate change on sea-level rise, and these are appropriate in the Northeast. They are 1) to retreat from advancing seas, 2) accommodate changes imposed by a higher sea level, and 3) protect areas/structures from sea level rise. In addition, all three coping strategies could be more effectively applied through education efforts that help concerned parties cope with potential coastal changes and avoid putting themselves in harms' way to begin with. For example, all stakeholders should be educated about the risks of building in hazard-prone areas and the potential for changes in storm frequency, intensity, and sea level. Detailed steps to be taken follows.

A strategy of retreat is appropriate when we desire to allow ecosystem migration. Retreat could include the following actions:

- Establish setbacks in building codes that require structures vulnerable to inundation be moved if threatened (similar codes are already in place in Maine for example);
- Purchase coastal land and prohibit its development;
- Include present and projected sea-level rise in planning and development, along with anticipatory building codes;
- Remove subsidized coastal flood insurance; and
- Provide for rolling easements to allow the public access to the changing shoreline.

Accommodation could entail the following steps:

- Regulate building development by instituting stronger and more appropriate building codes and restricted locations; and
- Develop and offer incentives to encourage responsible siting and building decisions.

A strategy designed to protect coastal lands can be appropriate along economically valuable shorelines that have been identified as high priority for protection and those efforts could include:

- Nourishment of protective beaches; and
- Construction of bulkheads and sea walls, although these actions may result in loss of sediments that nourish nearby beaches.

Fishing

Climate change impacts will vary stream by stream, depending on how stream flow is affected. Some strategies are now available to anglers and those in the fishing industry to cope with potential impacts of climate change. One strategy is to fish for alternative species; another is to travel north or to higher elevations to fish for cold-water species. Fisheries managers also could shift stocking patterns in favor of more cool and warm-water fish species. Education could be developed to increase the perceived attractiveness of cool and warm water species as well.

Strategies to address potential impacts on coastal fishing are limited but could involve improving adaptive management practices, and switching between target species as needed due to changes in available stocks. We have learned from experience that intense exploitation of valued fish stocks in the northwest Atlantic in combination with climatic shifts that are less favorable for reproduction and growth of important species can lead to fish stock collapses. The economic impacts of this reality have already reverberated throughout the social fabric of coastal communities in the northeastern United States and eastern Canada, where coastal fisheries have sustained livelihoods for many generations. We need to improve both fishery management practices and stock assessments, and be better prepared to reduce fishing mortality when necessary to promote stock recovery and help avoid fish stock collapses in the future (National Research Council, 1998).

In coastal waters, the increased populations of invertebrates and migrant fish species in the region's waters may compensate for species lost. This poses a problem for fisheries, as many of these will not support a fishing industry. The economic impacts of this reality clearly will reverberate throughout the social fabric of coastal communities, where coastal fisheries have sustained livelihoods for many generations.

Changes in the distribution and composition of fish populations will impact the economy of the region's fisheries and will require adjustments in those fisheries. For example, during its previous dominance, winter flounder accounted for half of the total income earned by coastal fishermen in one New England port, but now provides them with inconsistent sources of income. An increase in other species could provide an economic benefit, but fisheries will have to work to create market demand for the other newly established fish and shellfish populations in the region. Increased monitoring of fish stocks coupled with appropriate fishing effort (i.e., harvest species that are doing well) may mitigate some of the effects of changing distribution and composition of fish populations. Once again, education of the public regarding fishing options and market options will be key.

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6.6. Case Studies

CASE STUDY #1 – The 1960s Drought in New England and New York

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The drought of the 1960s was by far the longest, most severe, and most widespread that the northeastern United States has experienced at least since European settlement. The proximal cause of the drought was precipitation shortfalls, which began in 1960-1961 and lasted until 1968-1969. At its most intense, in July 1965, the effects of this drought on the water supplies and water quality of this densely populated region had become so severe that President Johnson declared a limited national emergency. He convened the inter-agency Water Resources Council to assess how the federal government could best mobilize its resources to assist state and local governments in dealing with the drought (U.S. Water Resources Council, 1965).

Figure 6.1 shows the accumulated precipitation deficiency from October 1961 to December 1965. By the summer of 1965, "extreme" drought conditions covered some 60,000 square miles, with "severe" drought covering an additional 60,000 square miles (Figure 6.2). Stream flows and groundwater levels were near or below their historical lows in a swath extending from the Massachusetts and New Hampshire coasts southwestward into West Virginia, and were in the lowest 25% of normals in virtually all of the country north of Richmond, Virginia, and east of Illinois. The accumulated stream flow deficiency in central Massachusetts between 1961 and mid-1966 was equivalent to two years of normal runoff (Barksdale et al., 1966).

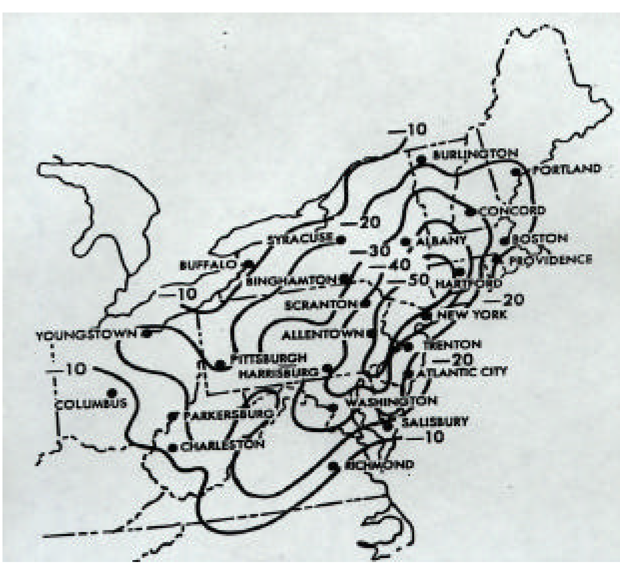

Figure 6.1. Accumulated precipitation deficiency (inches) from October 1961 to December 1965 (U.S. Water Resources Council, 1966).

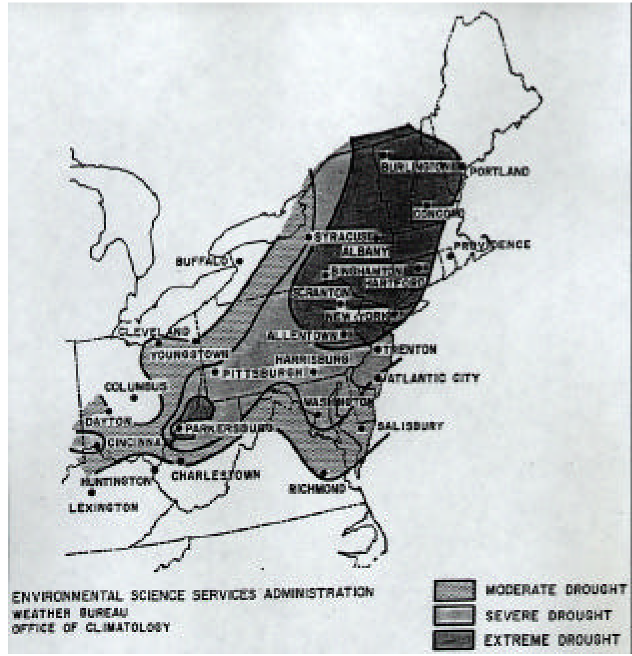

Figure 6.2. Summer of 1965 showing extreme drought conditions over 60,000 square miles with severe drought covering an additional 60,000 miles (U.S. Water Resources Council, 1965).

Because water-supply systems in the northeast were generally designed to be adequate in a repetition of the drought of the early 1930s, and because of the unanticipated growth in population and industry that had occurred since then, more than 100 public water supplies were experiencing or threatened by critical water shortages. In July 1965 the storage in New York City's reservoirs was at 48% of capacity. To conserve these supplies, an emergency decision by the Delaware River Commission allowed New York to reduce Supreme Court-mandated releases from its reservoirs to the Delaware River drainage. This reduced flows in the lower Delaware, allowing salt water to move upstream toward the intakes that supplied one-half of Philadelphia's water. Ground-water supplies as well as surface water for the Philadelphia-Camden area were in a critical condition, and supplies in northern New Jersey were in a "dangerous" condition (U.S. Water Resources Council; 1965, 1966).

The extremely low flows caused water-quality problems in addition to the landward migration of salt-water in estuaries: reduced dissolved oxygen, increased temperatures, and increased concentrations of pollutants. Scattered fish kills occurred in Maine, New Hampshire, and Massachusetts. Excessive concentrations of nutrients caused excessive growth of algae and other aquatic plant nuisances in lakes and reservoirs and produced taste and odor problems in some municipal water supplies.

Other effects of the drought included an increase in the number and severity of forest fires and increased forest tree mortality due to soil-moisture shortages and drought-induced insect attack. Excessively dry soils severely degraded pasture conditions, necessitating heavy supplemental feeding of livestock and curtailed agricultural operations in Pennsylvania, New Jersey, southeastern New York, and southern New England.

The 1960s drought in the Northeast was part of a "major aberration" in North America's precipitation regime, and was coincident with very wet conditions in the Southwest and Northern Plains. A detailed analysis of weather conditions indicated that the precipitation shortfalls occurred largely in the spring and summer and that temperatures during the drought were cooler than normal. The drought was "caused" by an anomalous upper-level trough off the east coast which induced persistent cold dry air flow from the northwest and caused storms to intensify farther out to sea than normal. This pattern was associated with abnormally cold sea-surface temperatures off the Northeast coast.

The New England-New York region has experienced at least nine periods of widespread meteorologic (caused by climatic conditions) and hydrologic (due to altered stream flow patterns) drought in the 20th Century, covering approximately the years 1908-1913; 1929-1936; 1938-1945; 1947-1951; 1955-1959; 1961-1969; 1979-1983; 1984-1988; and 1991-1995. The return period of the 1960s drought was estimated to be about 150 years (Russell et al., 1970). The early-1930s drought rivaled the 1960s event in areal coverage, but it was not nearly as severe or long-lasting.

The U.S. Geological Survey began gaging the flow of the Pemigewasset River at Plymouth, NH, in 1903, and that station has one of the longest continuous flow records in New England. The drainage area contributing flow is 622 mi^2, and the flow is unregulated. To reveal periods of hydrologic drought in central New Hampshire over the period of record (October 1903 - September 1996), I have constructed a time series of normalized monthly flow values, $q_{m,y}$, as

$$q_{m,y} = \frac{Q_{m,y} - E(Q_m)}{S(Q_m)}$$

where Q is the measured flow for month m in year y, $E(Q_m)$ is the mean of all the month-m flows, and $S(Q_m)$ is the standard deviation of all the month-m flows. Then to smooth the data, I calculated the 11-month moving average of the normalized values and plotted them in Figure 6.3. The drought periods mentioned above are apparent in the graph as extended periods when the line is below 0, and the extreme severity and duration of the 1960s drought is evident. Analysis of this record also indicates increased variability since the 1960s drought. It may be of interest to do further analyses of long-period flow records such as this.

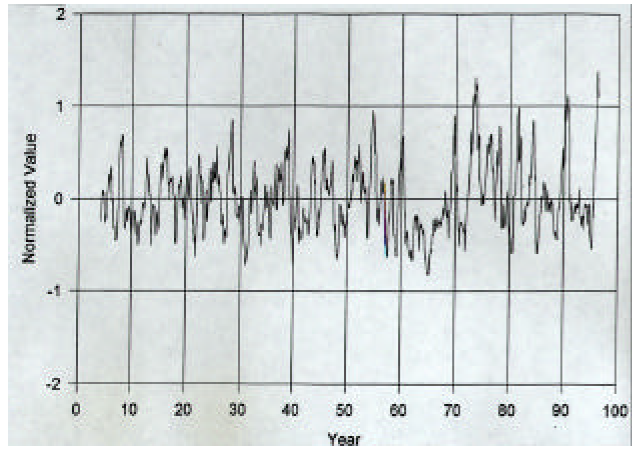

Figure 6.3. 11-month moving average of the normalized montly flow values for the Pemigewasset River, Plymouth, NH.

Namias (1966) speculated that the 1960s drought was triggered by a pool of anomalously warm sea-surface temperatures in the Pacific ocean north of Hawaii. However, the monthly El Niño-Southern Oscillation (ENSO) index was negative for most of the decade of the 1960s, indicating colder-than-normal temperatures in the equatorial Pacific (La Niña conditions). A visual comparison of the ENSO index with the New England-New York drought periods since 1950 suggests no consistent relation.

Studies by Piechota and Dracup (1996) and Dracup and Kahya (1994) related periods of high and low streamflows in various regions of the United States to El Niño and La Niña, respectively, for the period 1945-1990. Of 9 El Niño episodes, six were related to low flows in the Northeast, one to extremely high flows (1973), and two with flows in the normal range. Of 8 La Niña episodes, six were associated with high flow periods, one with extremely low flows (1964), and one with normal flows. Thus, although there appears to be some association of El Niño episodes with dry periods and La Niña episodes with wet periods, there does not seem to be a strong basis for predicting a recurrence of a drought of this severity based on El Niño/La Niña episodes alone. Perhaps other indices of atmospheric circulation modes such as the North Atlantic Oscillation and the Pacific-North America index are also related to New England drought.

In any case, the region has experienced significant multi-year droughts approximately once a decade in this century and, because of the increased development in the last 30 years and the limitations on water supply that have emerged in many parts of the region, it is clear that a drought approaching the 1960s severity, extent, and duration would have severe economic and environmental consequences. There would be great advantage to society in further understanding relationships between such events and atmospheric indices that can be predicted with some reliability.

CASE STUDY #2 – Effect of Warming on Snow at the Hubbard Brook Experimental Forest

By: C. A. Federer, Department of Natural Resources,
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A hydrologic model that simulates snow accumulation and melt can be used to estimate changes in snowpack that will result from climate change. The BROOK90 model has been applied to simulate snowpack under measured climate for two locations on the Hubbard Brook Experimental Forest, West Thornton NH. The simulation runs were then repeated for a simple climate warming in which all daily maximum and minimum temperatures were increased by 2ºC/3.6ºF. Snowpack is defined in this study as the snow water equivalent, which is the depth of water that would be produced by melting the snow.

BROOK90 Model

BROOK90 is a parameter-rich model designed to study the processes of evapotranspiration and soil water movement at a point, with some provision for stream flow generation by different flow paths. It is a major modification of the older BROOK2 hydrologic model (Federer and Lash, 1978). It simulates the water budget on a unit land area at a daily time step and is applicable to all land surfaces. Input of daily precipitation and maximum and minimum temperatures is required, and daily solar radiation, vapor pressure, and wind speed are desirable. The model then estimates interception and transpiration from a single layer plant canopy, soil and snow evaporation, snow accumulation and melt, soil water movement through multiple soil layers, stormflow by source area or pipe flow mechanisms, and delayed flow from soil drainage and a first-order groundwater storage. For the simulation here, the soil water, transpiration, and stream flow-generating components are not important as only the above-ground processes of snow accumulation and melt are relevant. The BROOK90 model is described more fully at http://www.nh.ultranet.com/~compassb/brook90.htm.

The separation of daily input precipitation into rain or snow can cause major problems for snow simulation. BROOK90 considers daily precipitation to be all snow if the maximum temperature for the day (Tmax)is below a constant value, set at 0.5°C/0.9ºF in this study, and all rain if the minimum temperature (Tmin) is above this. If Tmax is above and Tmin below 0.5°C/0.9ºF the fraction as snow is (0.5 - Tmin)/(Tmax - Tmin). Disagreement of simulated and measured snowpack can be large if large storms are called rain when they really are snow or vice versa.

Snowmelt is based on a degree-day melt factor for snow in nonforested areas, initially set at 4.5 mm d-1 °K-1 for this study. This means that for snow in the open on a day with a 10°C mean temperature, for instance, 45 mm of snow water equivalent will melt to liquid water. The degree-day factor is modified for slope and aspect and for forest cover as determined by leaf-area index and stem-area index, which are measures of the leaf (needle) and stem surfaces of the canopy.

The model also accounts for canopy interception of snow and rain, for temperature and unfrozen water content of the snowpack, and for snow evaporation or condensation, but all these have relatively minor importance.

Data

The Hubbard Brook Experimental Forest is located in the southwestern corner of the White Mountains of New Hampshire. Hubbard Brook is world-renowned for research on cycling of water, energy, and nutrients in forest ecosystems. Federer *et al.* (1990) have summarized the long-term weather and stream flow data set for Hubbard Brook. Data used in Federer *et al.* (1990) were obtained by scientists of the Hubbard Brook Ecosystem Study. The Hubbard Brook Experimental Forest is operated and maintained by the Northeastern Research Station, USDA Forest Service, Newtown Square, Pennsylvania.

For this study BROOK90 was used to simulate snowpack for Station 2, a south-facing slope at about 560 m (1840 ft) elevation in the middle of Hubbard Brook Watershed 1, and for Station 14, a north-facing slope at about 730 m (2400 ft) elevation in the middle of Watershed 7 (Figure 6.4). Long-term snowpack data have not been collected at the same locations as long-term temperature data, causing a minor complication for this study. For the south slope, daily minimum and maximum temperatures from Station 1 were decreased by 0.6°C/1.0ºF to account for its elevation below Station 2. For the north slope Station 14 temperatures were used directly. Daily precipitation from Watershed 1 was used for the south slope and from Watershed 7 for the north slope. Daily solar radiation data from the

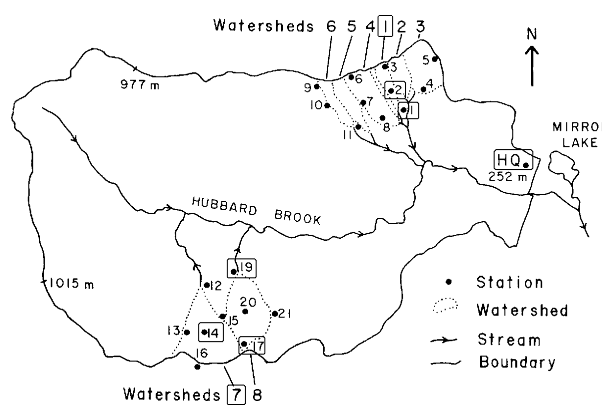

Figure 6.4. Map of the Hubbard Brook Experimental Forest, with locations used in this study indicated by rectangles.

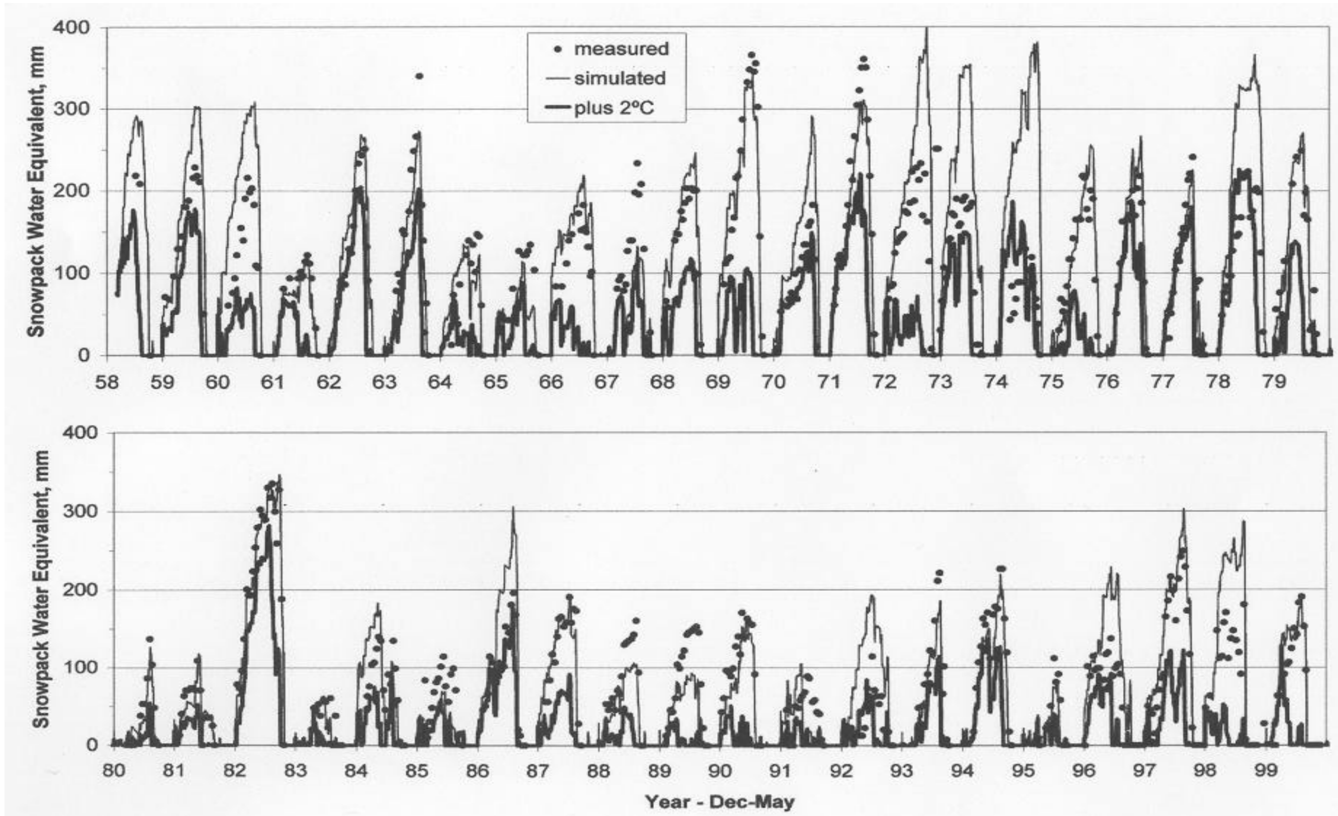

Figure 6.5. Simulated (thin line) and measured (points) snow water equivalent for a south-facing slope at 560 m elevation on the Hubbard Brook Experimental Forest, New Hampshire, and simulated water equivalent with a 2°C/ 3.6ºF warmer climate (thick line). Year is indicated at the beginning of the winter.

Headquarters station were used for both locations. Simulated results for the south slope were compared with snowpack data from Station 2. For the north slope simulated snowpack was compared with the average snowpack from Station 17 at 893 m and Station 19 at 610 m. For the south slope data were available from 1958 through 1999, and for the north slope from 1965 through 1999.

The BROOK90 model also can use daily vapor pressure and wind data but these were not available. The model assumed that the daily dewpoint is equal to the daily minimum temperature and that daily mean wind speed at 4 m height at an open weather station is a constant 3 m/s.

Forest cover on the south-facing slope is 100% northern hardwood forest last cut before 1920. BROOK90 forest and soil parameters normally used for south-facing slopes at Hubbard Brook were used here. Forest cover on the north-facing slope includes some spruce-fir forest, particularly at higher elevations. The north-facing simulation assumed a 25% evergreen cover. To slightly improve fit to measured snowpack on the north slope the melt factor was increased to 6.0 mm d-1 °K-1 and snowpack temperature and unfrozen water content were ignored.

Snowpack at Stations 2, 17, and 19 has been measured weekly in a small "snow course" area of typical forest. Water equivalent of the snowpack is measured at 10 points 2 m apart along a line by weighing a snow core removed by a snow tube, which has a serrated cutting edge. The 10 values are averaged.

To simulate climate warming the model was rerun with all daily maximum and minimum temperatures increased by 2°C/3.6ºF.

Results

Simulated snowpack agreed reasonably well with measured snowpack in most years for both north- and south-facing slopes at Hubbard Brook (Figures 6.5 and 6.6). However, in some years disagreement is large and persists through the season. Some of these discrepancies can be attributed to the rain-snow separation problem mentioned above. For instance, a rapid decrease in temperature late in the day after a storm preceding a cold front will cause an overestimate of the snow component of the storm. Such errors in determining the form of a large storm will persist through the season as either an underestimate or overestimate of snowpack.

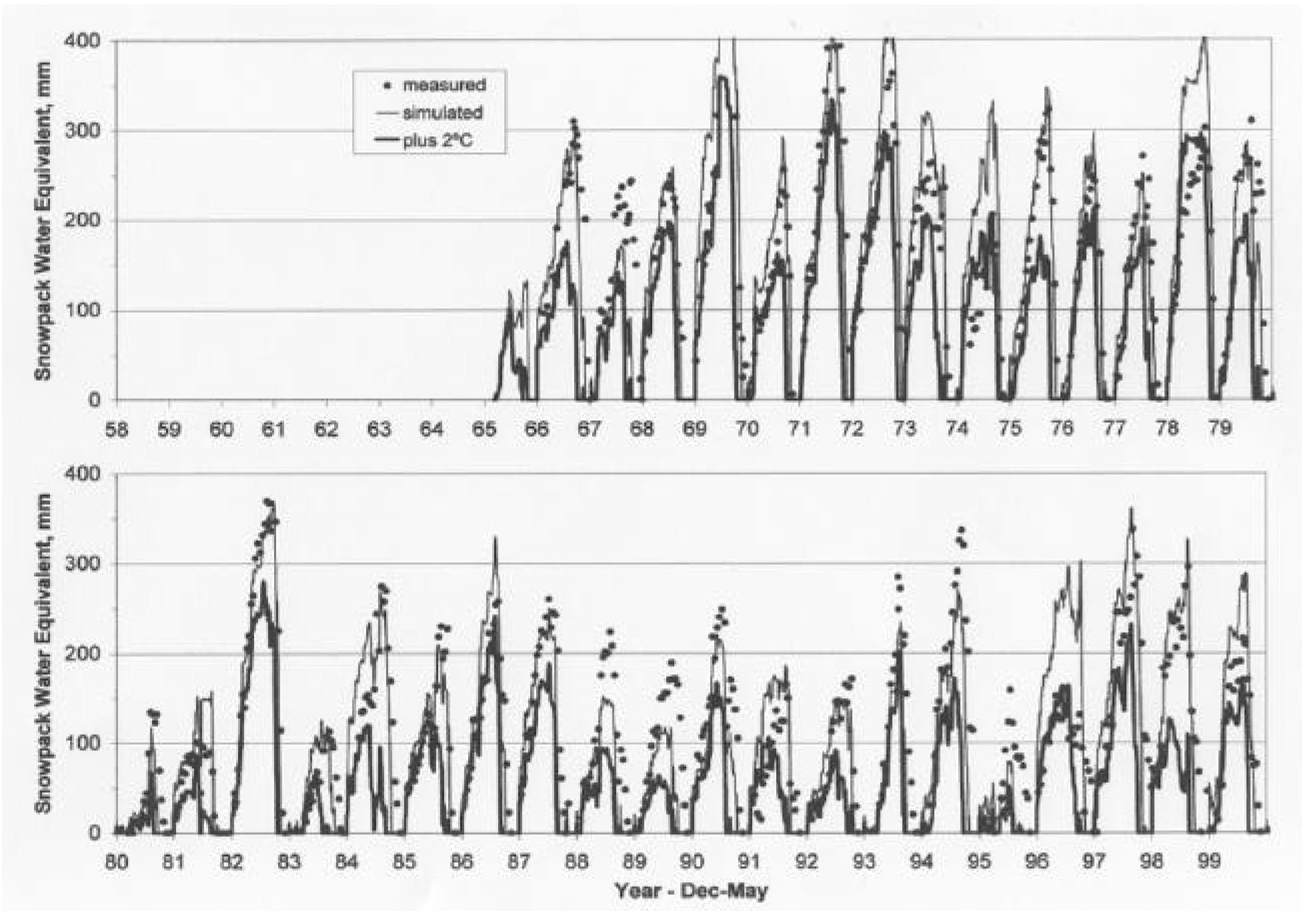

Figure 6.6. Simulated (thin line) and measured (points) snow water equivalent for a north-facing slope at 730 m elevation on the Hubbard Brook Experimental Forest, New Hampshire, and simulated water equivalent with a 2°C/3.6ºF warmer climate (thick line). Year is indicated at the beginning of the winter.

Results clearly reflect the high frequency of low snow years in the 1980's. Recovery in the 1990's has still not reached the average snowpacks of the 1960's and 1970's.

Simulated increase in minimum and maximum daily temperatures of 2°C/3.6ºF produces a major reduction in snowpack in all years (Figures 6.5 and 6.6). Differences between the two locations are relatively minor. Average February snowpack water equivalent was reduced from 161 to 76 mm for the south-facing slope and from 194 to 133 mm on the north-facing slope. February was chosen to best represent mid-winter snowpack.

Discussion

An increase of all winter temperatures by 2°C/3.6ºF in the White Mountains of New Hampshire clearly will cause large reductions in snowpack. For a southfacing deciduous forest at 1840 ft elevation the simulated reduction in February snowpack is 85 mm or 53%; for a north-facing slope at 2400 feet the reduction is 61 mm or 32%. Duration and depth throughout the season are correspondingly reduced.

The largest changes will occur for times and places where temperatures are currently just below freezing. Two degree increases in these conditions change snow to rain and change from freezing to melting. Thus deep snowpacks produced under cold conditions are not as seriously affected as shallow snowpacks produced in warmer conditions. This is demonstrated by the difference between the two simulated locations.

Simulation of climate change effects on snowpack in the Swiss Alps has shown similar results to those found here (Gellens et al., 2000). Output scenarios from global climate models (GCM's) were used in a water budget/snow model generally similar to BROOK90. The Hadley Center Model for 2050 indicated a 2-3°C/3.6-5.4ºF temperature increase and a 10% precipitation increase for eastern Switzerland. Simulation for the Landquart Basin showed a consequent 93 mm decrease in average March snowpack from 454 mm to 361 mm. This is comparable to the average reduction in February snowpack of 73 mm for a 2°C/3.6ºF warming in this study.

If climate change in New England includes increased precipitation as well as increased temperature, then the amount of snowpack reduction will be decreased somewhat. The change will depend on details in the relative changes of maximum and minimum temperatures and precipitation during snow season, particularly in the warmer months of December and March, and on the specifics of the interaction of precipitation changes with temperature changes. It is extremely unlikely, however, that snow precipitation would increase sufficiently to overcome the effects of warmer temperature in causing severe reduction of snowpack.

Year-to-year variation in snowpack is larger than the reduction by 2°C/3.6ºF warming. Therefore gradual reductions in mean snowpack content over time will not be as noticeable as periodic snow droughts like the 1980's in New England. Gellens et al. (2000) also conclude this for Switzerland.

While snowmaking at ski areas may be able to maintain mid-winter snow cover well into the future, warming temperatures will reduce opportunities for early and late season snowmaking and will increase the intensity of mid-winter melts. Gellens et al. (2000) found that a 2°C/3.6ºF warming will raise the minimum elevation of ski area profitability by 500 m in Switzerland. In New Hampshire the cross-country skiing and snowmobile industries will be even more severely impacted than the downhill ski industry and may become non-existent by 2100.

CASE STUDY #3 – The Relationship Between the Winter North Atlantic Oscillation (NAO) Index and Stream flow in New England

By: James A. Bradbury, Earth Sciences Department,
University of New Hampshire

Abstract

Winter stream flow variability at many inland sites in New Hampshire, Vermont, western Massachusetts and Connecticut show statistically significant correlations with the North Atlantic Oscillation (NAO) on annual and decadal time scales. A statistical analysis comparing stream flow at 40 sites in the New England region with the NAO index helps to improve our understanding of the relationship between them. Consistent correlations between regional temperature or precipitation are not seen with the NAO, but snowfall seems to be the most likely climate variable controlling the NAO/ New England (NE) stream flow relationship. These findings place our region in the context of the global climate system and may prove useful for long-range forecasting of annual or decadal-scale changes in the regional hydrologic cycle.

Drought in New England (NE)

Sustained precipitation deficiencies (meteorologic drought) can be devastating to forest ecology and agriculture, even in the New England region where water is normally thought to be in ample supply. In the 1960's the most severe drought on record was caused by persistent spring and summertime precipitation shortfalls (meteorologic drought) across the region (Namias, 1966). Naturally, the low precipitation levels were accompanied by low levels of stream flow (hydrologic drought) in rivers all over the seven states. The occurrence of hydrologic drought creates public water supply shortages, reduced water quality and a decrease of in-stream water uses such as hydroelectric power generation. Hydrologic drought causes harmful water quality issues such as higher concentrations of pollutants, increased water temperature and low levels of dissolved oxygen. Furthermore, the impacts of hydrologic drought typically continue beyond the end of meteorologic drought episodes because it can take months for water stored in surface and ground water reservoirs to recover from significant deficiencies. The recharge of subsurface reservoirs and aquifers can take even longer. There is a new urgency to understand what causes drought because as world population increases, the impacts of drought promise to be more severe, even with no increase in the frequency or duration of events [American Meteorological Society (AMS), 1997].

A Way to Predict Drought?

Identifying the relationships connecting local conditions and remote climate variables such as the NAO may be an important step toward predicting extreme climate events, such as regional drought. This can be done using statistical tools to compare regional climate variables (temperature, precipitation, stream flow… etc.) with indices for large-scale atmospheric circulation patterns, such as the NAO index (Figure 6.7). Once such patterns are established, the long-range predictability of regional climate may come to depend more on the predictability of the large-scale climate indices themselves. Modelers have had success at long-range forecasting with the El Niño/Southern Oscillation (ENSO), where the intricate coupling of the Pacific ocean temperatures and associated atmospheric variables has allowed for its predictability, with moderate success on seasonal and annual time scales (Barnston, 1995). Similar models applied to the North Atlantic Region offer hope that predicting significant multi-annual changes and trends in the NAO system may be possible (Sutton and Allen, 1997; Griffies and Bryan, 1997; Rodwell et al., 1999). Recent studies have found that the NAO may respond with a time delay to changes in stratospheric circulation and Atlantic

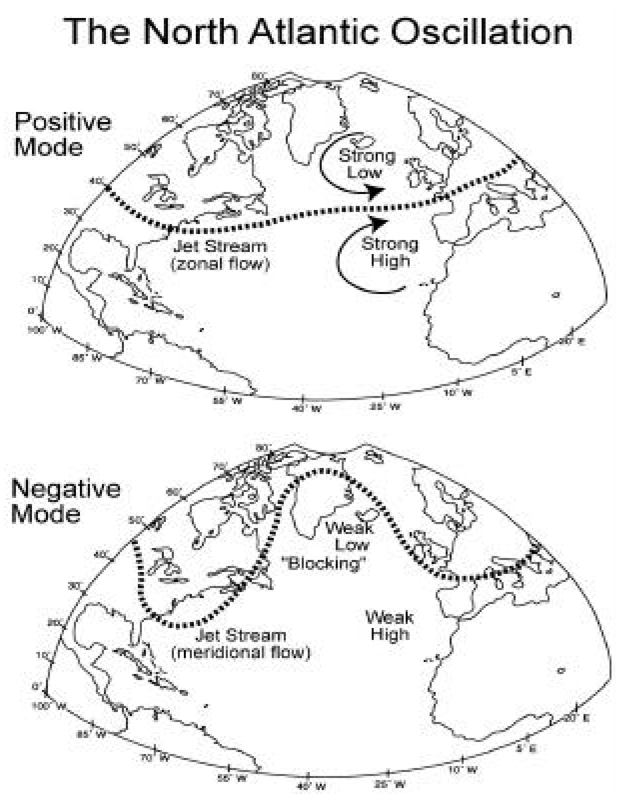

Figure 6.7. The positive (top) and negative (bottom) phases of the North Atlantic Oscillation (NAO). During positive NAO winters the atmospheric pressure gradient between Iceland and the Azores is at a maximum and the mid-latitude westerlies dominate air circulation in the N. Atlantic region. During negative NAO winters the Icelandic low is weak and acts as a blocking mechanism, causing the Jet Stream to buckle, resulting in a wide range of changes in Northern Hemisphere climate conditions (see text and table 1 for details).

sea surface temperature (SST), suggesting that seasonal and inter-annual prediction of the NAO index is closer to becoming a reality (Hurrell et al., 2001).

The North Atlantic Oscillation (NAO) Index

Winter weather patterns throughout the North Atlantic region have historically been greatly affected by changes in the NAO (Rogers and Van Loon, 1979; Hurrell and Van Loon, 1997). When the NAO changes between its two modes of variability, the North Atlantic Ocean region experiences changes in wind speed and direction, which affect heat and moisture transport to the surrounding continents and seas.

The NAO index, defined as the atmospheric sea-level pressure (SLP) difference between the Azores high and the Icelandic low (Rogers, 1984), simply describes the steepness of a north-south atmospheric pressure gradient between a low pressure system off the coast of Iceland and a high pressure system over the Azores (Figure 6.7). This index can be computed at any time of the year, but the significance of the NAO as a control on Northern Hemisphere climate variability appears to be most important during winter months (Hurrell and Van Loon, 1997), and most research related to the NAO involves winter climate data analysis.

The NAO and North Atlantic Region Relationships

Many climate researchers consider ocean and atmospheric variability in the North Atlantic region to be an important index for global climate change (Hurrell et al., 2001) and the NAO has been the most widely studied atmospheric pressure index in this region. When the NAO is in its positive index mode the Icelandic low tends to be at its furthest point north (Serreze et al., 1997), and mid-latitude westerlies onto Northern Europe increase (Hurrell, 1995) driving warm, moist air as far east as Siberia (Figure 6.7, top) (Kushnir, 1999; Rogers, 1997). During the negative index mode the Icelandic low is much weaker and sits farther southwest, centered between the southern tip of Greenland and Newfoundland (Serreze et al., 1997), causing a "blocking" of the Jet Stream resulting in greater meridional (North-South) air flow across the N. Atlantic region (Figure 6.7, bottom) (Greatbatch, 2000). In the negative NAO mode, southern Europe is known to experience more frequent cyclonic activity (Rogers, 1997), leaving northern Europe relatively cold and dry (Kushnir, 1999).

NAO and New England Winter Climate

Our understanding of how the NAO affects winter climate in the New England region is becoming increasingly clear. Table 6.1 highlights several NAO/New England region climatic teleconnection patterns. There is little evidence to support a teleconnection between regional precipitation or temperature and the NAO, however, regional storm track variability, first identified by Rogers (1990), and jet stream patterns along the eastern seaboard (Greatbatch, 2000) show important links to the NAO system. Also, Rogers and Van Loon (1979) found significant changes in sea surface temperatures (SST) off the New England coast, when they compared average conditions during extreme NAO events, and Hartley and Keebles (1998) found statistical evidence for an inverse relationship between regional snowfall and the NAO index. This means that New England winters char-

Table 6.1. New England regional relationships to the NAO.

Study Region	Data/Climatic Variables	Nature of Correlation	Response Season	Reference
East Coast	Temperature	+	winter	Rogers, 1984
New England Region	Temperature	none	winter	Hartley and Keebles, 1998; Hurrell, 1995
New England Region	Precipitation	none	winter	Hartley and Keebles, 1998; Hurrell, 1995
East coast (Nor'easters)	Cyclone frequency	-	winter	Hartley and Keebles, 1998
St. Lawrence River	Cyclone frequency	+	winter	Hartley and Keebles, 1998
New England Region	Snowfall	-	winter	Hartley and Keebles, 1998
New England Coast	SST*	+	Dec-Aug	Rogers and Van Loon, 1979
New England (inland)	Streamflow	+	winter	Bradbury, 2001 (this study)
Massachusetts	Tree ring widths	+	annual (?)	Cook et al., 1998
Connecticut	Tree ring widths	+	annual (?)	Cook et al., 1998

acterized by a positive NAO index have less snowfall than winters characterized by a negative NAO index. Stream flow amounts however are above average when the winter NAO index is positive.

Hartley and Keebles' (1998) study included an in-depth look at regional winter temperature, precipitation, snowfall, pressure patterns, and cyclonic activity. Their results, which concur with the results of previous studies, added some interesting details. They found that winters with below average snowfall typically occur during winters when pressure patterns resemble the positive phase of the NAO. The regional climate conditions during low snow winters are associated with more zonal (westerly) airflow (Figure 6.7) such that most of the (US coastal) Atlantic storm activity is displaced to the east (off the coast) and the St. Lawrence storm track becomes the dominant precipitation mechanism. High snow winters typically show the opposite conditions and more closely resemble the negative phase of the NAO. Heavy snow is accompanied by more frequent N. Atlantic "blocking" episodes, and more meridional airflow (Figure 6.7). These conditions produce more frequent advection of low-level cold Canadian air into the NE region, a greater number of "Nor'easters" along the Atlantic coast (McCartney, 1996), and (as a result) greater regional snowfall (Hartley and Keebles, 1998).

NAO and NE Winter Stream Flow

Current research comparing stream flow rates in the New England region with the North Atlantic Oscillation (NAO) index has revealed positive statistical correlations. Many continuous (monthly resolution) time series of stream flow from the U.S. Geological Survey Hydro-Climatic Data Network (Slack and Landwehr, 1992) are significantly correlated with the NAO index (see UCAR web site under references), and the strongest NAO/stream flow correlations appear during the winter (Dec. – March), at streams away from the coast, in New Hampshire, Vermont, Massachusetts, and Connecticut. Figure 6.8 illustrates the strength of the linear correlation between standardized winter average stream flow in the White River, VT and the winter NAO index. Thus, winters characterized by below average snowfall and thus higher temperatures are characterized by above average stream flow.

Multiple linear regression analysis of selected inland sites show that the NAO index explains a significant amount of the winter streamflow variability that is independent of that explained by precipitation and temperature. This means that a physical mechanism other than precipitation, or temperature driven snowmelt, must be found to explain the NAO/stream flow correlation. Interestingly, stream flow

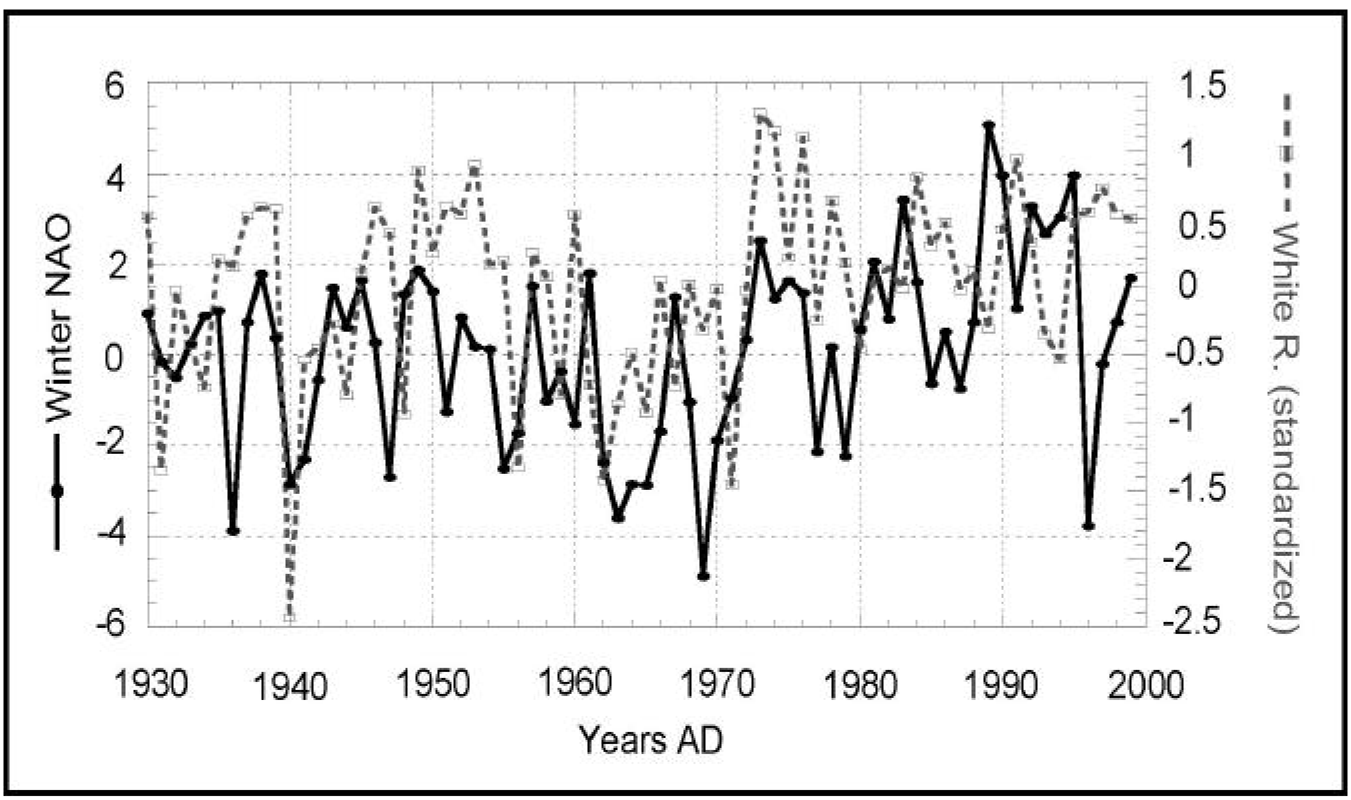

Figure 6.8. Time series plots of the winter NAO and standardized winter average streamflows from the White River in Eastern Vermont (R^2 = 0.092; alpha level = 0.10).

records from sites in Maine and Rhode Island show little to no sign of correlation with the NAO.

One possible physical explanation for the NAO/ stream flow teleconnection could be the winter snowfall variability that Hartley and Keebles (1998) attributed to the NAO. Since the temporal distribution of winter stream flow in the region is significantly affected by the proportion of precipitation that falls in the form of snow, rather than rain (Hartley and Dingman, 1993), a winter with greater snowfall would be expected to have lower average stream flows and vice versa. This is because the introduction of precipitation into the hydrologic cycle in the form of snow, rather than rain, effectively puts that water in temporary storage, rather than making it immediately available for runoff. Most of this snow is available months later for runoff, and soil moisture, once melting begins.

When the snowfall data are detrended, by polynomial regression, to remove decadal fluctuations the significance of the correlation between snowfall and the NAO index disappears, indicating that the NAO may be most closely associated with longer-term trends in regional climate, rather than just annual variability (Hartley and Keebles, 1998). Figure 6.9 tells a similar story.

Here the winter NAO exhibits a strong correlation with winter average stream flow, when both records are smoothed using a robust spline. In concurrence with Hartley and Keebles (1998) these results suggest that the strongest climatological association between the NAO and regional climate are on a multi-annual or decadal time scale. Of utmost interest is how well these records (Figure 6.9) track one another through the 1960's drought, suggesting that if prediction models for the NAO prove to be accurate, then the knowledge of this teleconnection may be particularly useful for future drought forecasting in the region. Piechota and Dracup (1999) proposed a similar method for long-range stream flow forecasting of spring-summer runoff in the Columbia River basin where time lag relationships with the ENSO have improved stream flow predictions at some stations from a 3 to 7 month lead.

Conclusions

Winter climate in the New England region shows subtle yet important patterns with the NAO. Regional precipitation and temperature variability appear uninfluenced by the NAO yet storm-tracking patterns caused by the NAO system have a significant impact on snowfall variability (Hartley and Keebles, 1998), possibly resulting in the NAO regional stream flow association identified here. The results of this study also reveal a significant long-term effect of the NAO on New England regional stream flow (Figure 6.9), suggesting that climate conditions associated with the negative phase of the NAO could be responsible for annual persistence of severe drought conditions. Without any direct evidence for a cause, Figure 6.9 clearly shows that the negative NAO trend during the 1960's accompanied well below average winter streamflows during this time period. Further evidence supporting a relationship between a negative NAO and early 1960's drought comes from Namias (1966) who partially attributed the persistence of this drought to the below average air temperatures, as well as below average SSTs (Sea Surface Temperatures), throughout the east coast region (both of these conditions are associated with a negative NAO, see Table 1).

New evidence of NAO/ snowfall teleconnections (Hartley and Keebles, 1998) and the NAO stream flow relationships (presented here) suggest that the NAO may be most closely associated with longer-term (decadal) trends in regional climate, and less so with annual variability. Hence, to the extent that the NAO proves to be a predictable climate index it may also become an important predictor of annual or multi-annual climate change in the region.

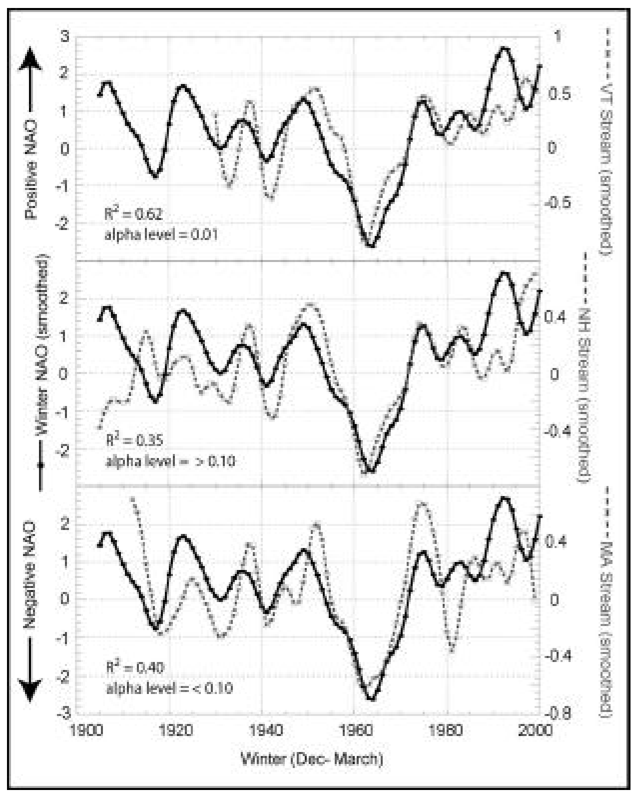

Figure 6.9. Standardized winter streamflow at the White River, VT (top), the Pemigewasset River, NH (middle), and a combination of the North and Westfield Rivers, MA (bottom), were smoothed and compared with a smoothed NAO index, revealing common trends in their long-term variability. A robust spline was used on each climate record (lambda = 0.07) to minimize periods of variability that were shorter than decadal-in-scale (smoothing weights for each record were determined objectively using spectral analysis).

CASE STUDY #4 – Climate Variability and Winter Flounder Abundance in Southern New England

By: Henry Walker, Atlantic Ecology Division, National Health and Environmental Effects Laboratory, Office of Research and Development, US Environmental Protection Agency

Between 1960 and 1990, the winter sea water temperature in Narragansett Bay warmed by almost 3.0°C/5.4°F, providing an opportunity to document marine ecosystem changes related to this magnitude of a temperature shift in Southern New England. In Narragansett Bay, warmer winters are correlated with smaller winter-spring phytoplankton blooms, an observation that has been experimentally reproduced by conducting a cooling experiment in marine mesocosms during a warm winter (Keller et al., 1999). During the past 25 years winter flounder abundances in southern New England have been in decline. One hypothesis is that warmer sea water temperatures could result in more of the winter marine phytoplankton bloom being consumed in the water column by pelagic food chains, with reduction in the amount of fixed carbon available to benthic (bottom dwelling) food chain members such as flounder (Oviatt, personal communication). Herring stocks (a pelagic food chain member), which feed in the water column have been on the increase. Another hypothesis would be that temperature increases could also affect predation and survival of winter flounder during critical early life stages (Keller and Klein-MacPhee, 2000). Are the seawater temperature increases, with the resulting reductions in the magnitude of the winter-spring phytoplankton bloom, and declines in flounder abundance due to climate change? Because we live in a highly variable climate in New England, and lack a mechanistic understanding of many details concerning effects of climate variation on marine food chains, we need to consider this situation more closely.

The abundance of winter flounder has been independently monitored and documented by Rhode Island Fish and Wildlife (RIFW) service, the University of Rhode Island (URI), and in the vicinity of Niantic River, Waterford Connecticut (Northeast Utilities Service Company, 2000), Figure 6.10. There is some debate about how much of the observed decline is due to heavy fishing pressure, and how much may be attributed to warmer winters in southern New England. The physiology and ecology of winter flounder provides some interesting clues.

The winter flounder (*Pseudopleuronectes americanus*, Cooper and Chapleau, 1998; Figure 6.11) is a former dominant member of the bottom dwelling fish community in southern New England. Most adult fish migrate into inshore waters in the late fall and early winter, and spawn in late winter and early spring when seawater temperatures are quite cold (Klein-MacPhee, 1978). To help accomplish this feat, winter flounder make use of unique antifreeze proteins found in a number of polar fish which allow them to survive in temperatures as low as -1.9°C/3.4°F (Halama, 2001; Wen and Laursen, 1992). In comparison, most fish

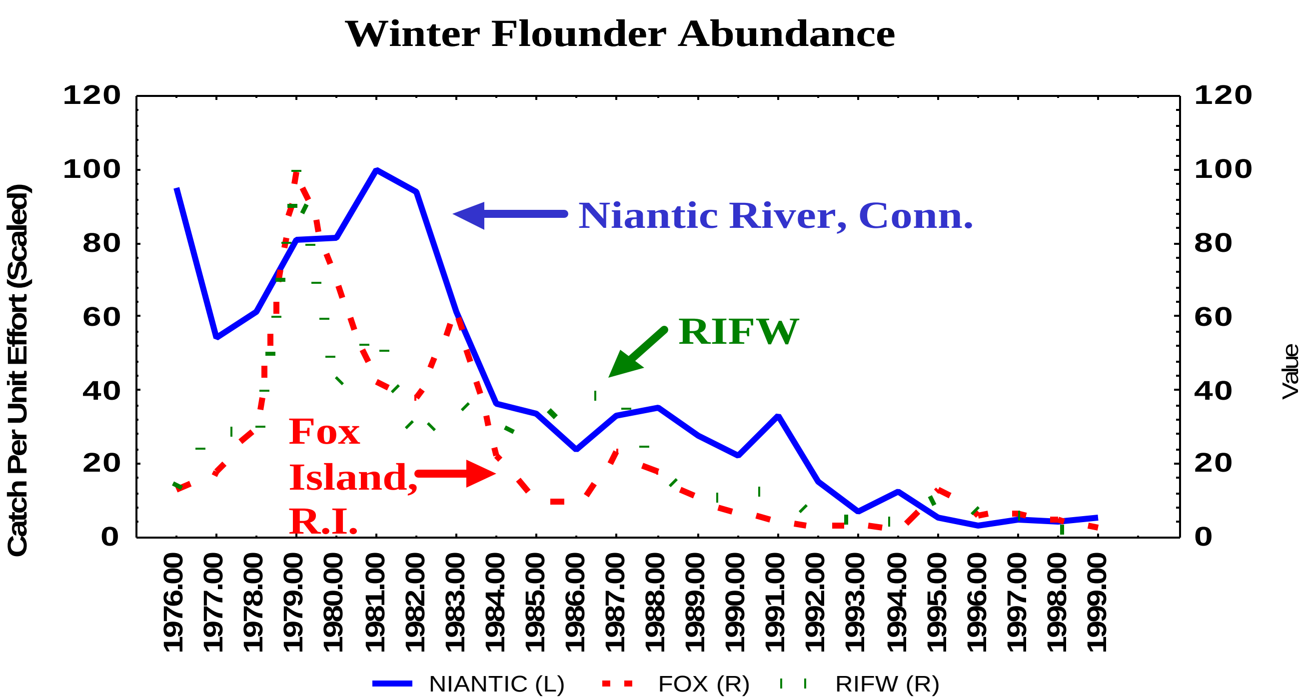

Figure 6.10. Winter Flounder Abundance in the vacinity of the Niantic River, Waterford Connecticut and Fox Island, Rhode Island from 1976 to 1999. RIFW refers to monitoring conducted by the Rhode Island Fish and Wildlife Service. Northeaste Utilities Service Company, 1999.

Figure 6.11. The winter flounder (*Pseudopleuronectes americanus*).

typically freeze at a temperature of -0.7ºC/1.3ºF(Halama, 2001; Hew and Yang, 1992). Winter flounder spawning occurs at night in the upper portions of estuaries. Eggs are attached to the bottom. Hatching rate, larval development rate, and mortality rates due to predation are temperature dependent. Variations in egg and larval survival during the first year determines the “Age-1 year class strength”. This type of early life history data is systematically collected and reported in the vicinity of the Millstone Nuclear Power Station in Waterford Connecticut (Northeast Utilities Service Company, 2000). Using these and other data, it appears that a significant component of the decline in winter flounder abundance in southern New England is associated with a shift from a period with cold winters and seawater temperatures in southern New England during the 1960s, into a period of relatively warmer winters during the following three decades. We have found that the February seawater temperature from the three years prior to recruitment of age 1 winter flounder is associated with about 70% of the interannual variation in the abundance (year class strength) of Age-1 winter flounder in Niantic Bay. A series of warm winters such as we have recently experienced in southern New England is clearly unfavorable for winter flounder.

According to the recent Intergovernmental Panel of Climate Change (IPCC, 2001), in the Northern Hemisphere the 1900s has been the warmest century in the last 1000 years, and the 1990s have been the warmest decade in the past century. For the New England region, the warmest decade (based on recorded temperatures – see Chapter 2) was the 1950s. Warming has been greatest over Northern Hemisphere continents during the winter, and the same is true for the New England region. While the New England Region has warmed by an annual average of 0.4ºC/0.7ºF over the past century (since 1895), due to its coastal location, Rhode Island’s annual temperature has warmed by 1.3ºC/2.3ºF over the same period of time. Warming during the winter months (December, January, February) in Rhode Island has increased a full 1.6ºC/3.0ºF since 1895.

With continuing increases in greenhouse gas concentrations in the atmosphere, we expect general global and regional, as well as seasonal (winter) warming trends to continue. If this warming trend continues toward milder southern New England winters in the next few decades, even with reductions in fishing effort winter flounder stocks could be slow to recover. To answer the question raised above (“Are seawater temperature increases, reductions in the winter-spring phytoplankton bloom, and declines in flounder abundance due to climate change?”), the answer at this point is “perhaps.”

References:

American Meteorological Society, Policy Statement. 1997. "Meteorological Drought", Bulletin of the American Meteorological Society, vol. 78, 5, pp. 847-849.

Barksdale, H.C., D. O'Bryan, and W.J. Schneider. 1966. Effect of drought on water resources of the Northeast. U.S. Geological Survey *Hydrologic Atlas* HA-243.

Barnston, A.G. 1995. "Our Improving capability in ENSO Forecasting", Weather, vol. 50, no. 12, pp. 419-430.

Cook, E.R., D'Arrigo, R.D., and Briffa, K.R. 1998. "A reconstruction of the North Atlantic Oscillation using Tree-ring Chronologies from North America and Europe", The Holocene, vol. 8, no.1, pp. 9-17

Cooper, J.A., and F. Chapleau. 1998. Monophyly and intrarelationships of the family Pleuronectidae (Pleuronectiformes), with a revised classification. Fish. Bull., U.S. 96:686-726.

Dracup, J.A. and E. Kahya. 1994. The relationships between U.S. stream flow and La Nina events. *Water Resources Research* 30(7):2133-2141.

Federer, C.A. and D. Lash. 1978. BROOK: A hydrologic simulation model for eastern forests. University of New Hampshire Water Resources Research Center Research Report 19. 84 p.

Federer, C.A., L.D. Flynn, C.W. Martin, J.W. Hornbeck, and R.S. Pierce. 1990. Thirty years of hydrometeorologic data at the Hubbard Brook Experimental Forest, New Hampshire. USDA Forest Service General Technical Report NE-141, 44 p.

Gellens, D., K. Barbieux, B. Schädler, E. Roulin, H. Aschwanden, and F. Gellens-Muelenberghs. 2000. Snow cover modelling as a tool for climate change assessment in a Swiss alpine catchment. Nordic Hydrology 31:73-88.

Greatbatch, R.J. 2000. "The North Atlantic Oscillation", Stochastic Environmental Research and Risk Assessment", vol. 14, pp. 213-242.

Griffies, S.M. and K. Bryan. 1997. "Predictability of North Atlantic Multidecadal Climate Variability", Science, vol. 275, pp. 181-184.

Halama, C. 2001. Structure and function of Type 1 anti-freeze protein from winter flounder. www.chem.uwec.edu/Chem406/Webpages/Carol/CAROL.HTM

Hartley, S. and S.L. Dingman. 1993. "Effects of Climatic Variability on Winter Spring Runoff in New England River Basins", Physical Geography, vol. 14, no. 4, pp. 379-393.

Hartley, S. and M.J. Keebles. 1998. "Synoptic Associations of winter Climate and Snowfall Variability in New England", International Journal of Climatology, vol. 18, pp. 281-298.

Hew, C.L. and D.S.C. Yang. 1992. Eur. J. Biochem. 203, 33-42.

Hurrell, J.W. 1995. "Decadal Trends in the North Atlantic Oscillation Regional Temperatures and Precipitation", Science, vol. 269, pp. 676-679.

Hurrell, J.W. and H. Van Loon. 1997. "Decadal Variations in Climate Associated with North Atlantic Oscillation", Climate Change, vol. 36, pp. 301-326.

Hurrell, J.W., Kushnir, Y., and Visbeck, M. 2001. "Perspectives: Climate. The North Atlantic Oscillation", Science, vol. 291, pp. 603-604.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis. Work Group, Contributions to the IPCC Third Assessment Report. http://www.picc.ch/.

Jeffries, H.P. 1994. The impacts of warming climate on fish populations. Maritimes. Spring: 12-15. Graduate School of Oceanography, University of Rhode Island, Narragansett, R.I.

Jeffries, H.P. and M. Terceiro. 1985. Cycle of changing abundances in the fishes of the Narragansett Bay area. Marine Ecology Progress Series. 25:239-244.

Jeffries, H.P. and W.C. Johnson. 1974. Seasonal distributionsof bottom fishes in the Narragansett Bay area: Seven-year variations in the abundance of winter flounder (*Pseudopleuronectes americanus*). Journal Fisheries Research Board of Canada. 31(6):1057-1066.

Keller, A.A., and G. Klein-MacPhee. 2000. Impact of elevated temperatureon the growth, survival, and trophic dynamics of winter flounder larvae: a mesocosm study. Can. J. Fish. Aquat. Sci. 57:2382-2392.

Keller, A.A., C.A. Oviatt, H.A. Walker, and J.D. Hawk. 1999. Predicted impacts of elevated temperature on the magnitude of the winter-spring phytoplankton bloom in tempearte coastal waters: a mesocosm study. Limnol. Oceanogr. 44: 344-356.

Klein-MacPhee, G. 1978. Synopsis of biological data for the winter flounder, *Pseudopleuronectes americanus* (Walbaum). NOAA Tech. Rep. NMFS Circ. 414. 43 pp

Kushnir, Y. 1999. “Europe’s Winter Prospects”, Nature, vol. 398, pp. 289-291.

McCartney, M. 1996. “North Atlantic Oscillation”, Oceanus, vol. 39, no. 2, pp. 13.

Namias, J. 1966. “Nature and Possible causes of the Northeastern United States Drought during 1962-1965”, Monthly Weather Review, vol. 94, no. 9, pp. 543-557.

New England Regional Climate Change Impacts (NECCI) Workshop – Summary Report. 1997. Workshop held at Durham, NH, September 3-5, 1997, the University of New Hampshire, Durham, NH, 149pp.

National Research Council. 1998. Review of Northeast Fishery Stock Assessments. Committee to Review Northeast Fishery Stock Assessment, Ocean Studies Board, Commission on Geosciences, Environment, and Resources. http://www.nap.edu/html/fisher/.

Northeast Utilities Service Company. 1999. Winter Flounder Studies. Annual Report: Millstone Power Station.

Northeast Utilities Service Company. 2000. Annual Report 1999: Monitoring the Marine Environment of Long Island Sound at Millstone Nuclear Power Station; Waterford, Connecticut.

Piechota, T.C. and J.A. Dracup. 1996. Drought and regional hydrologic variation in the United States: Association with the El Nino-Southern Oscillation. *Water Resources Research* 32(5):1359-1373.

Piechota, T.C. and J.A. Dracup. 1999. “Long-Range Streamflow Forecasting Using El Nino-Southern Oscillation Indicators”, Journal of Hydrologic Engineering, vol. 4, no. 2, pp. 144-151.

Rodwell, M.J., Rowell, D.P., and Folland, C.K. 1999. “Ocean Forcing of the Wintertime North Atlantic Oscillation and The European Climate”, Nature, vol. 398, pp. 320-323.

Rogers, J.C. 1997. “North Atlantic Storm Track Variability and It’s Association to the North Atlantic Oscillation and Climate Variability of Northern Europe”, Journal of Climate, vol. 10, pp. 1635-1647.

Rogers, J.C. 1984. “The Association Between the North Atlantic Oscillation and The Southern Oscillation in the Northern Hemisphere”, Monthly Weather Review, vol. 112, pp. 1999-2015.

Rogers, J.C. and Van Loon, H. 1979. “The See-Saw in Winter Temperatures Between Greenland and Northern Europe. Part 2: Some Oceanic and Atmospheric Effects in Middle and High Latitudes”, Monthly Weather Review, vol. 107, pp. 509-519.

Rogers, J.C. 1990. “Patterns of Low-Frequency Monthly Sea Level Pressure Variability (1899-1986) and Associated Wave Cyclone Frequencies”, Journal Of Climate, vol. 3, pp. 1364-1379.

Russell, C.S., D.G. Arey, and R.W. Kates. 1970. *Drought and Water Supply*. Johns Hopkins Press.

Serreze, M.C., Carse, F., Barry, R.G, and Rogers, J.C. 1997. “Icelandic Low Cyclone Activity: Climatological Features, Linkages with the NAO, and Relationships with Recent Changes in the Northern Hemisphere Circulation”, Journal of Climate, vol. 10, pp. 453-464.

Slack, J.R. and J.M. Landwehr. 1992. “Hydro-climatic Data network: A U.S. Geological Survey (USGS) Stream flow data set for the United States for the study of climate variations, 1874-1988.” U.S. Geological Survey Open File Report No. 92-129, USGS, Reston, VA.

Smith, R.A., G.E. Schwarz, and R.B. Alexander. 1997. Regional interpretation of water-quality monitoring data, Water Resources Research, v. 33, no. 12, pp. 2781-2798.

Sutton, R.T. and M.R. Allen, M.R. 1997. “Decadal Predictability of North Atlantic Sea Surface Temperature and Climate”, Nature, vol. 388, pp. 563-567.

U.S. Water Resources Council. 1965. Drought in the Northeastern United States. Report to the President.

U.S. Water Resources Council. 1966. Drought in the Northeastern United States - A Third Appraisal. Report to the President.

Wen, D. and R.A. Laursen. 1992, J. Biol. Chem. 26, 14102-14108.

Wainright, S.C. M.J. Fogarty, R.C. Greenfield, and B. Fry. 1993. Long-term changes in the Geroges Bank food web: trends in stable isotopic compositions of fish scales. Marine Biology, 115:481-493.

Chapter 7

Human Health

By: Barrett Rock, Lynne Carter, Ben Sherman, Stephen Hale, and Paul Epstein

7.1. Introduction

Climate change would impact human health in several ways. The effect could be direct, such as heat stroke, or by impacting the geographic range of diseases and vectors (carriers, such as ticks, that transmit disease from one host to another). Climate change could also produce indirect impacts on human health, through increased air pollution and decreased water quality.

In the New England region, climate impacts (both present and future) to human health fall into three major categories: 1) vector-borne diseases, 2) water/marine-related diseases, and 3) air pollution-related diseases. Other health-related issues include heat waves and the indirect affects from "surprise" events such as fires, flashfloods, and ice storms.

Health risks associated with climate change are difficult to assess with certainty. Present and potential health risks are complicated by such factors as poverty, quality and availability of healthcare, food quality and abundance, sanitation, water quality and quantity, public health infrastructure and related issues, air quality, genetics, and lifestyle choices. As a result, climate change impacts on human health vary among different populations and locales. Urban locations are more likely to be impacted by high temperatures, while more rural locations may be more susceptible to vector-borne diseases such as Lyme disease.

At present, climate-related health impacts have significant impacts on human health in the region such as seasonal allergies, winter cold and flu, and summertime air quality problems. The health and comfort of those living in the region would be affected by a range of direct and indirect impacts associated with future climate change. Causes for regional concern about the future include heat waves, enhanced air pollution, reduced water quality, new distributions of infectious diseases and disease carriers, saltwater encroachment into aquifers, alterations in marine ecology, storms, and droughts, and increased harmful algal blooms.

A number of regional characteristics could make some inhabitants and visitors vulnerable to climate-related health changes. High elevation sites favored by hikers increase their exposure to poor air quality (The Hiker Health Case Study). Large native populations of deer and mice co-existing in areas populated or visited by humans increase the likelihood of exposure to ticks infected with Lyme disease. The northern parts of the region are the location of the greatest loss in stratospheric ozone and the resulting increases in exposure to harmful ultraviolet-B radiation, which compromises our skin's ability to ward off disease. Because the New England region is downwind from much of the rest of the country and includes a number of large urban areas and transportation corridors, it receives airborne pollutants from areas upwind, as well as generating its own pollution. Since automobiles are a major source of NO_x (a precursor chemical for smog and ozone, along with naturally-produced VOCs, see Chapter 1), especially during the summer time months, levels of ground-level ozone could be exacerbated by climate changes resulting in more dry, hot days, thus a further challenge to the health of the region's human population.

Two illustrative case studies dealing with hiker health and Lyme disease are presented at the end of this chapter as a means of investigating these interactions more thoroughly. Each of the case studies includes a brief discussion of adaptation strategies and information needs.

7.2. Current Stresses on Human Health

Infectious and Vector-borne Diseases

Infectious and vector-borne diseases (e.g. mosquitoes and the encephalitis viruses they may carry) are extremely sensitive to climate conditions – especially temperature and humidity. Their geographic distribution responds actively to changes in minimum temperatures, which are projected to increase in parts of the region from 6? F to as much as 10? F by 2100.

Mild, possibly wet winters combined with warm, possibly wet summers punctuated by heavy rains, can stimulate mosquito breeding and biting. Northerly outbreaks of mosquitoes have occurred in particularly warm years when there have been several days of above 85? F temperatures. One strain of encephalitis – St. Louis encephalitis – has occurred after excessive rainfall in January and February followed by drought in July. Moreover, similar weather events could increase the incidence of eastern equine encephalomyelitis, which can infect humans and horses, as in Rhode Island and Massachusetts, two states that already have experienced outbreaks of this disease.

Climate change also may affect the spread of tick-borne Lyme disease, as increased numbers of ticks survive mild, wet winters and flourish during summer months. According to the Centers for Disease Control, the New England region accounts for 90% of the 100,000+ cases of Lyme disease reported nationwide since 1982. However, climate change may provide a health benefit to humans vulnerable to tick-borne diseases. Ticks that also can carry ehrlichiosis (a treatable bacterial disease) and a virus that can cause encephalitis, prefer cooler temperatures. If summer temperatures increase as projected, tick populations, and the diseases they carry, may actually decline as a result of this warming trend.

Red Tides

A changing climate could also exacerbate another growing health problem in the region: the incidence of red tides, fish kills, and bacterial contamination in shellfish. Hotter summers favor more toxic forms of algal blooms, such as blue-green algae and the dinoflagellates that often are the cause of red tides. Persistent red tides can reduce oxygen levels in the water, affecting sea grasses and shellfish beds. Other water-borne diseases that may affect the region could include cholera, which can exist both in the dormant and infectious forms, depending on pH, temperature, salinity, and nutrient levels in the water. Food-borne diseases, such as E. coli, salmonella, cyclospora, and hepatitis A, also may be enhanced by the warmer, moister conditions projected for the New England region.

Extreme Events

In January of 1998, a series of devastating ice storms hit northern New York and New England, causing extensive damage to forests, energy and transportation infrastructure, as well as impacting human health, and in general, disrupting life in the region in a number of significant ways. Many people across the region were without power for up to three weeks, resulting in inconvenience and frustration for many, a dramatic increase in colds and flu-like ailments, and carbon monoxide poisoning and deaths from asphyxiation for a few. These deaths were due to improper ventilation of power generators. Over the entire region (portions of New York, Vermont, New Hampshire and Maine) approximately 1.5 million people were without electricity for up to three weeks. At the height of the crisis, approximately 500,000 homes and businesses were without power.

The ice storm impacts included 17 deaths across New York and New England, many as noted above due to carbon monoxide poisoning and asphyxiation. In Canada, 26 deaths were reported, many due to hypothermia. Human health and safety impacts related to the storm were significant, but certainly would have been greater were it not for the rapid response from volunteers, state and local governments, the National Guard, and others.

Flooding

Other climate-related stresses on human health include the danger presented by extreme events such as floods, hurricanes, droughts, and very hot temperatures, where the frequency and intensity of any of these events could change (increase or decrease) with climate change. Each of these extreme events can pose direct and indirect health-related risks to vulnerable populations. Drowning, for instance, is an example of a direct risk posed by flooding. Flooding can also offer indirect risks to humans by, for example, providing new breeding sites for mosquitoes, which can carry disease or altering water quality.

Flooding, often a result of storm surges, hurricanes, and torrential rain, is dangerous for several reasons beyond the obvious and direct danger of drowning and damage to property. It has also been associated with outbreaks of Cryptosporidia, Giardia, and E. coli – all illness-causing organisms transmitted from human or animal wastes. Extreme rain events can overwhelm the capacity of existing sewage systems, as already occurs in many older cities in the region, causing a temporary closing of shellfish beds and posing a hazard to those who consume illegally obtained contaminated shellfish. Extreme rain events can also increase run-off from farms causing a release of bacteria and such organisms as *Cryptosporidium* into the environment and into water supplies. Cryptosporidiosis is a potentially deadly disease for those who are immuno-compromised by other factors, but for the healthy causes only transient flu-like symptoms. It can be a problem because once the *Cryptosporidium* organism is in a water supply it can be difficult to remove. Giardia has already contaminated many mountain streams, posing a health hazard to hikers foolish enough to drink untreated water from such streams.

Droughts

Droughts also wreak havoc on living systems. They concentrate microorganisms; encourage aphids, locusts, and white files; and, when interrupted by sudden rains, spur explosions of rodent populations that can, among other things, transmit hantavirus pulmonary syndrome. Although incidence of hantavirus is often associated with the Southwest, this disease also has surfaced in the region, particularly in New York. Beyond their role in triggering the growth of harmful organisms, droughts can seriously compromise a region's water supply with impacts that can go beyond the period of drought. For example, the drought of the mid-1960s had a serious effect on the health of freshwater estuaries throughout the region.

7.3. Future Impacts of Climate Change on Human Health

Infections and Vector-borne Diseases

The projected increases in temperature and precipitation in the future will likely promote the further expansion of current infections and vector-borne diseases (mosquitoes/encephalitis virus, deer ticks/Lyme disease virus, etc.).

Milder, wetter winters, combined with warmer, wetter summers, especially if punctuated by extreme rain events, would result in more frequent and more northerly outbreaks across the region. In the case of Lyme disease, deer and mouse population dynamics also play an important role in disease occurrence and distribution. Since ticks are sensitive to high temperatures, more southerly portions of the region may see a decline over present levels of outbreaks. Since "surprise" occurrences in infectious and vector-borne diseases cannot be predicted, no projections can be made.

Extreme Events

As noted above, "surprise" events such as the 1998 ice storm are impossible to predict. Although extreme events appear to be increasing in the 1990s (see Chapter 2), uncertainties exist in projecting an increase in the future. Assuming droughts and flooding were to occur in association with the projected future climate changes, alteration of water quality would impact human health.

Heat-related Mortality

While heat and cold are not presently significant causes of death in the region, cities of the region could experience relatively greater (versus other US cities) heat-related mortality due to climate warming. Three important factors play a role in reaching heat-related mortality thresholds: the effect of absolute temperature (highs); consecutive numbers of hot days; and humidity levels. The threshold effect occurs when a stress, for example temperature or duration of hot days and nights, goes beyond the level after which mortality rises rapidly.

The high humidity levels typical of the area are related to the heavy forest cover characterizing the New England region. Frequent rainfall and the evapotranspiration from the dense forest cover conspire to maintain and elevate high relative humidity levels across the region during summer months. Increasing nighttime and winter temperatures – a rise in minimum temperatures – are likely to be directly detrimental to human health. For example, during heat waves, there is less nighttime relief from heat stress. Moreover, higher winter temperatures will favor the viability of pests and pathogens that normally would die off during more severe winter months.

Indirect Effects

The indirect and synergistic (compounding) human health effects resulting from climate may also impact the health of those living in the region and potentially on those visiting. While some populations may adapt to these conditions easily, groups such as the urban poor, those on a fixed income, including the elderly, and those who enjoy the outdoors (e.g., hikers at elevations above 3,000 feet), may not fare as well. Those who do not heed health alert warnings or cannot afford to make changes, such as access to air conditioning, or who have existing ailments or little access to health care, may be particularly affected under either future climate scenario.

It should be noted that the U.S. public health infrastructure has evolved the capacity and experience to manage numerous public health risks to U.S. populations and thereby reduce their vulnerability to these risks. While the potential to be affected by many emerging climate-related health problems is real, many of them can be effectively dealt with by preventative actions. For example: a predicted heat wave may increase the risk of heat-related mortality, but establishing warning systems and access to air conditioned locations open to the public will reduce the vulnerability of those populations at risk. While this and other risk-reducing, adaptive and preventive measures are available, they are not without costs. Some of those costs are related to the actual activity undertaken, some are related to maintaining the public health infrastructure, and some are related to effectively reaching out to those with less access to public health measures.

Economic Impacts

Additional climate-related stresses on the public health infrastructure and the increased incidence of disease could have a wide range of economic impacts on the New England region. However, it is difficult to quantify future costs.

If climate change were to increasingly impact human health, better public health infrastructure would be needed to combat diseases new to the region or that may become resistant to existing drugs. Access to public health service – a problem today – could become an even greater problem tomorrow as demand increases. These and other coping options could be costly, requiring society to decide the extent of public resources it would be willing to commit to address these issues.

Significant direct and indirect costs also may be incurred through the increased use of technological responses to changing climates, such as air conditioning to address heat-related health problems. These costs could be significant to individual households and to communities that may need to provide additional infrastructure to meet higher electricity demands. Increased electricity demands result in increasing the level of greenhouse gases in the atmosphere and thereby increasing the amount of warming. We need to be mindful of the ultimate impacts of our choice of responses to climate changes – they could result in additional problems and they could enhance the human contributions to global warming.

7.4. Information and Data Needs

The human health sector may be more sensitive to climate change than the other sectors because many disease and vectors are climate dependent. However, little effort to date has been made within the human health community to correlate human health issues and climate variables such as air quality across the region. The two most significant gaps in information relate to the need for thorough analysis of climate-realted impacts on human health and the need for effective education efforts.

7.5. Adaptive Strategies

Strategies to address potential impacts of climate change on the health of those residing in and traveling throughout the region are varied in focus and in cost. Some options, listed below, relate generally to health impacts that are felt today as well as in the future, whether they are vector-borne, heat-related, or the result of extreme events. This list is not exhaustive and should be viewed only as a starting point.

- Develop monitoring and response programs to identify and detect emerging diseases and sites of potential vectors and train physicians and public health workers to recognize and treat emerging diseases;

- Educate the public on how to maintain their health if climate changes by, for example, using insect repellants, drinking fluids, avoiding certain habitats, heeding health alerts, and taking cooling breaks during hot weather;

- Develop an early warning system and preventive programs for populations at-risk from extreme events, vector-borne diseases, and other potentially health threatening events;

- Insulate buildings better and equip them with window screens, ceiling fans, and/or air conditioning to minimize the spread of disease and over-exposure to heat;

- Support research to investigate methods to curb the proliferation of problem species, including techniques designed to control vector populations; and

- Encourage fortification of sanitation systems to withstand extreme events such as flooding.

Illustrative Case Studies

CASE STUDY #1 – Hiker Health: The Effects of Ozone (O_3) and Other Pollutants on Pulmonary Function

By: Barrett Rock

Mount Washington and the major peaks region in the White Mountains National Forest, NH, hosts some 60,000 hikers per year (Kimball, 1997). During hot summer days this region is often impacted by elevated levels of ground-level ozone, suspended fine particles of soot, and aerosols (droplets) of strong acids of anthropogenic origin. In addition to limiting visibility (Figure 3.4), the exposure to moderate levels of ozone, in combination to fine particulates and strong acidic aerosols pose a health threat to hikers. This case study documents this human health risk.

Background

As noted in Chapter 1, variations in physical climate (temperature, precipitation, cloud conditions, etc.) are connected to chemical climate change (air quality, acid precipitation, etc.). Both types of change will have human health impacts. These impacts may be direct, such as changes in the range of diseases and disease vectors (carriers and hosts, such as ticks and their hosts, that transmit Lyme disease) or the impact of elevated ozone levels on lung function. In addition, climate change could produce indirect impacts on human health, through increases in diseases associated with air pollution.

One of the few case studies of the impact of air quality, and in particular ozone, under ambient conditions, was conducted on hikers engaged in day hikes on Mount Washington from a trail entrance located at Pinkham Notch (Korrick et al., 1998). This study of adults between the ages of 18 and 65 was conducted during the summers of 1991 and 1992 by research scientists from the Harvard Medical School, the Harvard School of Public Health, and the Appalachian Mountain Club (AMC). The hiker health study evaluated the acute effects of exposure to ambient ozone levels, fine particulate matter ($PM_{2.5}$) and aerosol acidity, on pulmonary function of healthy adults exposed while hiking on Mount Washington in the White Mountain National Forest (WMNF) in New Hampshire.

Mount Washington, and in fact all of the New England Region, is downwind from major sources of air pollutants (see Chapter 1, Fig. 1.1). Tropospheric ozone, as noted in Chapter 1 (Figure 1.2), is the photochemical product of reactions of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight and high temperatures. Due to Mount Washington's geographic location, it is downwind from industrial and urban areas (and their associated heavy automobile traffic) and thus, subjected to frequent occurrence of episodic ozone exceedances during warm summer months. As shown for Hartford, CT in Figure 1.3, the summer of 1991 was characterized by a greater number of hot days (at or above 90^{o}F) than was 1992. This pattern was also experienced across the region. Due to the connection between temperature/amount of sunlight and ozone formation, it is no surprise that higher ozone levels (both more frequent 1-hour and 8-hour exceedances and higher monthly maximum levels) characterize the summer of 1991 than the summer of 1992. The same relationship is seen for New Hampshire ozone levels. The year 1991 was characterized by high ozone levels during the summer months, while 1992 was not (Figure 5.6).

The AMC and the Mount Washington Observatory have been monitoring ozone levels along an elevational gradient (at the base of Mount Washington at Camp Dodge - elev. 1500'/480m, and at the summit at 6288'/1910m) since 1987. Between 1987 and 1993, ozone concentrations on the mountain ranged from 0 ppb (parts per billion) to 148 ppb. Average ozone exposures during the period of the hiker health study ranged from 21 to 74 ppb (Korrick et al., 1998).

Significant differences in ozone concentrations on a given date may vary considerably based on elevation. Because the base layer of the atmosphere (the troposphere – extending from ground level to 10-15km/6-9 miles above the Earth) is in contact with the surface, resulting in mixing, the lowermost portion of the troposphere is called the "mixing layer" or the "planetary boundary layer." The boundary or mixing layer extends up to 1km (3,280') or more above the surface, and varies in thickness based on thermal expansion, and thus, time of day. The layer of the troposphere above the mixing layer is termed the "stable layer" (due to the limited amount of turbulence characterizing this layer), and extends to the top of the troposphere. Long-distance transport of air pollutants may occur at the boundary between the mixing layer and the stable layer, and thus, hiking above approximately 3000' may expose the hiker to elevated levels of ozone and other pollutants not encountered at lower elevations. Cloud base may also occur at the juncture between the two layers, and since the cloud base commonly has the lowest pH values within a cloud, the most acidic cloud chemistry is encountered at this elevation. Figure 7.1 presents a diagrammatic representation of the layers within the troposphere.

Figure 7.2 presents both maximum and mean hourly ozone levels as measured at the base and summit of Mount Washington during the 74 days on which hikers were evaluated during the summers of 1991 and 1992 (Korrick *et al.*, 1998). The base monitoring station was located in the mixing layer of the troposphere, while the summit station was located in the stable layer. The differences in mean hourly ozone levels between the two stations is typical of studies conducted elsewhere (MCCP, 1989, 1990),

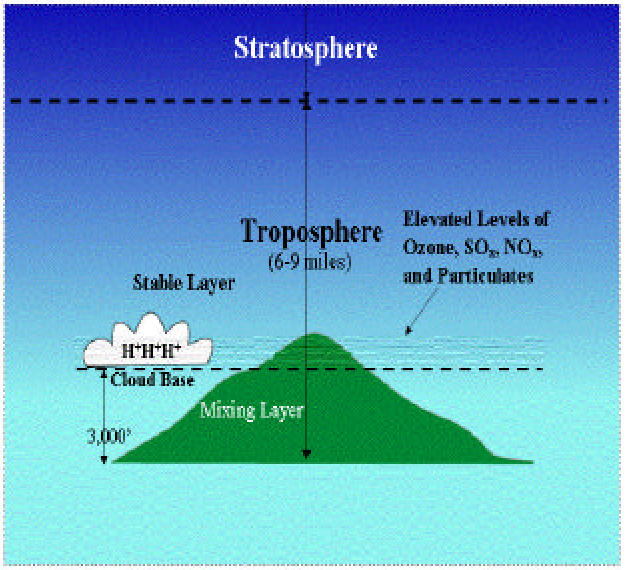

Figure 7.1. A diagrammatic representation of the mixing layer and stable layer at the base of the troposphere, and the affect that elevation has on exposure to both airborne pollutants (O_3, SO_x, NO_x and particulates) and acidic cloud moisture.

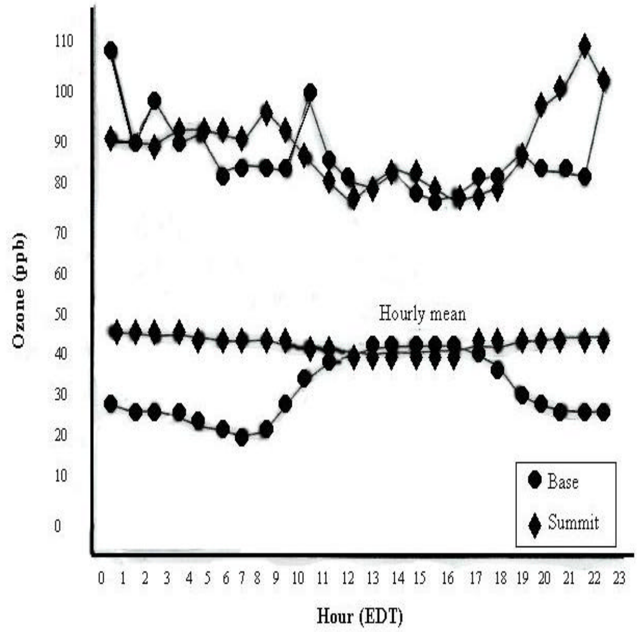

Figure 7.2. Maximum and mean hourly ozone levels (ppb) at the summit and base of Mt. Washington for 74 days on which study hikers were evaluated in summer 1991 and 1992. EDT, Eastern Daylight Savings Time. Note the diurnal pattern of the base station hourly mean ozone levels and the lack of such a diurnal pattern in the summit hourly mean ozone levels. Hourly maximum levels do not exhibit a diurnal pattern at either base or summit stations. Taken from Korrick et al. (1998).

exhibiting the diurnal variation typical of the mixing layer. Ozone is highly reactant with surface features, especially if the surfaces are moist, and is thus removed due to surface contact at night. As sunlight triggers the photochemical reaction that produces new ozone from NO_x and VOCs, a diurnal peak in the early afternoon hours is common. Summit levels of ozone tend to be much more constant over a 24 hour period, due both to long-distant transport and to the limited amount of surface contact and thus limited removal at that elevation overnight. Hourly maximum ozone levels over the two years do not show significant differences between summit and base stations but duration of exposure to elevated levels is greater at the summit. It is important to note that the mean hourly ozone levels at both stations during the time of day of most day hikes (prehike tests conducted from 0800-1039 hours; posthike tests 1500-1730 hours) resulted in an average exposure at or slightly above 40 ppb (Figure 7.3).

In July, 1997, the U.S. Environmental Protection Agency (EPA, 1997) implemented a new National Ambient Air Quality Standard (NAAQS) for ground-level ozone exposure. The previous standard, an exposure to a 1-hour average ozone level equal to or greater than 125 ppb of ozone was considered an exceedance, and hazardous to health. The new standard is more stringent and measures ozone concentrations over an 8-hour average. According to this new 8-hour standard, exceedance occurs if the annual daily maximum 8-hour average ozone concentrations are greater than 80 ppb. This 8-hour standard tends to account for more chronic, low-level ozone concentrations that the EPA believes can be a significant health and environmental hazard. Such chronic, low-levels were not considered in the original NAAQS. In 1998, an industry-led challenge of the more stringent 8-hour standard for ozone exposure had resulted in a return to the 1-hour standard. The basis for the industry challenge was that the 8-hour standard made state and local compliance more difficult, and that few health studies could be cited for the need for the new standard. The average exposure in the hiker health study was at or slightly above 40 ppb (Figure 7.3).

The effects of acute ozone exposure are associated with decreased pulmonary (lung) function, and inhalation and elevated levels of ozone can result in respiratory irritation in the form of shortness of breath, coughing, and pain while inhaling (Avol *et al.*, 1984; Horstman *et al.*, 1990; Kulle *et al.*, 1985; Folinsbee *et al.*, 1988). Controlled exposure chamber studies associate ozone-exposure to acute reduction in lung function and increased respiratory symptoms at exposure levels ranging from 80-400 ppb (Horstman *et al.*, 1990; Dimeo *et al.*, 1981). Less is known about the effects of exposure to ambient low levels of ozone in healthy, demographically-diverse adults. In addition, controlled-exposure chamber studies are often inconsistent when

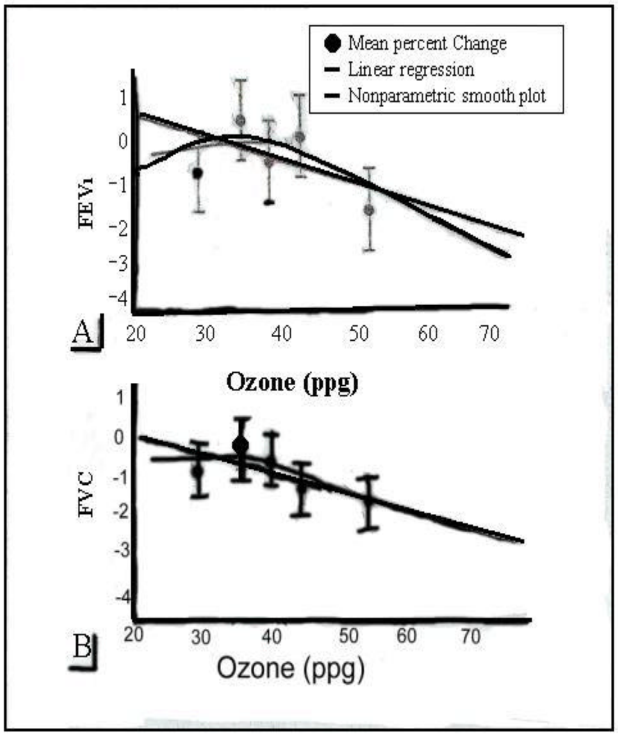

Figure 7.3. Post-hike percentage changes in (A) forced expiratory volume in 1 sec (FEV_1) and (B) forced vital capacity (FVC) versus mean O_3 exposure after adjustment for age, hours hiked, sex, former versus never smoker, history of physician-diagnosed asthma or severe wheeze symptoms, carrying a backpack, reaching the summit, and mean ambient temperature during pre-hike and post-hike spirometry. Note that for both measures of lung function, a significant change occurred in response to ozone levels above 40 ppb. Error bars indicate 95% confidence intervals for mean percentage change in FEV_1 and FVC for each quintile of O_3. Quintile test for trend: p = 0.08 for FEV_1; p = 0.007 for FVC. Taken from Korrick et al. (1998).

compared to natural settings (e.g. a chamber effect). Finally, chamber-based observations may differ from ambient studies regarding the critical exposure levels below which acute health effects are detectable. Little is known about the effect of chronic exposure to low levels of ozone (below 60ppb).

The hiker health study (Korrick et al., 1998) also evaluated the effects on hiker pulmonary function of exposure to fine particulate matter (particles smaller than 2.5? – $PM_{2.5}$) and strong aerosol acidity. Inhalation of fine particles is a human health concern because of their small size, allowing the particles to become lodged in the alveoli of lung tissue (Dockery and Pope, 1994). Strong aerosol acidity can be associated either with low pH cloud events (MCCP, 1989, 1990; Moss et al., 1998) or poor visibility sulfate haze events (Kimball, 1997). Exposure to both $PM_{2.5}$ and strong aerosol acidity has been associated with acute loss of pulmonary function (Dockery and Pope 1994; Raizenne et al., 1989).

The Study Population - Volunteers were solicited from adult hikers beginning a day hike at the trail entrance to several AMC trails (including one to Tuckermans Ravine) on the eastern slope of Mount Washington (elev. 2032'/ 620m). During a 78-day period (summer months) of 1991 and 1992, all hikers who volunteered were evaluated (n=766). A study researcher briefly explained the purpose of the study and performed spirometry (pulmonary function) measurements on all volunteers. The measurements of pulmonary function were performed immediately before hiking and within a half hour of completion of the hike. Three to eight forced exhalations were performed at the beginning and end of each hike. The spirometer was calibrated twice daily, before the pre-hike and post-hike assessments. A total of 78% of these volunteers (n=595) provided acceptable and reproducible spirometry data both before and after hiking. Some 120 hikers (of the 766 participating) did not return for the post-hike spirometry assessment. At the time of the hike, neither the study researcher nor the hiker volunteers were aware of the ambient ozone levels (Korrick et al., 1998).

Only current non-smokers were evaluated in the final study (n=530), but hikers with self-reported history of physician-diagnosed asthma or severe wheeze symptoms (n=40), as well as former smokers (n=125) were included. Of those included in the study, over half (n=396) reached the summit during their day hike. The average exercise period for the hikers (length of day hike) was 8 hours. As noted above, the mean ozone exposure level was at or above 40 ppb.

The Findings - Post-Hike percentage of change was determined and adjusted for hiker age, sex, smoking status (former vs. never), health history (asthma or wheeze), hours hiked, and ambient temperature. It was found that for Every 50 ppb increment in mean ambient O_3 there was a 2.6% decline in forced expiratory volume (FEV_1); 2.2% decline in forced vital capacity (FVC), and a 4-fold greater response (15% reduction) in hikers with a history of asthma or wheeze. Former smokers exhibited responses of increased sensitivity to a lesser degree than those with a history of asthma or wheeze. Lesser but measurable effects were seen due to $PM_{2.5}$ and strong acidic aerosol exposure. Longer exposure duration (8-12 hr. hikes vs. 2-8 hr. hikes) resulted in a doubling of levels of pulmonary function loss.

The results presented in this hiker health study indicate that the effects of ozone exposure were greater than have been described previously in either field studies or controlled exposure chamber studies. These results are surprising, especially since average ozone exposure levels were relatively low (approximately 40 ppb – Figure 7.3). This level of exposure is one third of the current EPA ambient air quality standard (1-hour exposure to 120 ppb ozone). These findings suggest that chronic exposure (8-hours duration) to low levels of ozone may be as damaging to pulmonary function as acute (short-term) exposure to higher levels of ozone. The effects of $PM_{2.5}$ and strong aerosol acidity were also seen to be greater than suggested by previous studies.

This study observed significant health effects of mean ambient of ozone, $PM_{2.5}$ and strong aerosol acidity in a wilderness area (parts of the WMNF) designated for protection – New Hampshire's Class-1 airsheds (Hill and Allen, 1994). Large numbers of visitors engage in outdoor activities in this area and thus, are at risk for acute health effects related to air pollution exposure. This is the first epidemiologic study to document the effects of both acute and chronic exposures to low ambient ozone concentrations. These findings relate directly to the recent revisions of EPA ambient air quality standards (revised from 8-hour, 80 ppb exposures to 1-hour, 120 ppb exposures). Physicians, public health officials and the general public must become aware of the potential acute health impacts of low-level exposures to air pollutants not only in urban settings, but also among individuals engaged in outdoor activities in certain wilderness areas.

Finally, these results are especially significant because they suggest that activities that are considered to be healthful (hiking in the clean mountain air) are in fact unhealthful, especially to sensitive persons (in hikers with a history of asthma or wheeze). Warm, sunny summer days that might seem to be ideal for "taking a hike" are in fact, the ideal conditions to produce elevated levels of ozone. Hazy summer days are likely to be characterized by elevated levels of ozone, $PM_{2.5}$ and strong aerosol acidity.

Lessons Learned

- This study is one of the few conducted under ambient conditions;
- Hikers exposed to moderate ambient levels of ozone (40-55 ppb) exhibited significant loss of lung function;
- Hikers with asthma or a history of wheeze had a four-fold greater response to moderate ambient levels of ozone than others;
- These results are especially surprising since the average exposure levels were relatively low, well below current EPA ambient air quality standards (either the 1 hour exposure to 120 ppb or the 8-hour exposure to 80 ppb ozone); and
- Current air quality in mountains across the region (the Adirondacks, Green, and White mountains) makes hiking potentially hazardous to human health for sensitive people.

Adaptive Strategies

Adaptive strategies will need to focus on identifying those areas and activities to be avoided in order to reduce the risk in sensitive individuals as well as identification of factors which increase sensitivity in specific populations and at-risk individuals. Since exposure to ambient and chronic levels of O_3 increases at elevations above 3,000', these findings make a significant contribution to our understanding of potential human health risks to changing chemical climate in the future.

Case Study #2 – A Changing Climate and Lyme Disease

By: Barrett Rock and Stephen Hale

Over the past century, an overall 0.88 C° (1.6°F) increase in the average temperature record of the planet has been documented. More importantly for biology, and in particular, diseases, is the minimum temperature (both nighttime and wintertime). Over the same hundred-year period, the planet has experienced an increase of 1.86 C° (3.3°F) in nighttime and winter temperatures. These minimum temperatures are increasing at twice the rate of the average annual temperature, a pattern seen in the New England Region. This pattern may account, in part, for the incursion of previously rare or unknown diseases into the region.

An important concept relates to the way in which we monitor the impact of increasing temperatures on diseases. A significant problem relates to attempts to model the spread of disease. Key to such modeling will be the identification and isolation of the factors, both the ecological and climatic, which can be connected to the spread of disease.

Another important concept relates to the "seasonality" of certain diseases. For instance, in Northern Argentina, dengue fever has gone from a disease having a season of six months of the year, to one having a nine-month season. Due to the unique latitudinal and elevational characteristics of the New England region, even subtle changes in the distribution of a disease such as Lyme disease may provide an opportunity to monitor the impact of past and future climate change on an important disease/host/climate relationship.

Background

One of the most important vector-borne diseases for the region is Lyme disease, borne by deer ticks.

Lyme Disease is caused by a bacterial spirochete (*Borrelia burgdorferi*), which is transmitted to humans and animals in the New England region via the bite of the black-legged deer tick (*Ixodes scapularis*). From 1980 to September 2001, there have been over 170,000 cases reported to the Centers for Disease Control. If treated in its early stages, the disease may be completely remedied with physician prescribed antibiotics. Individuals without treatment may develop debilitating chronic conditions of advanced Lyme Disease, including pain and arthritic damage to major joints (e.g., knees), nervous system disruption, and in rare instances complications leading to death.

Warmer, wetter winters, coupled with more moisture year-round may promote the breeding and abundance of these vectors, their biting rates and growth of the microorganisms involved. Thus, the types of the climate change projected by the Hadley (6°F increase in temperature, 30% increase in precipitation) and Canadian (10°F increase in temperature, 10% increase in precipitation) climate models for the next 100 years are likely to lead to significant impacts to human health in many ways. As can be seen in Figure 7.4, several states in the New England region reported significant numbers of cases of Lyme disease in 1998.

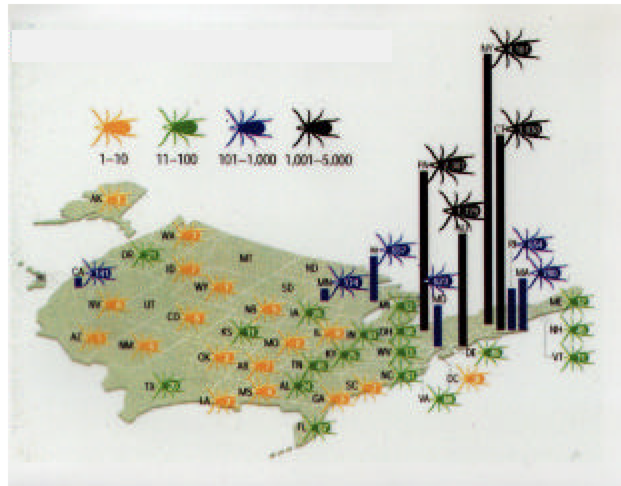

Figure 7.4. Reported cases of Lyme disease in 1998. (Discovery April, 1999)

Infectious and vector-borne diseases have been known to be extremely sensitive to climate conditions for some time (Macleod, 1934, 1935; Epstein, 1997). Their geographic distribution responds directly to changes in minimum wintertime temperatures, which are projected to increase in the New England region by as much as 10? F (the Canadian Climate Model scenario) over the next 100 years. Given the heterogeneous nature of the warming that has occurred across the region since 1895 (Chapter 2), some parts of the region may experience even greater warming in the future. Mather *et al*. (1996) has documented a direct spatial and temporal relationship between deer tick nymphal abundance and human Lyme disease, as well as a strong correlation between the spread of Lyme disease and precipitation/soil moisture (Mather, 1993). Thus, the deer ticks and the Lyme disease bacteria that they carry will be

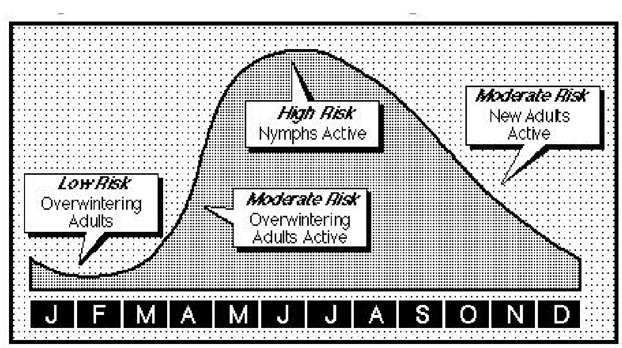

Figure 7.5. Lyme Disease: The Danger Months. (www.riaes.org/resources/ticklab/danger.jpg)

highly responsive to meteorological factors, especially temperature and humidity. Figure 7.5 presents the "danger months" when the likelihood of coming in contact with deer ticks is the highest. Figure 7.6 presents key components of the deer tick life cycle.

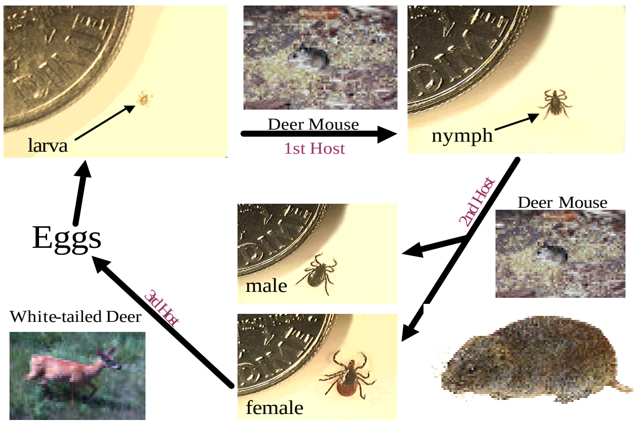

Figure 7.6. The life cycle of the Deer Tick.

The initial symptoms of infection by the Lyme Disease spirochete, include flu-like syndromes of headaches, fatigue, pain in the muscles and joints, and swollen lymph nodes. Additionally, a characteristic rash called erythema migrans may develop in some cases (Figure 7.7). Erythema migrans is a red circular rash, centered on the location of the tick bite. The rash may not be positive proof of inoculation with the spirochete, because allergic reactions to the tick bite can also induce erythema migrans. If the rash persists beyond a few days, then the likelihood of Lyme Disease transmission becomes greater.

Advanced symptoms of untreated Lyme Disease include arthritic pain and swelling in major joints, and nervous system dysfunctions (pain, numbness, temporary paralysis of the face). Some advanced symptoms can be severe and diverse; affecting organ systems such as the eyes, lungs, cardiovasculature, spleen, digestive organs (including the liver), and muscles. Moreover, it is possible for the spirochete to pass from an infected mother, across the placenta, to her fetus. While no documented cases exist, transmission to infants via nursing is hypothesized.

Figure 7.7. Visible symptoms of Lyme disease.

Milder wet winters, combined with warmer wet summers punctuated by heavy rains, as projected by the Hadley model could characterize the New England region in the next century, resulting in more frequent and more northerly outbreaks of Lyme disease throughout the region. This appears to be happening now: the incidence of Lyme disease in 1996 exceeded 16,000 cases, an increase of 37 percent over the previous year. On Massachusetts' Cape Cod alone, an estimated 3,500 people have been infected with this disease. The occurrence of deer ticks was unknown in southern Vermont prior to the 1960s, while today, the occurrence has become commonplace, and the ticks are now being found in northern Vermont. The highest number of cases reported in the United States for Lyme disease is the New England region, where the highest number of cases reported for 1998 were in New York and Connecticut. Massachusetts is ranked fifth (after Pennsylvania and New Jersey) in the number of cases reported (Figure 7.4).

Climate change also could provide a health benefit to humans vulnerable to tick-borne diseases because ticks are sensitive to high temperatures. If summer temperatures increase as projected in the Canadian model, especially in association with prolonged periods of drought, tick populations, and the diseases they carry, may decline with this more extreme warming trend. This may be especially true in southern and coastal portions of the region.

Uncertainties

Clearly, the challenge to predicting Lyme disease outbreaks is to tease out the effects of climate on all of the known (and likely still unknown) variables connected to the tick life cycle: masting, the occurrence of both deer and mice, etc. This is a work in progress.

The spread of Lyme disease appears to be dependent on a number of factors, some of which are still under active study at this time. Deer tick population dynamics are dependent on 1. the severity of wintertime minimum temperatures, 2. changing landuse patterns and resulting disturbance, 3. the population dynamics of white tail deer and white-footed mice, and 4. the production of acorn crops (mast) across the region.

Mast Production - Both deer and white-footed mice use acorns as a major food source and winter survival of both species depends both on the severity of the winter and on access to, and extent of, acorn crops. To better understand the impacts that potential climate change in the future may have on Lyme disease, we must learn more about these various factors and how they influence deer tick population dynamics.

Although some years are good mast years for oak (up to 50,000 acorns produced per mature tree) and others are poor mast years (fewer than 1,000 acorns per tree), the actual connection between climate and acorn production is poorly understood. Every third or fourth year tends to be a good mast year, and an assessment of past annual temperature/rainfall patterns and acorn production is needed in order to allow predictions of mast production based on climate.

Dry years are apparently good for mast production, and heavy mast production, coupled with a mild winter, will result in increases in mice and deer populations in the following year and (due to a larger reproducing population) the year following. In the years following a good mast year, the risk of contracting Lyme disease goes up, and years following a poor mast year, the risk of contracting the disease goes down. If a connection can be shown to exist between climate and one or more factors associated with the occurrence of the disease, an important predictive capability may be developed. Recall from the Species Migration Case Study in Chapter 5, under both climate model scenarios, oaks will become a more dominant component of regional forests over the next 100 years.

Land Use - The monitoring of changes in landuse patterns, and the use of a regionally-calibrated Palmer drought index may also prove to be useful in tracking potential vector distributional changes across the region. A detailed satellite-based assessment of land cover types such as forest, non-forest, and urban, and changes in land cover types over time needs to be conducted. In addition, an assessment of year-to-year changes in greenness and amount of vegetation, climate variables, mast production, tick population dynamics and disease incidence is also needed. Such studies should have a regional focus, since 75% of tick bites and Lyme disease occurrence is in the New England regional population. At present, no such study, focused on a long-term database, is available (Mather, pers. comm.).

Climate Variables - An assessment of data in Rhode Island across the past years has identified a distinct distribution of reported cases of Lyme disease. The years 1994, 1996 and 1998 were wet years and good years for ticks and Lyme disease outbreaks, while 1993, 1995 and 1997 were dry years, bad for ticks, with fewer cases of Lyme disease reported (Mather, pers. comm.). A lot of inter-year variability is seen in the tick distribution patterns, and the cases of Lyme disease recorded coincide very well, both spatially and temporally with tick distributions. An every other year distribution pattern is seen for ticks and disease in Rhode Island, which does not seem to be connected to heavy mast production years.

Finding an explanation for this yearly distribution has been more difficult. The years 1994 and 1996 were characterized by colder, wetter winters, and these are the years with a greater distribution of ticks. A loose association with precipitation or soil moisture and tick populations may be important to understanding the problem. Soil moisture is important because it controls survival of the tick nymphal stage across the summer months. If the soil is drying up by Memorial Day when nymphal stage ticks are emerging, many of them may not survive, resulting in a bad year for ticks. Fewer ticks mean fewer bites to people. In 1996, Rhode Island had over 100 inches of snowfall, and an extremely wet springtime. The snowmelt and other precipitation percolated into the soil and made for very wet ground, which helped sustain the tick population during the summer. There were peak population levels of the ticks even at the end of July in 1996, giving more opportunities for infections of people, and more opportunities for disease transmission (Mather, pers. comm.).

These data suggest that the nymphal stage is the most important stage in determining the population of ticks in a year (Figure 7.5). One interesting trend seen is that there is a form of “stair-step” function in the tick population spread (expansion of range). At the start of monitoring in 1993, at least one tick was found at 60% of the monitoring sites. In 1994, a strong increase in tick population was determined, and a greater proportion of sites had at least one tick. In 1995, a drier year resulted in a decrease in tick population. In 1996, another large tick population was measured and another stair-step expansion in their range. So it appears that ticks expand in favorable years, but in less favorable years, don’t necessarily go away. In the 1998 monitoring effort, ticks were found at 83% of all monitoring stations. This means that an expansion is occurring, but slowly and related to more favorable conditions for the ticks, rather than masting. Clearly, an integrated assessment of tick survival, soil moisture, masting, and climate needs to be conducted.

This is work in progress. A detailed Lyme disease study is needed to improve our understanding of the relationship that may exist between climate, mast production, deer and mice population dynamics, tick nymphal dynamics and the occurrence of Lyme disease.

Lessons Learned

While Lyme disease is a serious human health threat in the New England region, and will likely become more so as a result of milder winters and wetter summers in the future, the factors affecting the spread of the disease are poorly understood. The influence that future climate variables will have on these factors is also poorly understood. A focused study of Lyme disease, the factors that control its spread, and the role that climate may play in the future is needed.

Specific areas to be included in such a study are as follows.

? A better understanding of the key factors affecting Lyme disease transmission (masting vs. soil moisture or both) is needed.

? "At-risk" areas for high tick populations (fragmented areas, areas where humans and ticks are likely to come in contact) need to be identified and provided to people living in the area.

? Improved educational programs that introduce the public to the factors that influence tick population dynamics, as well as the methods of transmission of the infectious agent, are needed.

? Once the factors affecting Lyme disease transmission are known, "tick alert" announcements should be made public.

Adaptive Strategies

In targeted areas, physician education, improved diagnostics, and regionally based community-implemented tick control strategies should be initiated. Improved management of infectious diseases from ticks can be developed by knowing where the problem areas are. We cannot rely on the newly-developed vaccine produced as the only solution to Lyme disease. It doesn't protect against other tick-borne viruses, so there is still a health risk in exposure.

For reducing human exposure to the ticks, one method would be to begin issuing "disease impact statements" made as new land is developed for use. Examining the risks of new land use by bringing in a vector ecologist to examine plans would help reduce the risks of human infections. Currently, 75% of the Lyme disease infections are in people who reside in at-risk areas.

The average percentage of ticks that carry the disease is between 15 and 20% of the population. There has been research with regards to increasing populations of squirrels and other small rodents, because these animals are less competent hosts for Lyme, and the disease impact is diluted. It appears that there are increased numbers of ticks where potential host biodiversity is low, and decreased numbers where such biodiversity is high. More ticks are present in areas of fragmented woods—spaces where there is more "edge" of the woods. One explanation of this may be that there are more animals packed into these smaller spaces; therefore, there is a concentration of hosts for the ticks. In larger areas of woods, the population of hosts may be less concentrated.

References

Avol, E.L., W.S.Linn, T.G.Venet, D.A.Shamoo, and J.D.Hackney. 1984. Comparative respiratory effects of ozone and ambient oxidant pollution during heavy exercise. *Journal of Air Pollution Control Association*,34:804-809.

Dimeo, M.J., M.G.Glenn, M.J.Holtzman, J.R.Sheller, J.A.Nadel, and H.A.Boushey. 1981. Threshold concentration of ozone causing an increase in bronchial reactivity in humans and adaptation with repeated exposures. *American Review of Respiratory Disease*, 124:245-248.

Dockery, D.W. and C.A. Pope III. 1994. Acute respiratory effects of particulate air pollution. *Annual Review of Public Health*, 15:107-132.

Environmental Protection Agency. 1997. *Climate Change and Public Health*, US EPA, EPA 236-f-97-005.

Epstein, P.R. 1997. Climate, ecology and human health. *Consequences* 3:3-19.

Folinsbee, L.J., W.F.McDonnell, and D.H.Horstman. 1998. Pulmonary function and symptoms responses after 6.6-hour exposure to 0.12ppm ozone with moderate exercise. *Journal of Air Pollution Control Association*,38:28-35.

Hill, L.B. and G.A. Allen. 1994. Diurnal and elevational variations in ozone and aerosol concentrations in New Hampshire's Class-1 Airsheds. In: *Proceedings of the U.S. EPA/A&WMA International Symposium*. EPA 600-R-94-136. Pittsburgh, PA, Air & Waste Management Association, pp 646-650.

Horstman, D.H., L.J.Folinsbee, P.J.Ives, S. Abdul-Salaam, and W.F.McDonnell. 1990. Ozone concentration and pulmonary response relationships for 6.6-hour exposures with five hours of moderate exercise to 0.08, 0.10 and 0.12ppm. *American Review of Respiratory Disease*, 142:1158-1163.

Kimball, K. 1997. New England Regional Climate Change Impacts on recreation and tourism. In: *New England Regional Climate Change Impacts Workshop: Final Report*. Edited by B.Moore, III and B.N.Rock, Sept. 3-5, 1997, University of New Hampshire, pp129-131.

Korrick, S.A., L.M.Neas, D.W.Dockery, D.R.Gold, G.A.Allen, L.B.Hill, K.D.Kimball, B.A.Rosner, and F.E.Speizer. 1998. Effects of ozone and other pollutants on pulmonary function of adult hikers. *Environmental Health Perspectives*, 106:93-99.

Kulle,T.J., L.R.Sauder, J.R.Hebel, and M.D.Chatham. 1985. Ozone response relationships in healthy nonsmokers. *American Review of Respiratory Disease*, 132:36-41.

MCCP. 1989. *Mountain Cloud Chemistry Project: Quality Assurance Report for the 1988 Field Season.* EPA, Washington, D.C.

MCCP. 1990. *Mountain Cloud Chemistry Project: Quality Assurance Report for the 1989 Field Season.* EPA, Washington, D.C.

Macleod, J. 1934. *Ixodes ricinus* in relation to its physical environment. I. The influence of climate on development. *Parasitology* 26:282-305.

Macleod, J. 1935. *Ixodes ricinus* in relation to its physical environment. II. The factors governing survival and activity. *Parasitology* 27:123-144.

Mather, T.N., M.C. Nicholson, R. Hu, and N.J. Miller. 1996. Entomological correlates of *Babesia microti* prevalence in an area where *Ixodes scapularis* (Acari: Ixodidae) is endemic. *Journ. of Medical Entomology.* 33:866-870.

Moss, D.M, B.N.Rock, A.L.Bogle, and J.Bilkova. 1998. Anatomical evidence of the development of damage symptoms across a growing season in needles of red spruce from central New Hampshire. *Environmental and Experimental Botany,* 39:247-262.

Raizenne, M.E., R.T.Burnett, B.Stern, C.A.Franklin, and J.D.Spengler. 1989. Acute lung function responses to ambient acid aerosol exposures in children, *Environmental Health Perspective,* 79:179-185.

Chapter 8

Economic Importance and Linkages Associated with Climate Change in the New England Region

By:

Gregory A. Norris

8.1. Introduction

This chapter represents an initial effort to evaluate the nature of potential cause and effect impacts of climate change on the economy of the New England region (including upstate New York[1]). The economic impacts on three components of the regional economy were examined on a state-by-state basis. The three components are natural resources, tourism, and health care. In addition, it is recognized that climatic changes can have impacts on the economy of each component through myriad cause and effect chains. One such cause/effect chain was examined in detail: the potential consequences of regional climate change on fall foliage-related tourism.

Due to the narrow scope of this initial assessment, it must be seen as only the first in a series of studies needed to fully understand the true economic impacts of climate change on the region. It is important to note that while this initial effort has identified some of the impacts, it has also highlighted the complexity of the problem. Due to limitations in availability of appropriate data, the present study does not provide a quantitative assessment of any of the economic components considered.

[1] Upstate New York is defined herein as consisting of all of the state of New York except the following predominantly urban counties which are in the immediate vicinity of New York city: Nassau, Suffolk, Kings, Queens, New York (county), Bronx, Rockland, Westchester, Orange, and Putnam.

Four "links" have been identified in a chain of potential impacts stemming from climate changes to eventual economic responses (Figure 8.1). This chapter focuses on summarizing the implications of what is known about the last two links, with a particular emphasis on the economic impacts of behavioral changes. The Inplan Economic model was used in this initial analysis (Minnesota Implan Group, 1999).

8.2. Summary of Key Findings

The major conclusion from this initial analysis is that while each of these components of the economy are important to the people of the region in *absolute* terms, given the limited amount of data available it is not possible to quantify their economic impact on regional economic activity. The natural resources sectors employ roughly 100,000 people in New England plus upstate New York, where they pay roughly $630 million in wages and compensation (in 1996 dollars); the split between New England and upstate New York is roughly 50% each. Tourism employs 250,000 New Englanders and another 106,000 upstate New Yorkers, paying total wages of greater than $6 billion. Finally, health care employs 650,000 people in New England alone, where it pays in excess of $20 billion in wages and compensation. Converting these absolute figures into meaningful economic impacts is not presently possible due to the uncertainties regarding the full impact of climate change on each component. As will be seen in the detailed assessment of such impacts on fall-foliage tourism, appropriate datasets on fall tourism are not readily available for all of the states in the region.

In terms of the regional economy, of the three components considered, health care (comprised of the sectors "Hospitals, Doctors, and Dentists", and "Nursing and Protective Care") accounts for the largest share, over 9% of total employee compensation (wages plus benefits) in the New England region, with state-level shares ranging from 8.7% in New Hampshire to 11% in Rhode Island. The US average share of total employee compensation for this segment is 7.7%. This high level of importance means that a significant climate change disturbance to this sector would have a significant impact on the regional economy. Identifying

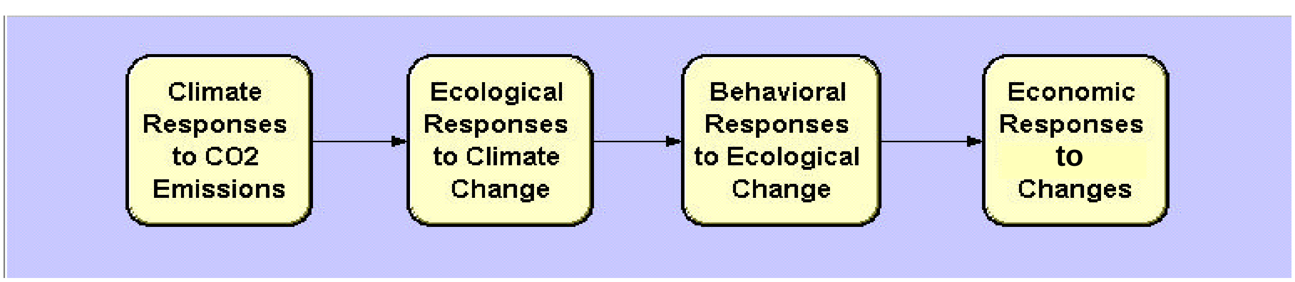

Figure 8.1. Links in the impact chain from greenhouse gasses to the economy.

the appropriate multipliers needed to convert a significant climate disturbance into a realistic economic impact has not been possible in this study.

Next in economic importance of the components considered is tourism. Because some of the output from this segment serves local consumption, we first extract only that portion of activity in tourist-related industries that serve visitors to the states. Tourism-related shares of these industry's output range from lows of 7-30% for general retail, to in excess of 50% for lodging and for non-auto transportation. This direct tourist impact accounts for just over 3% of total New England regional economic activity, and 3% of employment. Tourism's shares are highest in Vermont, exceeding 5% of employment there. Note that because these industries tend to pay lower than average wages, they account for smaller shares of total employee compensation (1.6% in the region, and 3% in Vermont). Again, determining the appropriate multipliers has not been done in this initial study.

Two obvious ways that climate change might impact the region's tourism are impacts on the ski industry and fall foliage-related tourism. Economic databases and models used for this analysis classify the ski industry as part of the sector "amusement and recreation services, not elsewhere classified." New economic models will need to be modified in order to identify and quantify the ski industry contributions to regional tourism. Out-of-state spending in this category accounts for just under 1% of Vermont's economic output, but generally under half a percent of the economic output for the remaining states in the region. The ski industry, while important for those directly involved, does not account for a major share of the regional economy, based on this nonspecific classification in the Inplan model.

The state offices of tourism in the region provided information that indicates fall foliage related tourism accounts for approximately 20-25% of total annual tourism in Vermont and Maine. Similar seasonal tourism data were not available from the other states in the region. Calculating the potential total regional economic impact of a climate-induced loss of maples and subsequent loss of foliage-related tourism is thus difficult. The regional economic importance of tourism, together with an economic model of the impacts of tourism on all other sectors in the regional economies due to economic linkages. The economics and linkages indicate that for every $1 spent on tourism, roughly 20-60 cents additional economic activity is generated elsewhere in the state, depending on the sector and the state. Note too, that this multiplier-based modeling of economic linkages does not account for the "synergistic" effects among tourism-related industries, when, for example, visitors to ski slopes also stay in hotels and eat in restaurants.

Taken together, these results make it possible to estimate that a 50% reduction in fall tourism could account for up to a 1% drop in Vermont employment, with smaller impacts in other states and for other economic measures such as output and wages. Such impacts are important in an absolute sense, since the total region's tourism employs over 350,000 people. A 50% drop in fall tourism could correspond to nearly 20,000 jobs lost if fall tourism accounts for just 10% of the region's total, which is a conservative estimate.

Finally, of the economic components considered, the natural resource-related industries account for the smallest share of the regional economies. With 1995 sales of 2.9 billion dollars in New England and 2.8 billion in upstate New York, this segment's output accounts for 2% of total economic output in Vermont, 1.6% in Maine, and roughly 1% for upstate New York. Shares of total natural resources employment are slightly higher, while those for employee compensation are lower, reflecting lower-than-average wages for this component.

Taken as a whole, these results point to the following general conclusions about assessing the potential economic importance of potential climate change impacts on the region. First, we note that Vermont, and to a lesser extent Maine, appear to lead the region in terms of the relative importance of both tourism and natural resource related industries. In Vermont, tourism-related spending accounts for 5% of the economy, and natural resources 2%. A Vermont ski association estimates that for every dollar spent in a ski area, 94 cents are generated in the state (Carter, 2001). Region-wide economic impacts of specific climate-induced impact on skiing or foliage-related tourism would be profound for those persons, companies, towns and sub-state regions directly involved. A second conclusion relates to the limited amount of available data.

A final conclusion is that the complexity of the economic assessment process make a thorough analysis beyond the scope of the present New England Regional Assessment. Developing a regionally-specific economic model will be necessary to fully quantify climate change impacts to the region.

8.3. Full Impact Chain Example: Fall Foliage-Related Tourism

Of particular significance to this initial investigation is the fact that although potential "climate change" is sometimes imagined to be a single result, it is instead a highly multifaceted phenomenon involving changes in both physical climate (temperature, precipitation) and chemical climate (air quality and acidic precipitation), both of which may have profound impacts on the forests of the New England region.

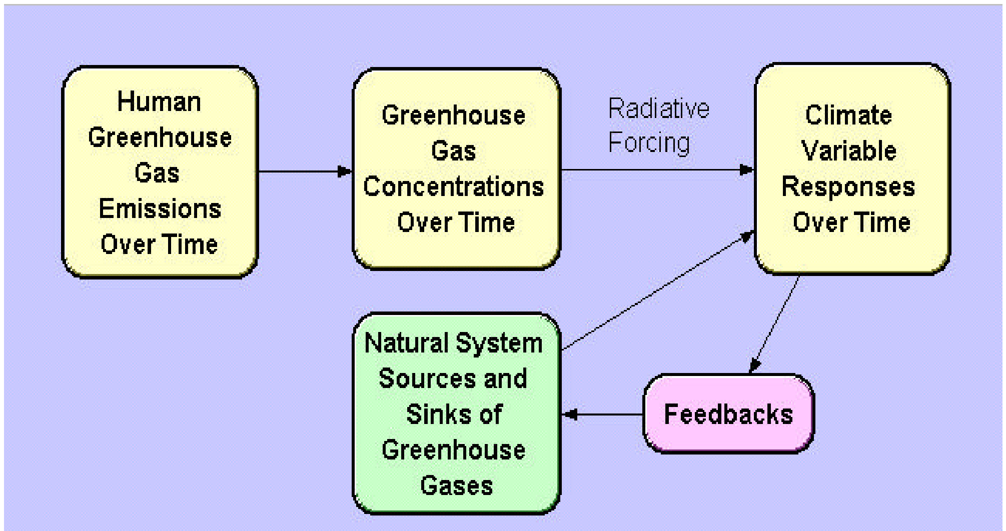

Figure 8.2. Schematic of Climate Response Linkages

A variety of climatic impacts are relevant to the potential response of forest ecosystems to climate change. A simplified view of important causal relationships is presented in Figure 8.2.

Forest Responses to Climate Change

The potential impacts of climate change upon fall foliage-related tourism relies on the responses of individual tree species. The most vibrant fall foliage is displayed by the red maple and sugar maple; it is the relative abundance of these two species, interspersed with evergreens, that makes the New England region such a popular destination for tourists pursuing fall foliage displays.

A recent study (Iverson and Prasad, 1998) examines the influence of climatic factors upon the relative abundance of 80 individual tree species at a regional level within the Eastern US. Their hierarchical "regression tree" models draw from among 33 separate variables within four categories, as summarized in Figure 8.3.

The study uses the models together with regional interpolations of GCM-based projections of future equilibrium climatic responses to a doubled global atmospheric concentration of CO_2, in order to develop regionalized projections of the physical climate's potential impacts upon the abundance of individual tree species at a regional level in the

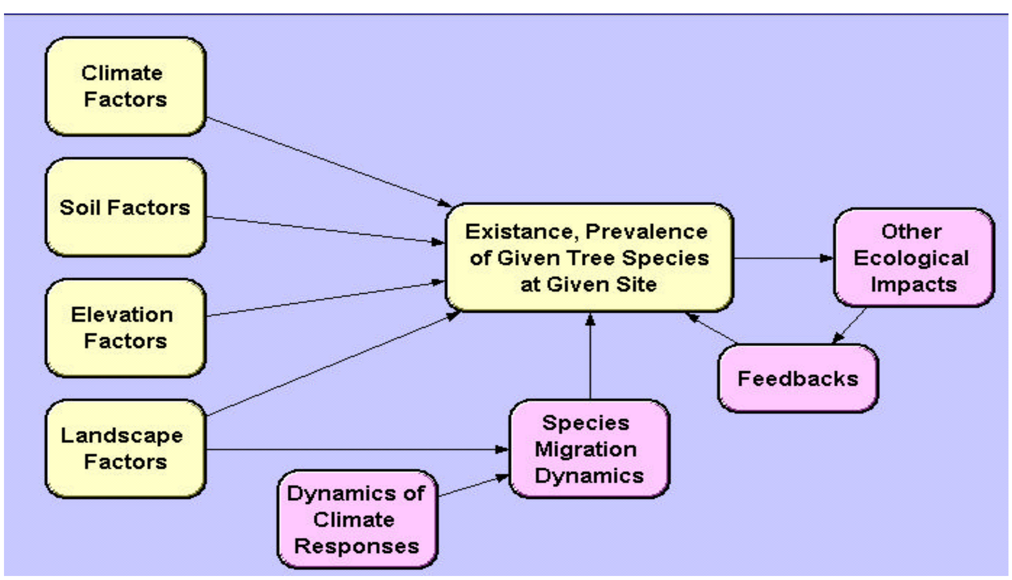

Figure 8.3. Schematic of Forest Response Linkages (gray balloons indicate additional factors which may be important but are not included in the initial 1998 model by Iverson and Prasad 1998)

Eastern US (Iverson et al., 1999; see Species Migration Case Study in Chapter 5). The model takes into account the influence of climate factors, soil factors, elevation and landscape factors upon the prevalence of species (Figure 8.3), as well as factors which may also be important in governing the actual regional response of tree species to climate changes, but which are not included in the model (Iverson and Prasad, 1998). These other factors include the dynamics of changes to climate (both physical and chemical), the dynamics of species migration, and interactions with other living elements of the ecosystem.

It must be emphasized that other uncertainties surround many facets of this modeling, including:

- the response of regional temperatures and precipitation to changes in atmospheric concentrations of greenhouse gases;
- the dynamics of climate response in relation to regional factors influencing climate (i.e., topography, coastal locations, etc.) and their interaction with the dynamics of species migration;
- the influence of human forest management practices over the coming century;
- the human response (business as usual vs. reduced CO_2 emissions); and
- the influence of other factors such as chemical climate impacts missing from the tree response model, and the uncertainties in the estimated values for the parameters which were included.

Thus, the model results should be looked upon as illustrative of the best sort of currently available scientific model-based results concerning foliage-relevant tree species responses to climate changes in our region, but not as *forecasts* of what will happen.

Tourist Behavior Responses to Forest Change

The uncertainties influencing this investigation do not end with modeling ecological response to climate change. The next link in the overall impact chain (Figure 8.1) is the behavioral response of tourists to changes in foliage displays, and this link has even greater uncertainties because social, cultural and emotional judgements must be considered.

Representatives at each of the seven states' offices of tourism were contacted, and asked for information concerning the factors which influence the decisions of fall tourists, as well as the importance of fall foliage-related tourism in their overall tourism market. Only two states (Vermont and Maine) were able to provide estimates of the relative significance of fall tourism within annual tourism totals. Vermont reported that 22% of its tourism occurs during the fall season, and Maine reported fall's share at 20%. It is interesting to note that only two of the seven states in the region were able to provide such data.

The following illustrates the very limited amount of relevant data which are readily available for use in an economic analysis. Only one state, Maine, was able to provide any information related to the factors which might influence visitors' decisions to undertake travel from out of state. The Maine Office of Tourism provided a detailed report written for that office by Longwoods International, a research consulting firm for the travel industry. The report did not address the fall tourism season directly, nor did it present results separately for visitors of different seasons, unfortunately. Results indicated that the most important reasons for visiting Maine, as cited by visitors who came for reasons other than business or visiting friends and family ("marketable tourism"), were:

- to tour the state (37%)
- to enjoy the outdoors (23%)
- to attend a special event (12%)
- for a beach vacation (9%)

Thus, the top two reasons for visiting (touring, and enjoying the outdoors) do have a strong *potential* connection to fall foliage for a significant percentage of visitors. Among three categories cited as of particular interest on trips by overnight "marketable" visitors, "Eco-tourism" was cited by 20% of visitors, ahead of "historic tourism" (18%) and "cultural tourism" (12%). Sight-seeing was rated highly by 58% of marketable visitors to Maine, and within this category, "beautiful scenery" ranked highest among 13 aspects of sight-seeing, being cited 90% of the time.

These survey results do not enable us to estimate what portion of fall tourism might respond negatively to a reduction in fall foliage. They certainly do not make it possible to estimate what the reduction in tourism spending might be if foliage brilliance was no longer an attraction. The results do confirm, however, that beautiful outdoor scenery is among the most important reason that visitors come to Maine. This, together with the cited shares of annual tourism occurring in the fall (20% for Maine and 22% for Vermont) indicates that significant impacts on tourism from a climate-induced regional loss of maples would be expected. More detailed state-level data on fall tourism and its ties to foliar displays are needed before we can estimate in detail at the regional level what would be the impacts of a loss of foliage-related tourism on the regional economy.

Economic Impacts of Tourist Behavior Changes

The final link in the impact chain concerns the consequences for the wider regional economy of changes in tourism. The way that tourism impacts the regional economy is through expenditures by tourists. These expenditures in turn can stimulate **direct, indirect,** and **induced** impacts.

Direct impacts include the revenues taken in, employment provided, and wages paid by the industries to which tourists spend money directly. These industries include lodging, food service, entertainment, general retail, and transportation (both public and private).

Indirect impacts occur as a result of expenditures by the directly impacted industries. For example, tourist spending on the lodging industry induces spending *by* the lodging industry on the goods and services of other sectors of the economy. These secondary purchases stimulate tertiary expenditures, and so on. Finally, induced impacts refer to the impacts generated by the spending activity of persons who are employed by the directly-impacted industries – namely, the "tourism" industries.

Data characterizing direct, state-level travel-related expenditures in 1996, as reported by the Travel Industry Association, (TIA 1998; 1999) are provided in Table 8.1a, for the New England states and upstate New York[2]. Table 8.1b shows the total wages paid by each sector in each state in 1996. Finally, Table 8.1c provides estimates of the employment (full-time equivalents) associated with these tourism sectors.

Indirect and induced impacts of tourism are estimable using economic impact assessment models, such as input/output models. Economic input/output models make use of data on the purchases made by each sector for the goods and services from all other sectors. The most detailed input/output tables in the USA are all based on the results of the US Department of Commerce's Bureau of Economic Analysis (BEA). As an example of indirect impacts stemming from direct tourism expenditures, Table 8.2 presents the total amount of indirect economic output stimulated by the hotel and lodging industry, per million dollars of output from that industry. Table 8.2 also presents results for the top industries whose output is stimulated by the purchases of the hotel and lodging industry.

As Table 8.2 shows, the economic impacts of tourism extend beyond the tourism industry, to include industries such

[2] The TIA data pertains to the entire state of New York, including the NYC metropolitan area. Here we have adjusted the TIA's figures to estimate only those expenditures occurring in upstate New York. See footnote 1 of this chapter for more details.

Table 8.1a. Direct state-level travel-related expenditures in 1996 (source: TIA 1999).

($M 1996)	Public Tranport	Auto Transport	Lodging	Food Service	Entertainment/ Recreation	General Retail
Upstate NY	1614	1444	2609	2678	318	1368
Connecticut	1917	495	582	752	210	298
Rhode Island	351	150	151	150	52	67
Massachusetts	3731	1112	2081	1807	583	885
Vermont	172	135	305	363	188	153
NH	671	205	294	355	172	150
Maine	393	321	367	455	150	202

Table 8.1b. Direct state-level travel-related payroll in 1996 (source: TIA 1999).

($M 1996)	Public Tranport	Auto Transport	Lodging	Food Service	Entertainment/ Recreation	General Retail
Upstate NY	583	112	615	722	143	192
Connecticut	189	43	151	213	109	53
Rhode Island	34	11	38	40	20	11
Massachusetts	653	91	591	522	281	133
Vermont	20	10	98	89	21	24
NH	47	16	84	90	53	21
Maine	35	19	91	117	49	30

Table 8.1c. Direct state-level travel-related employment in 1996 (source: TIA 1999).

($M 1996)	Public Tranport	Auto Transport	Lodging	Food Service	Entertainment/ Recreation	General Retail
Upstate NY	15	5.3	27	57	5.2	10
Connecticut	5.6	1.6	8.5	18.0	5.0	2.7
Rhode Island	1.1	0.5	2.4	4.0	1.3	0.6
Massachusetts	18.0	3.9	29.7	42.9	14.2	7.3
Vermont	0.8	0.6	6.8	9.0	1.5	0.5
NH	1.3	0.8	6.1	8.8	3.8	1.2
Maine	1.7	1.0	7.4	12.1	4.3	1.9

as real estate agents, banks, construction, utilities, advertising, etc. A significant share of this sort of indirect impact (and of the induced impacts as well) would occur in the same region as the direct impacts.

8.4. Data Gaps and Information Needs

Of the many data gaps, one important missing piece of data needed for estimating foliage-related tourism in the region was the share of total sales due to foliage-based tourism, for all states. This may require more than accounting for seasonal tourism, because the fall season share includes some spending not tied to foliage sightseeing (such as hunting and hiking). Even in Vermont and Maine, specific details related to fall foliar tourism are not available. The same is true for specific economic information on ski-related tourism which is not available by state or for the region. In the case of ski-related tourism, the best datasets may be held by ski companies which are reluctant to release them.

More broadly, any economic analysis relies on a chain of effects for the various causal links between climate changes and their economic impacts, and each link in this chain is modeled with a significant degree of uncertainty. As our understanding of these connections, and the inherent uncertainties improves, our ability to project economic impacts resulting from climate change will improve. Nevertheless, the current state-of-knowledge has allowed order-of-magnitude insights into the potential scale and nature of economic impacts of climate change for the region.

Table 8.2. Ouput in other industries induced by $1 million activity by hotel and lodging

Industry	Value of output stimulated (thousand $) by $1 million of hotel & lodging industry business
Real Estate Agents	53
Credit Agencies	48
Other Non-Farm Buildings	40
Electric Utilities	40
Wholesale Trade	34
Gas Utilities	27
Management Consulting Services	27
Communications except Radio and TV	26.3
Advertising	25.7
Miscellaneous Plastic Products	24
Banking	22
Personnel Supply Services	17
Auto Rental and Leasing	16
Crude Petroleum	16
Hotels and Lodging Places	3
Total, all sectors of the economy, not limited to those listed above: **886**	

8.5. Conclusions

Because of the uncertainties involved at every step in this initial analysis, it is not possible to make "forecasts" of climate change's economic impacts. It has been possible, however, to illustrate that the causal linkages between climate change and the region's economies are real, and to identify the current levels of information available or unavailable. The modeling approaches which characterize each of these linkages for a particular scenario of potential consequence for the region have been considered, and the significant data gaps that must be filled before a more quantitative analysis can be conducted have been identified.

It is clear that the types of climate change projected by the climate models used in this assessment would have profound impacts on many segments of the regions economy. While these impacts are significant, this initial effort does not provide hard numbers regarding the potential economic impacts. For this reason, a regionally-specific economic model must be developed and applied as an important next step in a regional socioeconomic analysis.

8.6. References

Iverson, L. and A. Prasad, 1998. "Predicting abundance of 80 tree species following climate change in the eastern United States." *Ecological Monographs,* 68(4): 465-485.

Iverson, L., A. Prasad, and M. Schwartz, 1999. "Modeling potential future individual tree-species distributions in the eastern United States under a climate change scenario: a case study with *Pinus virginiana*." *Ecological Modeling* 115:77-93.

Minnesota Implan Group, 1999. *The IMPLAN Regional Economic Model*. Stillwater, MN.

TIA 1998: Travel Industry Association of America. *The Economic Review of Travel in America.* Prepared by the US Travel Data Center, TIA, Washington, DC. December.

TIA 1999: Travel Industry Association of America. *Impact of Travel on State Economies.* Prepared by the US Travel Data Center, TIA, Washington, DC. January.

APPENDIX A

NEW ENGLAND REGIONAL ASSESSMENT STEERING COMMITTEE

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APPENDIX B

DISTRIBUTION OF NEW ENGLAND REGIONIAL ASSESSMENT PARTICIPANTS

The New England Region Assessment (NERA) was initiated in September 1997, with the *New England Climate Change Impacts* Workshop, held September 3-5, at the University of New Hampshire (UNH). Participants in this initial Workshop identified the three key Sectors of interest, and the key areas of concern to be addressed in more detail. Three additional Sector-specific Workshops were held in 1999: March 30, 1999 – Forestry Workshop; March 31, 1999 – Water Resources Workshop; and April 7, 1999 – Human Health Workshop. These Workshops were conducted to assess the current state-of-knowledge of the potential consequences of climate variability and change on the New England region, as well as to identify areas for which more information is needed. In the process, stakeholders participating in the Workshops identified key concerns regarding climate impacts to their specific Sectors. One of the main goals of the NERA effort has been to present the key findings in terms that are relevant and meaningful to the general public, and the participating stakeholders assisted us in reaching this goal. The overall NERA effort has been supported by the National Science Foundation.

Stakeholders participating in the NERA identified three key sectors (Forestry, Water Resources and Human Health) for detailed consideration, and three key concerns or issues likely to affect these sectors if climate change continues (Air Quality, Seasonal Dynamics and Extreme Events). The table below presents a summary of NERA Workshop participants, by category and by area (state) represented. Since many participants attended two or more Workshops, they have only been counted once in the table. The names of the participants in each of the four NERA Workshops are listed in Appendix C.

State	Local Gov.	Federal Agency	Energy/ Utility	Business/ Industry	NGOs	Education/ Outreach	Scientist/ Researcher	Interested Stakeholder	Total by State
AK							1		1
CAN	1								1
CT		1	1	1		1			4
DC		3					1		4
MA	2	7		3	5	3	7		27
ME	2		1	4		1	1		9
MD		3					1		4
NH	14	4	2	3	9	13	35	3	83
NY	1			1	1		3		6
PA		2							2
RI		2		1		2	6		11
VA		2							2
VT	3			2		1	6		12
Total	23	24	4	15	15	21	61	3	166

APPENDIX C
NERA WORKSHOP ATTENDEES

New England Regional Workshop
September 3-5, 1997

John Aber
Jim Abraham
Eleanor Abrams
Samuel Adams
Donald Anderson
Allan Auclair
Thomas Baerwald
Marian Baker
Patrick Barosh
David Bartlett
Howard Bernstein
Richard Birdsey
Doug Bogen
Robert Brower
Deirdre Buckley
Ann Bucklin
Karen Burnett-Kurie
Lynne Carter
David Cash
Michael Charpentier
Michael Cline
Kenneth Colburn
Nancy Cole
Priscilla Cookson
Robert Corell
Michael Disharoon
Claudette Donnelly
Richard Donnelly
Lesley-Ann Dupigny-Giroux
Petya Entcheva
Paul Epstein
Ivan Fernandez
Douglas Forbes
Tim Foresman
Fred Friedman
Harold Garabedian
Patrick Garner
Graham Giese
Lewis Gilbert
Daniel Goldin
Joel Gordes
Cynthia Greene
Timothy Gubbels
Perry Hagenstein
Stephen Hale
Steven Hamburg
Kate Hartnett
Paul Harris
Denise Hart
Brenda Hausauer
James Hawk
Wanda Haxton
Douglas Hill
Lloyd Irland
Glenn Juday
Naida Kaen
Barry Keim
Thomas Kelly
John Kermond
Ken Kimball
Karl Kreutz
Clara Kustra
Amy Langston
Don LaTourette
Gary Lauten
Rob Leatherbee
Stuart Leiderman
Michael MacCracken
Norman MacDonald
Jeffrey MacGillivray
Paul Mayewski
Sharon Meeker
David Meeker
Jerry Melillo
Eric Meyerson
Rakesh Minocha
Berrien Moore III
David Moss
George Musler
Scott Nixon
Alan Nogee
Ellen O'Donnell
Mila Paul
Iqbal Pittalwala
James Platts
Ronald Prinn
David Reusch
Mary Reynolds
Barry Rock
Fay Rubin
James Russell
Larry Ryan
William Salas
Tim Scherbatskoy
Nancy Sherman
Frederick Short
John Slater
Molly Smith
Elske Smith
Leo Spencer
Shannon Spencer
Daniel Sundquist
Jennifer Supple
Marika Tatsutani
Mary Tebo
Marc Tremblay
Mark Twickler
Thomas Varrell
Henry Veilleux
Eric VonMagnus
Cameron Wake
Margeret Weeks
Tom Wessels
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Paul Hubbe
Lloyd Irland
Leslie Kane
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John Lanier
Eugene Lecomte
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David Marvin
Will McWilliams
Rakesh Minocha
Morten Moesswilde
Berrien Moore
Gregory Norris
Alan Page
Jan Pendlebury
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Mary Reynolds
Keith Robinson
Barry Rock
Michael Routhier
Dork Sahagian
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Morten Moesswilde
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APPENDIX D

THE NEW ENGLAND REGIONAL ASSESSMENT REVIEW PROCESS

The review process for the New England Regional Assessment (NERA) has taken four separate forms: an internal Website review by Workshop participants; an internal review by members of the NERA Steering Committee; an external review by scientists; and an external review by stakeholders. The two external reviews were facilitated by the New Hampshire Department of Environmental Services (DES) Local Impact Assessment Project (LIAP). This LIAP effort, coordinated by the DES and funded by the US EPA, brought together approximately 50 researchers and scientists (primarily from the Forestry and Water Resources Sectors), as well as over 60 stakeholders, to evaluate the NERA *Overview* Document. None of the LIAP evaluators had participated in the NERA process. In the case of the research scientists, the focus of the review was on assessing the accuracy and validity of the science presented in the NERA *Overview* for the specific Sectors. In the case of the stakeholders, the focus of the review was on the impact of the material presented and on the usefulness of the public message delivered.

The table below characterizes the participants in the external review, which consisted of both scientists and stakeholders. Participants in the external reviews were sent draft copies of the NERA Overview prior to attending day-long evaluation workshops. Both written and oral evaluations were solicited. All written and oral reviews were considered and most were incorporated into the final version of the NERA *Overview* Document.

	Forestry	Water	Human Health	Economists	Biologists/ Wildlife	Climate Scientists	Recreation	Real Estate	Total
Scientists	17	10	4	5	10	4	3		49
Stakeholders	11	26	4	2	9		10	2	64
Total	28	36	8	7	19	4	13	2	113

Acknowledgements

The New England Regional Assessment (NERA) is the product of a four-year effort to characterize the impacts to the region of a changing climate since 1895, the current state-of-understanding of factors known to influence our regional climate, and projections of possible future regional climates. Many people have been involved in this project, including the authors of the chapters, the members of the Steering Committee (see Appendix A) and many stakeholders (Appendix C). Dr. Lynne Carter, of the National Assessment Coordination Office (NACO), and Henry Walker, US Environmental Protection Agency, were especially active in the review process of both the Overview and Foundation NERA documents. A number of state and regional groups have also taken an active role in assisting in the review of the final document and in publicizing its release. These include the New Hampshire Department of Environmental Services, an EPA-sponsored New Hampshire Local Impacts Assessment Project (LIAP) on global climate change, and the New England Science Center Collaborative. The LIAP program coordinated both a scientific review and a stakeholder review as summarized in Appendix D. In addition, many individuals have been involved in the production of the final documents, including Ryan Huntley, Clara Kustra, Faith Sheridan, Kristi Donahue, and Shannon Chisholm, all from the University of New Hampshire. Finally, we wish to acknowledge the funding provided in support of the effort by the National Science Foundation (NSF).