CHAPTER 6

CLIMATE IMPACTS ON REGIONAL WATER

By Barrett Rock, Lynne Carter, Henry Walker, James Bradbury, Larry Dingman and Tony Federer

Introduction

The New England region is not 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 our 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. The Canadian model projects only a modest increase (approximately 10%) in precipitation for the region over the next century, accompanied by periods of potential drought. The Hadley model projects a significant increase (approximately 30%). How would either of these projections, coupled with the warming projected by both models, impact the New England region?

Climate change could affect many facets of life in the region, with those that are climate-dependent most vulnerable. Climate change that would alter either quantity and/or quality could directly affect the viability of 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 could be impacted by possible climate-induced rise in sea level as well as by water quality issues (harmful algal blooms, wetland loss, habitat degradation, etc.).

In the New England region, future climate impacts to the Water Sector fall into four central 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. Warmer, wetter winters, coupled with more moisture year-round (the Hadley projection) may lead to flooding, causing a flushing of sewage and other wastes from urban areas into wetlands and coastal marine waters. 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.

This chapter investigates some of the documented impacts (current stresses) of recent climate trends for the region, and the impacts of potential climate changes over the next 100 years projected by the Climate Models, including potential benefits. It also considers reasonable coping strategies to address the impact of these changes, and identifies with significant information gaps and “missing pieces” that are needed to more fully understand just how climate change could affect regional water resources. Finally, illustrative Case Studies are included to provide more details on how current climate variability has impacted the water sector.

The region is famous for its "Nor'easters" along the coast, "lake effect" snowstorms in western New York…

Current Status and Stresses

Current Variability in Regional Temperature and Precipitation

A changing climate characterizes the New England region: severe ice storms, summertime heat-waves, spring and fall floods, and long-term and short-term droughts. 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. 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 geographically and seasonally very heterogeneous. 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. Seven of the last 20 years have been characterized by significant regional drought, with six years occurring in the 1960s (see the Mid-1960s Drought Case Study). Changes in the type of precipitation falling during winter months (snow vs. rain) also have a profound impact on water storage vs. runoff, in turn impacting regional hydrology (see the winter NAO index/surface hydrology Case Study).

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 the general public include sea-level rise, water quality issues and the impact of a changing climate on commercial and sports fishing.

Sea-Level Rise

One of the most likely impacts of the warming will be rising sea levels, resulting from the thermal expansion of sea water (as water warms, its volume increases), the addition of fresh water from melting glaciers, ice sheets, and snow pack, as well as local subsidence. Sea-level rise, which is already occurring, could inundate low-lying areas of the New England region, many of which include densely populated areas. 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. With the retreat of glacial ice from the region 20,000 years ago, sea coasts began to rebound (or uplift) to a greater or lesser degree from the weight of the ice. The greater the amount of ice removed, the greater the degree of

Warmer sea surface temperatures off the Atlantic Coast lead to lower snowfall totals in southern New England …

rebound. While portions of the Maine coast may still be rebounding, the coastal areas to the south appear to be subsiding following a period of rebound. About 33 acres of land are lost on Massachusetts' Cape Cod each year—73 % due to advancing seawater and 27% to erosion.

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. A one degree change in ocean temperature would mean a one meter rise in sea level. 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.

One result of rising sea level is that the saltwater wedge, vital to the health of an estuary, would migrate upstream unless freshwater runoff is increased, causing a shift of marine ecosystems upriver. Shoreline construction often prevents wetland migration, then habitat shifts that might have occurred because of sea-level rise are prevented.

Current Impacts of a Changing Climate on Commercial Fishing

The Winter Flounder Case Study addresses the issue of current climate change impacts on abundance of this commercially important marine species. The winter flounder may well be an indicator species sensitive to increases in water temperatures. 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.

Consequences of Climate Change in Coastal Ecosystems

During the past 50 years we have seen large variations in New England 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 (nearly 6^{o} F), almost a 1-degree change per decade between 1960 and 1990. 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.

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. Although speculative, warmer winters may have been a contributing factor in the decline of commercially important ground fish in southern New England in recent decades.

As temperatures increase … the current levels of variability in regional temperatures and precipitation can be expected to continue, and perhaps increase.

Freshwater Issues

Climate change impacts on freshwater in the New England region have affected both water quantity and water quality. As will be seen from the NAO Surface Hydrology Case Study, dramatic changes in amounts and forms (rain vs. snow) of meteorologic water 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) will result in overflows of waste water treatment facilities, leading to poor water quality, just as too little water results in concentration of toxics, also leading to poor water quality.

Climate Change Impacts on Fresh Water Quality and Quantity

The USGS is well known for its water quantity data, collecting stream flow data at multiple sites across the New England region, often done in conjunction with monitoring water usage and flow requirements. A problem with all of these data is that they are collected downstream from major impediments or dams – which could influence the characterization of the impacts of climate change.

Water quality data for New England are not consistent. These data vary from state to state, with some states having good, long-term monitoring programs, while others have abandoned their monitoring programs. The National Stream Quality Accounting Network (NASQUAN) ran from the mid-1970s to the early 1990s but was discontinued because few were using the data. 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.

We know that New England as a region has suffered severe drought and flooding. We must be careful about how we manage our water resources in the dry periods. 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 a lot in terms of adaptation strategies by learning to adapt to changing circumstances.

Impacts of Future Climate Change

Current Trends

Global and regional computer models, although imperfect at describing local conditions, suggest that the current temperature and precipitation trends may continue and both scenarios suggest warmer, shorter winters. 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,” drought has been and remains a significant concern for this region.

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Current Variability in Regional Temperature and Precipitation

As temperatures increase in the future, the current levels of variability in regional temperatures and precipitation can be expected to continue, and perhaps increase. Since much of the current variability is not well understood, improving our understanding about cause and effect relationships across the region is needed.

Potential Benefits

Given warmer and wetter winters, some benefits may be derived in the form of improved groundwater recharge to the region. Such benefits assume that the ground would not be frozen and that the bulk of the precipitation would fall as rain. Longer growing seasons could also benefit coastal ecosystems and milder winters could benefit selected freshwater and marine organisms, while adversely impacting others (see the Winter Flounder Case Study). On balance, the adverse effects of climate change are likely to outweigh the benefits.

Sea-Level Rise

Saltwater intrusion could convert some areas of coastal freshwater wetlands to salt marshes. Groundwater could also be affected, as brackish water infiltrates aquifers that supply drinking water to coastal communities. Saltwater intrusion combined with low freshwater flow, could result in a higher chloride water content in important aquifer systems and water supplies. Low flow, a rise in sea level, or both could affect the water supplies in coastal regions.

In addition, as sea level continues to rise, the amount of the region's 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 lower sea levels. Even if storm strength were not increased, higher sea levels will result in more damage.

Future Impacts of a Changing Climate on Commercial Fishing

Scientists suggest that warmer late winter-early spring temperatures combined with continued sea-level rise could have a significant impact for commercial fishing. The greatest portion of U.S. commercial fishery catches (except Alaska) are estuarine- dependent, with 32% of the fisheries of Cape Cod and north estuarine-dependent. Coastal wetlands, estuaries, and other intertidal areas (e.g. mud flats) are important nursery grounds for many species of comercial fish and shellfish and important feeding grounds for many migrating waterfowl. Because these ecosystems often are adapted to specific temperature, salinity, and tidal conditions, commercial species and whole ecosystems could be lost if the upstream conditions are not suitable for migration or the species are unable to migrate in response to changing sea level. A sea-level rise that is rapid enough to damage coastal wetlands would cause a significant decline in coastal fisheries. Shoreline construction which prevents erosion or submergence or is otherwise unsuitable would prevent estuarine and intertidal habitat shifts that might have

Just as recreational freshwater fishing would be compromised by climate change, so too would recreational and commercial coastal fishing.

occurred due to sea-level rise. Preserving estuarine and intertidal habitats will become more of a significant concern, as the future climate changes.

Consequences of Climate Change in Coastal Ecosystems

Wintertime temperature increases 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 Maine. Reductions in amount of plant debris transported to the bottom during warmer winters may be a significant contributing factor in the decline of commercially-important ground fish in southern New England in the future.

Freshwater Issues

Climate change impacts on freshwater in the New England region will affect both water quantity and water quality. Dramatic changes in amounts and forms (rain vs. snow) of meteorologic water added to the hydrologic system will have profound impacts on stream flow and surface water conditions. Increased storm intensities and drought periods will have significant impacts on quality of the region's freshwater supplies. Although the region is unlikely to become water limited as the result of climate change, regional water quality will be reduced.

Freshwater Fishing: Environmental Impacts

A continued warming trend would impact freshwater fishing in the New England region. Significant losses of cold-water species would occur if climate change results in loss of cold-water habitats. Just as recreational freshwater fishing would be compromised by climate change, so too would recreational and commercial coastal fishing.

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.

Stream flow in the region also would be affected but is much harder to project than changes in temperature. 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, causing floods in the spring, eggs could be destroyed and food availability reduced.

Coping Strategies

Three strategies are available to cope with the effects of climate change on sea-level rise in the Northeast: to retreat from advancing seas, accommodate changes imposed by a higher sea level, or protect areas/structures from sea level rise. All three coping strategies could

The increase in lobster could provide an economic benefit…

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. 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.

Few strategies are now available to anglers and those in the fishing industry to cope with potential impacts of climate change. Climate change impacts will vary stream by stream, depending on whether and how stream flow is affected. However, one strategy is to fish for alternative species. Fisheries managers also could shift stocking patterns in favor of more cool and warm-water fish species. Education might increase the perceived attractiveness of cool and warm water species as well.

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. Winter flounder accounted for half of the total income earned by coastal fishermen in one New England port, but now provides them with no significant income. Lobster catches however, are on the increase. The increase in lobster could provide an economic benefit, but fisheries will have to work to create market demand for the other newly established fish and shellfish populations, which will change with the climate.

Information Needs and Data Gaps

The following information needs and data have been identified.

1. A regional geographic information system (GIS) for monitoring and characterizing land cover and land use change over time is needed;
2. A resurrection of the NASQAN program is needed — a national effort to monitor water quality across the country;
3. More studies need to be developed to estimate the percent of the total load in the region that could be from various sources, both natural and anthropogenic, based on the watershed information and GIS data gathering;
4. A regional water quality model for the New England region must be developed;
5. An improved understanding of the role that the NAO plays in regional weather is needed;
6. Improved understanding about cause and effect relationships that determine variability in regional temperatures and precipitation;

CASE STUDY 1

The 1960's Drought in New England and New York

by S. Lawrence Dingman

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 and 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 it.

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). Streamflows and ground-water levels were near or below their historical lows in a swath extending from the Massachusetts and New Hampshire coasts southwestward into West Virginia. The accumulated streamflow deficiency in central Massachusetts between 1961 and mid-1966 was equivalent to two years of normal runoff.

Because water-supply systems in the northeast were generally designed to be adequate in a repitition 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 suppliers were experiencing critical water shortages.

The exteremely low flows caused water-quality problems in addition to the landward migraton 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 harmful algal blooms in lakes and reservoirs and produced taste and odor problems in some municipal water supplies.

Figure 6.1 Accumulated precipitation deficiency from October 1961 to December 1965.

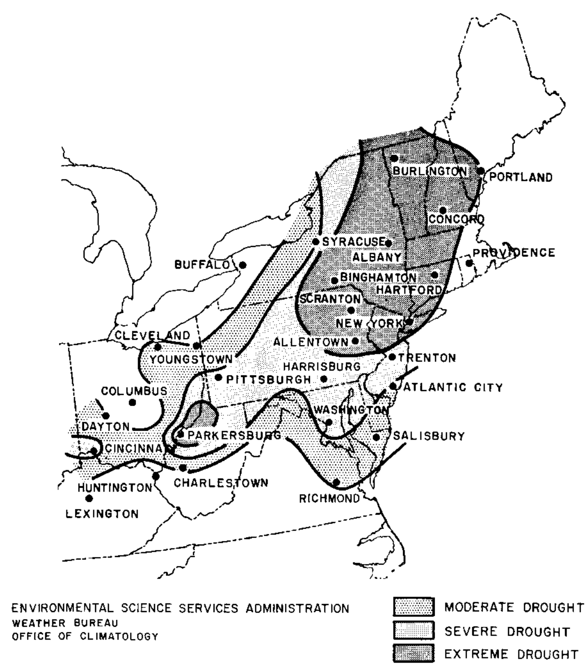

Figure 6.2 Summer of 1965 showing extreme drought conditions over 60,000 square miles with severe drought covering an additional 60,000 miles.

The 1960s drought 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.

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 southeastern New York and southern New England.

The 1960s drought 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 New England-New York region has experienced at least nine periods of widespread meteorologic and hydrologic 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.

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. The smoothed data, with an 11-month moving average of the normalized values are plotted 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 has been 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).

Periods of high and low streamflows in various regions of the United States were compared to El Nino and La Nina, respectively, for the period 1945-1990. 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. The significant drought of 1999 occurred during La Niña conditions. 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.

The region has experienced significant multi-year droughts approximately once a decade in this century. Because of increased development in the last 30 years and resulting limitations on water supply that have emerged in many parts of the region, it is clear that a future drought approaching the 1960s severity, extent, and duration would have severe economic and environmental consequences. We must develop a better understanding of relationships between such events and atmospheric indices that can predict drought with some reliability.

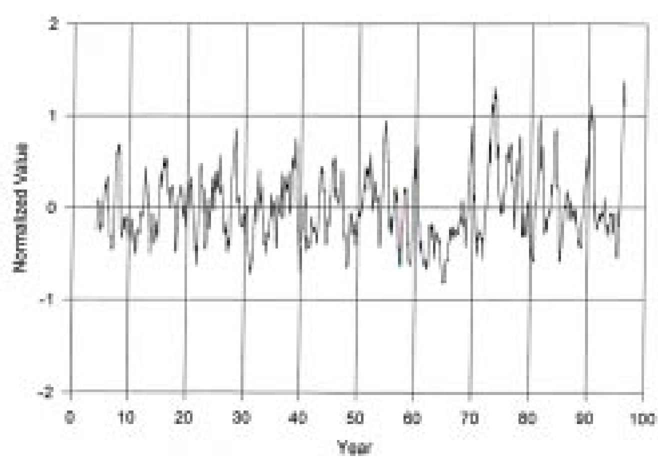

Figure 6.3 11-month moving average of the normalized montly flow values.

CASE STUDY 2

Effects of Warming on Snow at the Hubbard Brook Experimental Forest

by C. A. Federer

A hydrologic model that simulates snow accumulation and melt was 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 2˚C/3.6˚F. Snowpack is defined as the snow water equivalent.

BROOK90 Model

BROOK90 is designed to study the processes of evapotranspiration and soil water movement at a point, with some provision for streamflow generation by different flow paths. 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. 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/0.9°F in this study, and all rain if the minimum temperature (Tmin) is above this.

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/50°F mean temperature, for instance, 45 mm/8 in. of snow water equivalent will melt to liquid water.

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 (figure 6.4). Data used in this publication were obtained by scientists of the Hubbard Brook Ecosystem Study.

For this case 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). For the south slope, daily minimum and maximum temperatures from Station 1 were decreased by 0.6°C/1.1˚F 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. For the north slope simulated snowpack was compared with the average snowpack from Station 17 at 893 m (2930 ft.) and Station 19 at 610 m(2001 ft.). For the south slope data were available from 1958 through 1999, and for the north slope from 1965 through 1999.

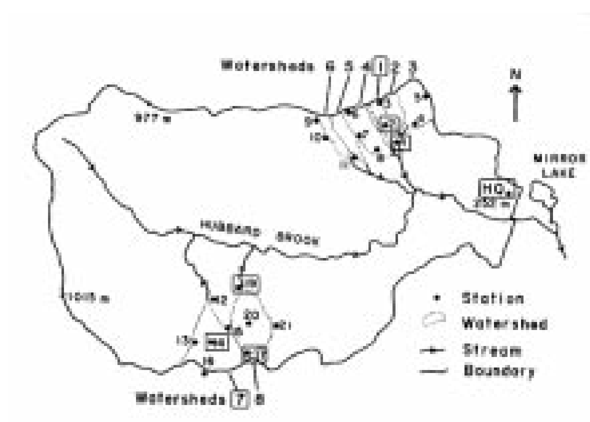

FIGURE 6.4 The Hubbard Brook Experimental Forest, with locations used in this study indicated by rectangles.

Results clearly reflect the high frequency of low snow years in the 1980's and 1990'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.

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 (6.6 ft.) 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/3.6˚F.

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.

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

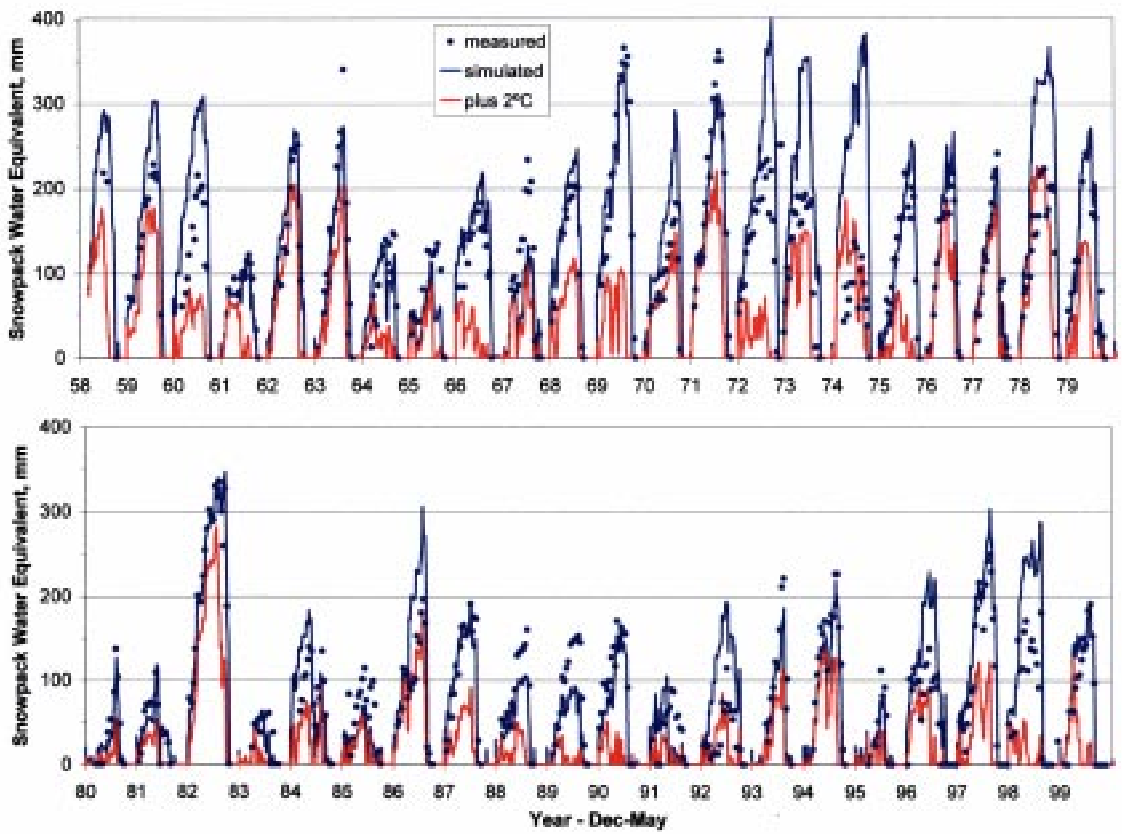

FIGURE 6.5 Simulated (blue line) and measured (blue points) snow water equivalent for a south-facing slope at 560 m elevation on the Hubbard Brook Experimental Forest, New Hampshire, and simulated water equivalent with a 2° C warmer climate (red line). Year is indicated at the beginning of the winter.

Simulated increase in minimum and maximum daily temperatures of 2° C/3.6° F produces a major reduction in snowpack in all years (Figures 6.5 and 6.6). Average February snowpack water equivalent was reduced from 161 to 76 mm (6.3-3.0 in.) for the south-facing slope and from 194 to 133 mm (7.6-5.2 in.)on the north-facing slope. February was chosen to best represent mid-winter snowpack.

Discussion

An increase of all winter temperatures by 2°C/3.6° F 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 (3.3 in.) or 53%; for a north-facing slope at 2400 feet the reduction is 61 mm (2.4 in.)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.

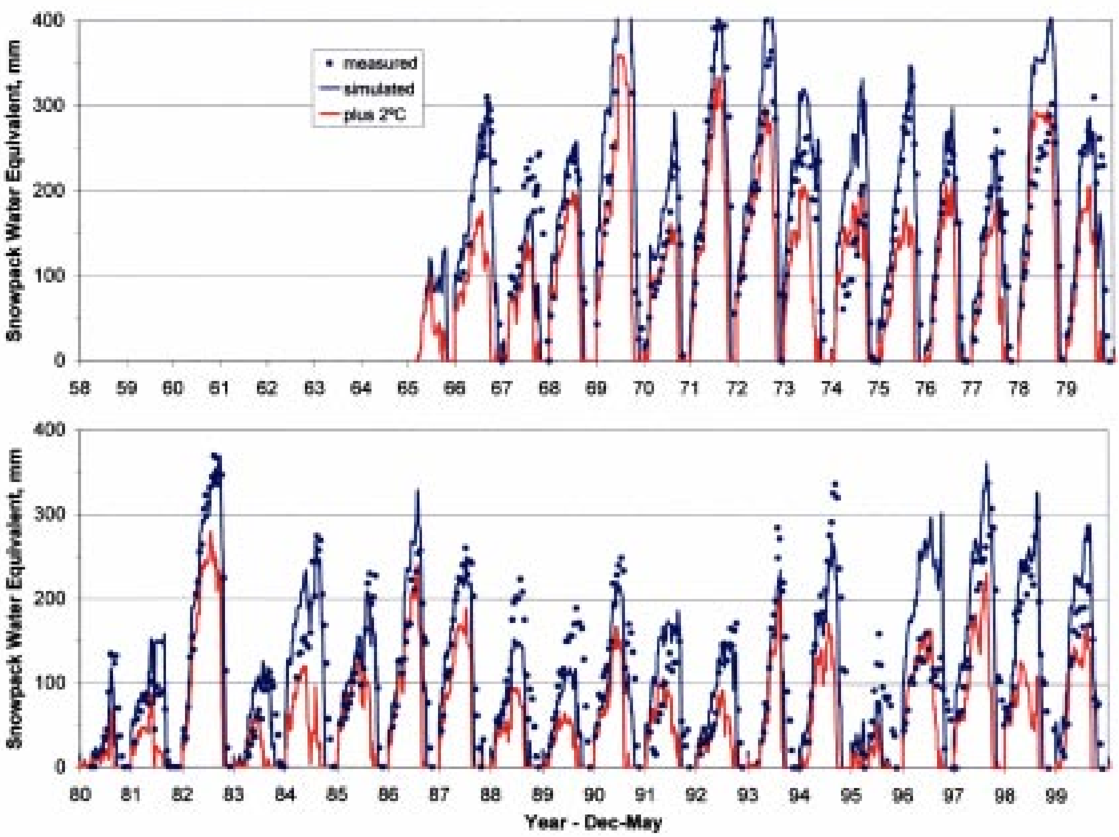

FIGURE 6.6 Simulated (blue line) and measured (blue points) snow water equivalent for a north-facing slope at 730 m (24oo ft.) elevation on the Hubbard Brook Experimental Forest, New Hampshire, and simulated water equivalent with a 2° C/3.6˚F warmer climate (red line). Year is indicated at the beginning of the winter.

...in New Hampshire the cross-country skiing and snowmobile industries will be even more severely impacted than the ski industry and may become non-existent by 2100.

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°- 5.4°F 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 (17.0 - 14.2 in.). This is comparable to the average reduction in February snowpack of 73 mm (2.9 in.) for a 2°C/3.6°F 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 (3.6°F) 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.

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. Researchers have found that a 2°C (3.6˚F) warming will raise the minimum elvation of ski area profitability by 500 m (1640 ft.) in Switzerland. Due to these elevational differences, in New Hampshire the cross-country skiing and snowmobile industries will be even more severely impacted than the ski industry and may become non-existent by 2100.

CASE STUDY 3

The Relationship Between the Winter North Atlantic Oscillation (NAO) Index and Streamflow

by James A. Bradbury

Winter streamflow 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. 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) streamflow teleconnection.

Drought in the New England Region

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. Naturally, the low precipitation levels were accompanied by low levels of streamflow (hydrologic drought) in rivers all over the seven states, causing 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.

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, streamflow… etc.) with indices for large-scale atmospheric circulation patterns, such as the NAO index (Figure 6.7). Modelers have had success at long-range forecasting with the El Niño/Southern Oscillation (ENSO), where the intricate coupling of the Pacific ocean and associated atmospheric variables has allowed for its predictability, with moderate success on seasonal and annual time scales. 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.

The North Atlantic Oscillation (NAO) Index

Winter weather patterns throughout the North Atlantic region have historically been greatly affected by changes in the NAO. 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, 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, and most research related to the NAO involves winter climate data analysis.

The NAO and North Atlantic Region Teleconnections

Many climate researchers consider ocean and atmospheric variability in the North Atlantic region to be an important index for global climate change. When the NAO is in its positive index mode the Icelandic low tends to be at its furthest point north, and mid-latitude westerlies onto Northern Europe increase driving warm, moist air as far east as Siberia (Figure 6.7, top). During the negative index mode the Icelandic low is much weaker and sits farther southwest, centered between the southern tip of Greenland

Our understanding of how the NAO affects winter climate in the New England region is becoming increasingly clear.

and Newfoundland, causing a "blocking" of the Jet Stream and meridional air flow across the N. Atlantic region (Figure 6.7, bottom). In the negative NAO mode, southern Europe is known to experience more frequent cyclonic activity, leaving northern Europe relatively cold and dry.

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 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 and jet stream patterns along the eastern seaboard show important links to the NAO system. Significant changes in sea surface temperatures (SST) off the New England coast have been found when compared with conditions during extreme NAO events. Statistical evidence for an inverse relationship has been found between regional snowfall and the NAO winter index. This means that New England winters characterized by a positive NAO index have less snowfall than winters characterized by a negative NAO index. Streamflow amounts however are above average when the winter NAO index is positive.

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 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 and (as a result) greater regional snowfall.

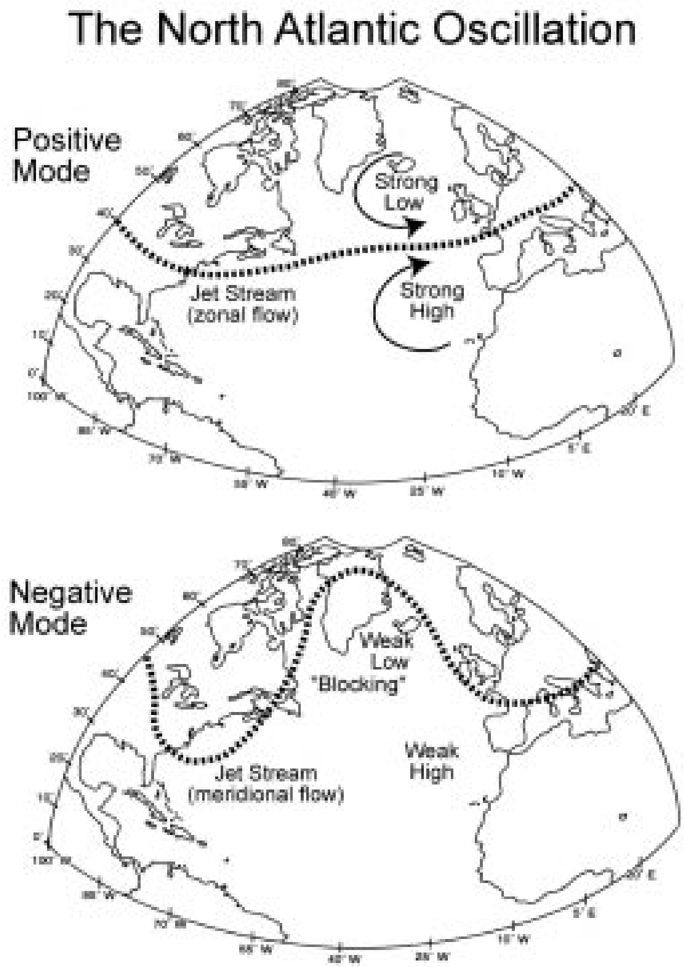

FIGURE 6.7 The positive (top) and negative (bottom) phases of the North Atlantic Oscillation (NAO). During positive NAO winters, the atmospheric pressure gradient between Iceland and the Azores is at a maximum and the mid-latitude westerlies dominate air circulation in the N. Atlantic region. During 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.

… winters characterized by below average snowfall are characterized by above average streamflow.

NAO and NE Winter Streamflow

Current research comparing streamflow rates in the New England region with the North Atlantic Oscillation (NAO) index has revealed positive statistical correlations. Time series of streamflow from the U.S. Geological Survey Hydro-Climatic Data Network are significantly correlated with the NAO index, and the strongest NAO/ streamflow 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 streamflow in the White River, VT and the winter NAO index. Thus, winters characterized by below average snowfall are characterized by above average streamflow.

A physical mechanism other than precipitation, or temperature driven snowmelt, must be found to explain the NAO/ streamflow correlation. Interestingly, streamflow 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/ streamflow teleconnection could be the winter snowfall variability attributed to the NAO. Since the temporal distribution of winter streamflow in the region is significantly affected by the proportion of precipitation that falls in the form of snow, rather than rain, a winter with greater snowfall would be expected to have lower average streamflows 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.

The NAO may be most closely associated with longer-term trends in regional climate, rather than just annual variability. Figure 6.9 tells a similar story.

The winter NAO exhibits a strong correlation with winter average streamflow, when both records are smoothed. 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

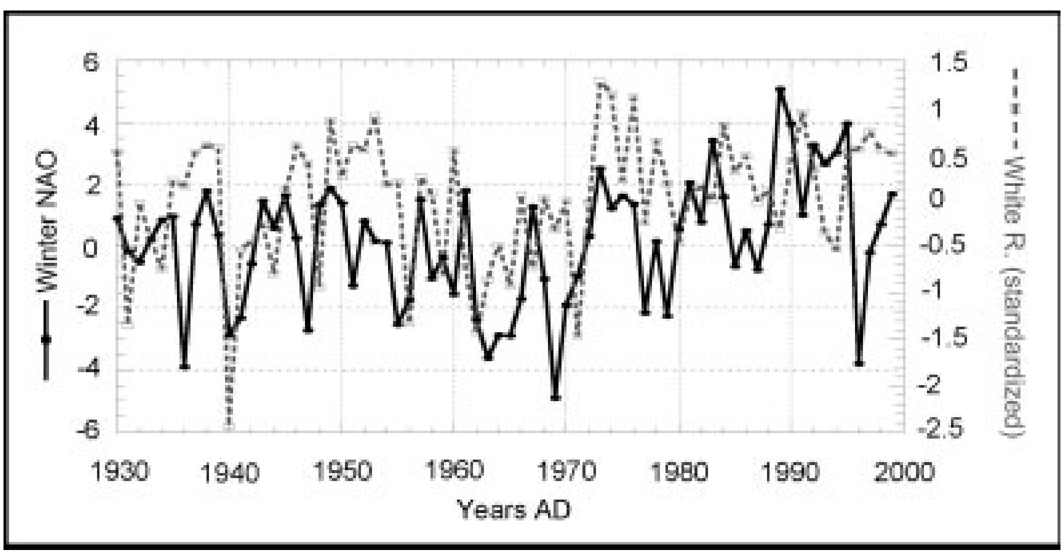

FIGURE 6.8 Time series plots of the winter NAO and standardized winter average streamflows for the White River in Eastern Vermont (R^2=0.092; alpha level =0.10).

The NAO may be most closely associated with longer-term trends in regional climate, and less so with annual variability.

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.

Conclusions

Winter climate in the New England region shows subtle yet important teleconnection 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, possibly resulting in the NAO regional streamflow association identified here. The results of this study also reveal a significant long-term effect of the NAO on New England regional streamflow (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. 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 studies which attribute the persistence of this drought to the below average air temperatures, as well as below average SSTs, throughout the east coast region (both of these conditions are associated with a negative NAO, see table 1).

The NAO streamflow teleconnections (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.

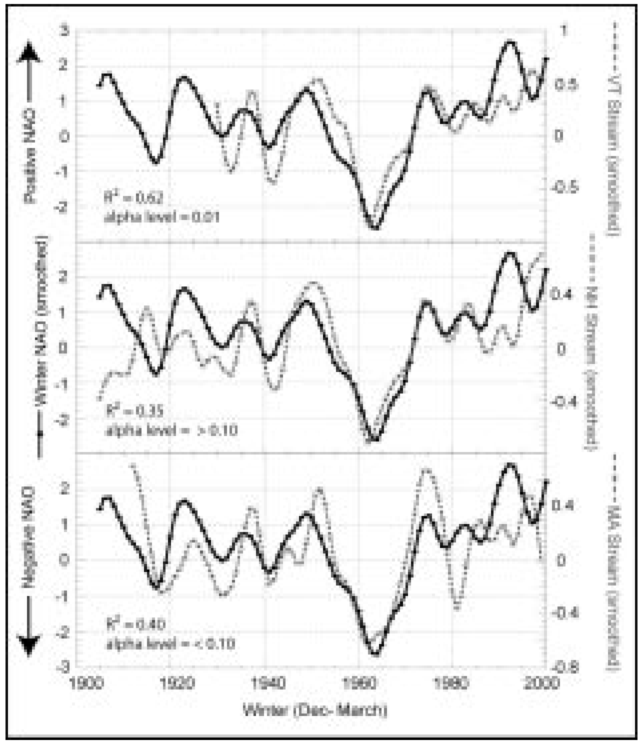

FIGURE 6.9 Standardized winter streamflow at the White River, VT (top), the Pemigewasset River, NH (middle), and a combination of the North and Westfield Rivers, MA (bottom) were smoothed and compared with a smoothed NAO index, revealing comon trends in their long-term variability.

CASE STUDY 4

Climate Variability and Winter Flounder Abundance in Southern New England

by Henry Walker

Between 1960 and 1990, the winter sea water temperature in Narragansett Bay warmed by almost 3°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.

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. 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. 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?

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 (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,* 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. 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 (28.6˚F). In comparison, most fish typically freeze at a temperature of -0.7° C (30.7˚ F). 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. It appears that a significant component of the decline in

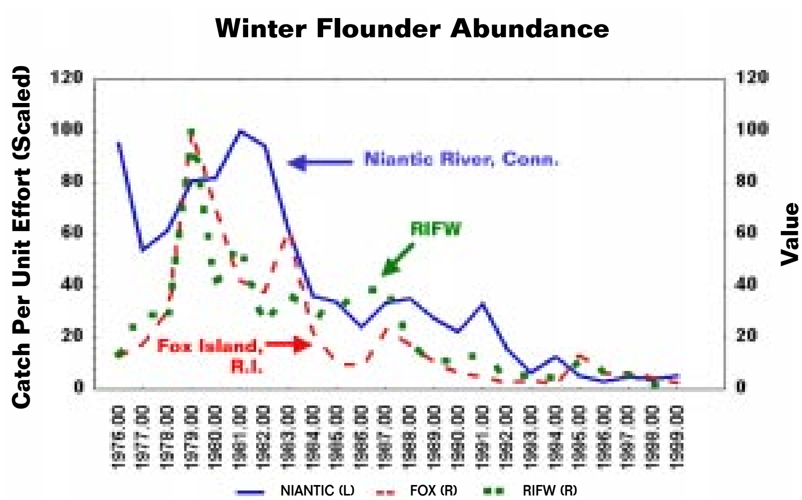

FIGURE 6.10 Abundance of winter flounder determined by the Rhode Island Fish and Wildlife service (RIFW) and others in the Niantic River and at Fox Island.

A series of warm winters such as we have recently experienced in southern New England is clearly unfavorable for winter flounder.

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. 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. 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 0.4˚ C (0.7º F) over the past century (since 1895), due to its coastal location, Rhode Island's annual temperature has warmed by 1.3˚ C (2.3º F) over the same period of time. Warming during the winter months (December, January, February) in Rhode Island has increased a full 1.7˚ C (3.0º F) since 1895.

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."

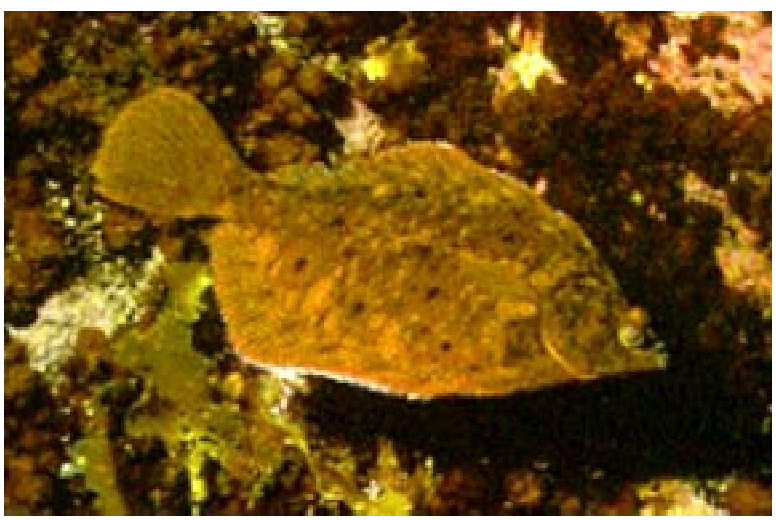

FIGURE 6.11 The winter flounder